A GLOBAL METHODOLOGY FOR REACTIVE POWER MANAGEMENT AND VOLTAGE CONTROL IN POWER SYSTEMS

by

Luiz Danilo Barbosa Terra

AUGUST 1989

A thesis submitted for the degree of Doctor of Philosophy of the University of London and for the Diploma of Membership of the Imperial College.

Department of Electrical Engineering
Imperial College,
London, S.W.7.

ABSTRACT

A review of steady-state reactive power (var) management and voltage control problems in power systems has been carried out. This review has enabled overlap, duplication and deficiencies in the existing approaches to be identified and priorities for action to be determined to improve system security. As a result a new methodology has been developed to provide a global framework for var management and voltage control in power systems planning and scheduling.

A unique approach has been devised to the solution of the security-constrained preventive and corrective var scheduling problems. This approach takes advantage of the special structure of these problems to achieve significant gains in computational efficiency and reductions in computer memory requirements. The set of equations, composed of the base case and specified contingencies, is partitioned in such a way that a dynamic set of the most sensitive control variables is associated with each contingency. A parallel processing scheme produces the required solution.

The formulation of the problems and the development of the specialized solution algorithms make use of Optimal Power Flow, Linear Programming, Sensitivity Analysis, Clustering and Hierarchical Decomposition and Coordination techniques. Difficulties arising in applying existing load flow methods for var oriented contingency screening, security assessment, sensitivity analysis and optimisation have motivated a comparative study of the subject, eventually leading to (a) the development of three var-only load flow algorithms, (b) the development of a contingency selection program, (c) the

development of techniques and procedures to determine effectiveness of control variables in contingency situations and (d) the development of an optimal var-only load flow algorithm.

The application of the above methodology is demonstrated by numerical testing on power systems of different sizes and characteristics. Additionally, the computational experience has been reported, as well as comments on a number of computational options and suggestions for future work. Finally, aiming to provide an efficient way of reproducing realistic operational planning problems for educational, training and research purposes, a personal microcomputer educational package has been created.

ACKNOWLEDGEMENTS

This project was conducted under the supervision of Dr M.J. Short, whose constant support proved invaluable. The encouragement of Dr. B.J. Cory, head of the Energy and Power System Group, throughout the project is acknowledged.

Acknowledgements are due to CAPES of Brasil and Universidade Federal de Minas Gerais for their financial support, to Pontificia Universidade Catolica de Minas Gerais and Centro Federal de Educacao Tecnologica de Minas Gerais for leave of absence, and to the Committee of Vice-Chancellors and Principals of the Universities of the United Kingdom for having awarded me the ORS-Award for three consecutive years.

It has been a great pleasure working with Dr. Ricardo B. Prada, of PUC-RJ, who contributed a great deal of his time towards the discussion of various topics. Other people whose assistance has been quite invaluable to me, include Dr. R.B.I. Johnson during the early stages of this project, and Mr. M.W. Rowe during the preparation of the manuscripts.

I have received assistance from a great many people during the four years while I was working in this project, and for this I am extremely thankful.

I dedicate this work to Bruno, Tais, Cassio and Gilda.

CONTENTS

		Page
Chapter 1	Bibliographical Review	15
1.1	Introduction	15
1.2	Preliminary Considerations	16
1.3	Should We Include VAR/Voltage Control in Control Centres?	18
1.4	Need for a New Approach for VAR/Voltage Control	19
1.5	Some Reasons for the Increase of VAR Problems	20
1.6	Operator's Responsibility	20
1.7	Failure of Communication Between the Operating and Planning Personnel	21
1.8	Reactive Power Scheduling, Practices and Tendencies	21
1.9	Reactive Power Shortage/Surplus, Breakout, Load Shedding	23
1.10	Hierarchical Classification of VAR/Voltage Control	23
1.11	Present Techniques of System of Voltage Control	25
1.12	Planning Criteria and Solution Methods	26
1.13	Similarities Between Planning, Operational Planning and Operational Studies	28
1.14	Desired Future Voltage Control Scheme	30
1.15	Conclusions	32
Chapter 2	Global Framework - Conceptual Design	33
2.1	Introduction	33
2.2	VAR/Voltage Optimisation and Potential Accident Analysis	33
2.3	Security Decisions and Security Functions	37
2.4	Security Functions from a VAR/Voltage Viewpoint	39
2.5	Corrective Versus Preventive Strategy	44
2.6	The Global Framework	47
2.7	Conceptual Model, Software System	51

page

Chapter 3 VAR-Oriented Load Flow Model 55

3.1 Introduction 55

3.2 Problem Formulation 56

3.3 Methods of Solution 58

3.4 Comparative Study 66

3.5 The Physical Interpretation of the CRIC 88

3.6 E&PSG - A Novel Load Flow Algorithm 95

Chapter 4 VAR/Voltage Contingency Analysis 109

4.1 Introduction 109

4.2 Contingency Analysis Stages 110

4.3 Contingency Selection Techniques 112

4.4 E&PSG Contingency Selection Technique - The Basic Model 128

4.5 E&PSG Contingency Selection Improvements on the Basic Model 142

4.6 E&PSG Contingency Selection - Further Developments 150

4.7 A New Compensation Technique 158

4.8 Final Evaluation of the New Methodology 175

4.9 E&PSG Contingency Evaluation 181

Chapter 5 VAR Optimal Power Flow 189

5.1 Introduction 189

5.2 Preliminary Considerations 190

5.3 The Background of Previous Work 194

5.4 The Model of this Thesis 200

5.5 Optimal Step Length 207

5.6 Application of the Methodology 217

page

5.7 Adaptive Limit Enforcement - An Innovative Feature 222

5.8 Numerical Results and Comparisons 225

Chapter 6 Reactive Power Expansion Planning 241

6.1 Introduction 241

6.2 Modelling the New VAR Sources to be Added to the System 242

6.3 Sensitivity of the System Performance with Respect to the Variables and Parameters 244

6.4 Hierarchical Methodology of Solution 248

6.6 Demonstrative Examples 251

Chapter 7 Security-Constrained Reactive Power Dispatch 263

7.1 Introduction 263

7.2 Background 263

7.3 Formulation of the Problem 265

7.4 Methodology of Solution 267

7.5 An Example 280

7.6 Numerical Results and Comparisons 291

7.7 Conclusions 302

Chapter 8 Conclusions 303

References 309

Notation 321

Appendix A E&PSG - A Software Environment for Power Systems Security Analysis and Optimisation 325

Appendix B Network Test Systems 354

LIST OF FIGURES

Fig.		Page
1.1	Practices in VAR Scheduling	25
1.2	The way studies are performed	29
2.1	Power System Planning and Operational Planning Environment	35
2.2	Potential Accident Analysis	37
2.3	The State Transition Diagram	38
2.4	VAR/Voltage Security-Related Decisions	41
2.5	Base Case Intact System	44
2.6	Contingency Case - Outage of Line 2	44
2.7	Corrective Versus Preventive Strategy	45
2.8	Voltage Control Scheme - Conceptual Model	48
2.9	Software System Diagram	52
3.1	Compensation Schemes for High r/x Branch Ratios	60
3.2	Load Flow Test Program Flow Chart	67
3.3	Newton/Raphson Load Flow Algorithm	67
3.4	CRIC Load Flow Algorithm	68
3.5	Decoupled Load Flow Algorithm	69
3.6	Fast Decoupled Load Flow Algorithm	70
3.7	Maximum Mismatch Reduction Rates IEEE 14-Bus Test System - Base Case	76
3.8	Two-Busbar System	89
3.9	Two-Bus System - Active Power Versus Angle	91
3.10	Two-Bus System - V_i V_j Versus Angle	92
3.11	Generalized Branch	93
3.12	False Slack Busbar (FS)	101

Fig.		page
3.13	E&PSG Load Flow Algorithm	104
3.14	Fast E&PSG Load Flow Algorithm	105
4.1	Performance Indices - IEEE 30-Bus Test System	134
4.2	E&PSG Contingency Selection - Basic Algorithm	135
4.3a	Cumulative Relative Frequency (e_1%)	
	E&PSG Contingency Selection - Basic Algorithm	138
4.3b	Cumulative Relative Frequency (e_∞%)	
	E&PSG Contingency Selection - Basic Algorithm	139
4.3c	Frequency Histogram (e_1%)	
	E&PSG Contingency Selection - Basic Algorithm	140
4.3d	Frequency Histogram (e_∞%)	
	E&PSG Contingency Selection - Basic Algorithm	141
4.4a	Cumulative Relative Frequency (e_1%)	
	E&PSG Contingency Selection - Version 1	146
4.4b	Cumulative Relative Frequency (e_∞%)	
	E&PSG Contingency Selection - Version 1	147
4.4c	Frequency Histogram (e_1%)	
	E&PSG Contingency Selection - Version 1	148
4.4d	Frequency Histogram (e_∞%)	
	E&PSG Contingency Selection - Version 1	149
4.5	IEEE 30-Bus Test System	
	System-wide effects of branch 1 outage	156
4.6	VAR Compensation Scheme	161
4.7a	Cumulative Relative Frequency (e_1%)	
	E&PSG Contingency Selection - Version 2	171
4.7b	Cumulative Relative Frequency (e_∞%)	
	E&PSG Contingency Selection - Version 2	172

Fig.		page
4.7c	Frequency Histogram (e_1%) E&PSG Contingency Selection - Version 2	173
4.7d	Frequency Histogram (e_∞%) E&PSG Contingency Selection - Version 2	174
4.8a	Box-and-Whisker Plot-Unit Norm Percent Error e_1%	176
4.8b	Box-and-Whisker Plot-Infinite Norm Percent Error e_∞%	177
4.9	Representation of the Voltage Control	183
5.1	Steepest Descent Algorithm	205
5.2	Main Phases of the Optimisation Process	222
5.3	VAR Output and Voltage Limits at PV Buses	224
5.4	Flow Chart of the Adaptive Limit Enforcement Optimisation Algorithm	227
7.1	Security-Constrained VAR Dispatch Strategy	268
7.2	Subsystem Interaction	275
7.3	Coordination-Decomposition Scheme	276
7.4	6-Bus System	280
7.5	PI - Initial Values	282
7.6	Reduction of the Objective Function Values	286
7.7	Decomposition/Coordination Data Flow	287
7.8	IEEE 30-Bus Test System - The Worst Case List	293

LIST OF TABLES

Table		Page
1.1	Number of Utilities Surveyed per Country	22
1.2	Practices in Reactive Power Scheduling	22
1.3	Hierarchical Structure of Control of VAR/Voltage	24
1.4	Timescale and Aims of Reactive Power Studies during the Planning Phase	26
1.5	Timescale and Aims of Reactive Power Studies during the Operational Planning and Operational Phases	28
2.1	The Modern Power System Control Centre Functions	39
2.2	System States from a VAR/Voltage Viewpoint	40
3.1	Test #1 - Ward Hale 6-Bus Test System Effect of the Branch Resistance on the Iteration Rate	72
3.2a	Test #1 - Ward Hale 6-Bus Test System Base Case Results - Busbar Status	73
3.2b	Test #1 - Ward Hale 6-Bus Test System Base Case Results - Branch Flows and Losses	73
3.3a	Test #1 - Ward Hale 6-Bus Test System (R/Ro=3.5) Case Results - Busbar Status	73
3.3b	Test #1 - Ward Hale 6-Bus Test System (R/Ro=3.5)Case Results - Branch Flows and Losses	74
3.4	Ward Hale 6-Bus Test System Rate of Convergence for the (R/Ro=3.5) Case	74
3.5	Test #2 - IEEE 14-Bus Test System Effect of the Branch Resistance on the Iteration Rate	75
3.6a	IEEE 14-Bus Test Test System - Base Case Results Busbar Status	77
3.6b	IEEE 14-Bus Test System Base Case Results - Branch Flows and Losses	77
3.7a	Test #2 - IEEE 14-Bus Test System (R/Ro=4.0)Case Results - Busbar Status	78
3.7b	Test #2 - IEEE 14-Bus Test System (R/Ro=4.0) Case Results - Branch Flows and Losses	79
3.8	IEEE 14-Bus Test System Rate of Convergence for the (R/Ro=4.0) Case	80
3.9	Test #3 - IEEE 14-Bus Test System Effect of the Loading on the Iteration Rate	81
3.10a	IEEE 14-Bus Test System (S/So=3.5) Case Results - Busbar Status	82

Table		page
3.10b	IEEE 14-Bus Test System (S/So=3.5) Case Results - Branch Flows and Losses	82
3.11	IEEE 14-Bus Test System Rate of Convergence for the (S/So=3.5) Case	83
3.12	Test #4 - CEMIG 32-Bus Test System Effect of the Branch Resistance on the Iteration Rate	84
3.13	CEMIG 32-Bus Test System - Busbar Status	85
3.14	CEMIG 32-Bus Test System - Branch Flow and Losses	86
3.15	CEMIG 32-Bus Test System - Rate of Convergence	87
3.16	E&PSG Load Flow Performance	107
3.17	Computer Time Requirements for Modern Power System Control Centres	108
3.18	E&PSG Load Flow Program Current Capabilities	108
4.1	Typical Performance Index Output	133
4.2a	Voltage Magnitude PI Accuracies, IEEE 30-Bus Test System E&PSG Contingency Selection Basic Algorithm	137
4.2b	Frequency Distribution of the Unit Norm Percent Error (e1%)-E&PSG Contingency Selection Basic Algorithm	138
4.2c	Frequency Distribution of the Infinite Norm Percent Error (e_∞%)-E&PSG Contingency Selection-Version 1 Algorithm	139
4.3a	Voltage Magnitude PI Accuracies, IEEE 30-Bus Test System E&PSG Contingency Selection-Version 1 Algorithm	145
4.3b	Frequency Distribution of the Unit Norm Percent Error (e_1%)-E&PSG Contingency Selection-Version 1 Algorithm	146
4.3c	Frequency Distribution of the Infinite Norm Percent Error (e_∞%)-E&PSG Contingency Selection-Version 1 Algorithm	147
4.4	Accuracy Comparison between E&PSG Contingency Selection Algorithms	150
4.5	Effects of Branch Outages on the Bus Reactive Power Mismatch and Voltage Variation Vectors	155
4.6a	Voltage Magnitude PI Accuracies, IEEE 30-Bus Test System E&PSG Contingency Selection-Version 2 Algorithm	170
4.6b	Frequency Distribution of the Unit Norm Percent Error (e_1%)-E&PSG Contingency Selection-Version 2 Algorithm	171
4.6c	Frequency Distribution of the Infinite Norm Percent Error (e_∞%)-E&PSG Contingency Selection-Version 2 Algorithm	172
4.7	Frequency Distribution of e_i-IEEE 57-Bus Test System	179

Table		page
4.8	IEEE 118-Bus Test System The Worst-Case-List	180
4.9	E&PSG Contingency Selection Computing Time	181
5.1	Optimisation Results-Number of Iterations and Weights	218
5.2	Optimisation Results for the IEEE 14-Bus Test System	219
5.3	Adaptive Limit Enforcement Optimisation Algorithm Description of the Computing Subroutines	226
5.4	Adaptive Limit Enforcement Optimisation Method Number of Iterations and Computing Times	228
5.5aI	Optimisation Results for the IEEE 30-Bus Test System Before Optimisation	232
5.5aII	Optimisation Results for the IEEE 30-Bus Test System After Optimisation	233
5.5bI	Optimisation Results for the IEEE 39-Bus Test System Before Optimisation	234
5.5bII	Optimisation Results for the IEEE 39-Bus Test System After Optimisation	235
5.5cI	Optimisation Results for the IEEE 57-Bus Test System Before Optimisation	236
5.5cII	Optimisation Results for the IEEE 57-Bus Test System After Optimisation	237
5.5dI	Optimisation Results for the IEEE 118-Bus Test System Before Optimisation	238
5.5dII	Optimisation Results for the IEEE 118-Bus Test System After Optimisation	238
5.6	Comparison of the New Methodology	229
6.1	Optimisation Results - Voltage Profiles and Output of VAR Sources	258
6.2	Variables at their Limits and Transmission Losses	259
6.3	VAR Expansion Results	259
7.1	Busbar Data	281
7.2	Intact System Initial Values	281
7.3	Subsystem Optimisation Results	285
7.4a	LP Results	288
7.4b	LP Results for $\Delta V_3^{max}=0.0356$	289
7.5	Performance Index (K=6 Preventive Secure)	290
7.6	Intact System Final (Preventive) Results	291

Table		page
7.7	Expansion Plan for Contingency 7	291
7.8	Worst-Case-List Insecurity Summary	294
7.9	Final Results (WCL 4-Preventive/1-Corrective)	295
7.10	Subsystem Optimisation - IEEE 30-Bus Test System	298
7.11	Performance Index (After Security Enhancement) Results	299
7.12	Security Enhancement Results	300

CHAPTER 1

BIBLIOGRAPHICAL REVIEW

1.1 INTRODUCTION

This thesis is the result of an investigation of the need for a global approach to voltage/var studies for use in planning, operational planning and control of electrical power systems.

The convenience of adopting a new methodology in var/voltage control is briefly discussed as a tool which increases security while avoiding loading additional burdens on the operators when performing var/voltage monitoring, scheduling and control.

A short description follows of what is meant by voltage control, var scheduling and planning. An integrated system of software for monitoring and control of voltage and var scheduling is conceived and discussed in detail, particularly focussing on strategies which are for various reasons more advanced and more appropriate than others.

Problems arising in the inclusion of var scheduling in the operation of electrical power system are outlined. It is concluded that using var optimization with economical objectives, on-line, so as, for instance, to minimise cost of operation, is neither feasible nor desirable, at least at present. A method which guarantees feasible computation of control actions to be taken to remedy the voltage problems resulting in a section of a system because of a disturbance would be a sufficient objective for on-line applications.

A great aid in power system planning would be the conception of software which can be used to analyse the problems that may arise and generate pseudo-solutions which take into account and reflect the daily experience of the operator. This will eventually allow the

building of an expert system. A method which encompasses such needs has been devised and is presented. As well as a global framework for reactive power planning and scheduling, a var security assessment methodology was designed. This includes developments of several techniques ranging from fast contingency screening to non-linear optimal power flow. Hierarchical coordination and decomposition techniques are used.

A list of reactive power topics for inclusion in future developments is appended. Some considerations about difficulties with the existing simplified load flow methods, as well as a comparative study on this subject, are also reported.

A package of load flow programs including decoupled, fast decoupled, complete Newton and Carpentier methods have been developed and annexed. In particular, as a by-product of this research, an interactive contingency analysis system of software for IBM PC microcomputers has been developed based on var-oriented load flow methods. This is intended to be used for educational purposes.

1.2 PRELIMINARY CONSIDERATIONS

In 1978 T. DyLiacco [1] estimated that the Operating Functions in use by control centres until 1978 were Supervisory Control (SC), Automatic Generation Control (AGC) and Economic Dispatch (ED). Maintenance of security (SA) was adopted from 1978 on, while Automatic Control of System Voltage (ACV) was not then a common practice. In 1981, another review paper by Talukdar and Wu [2] reckoned that the situation then remained practically the same. At present, although there have been plenty of reported needs for such a methodology, the situation does not seem to be radically altered, as

far as can be deduced from recent publications describing new tools and facilities in control centres installed recently [3,4,5]. Many people are sceptical about the immediate possibilities of implementation of such schemes. Bistrom and Lindstrom [5], for instance, wrote:

"The literature was full of optimistic descriptions of load flow (LF), economic dispatching (EDC), state estimation (SE) etc. Within Europe, especially in our own neighborhood, very little was really in operation."

However, in a most recent event, 1987 Power Industry Computer Application Conference (PICA 87), held in Montreal, Canada in May'87, all articles in the section "Energy Management Systems", in which advances in control centres were reported, related that in one way or another, automatic voltage control either has recently been implanted or has been under development. In the following, these are summarized. Griffith et al. [6] described the last software module which was installed by the Gulf States Utilities Company. This software is a Constrained Dispatch (CONSDIP) which runs on a set time cycle or every time the State Estimator provides a new state of the system. The program was said to be used only to alleviate or recommend corrective actions. The objective, when limit violation occurs, was to adjust variables that are directly controllable by the operator. It was also said that actions to adjust generation limits could be enabled by the operator or preset to work automatically after CONDISP ran. Trefny et al. [7] reported various newly implemented functions in the new Houston Lighting & Power Co. control centre, including among others, Security Constrained Dispatch and Voltage Control. Beltran et al. [8] reported implementation of a new program for monitoring and automatic bus voltage control which would

permit EDELCA's Regional Load Dispatch Office to remotely control Mvar generation for each HV busbar. Wrubel and Hoffman [9] reported that the new Newark-Public Service Electric and Gas Co. EMS would be provided with a software feature for which anticipated future uses include implementing control parameters recommended by Optimal Power Flow (OPF) programs - as for example changing transformers tap positions, and controlling the terminal voltages on generators.

1.3 SHOULD WE INCLUDE VAR/VOLTAGE CONTROL IN CONTROL CENTRES?

Reactive power/voltage control is considered by some authorities to be probably the most significant advance in power system security in modern times; it is thought that it will have a major effect on preventing breakout[1] and will influence the service continuity of the bulk power system in the next decade. The huge number of research publications and actual development projects in industry attempting to resolve var/voltage monitoring and control give strong evidence of this. Some of these new development projects are briefly cited in the following for reference purposes. The method presented in [10] is claimed to be the first actually implemented in a control centre. It simulates reactive switching in a Security Analysis function. It has been tested and implemented at the Florida Power and Light System Control Centre, and it was said to be operational since July 1984. In [11] Feinstein et al. describe a computer program to calculate the reactive power load and reserve for the Con Edison system in a real-time environment at the Con Edison Energy Centre in New York

1 Total collapse of the system.

City. It is said to be the first phase of a comprehensive plan to manage and dispatch reactive power. Carpentier [12] announces the EdF's CASOAR project. The French project, which began in 1986, is scheduled for completion in 1992 to renew all computer applications of the French national control centre. It is said to have real-time secure automatic control of the power system as main objective and to contain a series of var/voltage control facilities including on-line simulation of network changes by the operator. An automatic var/voltage control program designed by Leeds and Northrup Co. and implemented in the new TransAlta Utilities System Control Centre is described in [13]. This paper also reports a series of new practical var problems found by Pennsylvania-New Jersey-Maryland Interconnection (PJM), which is thought to be resolved by adopting an on-line var monitoring project described in [14]. The project is expected to analyse the var operating conditions, and offer corrective advice to the dispatcher. Attempts to apply optimization methods mixed with heuristic procedures to var scheduling are reported as being developed and tested at ENEL in Italy [15].

1.4 NEED FOR A NEW APPROACH FOR VAR/VOLTAGE CONTROL

In a survey carried out by the IEEE on current operational problems in power systems [16], it has been found that most respondents consider that the present method, program or facility for voltage and var Control has inadequate speed, size, data or functional characteristics. It has been established that such a method, program, or facility needs work done on analysis of problem areas for further developmental activity and that the approach should have computer aided monitoring or assessment features, particularly

for emergencies. The survey has also found out that these concerns were expressed because they reduce the probability of serious overloads, out-of-limits voltages, or service outages. In that survey it was also reported that additional operational concerns in matters such as outage reporting, security and voltage control, which had not appeared on the formal questionnaire, were recorded by persons responding to the questionnaire.

1.5 SOME REASONS FOR THE INCREASE OF VAR PROBLEMS

In a paper prepared by IEEE-Current Operations Systems (COPs) [17] with the goal of focussing the attention of the industry on high priority problems faced by those who are involved in the actual operation of power systems, specific attention was focussed on the scheduling, operation and monitoring of EHV var components. Among reasons presented for the increase in the number of power systems experiencing var problems were: 1) the high percentage of the large utilities around the world which contain or are interconnected with extensive EHV systems, 2) the increasing dependence on large power transfers due to major increases in fuel costs, 3) the environmental constraints affecting many metropolitan areas and power systems, and 4) the restrictions on right-of-way development which have made many areas dependent on a limited number of transmission corridors.

1.6 OPERATOR'S RESPONSIBILITY

A series of additional responsibilities which have been placed upon the operator in order to keep the system reliable and secure are admitted to be a serious problem, especially considering the lack of

tools to cope properly with monitoring and simulating var problems. Furthermore, the inefficacy of the existing methods to analyse the system data from a var point of view was recognized, and the need for a better a method was stressed.

1.7 FAILURE OF COMMUNICATION BETWEEN THE OPERATING AND PLANNING PERSONNEL

Another problem widely discussed was the failure of communication between the operating and planning personnel, which has recently become more serious. Several comments were made on this subject, including an explicit statement by H. Amchin of American Electric Power Company (AEP), in which he attributed the source of var problems to a failure of communication between planning and operating personnel. It was recognized that in the past planning studies could be made with respect to thermal limits, but with the present changed conditions, planning studies have to include var limits as well.

1.8 REACTIVE POWER SCHEDULING, PRACTICES AND TENDENCIES

Another recent survey carried out by CIGRE [18] among more than fifty-four utilities all over the world shows that var scheduling is of interest to various utilities: a few of them perform it in a systematic way and others are developing methodologies. It was found that, although there were considerable differences between Utilities that answered the questionnaire, some problems, such as data transfer from longer term scheduling and to shorter term (on-line operation), are common to most of the Utilities. Other interesting points shown

by this survey are: (1) about half of the Utilities have revised scheduling procedures during the past five years, (2) var scheduling is performed as a second step (that is after active power scheduling), (3) only two Utilities seem to be in an advanced experimental phase and (4) various others plan to perform var scheduling in the near future. Table 1.1 gives an idea of the comprehensiveness of such a survey while Table 1.2 shows that many utilities either have been doing var scheduling and planning as a second step or have not done it at all.

Table 1.1 Number of Utilities Surveyed per Country.

Country	Number of Utilities	Country	Number of Utilities	Country	Number of Utilities
IT	1	SE	1	BE	3
CA	2	ES	6	BR	4
DE	3	CN	1	GB	2
ZA	1	JP	6	AU	5
IE	1	NL	1	HU	1
DK	1	CH	7	SF	1
NO	3	DZ	1	VE	Pool
FR	1	TH	1	US	8

Source: Cigre, Short-term Scheduling, Electra,No.106,1986

Table 1.2 Practices in Reactive Power Scheduling (See Fig. 1.1)

Scheduling of Reactive Power	Number of Utilities	Percentage (%)
1. Second step	9	15.0
2. Integrated with active	1	1.7
3. Made only for some typical hours	5	8.3
4. Planned for near future	14	23.3
5. Performed off line in planning phase	2	3.3
6. Not done	29	48.3

Source: Cigre, Short-term Scheduling, Electra,No.106, 1986

1.9 REACTIVE POWER SHORTAGE/SURPLUS, BREAKOUT, LOAD SHEDDING

Recent breakouts are now recognized as being caused by reactive power surplus or shortage [19,20]. In [19],CIGRE not only recognizes the need for including var/voltage control actions in planning calculations but it also draws up procedures, guide lines and recommendations to do so. That report gives an explanation of the voltage collapse problems and the causes of many disturbances including the main results of the analysis made at EDF of twenty major disturbances in the world leading to voltage collapse. It is interesting to notice that undervoltage load shedding control is accepted as being necessary to contain a local disturbance in order to prevent a major network voltage collapse. Reference [20] outlines measures to control reactive power surplus and shortage which were identified as one of the causes of system breakdown. Among other corrective procedures, strategic load shedding at major load centres was considered to be as effective a counter to a system suffering a reactive power deficiency as underfrequency load shedding is for a system generation deficiency.

1.10 HIERARCHICAL CLASSIFICATION OF VAR/VOLTAGE CONTROL

Control of reactive power/voltage falls naturally into a hierarchical structure normally denoted as primary, secondary and tertiary control [21,22]. Table 1.3 shows a classification of these voltage control schemes.

Table 1.3 Hierarchical Structure of Control of VAR/Voltage

Type Category Timescale Nature	Objective	Advantages/ Disadvantages
Primary Automatic Local control <1 min. (devices) Automatic voltage regulators (AVR) of synchronous machines which operates through units excitation/ voltage control system and with a longer timescale under-load tap-changing (tcul) transformers.	To compensate for small voltage or var disturbance in order to maintain a constant voltage profile in the network.	.maintain security .can improve economy by releasing extra capacity to transmit active power. --- .inadequate to deal with large changes in system state or structural disturbances.
Secondary Manual Regional control >1 min. (area) Operators must modify the input reference values on primary AVR in order to achieve a satisfactory voltage level.	To compensate for large changes in system state or structural disturbances. It coordinates the actions of primary control within an area.	.improve security --- .difficulty to identify independent zones. .difficulty in separating system effects in one part of the system from those in another. .not automatic .places an additional burden on operating personnel.
Tertiary Manual Global control >10 min.(system) Coordination of the regioal secondary control to satisfy global system criteria.	To perform overall optimisation at system level. It coordinates the secondary voltage control system.	.improve security and to a lesser extent economy. --- .not automatic .automatic tools in early stages of development.

Although there are various difficulties to be overcome in terms of selection of pilot points and strategy of control, secondary control is an interesting idea that has been used mainly in Italy [29-31] and France [28,32]. Secondary control can be automated by monitoring certain key busbars, which are chosen based on engineering intuition, and making adjustments based on these pilot points

voltages [22]. Each region contains one pilot point and a number of PV busbars where

$$Q_i = Q_i^{min} + \alpha\ (Q_i^{max} - Q_i^{min}) \qquad (1.1)$$

Each PV busbar associated with the pilot point has the same participation in regulating the pilot point voltage. The upper and lower var limits corresponding to α=1 or α=0 respectively are reached simultaneously by all PV busbars. Another control strategy and methodology, to select optimally the pilot points,is proposed by reference [22].

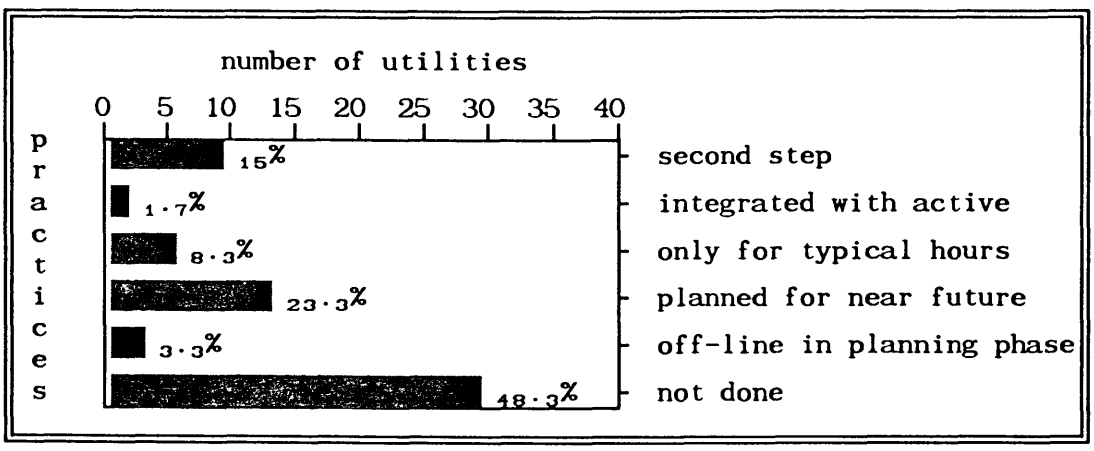


Fig. 1.1 Practices in var scheduling

1.11 PRESENT TECHNIQUES OF SYSTEM OF VOLTAGE CONTROL

A useful description of the present techniques of system voltage control emphasising the predictive nature of the methodology through long term and operational planning can be extracted from Allison [21]. The view of the problem according to this publication is summarised in Tables 1.4 and 1.5.

Table 1.4 Timescale and Aims of Reactive Power Studies during the Planning Phase

STAGE	TIMESCALE	AIM OF THE STUDIES
System Design	many years ahead	1. VAR capabilities of plants 2. Rating of new generating plant, tapping ranges, impedances of transformers and generators.
Planning	5 to 10 years ahead	1. To determine upper and lower voltage limits so as equipments are not overstressed at upper limit and satisfactory system performance at lower limit. 2. To limit the step change during switching. 3. To provide var reserve over expected range of conditions.
Source: M. R. Allison (1986) Future Voltage Control Requirements in the CEGB [21]		

1.12 PLANNING CRITERIA AND SOLUTION METHODS

CIGRE has promoted exercises which are able to show common practices adopted by different countries. In [23] for instance, Brazil, Canada, Federal Republic of Germany, Norway and South Africa have participated in solving the compensation problem for a long transmission system. An interesting point agreed by the five countries and reported in the paper was that loss optimization was not considered a priority criteria in determining var compensation for long transmission systems. Voltage control is the primary problem to be solved and the var compensation required to solve this problem is believed to be not far from optimum operation related to losses. In another CIGRE publication [24] reporting results of an international var compensation exercise on a meshed network example with participation of Belgium, Brazil, France, F.R. Germany, Italy, Norway, United Kingdom and United States of America, the solution

methods used by the contributors were given. In calculations carried out by Belgium, Brazil, France, Norway and United States optimal power flow programmes have been used. Italy has used an optimal dispatch programme while the Federal Republic of Germany and United Kingdom have used ordinary load flow programmes. It was also reported that only steady-state network analyses had been carried out. It is worth reproducing here the planning criteria for reactive power compensation and voltage stated in the CIGRE publication:

"a) Reactive power should not be transported over long distances. b) In normal intact network situations reactive power should be produced and consumed locally. c) The network should be operated at the upper voltage limits in high load conditions to achieve higher stability margins and to reduce active and reactive power transmission losses. d) The amount of reactive power reserves should be sufficient to ensure acceptable transmission capacities in the network during system disturbance conditions."

The British interpretation of the above general criteria is also explicitly expressed in that document:

"The allocation of reactive power compensation for all load conditions should ensure that the following conditions are met: (a) The system voltage levels are kept within the declared values[2], under agreed credible planned outage conditions, which ensure that equipment is not overstressed at the high levels or that the voltage is not too low to meet consumer's requirements, planned transfers and maintain power station auxiliaries. (b) The change of voltage following switching or a fault clearance is limited to 6 per cent for

2 From [21], we learn that the CEGB system is generally planned and operated so that voltages are maintained within ±5% at 275 kV.

a single circuit outage. (c) Ensure that adequate var reserves are available so that the system voltages can be restored satisfactorily following any agreeable credible outage conditions. (d) System costs of compensation and losses are minimized consistent with meeting the requirements of (a), (b) and (c)."

1.13 SIMILARITIES BETWEEN PLANNING, OPERATIONAL PLANNING AND OPERATIONAL STUDIES

An examination of Tables 1.4 and 1.5 reveals many similarities between planning, operational planning and operational studies as far as objectives and solution methods are concerned. It has already been

Table 1.5 Timescale and Aims of Reactive Power Studies during the Operational Planning and Operational Phases

STAGE	TIMESCALE	AIM OF THE STUDIES
Early Stage	1 year ahead	1. To see how the system will be operated in the following year. 2. To identify any particular reactive power problem.
Shorter Timescale	6 weeks ahead	1. Generator scheduling. 2. To investigate particular problems.
Final	1 week ahead 1 day ahead	1. To set up the target voltages and 2. inter-area var transfers. If for a particular reason, adjustment of previously target is thought to be necessary.
Operator	on-line	To meet target voltage and var reserve requirements by switching in and out various compensation devices.
Source: M.R. Allison (1986) Future Voltage Control Requirements in the CEGB [21]		

shown that the tools traditionally used in both phases are the same, namely optimal power flow, AC and DC load flow programmes. While in planning studies a foreseen network situation is aimed to be improved in the operational phase, the objective is to improve the actual network situation.

The commonalities of the analytical problems of these two areas tend to be obscured by the organizational subdivision of power companies into planning and operation departments [26]. Another point is the intrinsic conflicting profiles of a planning and of an operational engineer. For instance, in solving the same problem, an experienced planning engineer will be naturally biassed towards overstressing the economic objectives. Thus he would minimize the expansion cost by eliminating all var sources, whilst the control engineer would overstress security, say, by maximizing the sources of var. In other words from the point of view of an operational engineer an unlimited set of controls would be ideal, whilst from the point of view of a planning engineer no additional components at all would be the ideal. Figure 1.2 shows the way engineering problems are classically performed.

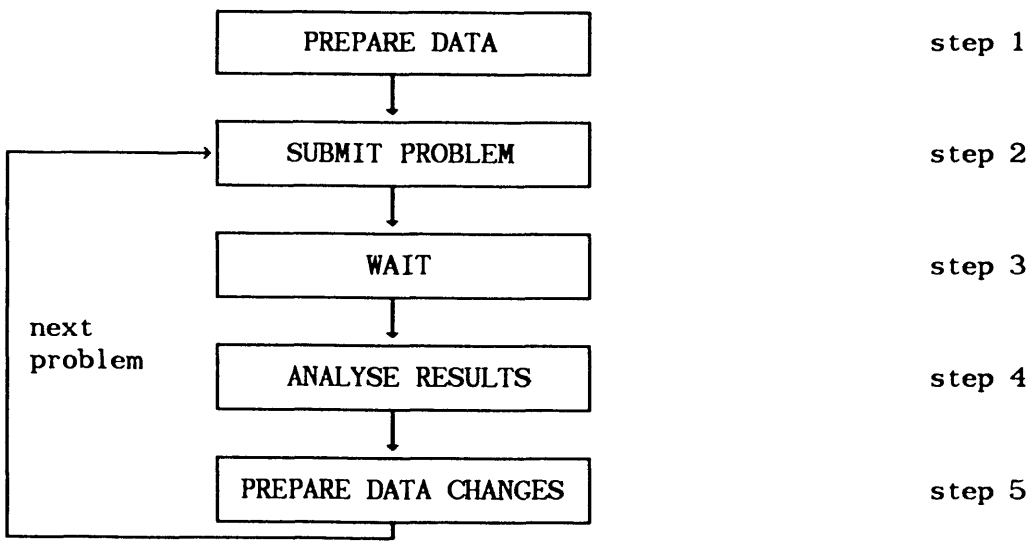


Fig. 1.2 The way studies are performed

Tinney [26] observed that interactive systems had minimized step 3 and simplified step 2, but had helped little on other steps. Parallel processing was hoped to further improve step 3, enabling acceptable solution times for problems which still take too long for convenient interactive solutions. The bottlenecks are steps 1 and 4 and 5. The literature is replete of reporting the necessity of automating these methods [27]. For instance, Reed [13] is well worth quoting

"As the knowledge of reactive power contingency problems increased, so did the complexities of correlating the AC load flow data. In order to properly analyze the PJM system, it became necessary to run approximately 300 AC load flows for each weekly analysis. The recording and correlation of this data became a very difficult and time-consuming task. In order to increase the Operations Planning engineer's analysis of the var problems, it became necessary to establish a data-base which accepted AC load flow output of pre-contingency and post-contingency values."

He continues by admitting that although not reducing the required number of AC load flows to be run and not eliminating the need for the engineer to select the proper contingencies requiring analysis, the data base would permit the engineer to consider various indicators or system parameters that influence voltage drop as well as the system conditions under these voltage drops that might be encountered.

1.14 DESIRED FUTURE VOLTAGE CONTROL SCHEME

A desired future voltage control scheme should involve all predictive phases of studies as well as integrating the planning and operation. Allison [21] gives a clear description of the future

requirements of a Centralized Automatic Voltage Control scheme. He states that benefits should be demonstrated in at least one, preferably more, of the following areas: (a) voltage quality, (b) increased security, (c) improved system economy and (d) operational convenience. He believes, "although not specifically part of a voltage control scheme, an AC security assessor is complementary to it and should be provided to permit short term predictive studies to assist the control engineer to avoid insecurities and to assess the effects of any scheduled or unexpected line or generator outages, taking account of critical contingencies so that reactive power may be dispatched in a preventive mode." He also states, "initially, critical contingencies might be introduced to the scheme manually, although it is possible to envisage that eventually they may be taken automatically from an independent AC security assessment system". Finally, he concludes, "the security assessor should include a method for forecasting future network loadings together with manual adjustment of generation so that system conditions may be examined up to, say, one hour ahead."

Murray and Farrant [25] also recognize that the most practical means of monitoring security is in the predictive phase. They pointed out that it was unlikely that on-line programs would be used at the time of occurrence of major system disturbances, either for not being possible to obtain program outcomes sufficiently fast, or, even it were possible, the control engineer could not assimilate the output and act on the results. On the other hand, they admitted that establishing a complete set of data of system conditions, particularly if it was intended to examine AC voltage conditions, was a difficulty encountered at the planning phase.

1.15 CONCLUSIONS

It seems clear that:

(a) the use of var/voltage monitoring, scheduling and control is expanding in USA, France, Italy and, as far as can be judged, in this country also, and

(b) this expansion will continue. Of course there are problems, mainly due to the early stage of development of the field and, in the past, lack of interest in solutions that would include the reactive power step in former methods for system optimization and security assessment and enhancement.

(c) Algorithm developments alone are not believed to provide solutions of these problems, but should be accompanied by hardware improvements and incorporate emerging techniques, such as,for instance, parallel computing and expert system. Data handling, with automated postprocessing that would reduce the amount of output from the computer by performing much of the analysis currently performed on a manual basis, should also be taken into account.

A review of the range of steady-state var/voltage problems, needs and practices has been carried out and presented in this chapter. It is hoped that this review has made possible:

1. the identification of overlap, duplication and deficiencies in the existing approaches, and
2. the determination of priorities for action to improve the global system security and the discovery of new ways in which improvement can be effected.

The resulting methodology devised to deal with these problems will be described in the following chapters.

CHAPTER 2

GLOBAL FRAMEWORK - CONCEPTUAL DESIGN

2.1 INTRODUCTION

The previous chapter reviewed the evidence for the need for a new framework for the management of var components and voltage control, and for the study and analysis of var/voltage problems. In this chapter: (i) the conceptual design of this framework is presented, (ii) difficulties involved in its implementation are highlighted, and (iii) guidelines are given for defining the requirements of the algorithms described in the following chapters. Ways are also suggested of (iv) integrating the proposed methodology into the existing software in a modern control centre. Finally, in order to establish clearly the meaning of the concepts involved, it is necessary (v) to review some definitions, and (vi) to extend the concepts from the new viewpoint.

2.2 VAR/VOLTAGE OPTIMISATION AND POTENTIAL ACCIDENT ANALYSIS

The overall var/voltage problem of the static optimisation of snapshots of the power network may be stated as the two separate sub-problems of var dispatch and var expansion as far as objectives are concerned:

VAR Dispatch (Operational Planning and Operation)

Given a load and generation pattern and a network configuration, determine the output of generators and other var sources as well as tap settings of transformers such that some performance specification

of the system is satisfied. The important point is that neither new devices nor new facilities are added to the system.

VAR Expansion (Planning)

Of course, switching and control equipment should be planned and installed well ahead of time to make possible the control of var/voltage parameters. The problem here is to determine a set of facilities or devices to be added to the electric system in order to improve its performance. Devices or facilities are considered to be added to the system, with the objective of minimising the cost of this expansion.

Economy and Security Considerations

For the time being, let us take the concept of security in a broad sense as the maintenance of the supply without violation of operating limits. Since one could allocate unlimited resources in terms of devices and facilities to increase the ability of the power system to meet the load demand within given operational limits, the primary objective in system planning should be to minimise the cost of this installation while providing an acceptable level of security. On the other hand, in operating the system use is made of the devices and facilities that are already available. Therefore, there is no expansion cost. The primary objective here is to find the best scheduling of the var control variables so as to maximise security. Of course, there is the cost of operation. For instance, transmission losses can be minimised, but in var dispatch, this should come as a secondary objective.

The above considerations, as well as the common characteristics of the planning and operation of a power system from the var

viewpoint, are depicted in Fig. 2.1.

Block 1 shows the planning environment, with the primary objective, represented by the box labelled "economy", in the dominant position. Block 2 represents the operational environment. The box labelled "security" appears in the dominant position so as to emphasise its primary importance. The interface of both environments is shown by the boxes in the area where Blocks 1 and 2 overlap. The small boxes, which represent the specificity of each environment, are discussed in the following:-

VAR resources:- As has already been mentioned, in solving the var expansion planning problem, the resources are ideal or unlimited, but they are actual or limited in solving the var dispatch problem.

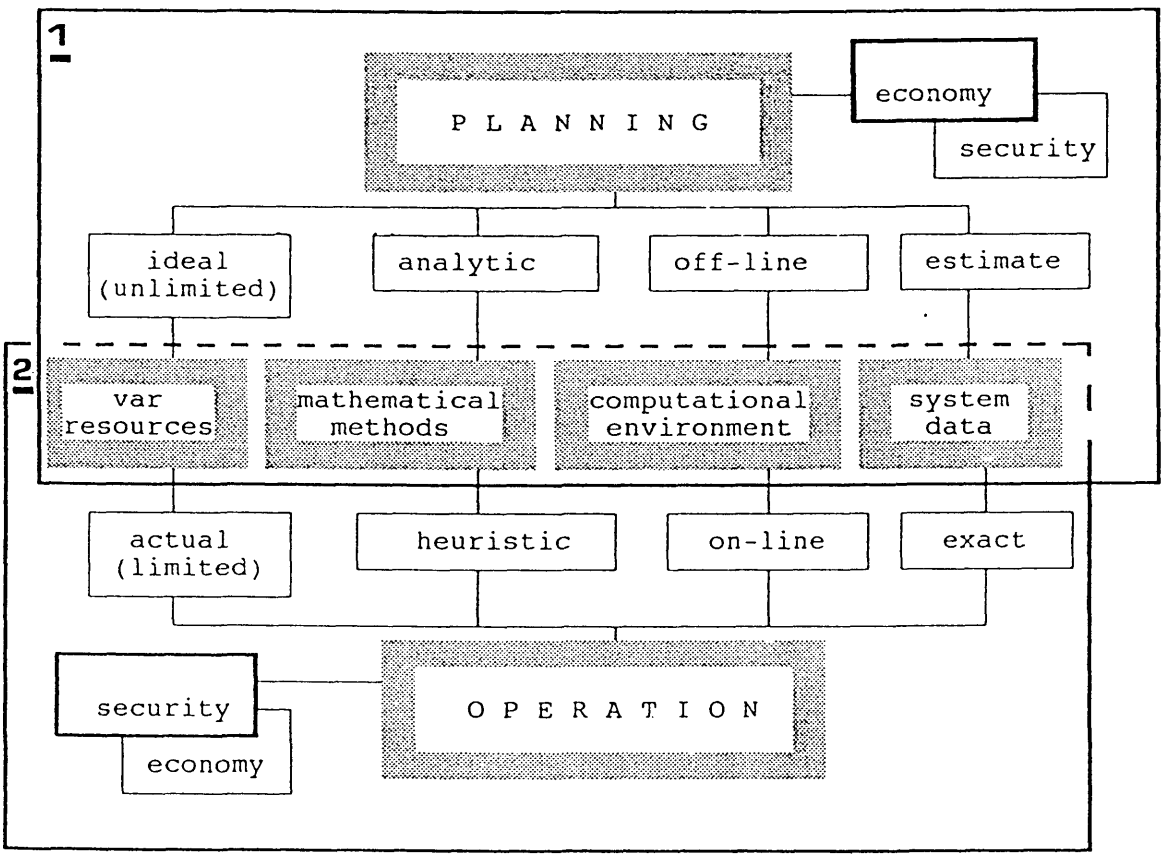


Fig. 2.1 Power System Planning and Operational Environment

Mathematical methods:- In planning studies there is less pressure of time. The studies can therefore include more elaborate modelling and can use sophisticated analytic methodologies at the expense of CPU time. For instance, state-of-the-art optimisation packages can be used and quite long simulation times may be allowed. On the other hand, in the actual operation of the system the short time available for simulation makes it mandatory to adopt simplifications in the modelling in favour of speed of response. Subjective aspects, such as "the experience of the operator", are to be incorporated into the mathematical model yielding heuristic, but very fast, procedures.

Computational environment:- Whilst planning studies are typically off-line with a predominance of batch processing, on-line computing and interactive processing are natural requirements in system operation.

System data:- In the operation of the system, real time analog and digital measurements are available. "State estimation" has to be used to provide the data base. In system planning the anticipated condition of the network is studied. The data base is derived from (i) known network and plant data and (ii) load forecasts.

Potential Accident Analysis - A Conceptual Environment

From the previous analysis one can deduce that the var/voltage security-optimisation methodology follows an organizational top down structure: from system planning through system operation. In the following, a conceptual study environment is suggested aiming to provide a feedback loop, whereby advantage is taken of the practices common to both system planning and operation. Figure 2.2 shows the proposed scheme.

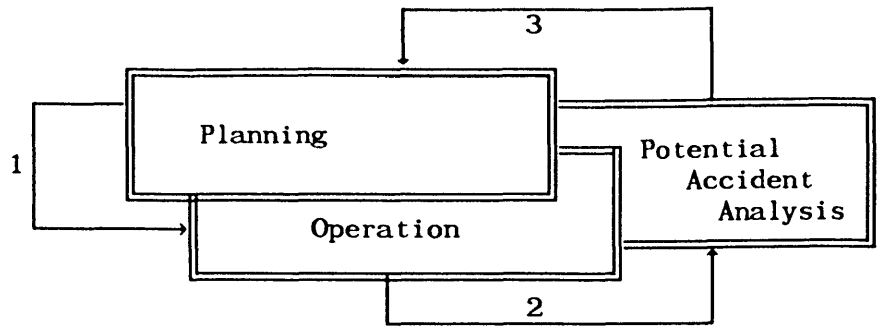


Fig. 2.2 Potential Accident Analysis

The strengths existing in both system planning and operational techniques are to be retained in this new environment whilst the weaknesses are to be dropped. Thus unlimited plant resources are assumed to be available. Accurate system modelling and analytic mathematical models are to be used. An on-line interactive computational environment with exact system data would provide accurate results and better knowledge of the power system. The planner's philosophy may now be cross-referenced with the operator's viewpoint and experience. Before giving the details of the implementation of this scheme in a modern control centre, it is imperative to formalise security better in order to define the so called security-related decisions and the security functions.

2.3 SECURITY DECISIONS AND SECURITY FUNCTIONS

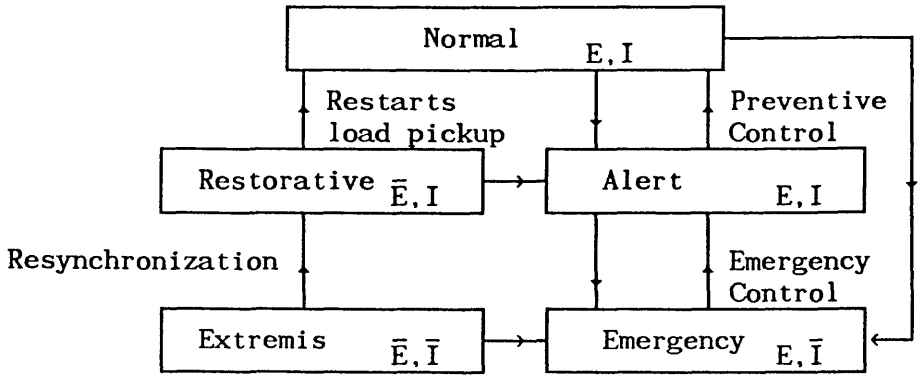
First, it is necessary to define the operational states of operation of a power system. As these are widely known concepts we shall simply take them from reference [33] and reproduce them in Fig. 2.3, without further comments. However, a complete discussion on this subject can be found in references [1] and [34].

In the same fashion, the following steps, taken from DyLiacco

[1], are used to define the sequence of operating decisions:-

1. Using real time system measurements, identify whether the power system is NORMAL or not.If the system is in an EMERGENCY,go to step 4. If load has been lost, go to step 5.
2. If the system is NORMAL, determine whether it is SECURE or INSECURE in the event of a next contingency.
3. If it is INSECURE - i.e., there is at least one contingency that can cause an EMERGENCY - determine what preventive action should be taken to make the system SECURE.
4. Execute proper corrective action to make the system NORMAL.
5. Restore service to system loads

The function in step 1 is called SECURITY MONITORING, the function in step 2 is called SECURITY ANALYSIS, and the function in step 3 is called EMERGENCY CONTROL AND RESTORATIVE CONTROL.



E = Equality constraint
I = Inequality constraint
- = Negation

Fig. 2.3 The State Transition Diagram
(Taken from O.I. Elgerd [33])

Table 2.1, adapted from [34], provides additional clarification and illustration of the concepts and terminology.

2.4 SECURITY FUNCTIONS FROM A VAR/VOLTAGE VIEWPOINT

Security is conceptualised with respect to a set of next contingencies. However, the common practice of using the N-1 criterion [36] for assessing a contingency for active power has proved to be inadequate from the var viewpoint.In addition to automatic contingency selection, it is also desirable to take account of contingencies based on engineering judgment and experience [37]. This may involve considering a few high probability N-2 contingencies, network and load level changes and var source outages [74],[162].

Table 2.1 The Modern Power System Control Centre Functions
Source: F.F.Wu and T.DyLyacco, Short Course, Helsinki, Finland, 1988. [34]

Class	Function	Descriptions
Traditional	Scada Functions	Supervisory Control Data Acquisition
	Generation Control	Automatic Generation Control(AGC) Economic Dispatch (ED)
Group A	Security Functions	State Estimator (SE) On-line Load Flow (OLF) Contingency Evaluation (CE)
Group B	Security Functions based on Optimal Power Flow (OPF)	Constrained Economic Dispatch Contingency-Constrained Dispatch Emergency Dispatch Voltage/Reactive Power Control
Others	Special Functions	Load Shedding Automatic System Trouble Analysis On-line Short Circuit Automatic Circuit Restoration Others
Observations: a) The implementation of the SCADA functions alone requires a major investment. b) Of the approximately 280 control centres throughout the world, about 135 centers, or almost 50%, have Group A Security Functions. c) Of the 47 generation-transmission control centre projects which are scheduled to be in service in 1986-1990 40 centers or about 85% will have Group A Security Functions.d) New control centre projects are now beginning to call for Group B Security Functions.		

Therefore, it is important to define formally the security functions from a var viewpoint. First of all, consider that power system states can be represented by a variable, labelled PS, which can assume the values EMERGENCY, NORMAL_SECURE, NORMAL_INSECURE and ALERT, as shown in Table 2.2. Secondly, let us define the possible control actions as EMERGENCY CONTROL and CORRECTIVE CONTROL, the former representing the control action necessary to bring the system from the EMERGENCY STATE to the NORMAL_SECURE STATE and the latter being the control action necessary to bring the system from a NORMAL_INSECURE state to a NORMAL_SECURE STATE. The concept of POTENTIAL CONTROL will be introduced later.

Table 2.2 System states from a var/voltage viewpoint

System State (PS)	Characteristics
NORMAL	No operating limit violated for the base case intact system.
NORMAL_SECURE	No limit violated. In the event of a contingency, there will be no violations
NORMAL_INSECURE	No limit violated. In the event of a contingency, there will be violations
ALERT	No limit violated. Any violation caused by a contingency can be corrected by a known appropriate control action.
EMERGENCY	Operating limits are violated.

It is now possible to interpret the var/voltage security decisions in a form analogous to the prevalent terminology for active power security analysis. Thereby, the var/voltage sequence of operating decisions are derived and presented in Fig. 2.4.

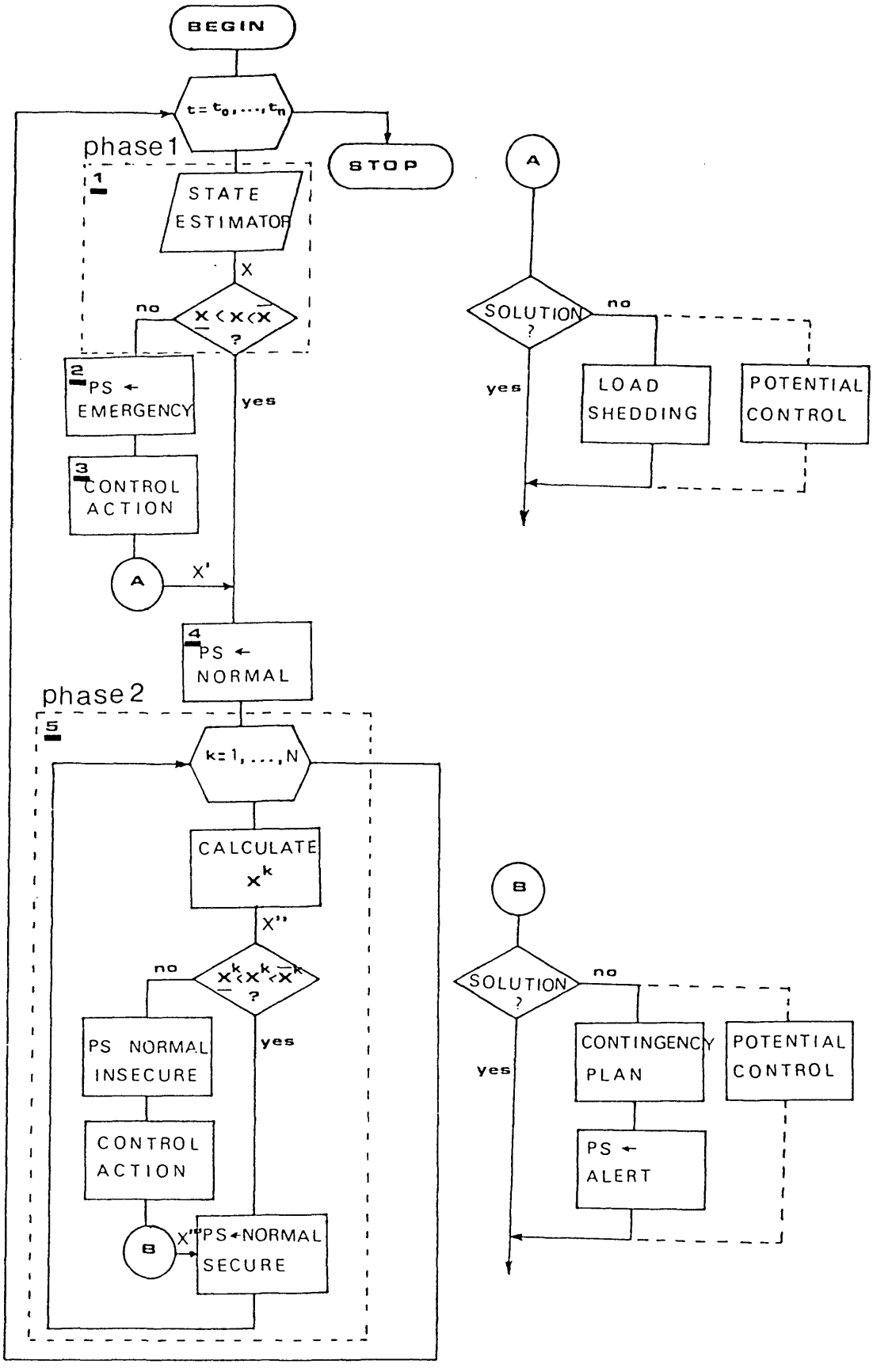


Fig. 2.4 VAR/Voltage Security-Related Decisions

Block 1 represents the Security Monitoring Function. If any voltage magnitude is out of bound the power system is in an emergency state. This is represented by block 2: PS assumes the value EMERGENCY. In this case corrective action should be taken so as to bring the system back to the normal state. Blocks 3 and 4. A new operational point x' is calculated.

At this point at least three problems arise:

1) The var reserve can be insufficient. The corrective action may not exist with the number of feasible controls available.
2) Should a solution in terms of adjustments of reactive control variables exist, it has to be calculated in a very small time interval.
3) This speed requirement is not met by today's existing (optimal power flow) techniques.

Function A shows the strategy adopted to cope with these problems: An ideal scenario is created by expanding the number of controls and relaxing their limits. The best answer in terms of system expansion would be to pinpoint the weak points of the system. These results, in a sense, represent the "feeling" of an expert operator. This procedure besides being a follow-up of the planning, showing if the system was well planned, would lead to recommendations for future expansion and enable logging of important information. There is no pressure of time for running this procedure. Consequently, exact mathematical packages can be used and some idle computational time utilised. We call this strategy: "potential control"; because it is the control action that could have been taken

if the system had been ideally planned.

Block 5 is called Security Analysis. A list of contingencies is evaluated. For each contingency (k) a new state $\underline{x}''$ is calculated. Once the new state $\underline{x}''$ has been found, then if any voltage magnitudes are out of bounds (here the limits are more loose) the system is in a normal but insecure state (PS assumes the value NORMAL_INSECURE), and a preventive control action has to be sought to bring the system back to normal-secure state. It is necessary to calculate a new state $\underline{x}'''$ so that the system remains in the normal-secure state for all planned contingencies.

All the problems of the Security Monitoring Function remain and there are new problems to add:

4) How to select the harmful contingency list? The existing screening techniques produce very inaccurate results for the var/voltage problem.
5) How to find out the control action which is able to bring the system to a normal secure state for all the contingencies on this list is, as yet, an unsolved problem.
6) The size and complexity of the problem is tremendously increased. Moreover, the impact of the contingency produces very ill-conditioned problems for which traditional load flow techniques are bound to fail.

Function B in Fig. 2.4 shows the strategy adopted for this phase. It is essentially the same one adopted in the previous phase. An extra feature is that those contingencies (k) which are found to overconstrain the preventive solution are dropped and solved in a corrective mode. A contingency plan is then calculated for each of

these (k) contingencies. The concepts of corrective and preventive strategies will be formalised in the next section. Finally, for the sake of completeness, as an extreme resource, an optimal power flow program might be used to determine the minimum amount of load to be dropped and at what points in the network the component loads are located.

The load shedding solution may be compared to the cost of the expansion and logged. This would show whether or not a var expansion plan would have been beneficial.

2.5 CORRECTIVE VERSUS PREVENTIVE STRATEGY

Consider the simple system of Fig. 2.5 characterized by the voltage profile of V_g=1.0 p.u. and V_l=0.98 p.u. . Let the voltage limits be V^{min}=0.975 and V^{max}=1.05

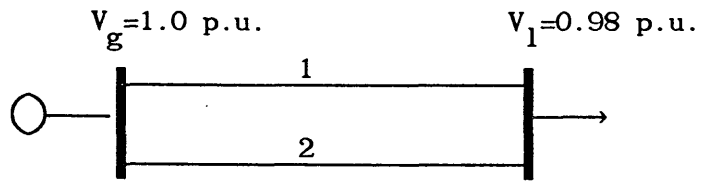


Fig. 2.5 Base Case - Intact System

Consider now the outage of one line as in Fig. 2.6

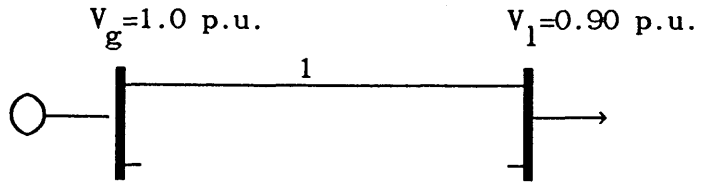


Fig. 2.6 Contingency Case - Outage of Line 2

If no adjustments are made at the generator bus, the new voltages will be as shown, i.e., V_g=1.0 and V_l=0.90, out of range. Two strategies can be adopted to solve this problem:

Corrective

After the occurrence of the outage a new set point at the generator is sought, and action is taken to modify the generator voltage. For instance, adding ΔV_g=0.05 p.u. to the generator voltage, will produce the new profile: V_g=1.05 and V_l=.98.

Preventive

In this case the action is taken before the occurrence of the outage. The final setting of the generator voltage is supposed to prevent any violation after the occurrence of the outage.
So in this instance, V_g is set to 1.05 for the base case intact system.

These strategies are represented in Fig. 2.7

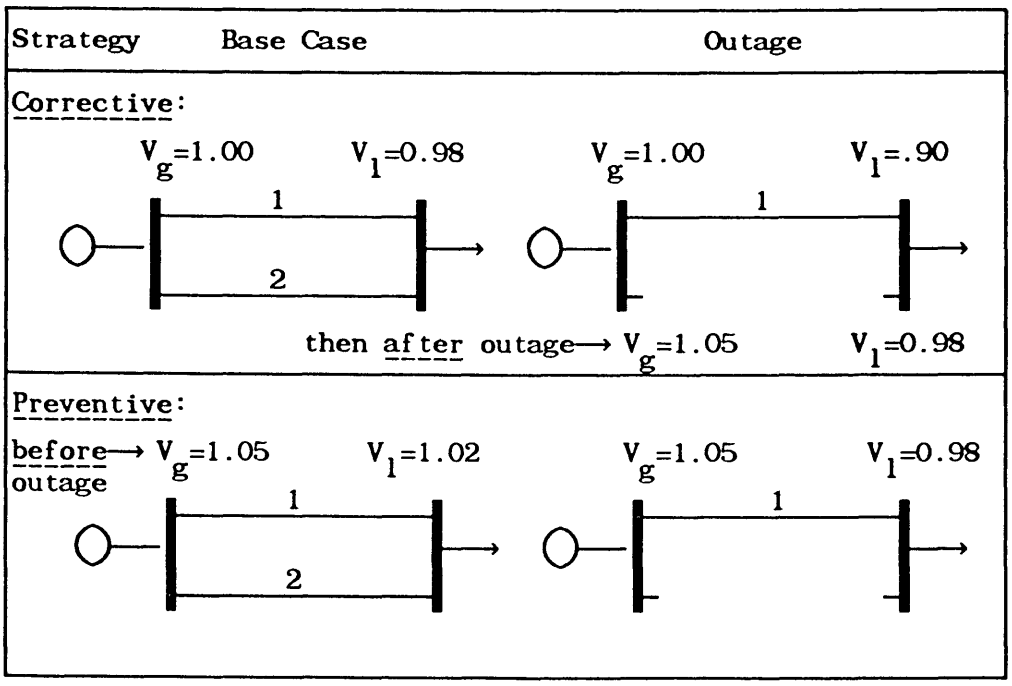


Fig. 2.7 Corrective versus Preventive Strategy

It is clear that complete preventive planning is ideal for the

sake of security. However, when many contingencies are considered there are cases where the preventive solution does not exist or, if it exists, it is very expensive. In practice the system is made secure in a preventive sense for some contingencies and in a corrective sense for others. Introducing the following definition may clarify this concept.

N-K preventive secure, K corrective secure

Given a set of N contingencies, an operational preventive point is sought which is secure for these N contingencies. If the reactive power resources do not allow feasibility for some of these contingencies, say K of them, an operational preventive point is found for N-K contingencies. In this case a contingency corrective plan is determined for the K contingencies,i.e., a corrective operational point is determined for each of them. We say that the system is N-K preventive secure and K corrective secure.

This situation arises when definitely conflicting control actions are required for correcting limit violation in two, or more, distinct contingencies. Another important factor is the type of control device available. Sometimes it can be interesting to adopt a corrective strategy. Load shedding, for instance, would only be considered as a corrective strategy, when all else had failed.

In this thesis a methodology is developed which solves the above problem, that is:

- Select a harmful set of N contingencies.
- Find a complete preventive solution for all N contingencies, if it exists.
- If a solution does not exist for all N contingencies, find a preventive solution for N-K contingencies and a

corrective solution for K of them.

Additionally, a conceptual framework is proposed for implementation in modern control centres, which enables:

- o evaluation of the cost of adding the control resources necessary to increase security and provision of the N-preventive solution.
- o determination of the var reserve necessary to enforce the N-preventive solution.
- o evaluation of the tradeoff between the expansion cost and the cost of post-disturbance infeasibilities, such as load shedding and fines.
- o accumulation of experience and knowledge of the power system and consequently improved design decisions at the engineering level, resulting in benefits such as procedures for abnormal operation, better modelling, modified optimum criteria, new operating limits, etc.

2.6 THE GLOBAL FRAMEWORK

Figure 2.8 shows the overview of the global framework developed. A scheme has been conceived that is composed of three main phases:

Phase 1	Contingency Analysis, Sensitivity Analysis and Clustering.
Phase 2	Contingency-Constrained Reactive Power Flow: Preventive Mode.
Phase 3	Contingency-Constrained Reactive Power Flow: Corrective Mode.

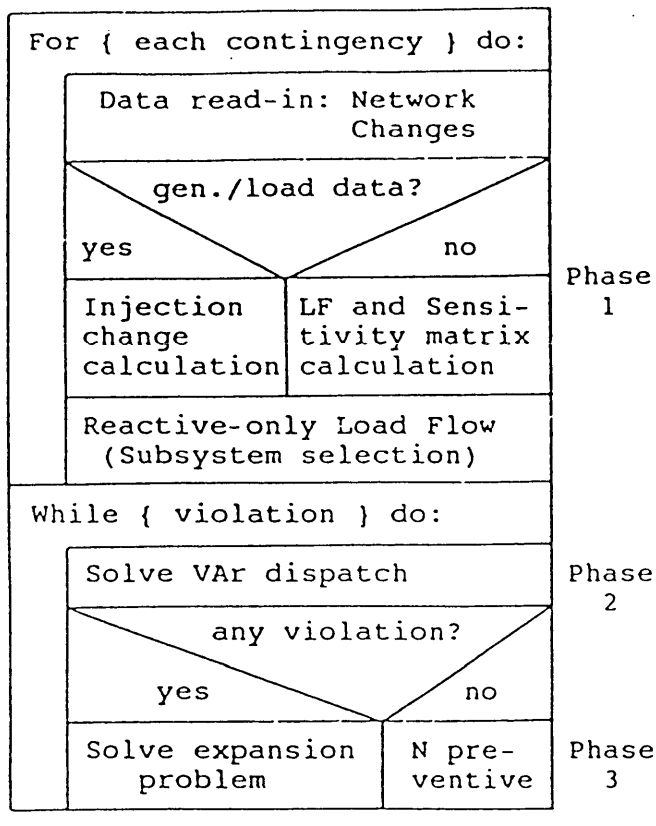


Fig. 2.8 Voltage Control Scheme - Conceptual Model

Each of these phases is described below:

Phase 1 - Contingency Analysis, Sensitivity Analysis and Clustering

This phase provides data entry, file editing facilities, menus and help screens. One of the development requirements of this phase was to provide data management facilities to minimise the time spent in analysis of results and re-submission of alternative formulations. The feasibility of these features has been shown by designing and implementing a prototype software environment which has been used for research and testing of strategies and algorithms. As a final

by-product of this phase an educational package for power system operational planning has been created [155] (See Appendix A). The research requirements which emerged from this phase have included:

1) finding a load flow methodology to solve ill-conditioned systems, including high r/x ratios and heavily-loaded systems. (See Chapter 3)

2) developing a contingency analysis method for the var/voltage problem. (See Chapter 4)

3) shortening computation time by previously computing the coefficients of the sensitivities of all controls. This idea lead to the investigation of two different approaches: (i) Pre-processing based on sensitivity analysis and mapping of the network so as to select a few of the most effective control variables. (ii) Decomposition of the set of controls so as to allow formulation of smaller optimisation problems which may be solved in a sufficiently small time interval. (See Chapters 4 and 7)

Phase 2 - Contingency-Constrained Reactive Power Flow:

Preventive Mode

In this phase, each contingency forms a var optimisation subsystem. A reactive optimal load flow determines a feasible solution for each subsystem. Techniques of hierarchical decomposition and coordination have been studied and improved solution techniques developed. The main research requirements posed by this phase have raised the following problems:

1) to survey the optimal power flow techniques and develop one aiming to solve the var-only problem, to improve convergence characteristics, and to shorten computation time. (See Chapter 5)

2) to contribute to bettering the formulation and solution of the contingency constrained var-dispatch problem. (See Chapter 7)

3) to determine the critical limits in the case of overconstrained insoluble problems. (See Chapters 6 and 7)

Phase 3 - Contingency-Constrained Reactive Power Flow: Corrective Mode

Using information received from phases 1 and 2, this phase determines the pattern of expansion (or load shedding) for those contingencies which are found not feasible in phase 2. This module first relaxes the limits of the constraints until the violations disappear because the violations in phase 2 are minimum ones. If desired this can be done by enlarging one limit at a time, and iterating with Phase 2. If not, the limits are relaxed and a corrective operational point is found for each contingency that has not passed phase 2. (See Chapters 6 and 7)

Potential Control Variables:- During the subsystem selection of phase 1, each busbar which presents a large sensitivity coefficient is selected as a candidate for shunt capacitor allocation. Of course these candidates would be considered for allocation at the corrective phase.

2.7 CONCEPTUAL MODEL, SOFTWARE SYSTEM

A system of software is suggested with the aim of integrating the above methodology into the existing software at a modern energy control centre [162]. Figure 2.9 shows the software system representation. Square blocks represent computer programs, dotted lines represent data flows and the solid lines are the flow of control. All input data is placed on the right hand side of the diagram and the output data are shown on the left hand side. The system is composed of six modules.

Module I: Network configuration data read-in. The system reads data such as: the network configuration, the number of generators with var availability, shunt capacitor/reactor, tcul transformers, changes in the network configuration and/or changes of the type of busbar; for example: from PV to PQ or vice-versa.

Module II: Pre-processing. This module performs contingency screening and sensitivity analysis. It creates a file which is composed of network matrices for the load flow program and sensitivity coefficients for the optimisation phases. The mapping of the dependent variable and the most effective control are calculated, including the potential control variable for the actual configuration.

Module III: Power system data read-in. This module reads in the following data every cycle: Economic Dispatch results, including distribution factors for the active power, var limits for generators from capability curves, voltage limits, tcul limits, etc.

Module IV: Optimal reactive power flow. This module calculates a secure point of operation for the present system data.

Module V: VAR-constrained dispatch. If time allows, this module

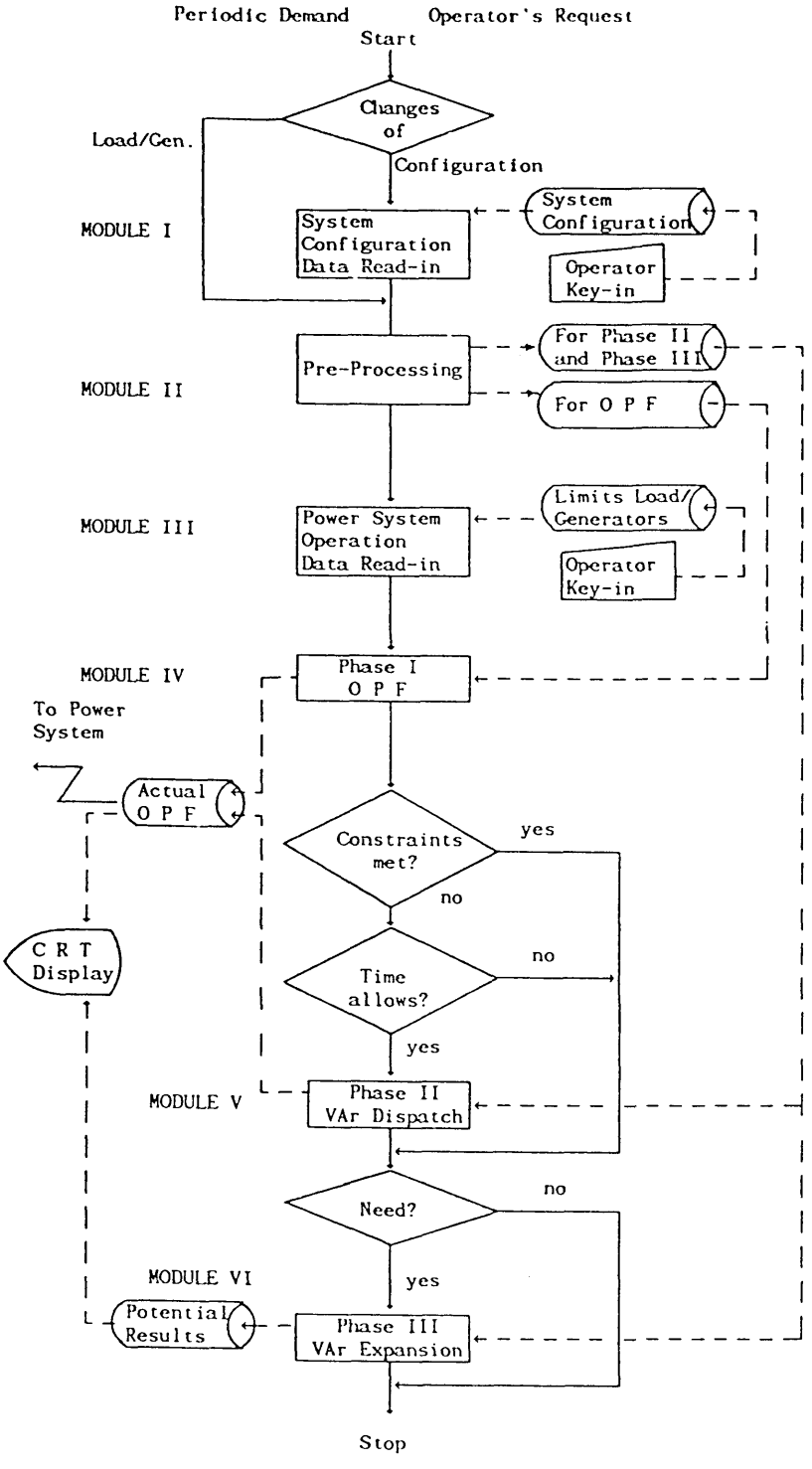


Fig. 2.9 Software System Diagram

calculates the optimal preventive operational point for a set of harmful contingencies. It also generates the Lagrange multipliers for the next module.

Module VI: VAR-constrained expansion and potential accident analysis. Should the preventive solution not exist, this module calculates a contingency corrective plan for the harmful set of contingencies. If such a solution also fails, the limits are relaxed, and the potential candidate buses are considered for var allocation.

Frequency of Execution

This scheme may be executed cyclically. For example, following the state estimator or following the Economic Dispatch. On study mode it can run under the operator's request, for example for testing operating plans. Displays are given of the optimum possible operational point and the adjustments of control variables which are necessary in order to reach that point.

The software system may also run cyclically in low priority, say hourly, in order to find out the best expansion plan under the current system configuration, but under an ideal scenario in terms of var sources. This outcome would show possible deficiencies in the previous planning as well as determining weak areas in the system and yield prospective strategies for future planning studies.

An execution at the end of a period, say daily, may digest the files of the day, i.e., the periodic results, and may record those points which occur frequently. This result after being merged, ranked and sorted with previous results will form a data-base. Such information, in a way, represents the "feeling" of an expert operator and will be very useful to planning staff.

Advantages and Benefits

Among immediate advantages of this procedure we list some which have been widely demanded by the electrical utility industry: (i) optimised display to the operator: simple and with a reduced number of variables to ease the decision process; (ii) testing of scenarios, heuristic methods and practical procedures in use by operation personnel; (iv) tuning of different objective functions in var optimisation according to the peculiarities of each user (utility); (v) test, validation and upgrade of analytical methods such as sensitivity analysis, non-linear programming, linear programming.

The important point is that potential accidents are continuously and realistically analysed. A historical data-base which has passed through a great amount of analytical engineering work would be available to the system planning staff. Accurate information about weak areas and components that are likely to fail together with the solutions in terms of resources allocation from the point of view of the operator would provide a better way to design a high level of security at a low cost.

Moreover, this scheme creates a channel of intercommunication between the operators and the planning personnel - improving their relationship and exchange of experiences and points of view.

CHAPTER 3

VAR-ORIENTED LOAD FLOW MODEL

3.1 INTRODUCTION

The fundamental tool to allow any further var/voltage developments is a robust AC load flow method. It was suspected at the very beginning of this research[1] (1985) that the state-of-the-art load flow techniques had failed to meet the requirements of accuracy, speed, robustness and compactness for solving var/voltage problems, particularly for ill-conditioned high r/x ratio networks and for heavily loaded systems. However, the load flow techniques for solving the active power counterpart were very well established. Consequently, it would be desirable that any new methods for solving the var problems should have an evolutionary rather than a revolutionary approach. In view of these considerations, the development of a robust load flow method was essential, with most of the computational algorithms being written so as to allow for the implementation of the conceptual model formulated in the previous chapter. The load flow algorithm should be decoupled so as to allow for solving the var/voltage problem as a second step and should meet the following requirements, in order of priority: (i) accuracy - it should be able to converge to small tolerances (ii) robustness - it should be able to handle ill-conditioned cases (iv) compactness - the

---

1 This statement is based upon previous E&PSG experience communicated to us by Dr. R.B.I.Johnson and through comments during meetings with engineers from the CEGB.

memory requirements should allow implementation on personal microcomputers[2] (v) speed - it should give acceptable time response, at least if used in interactive planning, and ideally for on-line application. The above subjects are dealt with in this chapter in the following order. First, a brief critical review of the relevant load flow techniques is presented. Next, a comparative study resulting in the selection of the most suitable approach is detailed. Then, new theoretical aspects of the selected methodology are described, as well as extensions and improvements. Finally, a computational implementation is developed and numerical results are presented.

3.2 PROBLEM FORMULATION

Consider a network with N_{bus} busbars classified according to the following specification of their variables:-

- o PV busbars, where P and V are independent variables
- o PQ busbars, where P and Q are independent variables
- o SW busbars, where V and θ are independent variables

The net active and reactive power injected into each busbar of the system should satisfy

$$\Delta P_i = P_i^{sp} - P_i(\underline{V},\underline{\theta}) = 0 \quad \text{for all PQ and PV busbars} \tag{3.1}$$

$$\Delta Q_i = Q_i^{sp} - Q_i(\underline{V},\underline{\theta}) = 0 \quad \text{for all PQ busbars} \tag{3.2}$$

with,

$$P_i^{sp} = P_{g_i}^{sp} - P_{d_i}^{sp} \tag{3.3}$$

$$Q_i^{sp} = Q_{g_i}^{sp} - Q_{d_i}^{sp} \tag{3.4}$$

---

2 The reasons for this requirement are twofold: (i) to be able to utilize low-cost personal microcomputer technology and (ii) to enable continuation of this research at UFMG Brazil.

$$P_i(\underline{V},\underline{\theta}) = V_i \sum_{j\in I} V_j \left(G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) \quad (3.5)$$

$$Q_i(\underline{V},\underline{\theta}) = V_i \sum_{j\in I} V_j \left(G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) \quad (3.6)$$

where, the superscript sp means a fixed specified value, subscripts g and d indicate generation and demand respectively, I is the set of busbars directly connected to busbar i, including busbar i. G_{ij} and B_{ij} are the real and imaginary parts of the complex element Y_{ij} of the passive network matrix Y_{bus}, respectively. P_i and Q_i are the net active and reactive powers injected into busbar i. V_i , V_j and θ_i, θ_j, are voltage magnitudes and voltage angles at busbars i and j, respectively.

The load flow problem consists of solving numerically the non-linear system of equations (3.1-3.2) for the busbar voltages. This solution yields all information necessary to evaluate branch flows, losses, active power injection at the SW busbar, and reactive power injections at the SW and PV busbars.

Numerical Characteristics

In principle, the load flow problem is a well-behaved numerical problem. The general requirements of numerical methods for solving systems of non-linear equations are a good enough initial guess and a diagonal dominance of the Jacobian of the system. In general, these two requirements are naturally met by the load flow problem. The main reasons are: (i) Electrical equipment is designed to give optimum performance at nominal voltage values, therefore, a flat voltage profile is a natural initial value. (ii) The load flow equations represent the balance of currents at every busbar of the system (Kirchhoff's first law), therefore the Jacobian has the same

structure as the network matrix and diagonal dominance is in general assured for nominal values of the variables. Besides, as with the individual components, the network topology and electrical characteristics are designed to perform well at nominal values. However, situations may develop where the load flow problem becomes an ill-conditioned problem, such as outages and heavy loading.

Ill-Conditioning

Let us now examine the circumstances in which the load flow problem becomes ill-conditioned. An examination of (3.1) through (3.6) reveals that these circumstances can be caused either by a bad specification of the independent variables or by unusual values of the parameters G and B. A bad specification of the independent variables means stringent loading conditions and random changes in the topology may cause unusual values for G and B. Instead of constituting an exception, these conditions seem to be the rule in actual system operation when contingency situations lead to random changes in both network topology and load levels. Therefore, a method of solution must be found that can handle this kind of problem.

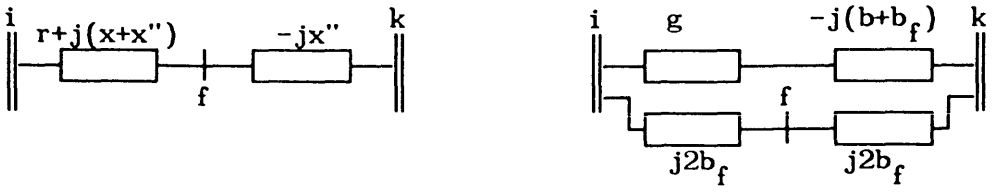
3.3 METHODS OF SOLUTION

The first idea for a general treatment of the load flow problem is to replace the root-finding method of solution of the non-linear set of equations by an optimisation approach. Thereby, a scalar cost function of the mismatches (3.1-3.2) can be defined, and through its mimimisation a solution can always be determined. Should such a feasible solution exist, the optimal value of the cost function is zero. A similar course of action was followed in [39-43]. Using

rectangular coordinates, the Taylor-series expansion of the load flow equations is expressed up to the 2nd order terms. Then a quadratic cost function of the mismatches is defined and solved for a scalar multiplier μ .The analysis of the μ value during the iteration process allows for termination if the load flow solution does not exist or if the problem does not converge due to the precision deficiency in the computer. This method seems to be very efficient for dealing with ill-conditioned problems. Unfortunately, it requires rectangular coordinates and its application is restricted to the complete Newton/Raphson method, besides requiring additional storage and computing time. So it was thought not to be appropriate for the developments in this thesis, but the idea of adopting the optimisation approach to detect unfeasible problems was taken into consideration and will be used later.

A particular problem in the load flow solution arises when the series branch impedances present high r/x ratios (unity or higher). These situations occur with high voltage lines with series capacitor compensation, low voltage lines, and cables. The Fast Decoupled Load Flow algorithm is particularly sensitive to such high r/x ratios. There are two approaches to the solution of this problem: series or parallel compensation. The series approach described by DyLiacco [42], shown in Fig 3.1a, splits a branch with impedance r+jx into a series circuit of two branches having impedances r+j(x+x") and -jx" with one intermediate dummy bus f. The parallel approach of Deckman et al. [44] was developed because there are cases where the series compensation has to be so large that the voltage of the dummy bus f becomes unusual, which itself causes convergence problems. The parallel compensation of Fig. 3.1b works better in such cases. The susceptance of the branch is artificially increased by the addition

of b_f, which is cancelled out by a dummy bus f and two dummy branches. The voltage at bus f is now always at the midpoint between the voltages of buses i and k.



a. Series b. Parallel

Fig. 3.1 Compensation Schemes for High r/x Branch Ratios

Although these schemes of compensation can be implemented automatically in a computer program, being made transparent to the program user, by no means do they constitute a definitive solution for the problem of high r/x ratios in as much as a dummy bus should be introduced for every high r/x branch, and this can increase enormously the dimensions of the problem to be solved.

An alternative method for resolving this problem was proposed by Haley and Ayres [45]. The load flow problem is formulated by using current injection equations in $N_{bus}+1$ dependent complex variables. This method requires customised sparse routines, and tuning of rotation operators to the complex bus injections and the complex bus voltages, which can be seen as a disadvantage. The use of complex variables and the significantly different matrices do not make the method attractive for the evolutionary approach adopted in this thesis.

Another approach to the high r/x branch ratio has been described by Rajicic and Bose [46]. An improvement in the number of iterations in relation to the above compensation approach is claimed to be achieved when experimentally determined coefficients are applied to

the elements of the Jacobian matrix B' of the Fast Decoupled Load Flow. The problem with this method is that it requires exhaustive experimentation to find the coefficients for a given network.

The first numerical studies involved Gauss/Seidel methods, including mixed versions involving combinations of Newton/Raphson techniques for the active problem and Gauss/Seidel for the reactive power problem. Accordingly, a program adhering to rules given by Behnam-Guilani [38] has been developed and tested. The results were found to be completely unsatisfactory. One problem with the method/program is that it never converged to the degree of tolerance set. Therefore, this approach was abandoned and attention has since been directed to Newton/Raphson methods.

A detailed comparative study has been made of various ways of decoupling the active and reactive power problems. Although, the main goal was to select a reliable decoupled algorithm, the complete Newton/Raphson method was included in the comparison in order to provide an accurate standard for comparing the approximations tried. The Decoupled Load Flow algorithm, in spite of its well known convergence problems, was also included with the hope of gaining insight into the various possibilities of updating the simplified Jacobian matrices and making approximations in them. In the following the basic algorithms are developed and their main characteristics discussed.

Newton Raphson Method (NR)

In the complete Newton Raphson method described by Tinney and Hart [47],(3.1) and (3.2) are linearised around an initial guess,

$$\begin{bmatrix} [\,\Delta P\,] \\ [\,\Delta Q\,] \end{bmatrix} = \begin{bmatrix} [\,H\,] & [\,N\,] \\ [\,M\,] & [\,L\,] \end{bmatrix} \begin{bmatrix} [\,\Delta\theta\,] \\ [\,\Delta V\,] \end{bmatrix} \qquad (3.7)$$

where,

$$[\,H\,] = [\,\partial P/\partial\theta\,] \qquad [\,N\,] = [\,\partial P/\partial V\,]$$
$$[\,M\,] = [\,\partial Q/\partial\theta\,] \qquad [\,L\,] = [\,\partial Q/\partial V\,] \tag{3.8}$$

or, in terms of components,

$$[\,H\,]\begin{cases} H_{ij}=\partial P_i/\partial\theta_j=V_iV_j(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \\ H_{ii}=\partial P_i/\partial\theta_i=-V_i^2 B_{ii}-V_i\sum_{j\in I} V_j(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \end{cases} \tag{3.9}$$

$$[\,N\,]\begin{cases} N_{ij}=\partial P_i/\partial V_j=V_i(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ N_{ii}=\partial P_i/\partial V_i=V_iG_{ii} + \sum_{j\in I} V_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \end{cases} \tag{3.10}$$

$$[\,M\,]\begin{cases} M_{ij}=\partial Q_i/\partial\theta_j=- V_iV_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ M_{ii}=\partial Q_i/\partial\theta_i=- V_i^2G_{ii}+V_i\sum_{j\in I} V_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \end{cases} \tag{3.11}$$

$$[\,L\,]\begin{cases} L_{ij}=\partial Q_i/\partial V_j=V_i(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \\ L_{ii}=\partial Q_i/\partial V_i=- V_iB_{ii}+\sum_{j\in I} V_j(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \end{cases} \tag{3.12}$$

Equations (3.9) through (3.12) show that the Jacobian matrix of (3.7) has the same characteristic of sparsity as the network matrix Y_{bus}. If the elements $Y_{ij} = G_{ij}+j\,B_{ij}$ are zero then H_{ij}, N_{ij}, M_{ij} and L_{ij} are also zero. The elements H_{ii}, N_{ii}, M_{ii}, and L_{ii} can be written as a function of the net active and reactive power injected at busbar i:

$$H_{ii} = - Q_i - V_i^2 B_{ii} \tag{3.13}$$
$$N_{ii} = P_i/V_i + V_i G_{ii} \tag{3.14}$$
$$M_{ii} = P_i - V_i^2 G_{ii} \tag{3.15}$$
$$L_{ii} = Q_i/V_i - V_i B_{ii} \tag{3.16}$$

The Jacobian matrix is factorised, using sparsity techniques, and (3.7) is solved iteratively for voltage angles and magnitudes until (3.1) and (3.2) are satisfied to an acceptable degree of accuracy, ϵ. At iteration υ,

$$\begin{bmatrix} [\ \Delta\theta\ ] \\ [\ \Delta V\ ] \end{bmatrix}_{\upsilon} = \begin{bmatrix} [\ H\ ] & [\ N\ ] \\ [\ M\ ] & [\ L\ ] \end{bmatrix}^{-1}_{\upsilon-1} \begin{bmatrix} [\ \Delta P\ ] \\ [\ \Delta Q\ ] \end{bmatrix}_{\upsilon-1} \tag{3.17}$$

$$[\ \theta\ ]_{\upsilon} = [\ \theta\ ]_{\upsilon-1} + [\ \Delta\theta\ ]_{\upsilon} \tag{3.18}$$

$$[\ V\ ]_{\upsilon} = [\ V\ ]_{\upsilon-1} + [\ \Delta V\ ]_{\upsilon} \tag{3.19}$$

The complete Newton Raphson method is reliable and presents excellent convergence characteristics. However, the coupling between voltage angle and voltage magnitude makes it inadequate for solving var-only problems.

Decoupled Load Flow (DLF)

For Extra High Voltage (EHV) systems, where the ratio r/x is small and the conditions of loading are normal, the interaction between voltage angle and voltage magnitude is small, and therefore it is a valid assumption to neglect the sub-matrices [M] and [N] in (3.7). This assumption together with an alternated scheme of updating [V] and [θ] yields the so called Decoupled Load Flow method, described by Stott [48].

$$[\ \Delta\theta\ ]_{\upsilon} = [\ H\ ]^{-1}_{\upsilon-1}\ [\ \Delta P\ ]_{\upsilon-1} \tag{3.20}$$

$$[\ \theta\ ]_{\upsilon} = [\ \theta\ ]_{\upsilon-1} + [\ \Delta\theta\ ]_{\upsilon} \tag{3.21}$$

$$[\ \Delta V\ ]_{\upsilon} = [\ L\ ]^{-1}_{\upsilon-1}\ [\ \Delta Q\ ]_{\upsilon-1} \tag{3.22}$$

$$[\ V\ ]_{\upsilon} = [\ V\ ]_{\upsilon-1} + [\ \Delta V\ ]_{\upsilon} \tag{3.23}$$

The alternated scheme of iteration allows a value for θ obtained at iteration υ to be used immediately for calculating ΔQ at the same iteration. Solving (3.20) and (3.21), as well as (3.22) and (3.23), is called half iteration. There are cases where the speed of convergence of each problem is different, and the iteration scheme allows iterations to be performed only on the non-converged sub-problem.

Fast Decoupled Load Flow (FD)

Further simplification is obtained by making the following approximations,

$$\cos \theta_{ij} \cong 1 \tag{3.24}$$

$$B_{ij} >> G_{ij} \sin \theta_{ij} \tag{3.25}$$

$$B_{ii} V_i^2 >> Q_i \tag{3.26}$$

$$V_i \cong 1 \tag{3.27}$$

With these approximations the Jacobian matrices become independent of the operational point, and (3.20) through (3.23) can be rewritten as

$$[\ \Delta\theta\ ]_\upsilon = [\ B'\ ]^{-1}\ [\ \Delta P/V\ ]_{\upsilon-1} \tag{3.28}$$

$$[\ \theta\ ]_\upsilon = [\ \theta\ ]_{\upsilon-1} + [\ \Delta\theta\ ]_\upsilon \tag{3.29}$$

$$[\ \Delta V\ ]_\upsilon = [\ B''\ ]^{-1}\ [\ \Delta Q/V\ ]_{\upsilon-1} \tag{3.30}$$

$$[\ V\ ]_\upsilon = [\ V\ ]_{\upsilon-1} + [\ \Delta V\ ]_\upsilon \tag{3.31}$$

Equations (3.28) through (3.31) form the Fast Decoupled Load Flow described by Stott and Alsac [49]. This load flow algorithm is widely used in the power system industry. It has many advantages and applications. Very good results are obtained when it is used respecting the assumptions and simplifications made in its

formulation. However it is, of course, bound to fail when applied in completely adverse situations, for example, with heavily loaded systems and other abnormal conditions, as is the case in contingency situations. Deriving sensitivity coefficients from B' and B'' does not produce sufficient accuracy for further developments in var-only load flow. Moreover the approximations made in attempting to solve the var-only problem, iterating with (3.30) and (3.31) alone, yield very poor estimates of the voltage magnitude.

Carpentier's Reactive Implicit Coupling (CRIC)

Fortunately, the implicit representation of the angle variations proposed by Carpentier [50] solves the problem and, once an active power solution has been reached, allows the performance of var-only iterations.

In (3.7), after a load flow solution, if the active injections are held constant when V and Q are allowed to vary, $\Delta P=0$, but not $\Delta\theta$. Thus

$$[\ H\ ]\ [\ \Delta\theta\ ] + [\ N\ ]\ [\ \Delta V\ ] = [\ 0\ ] \tag{3.32}$$

Equation (3.32) allows the var equation to be written as a function of the voltage magnitude alone:

$$[\ \Delta Q\ ] = [\ L'\ ]\ [\ \Delta V\ ] \tag{3.33}$$

$$[\ L'\ ] = [\ L\ ] - [\ M\ ][\ H\ ]^{-1}[\ N\ ] \tag{3.34}$$

Several different iterative computational schemes were tried, based upon combinations of (3.20), (3.28) and (3.33). The following combination has proved to be the most effective and, therefore, has initially been selected.

$$[\ \Delta\theta\ ]_{\upsilon} = [\ H\ ]^{-1}_{\upsilon-1}\ [\ \Delta P\ ]_{\upsilon-1} \tag{3.35}$$

$$[\ \theta\ ]_{\upsilon} = [\ \theta\ ]_{\upsilon-1} + [\ \Delta\theta\ ]_{\upsilon} \tag{3.36}$$

$$[\ \Delta V\ ]_{\upsilon} = [\ L'\ ]^{-1}_{\upsilon-1}\ [\ \Delta Q\ ]_{\upsilon-1} \tag{3.37}$$

$$[\ V\ ]_{\upsilon} = [\ V\ ]_{\upsilon-1} + [\ \Delta V\ ]_{\upsilon} \tag{3.38}$$

3.4 COMPARATIVE STUDY

Algorithm Developments

A formal testing procedure was designed to compare the adequacy of each method. In order to achieve maximum uniformity in the testing of the four load flow methods discussed above, they were implemented in the same computer program, which has been written from scratch. Since each different load flow method in the program shares the same common subroutines a direct comparison of the strengths of each method itself is assured, rather than the effects of varying programming implementation. The methods described in [45] and [46] are also compared as far as is permitted by the results published in these references.

The logic of the core program is shown in Fig. 3.2 and the logic of each load flow implementation is shown in Fig. 3.3 through Fig. 3.6.

Check for correctness

The algorithms have been extensively tested using several test networks and analyzing the results for correctness. In particular, reference [51] was chosen for comparison because a complete load flow output is given there with accuracy to 6 decimal places, including voltages, generator outputs, network matrix, losses and branch flows. The results of the new algorithms fully agreed with those given in reference 51. Step-by-step results published by Stott [43] have also been reproduced by the new algorithms.

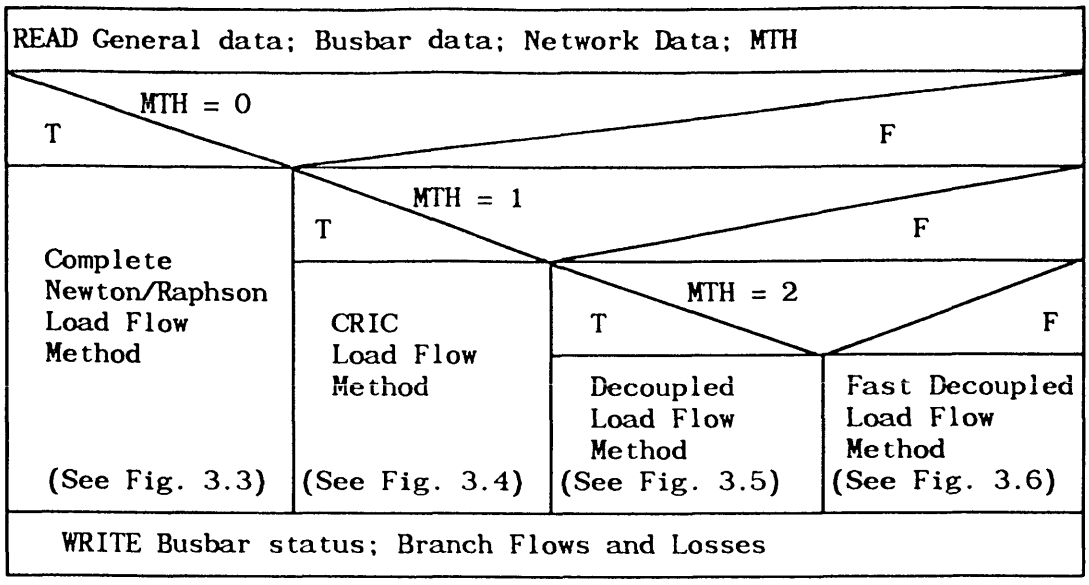


Fig. 3.2 Load Flow Test Program Flow Chart

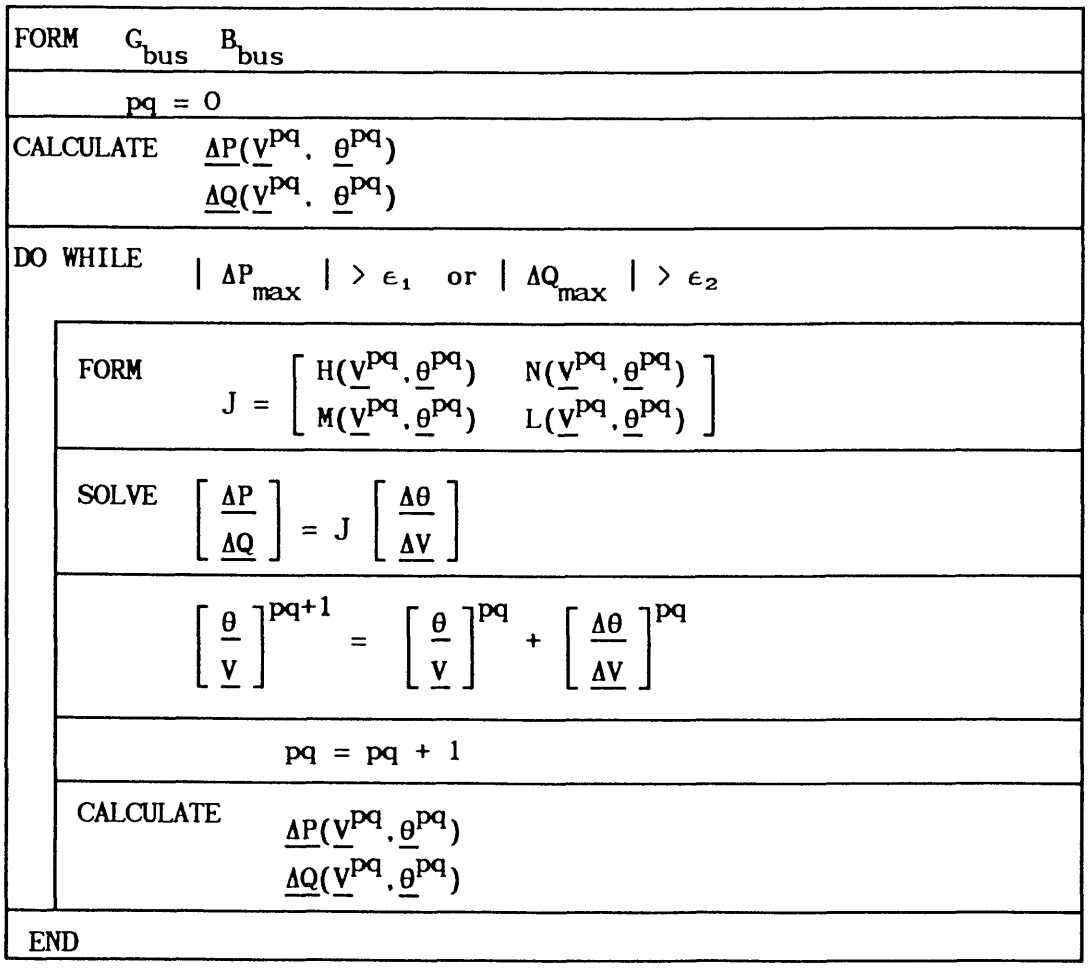


Fig. 3.3 Newton/Raphson Load Flow Algorithm

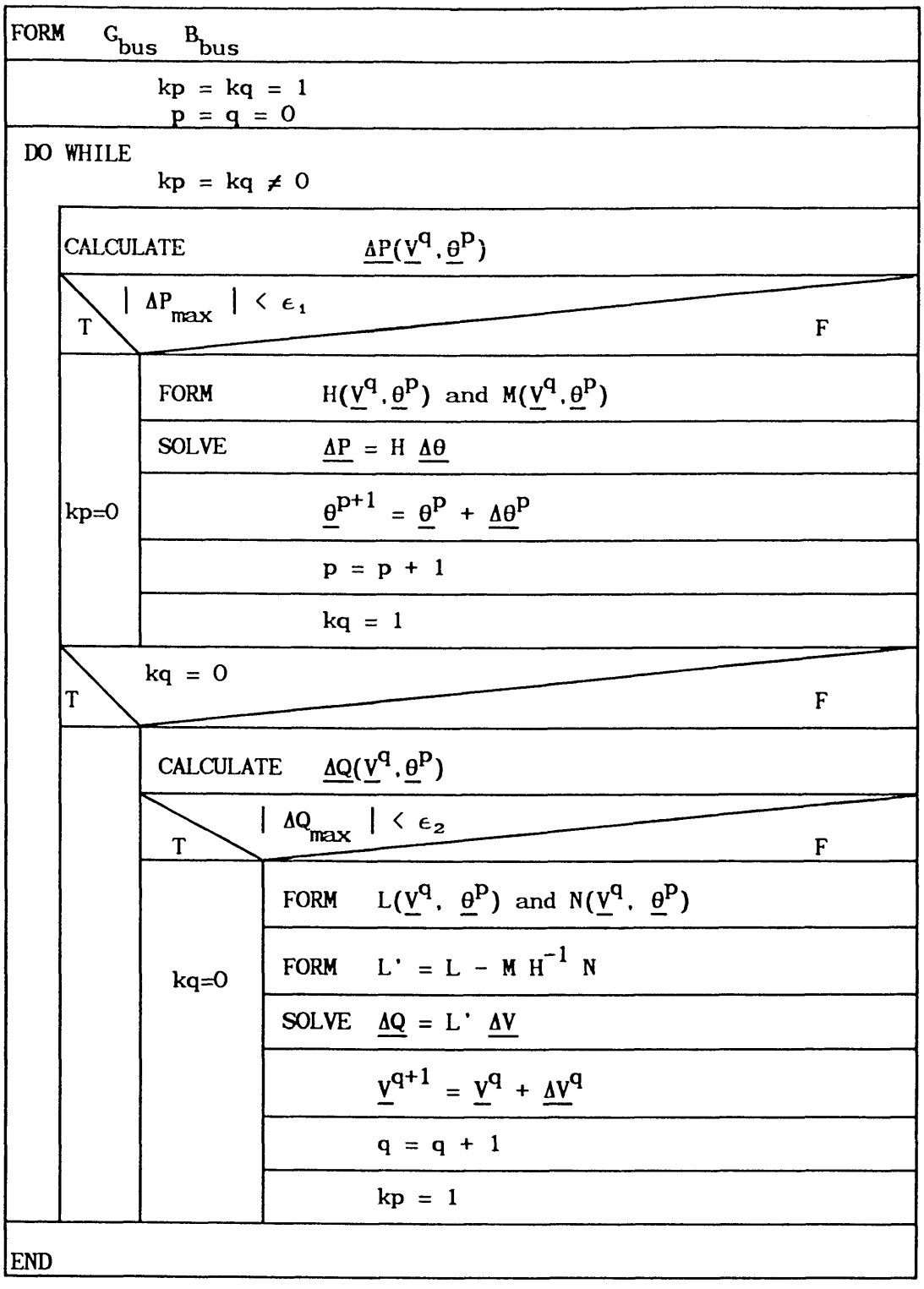


Fig. 3.4 CRIC Load Flow Algorithm

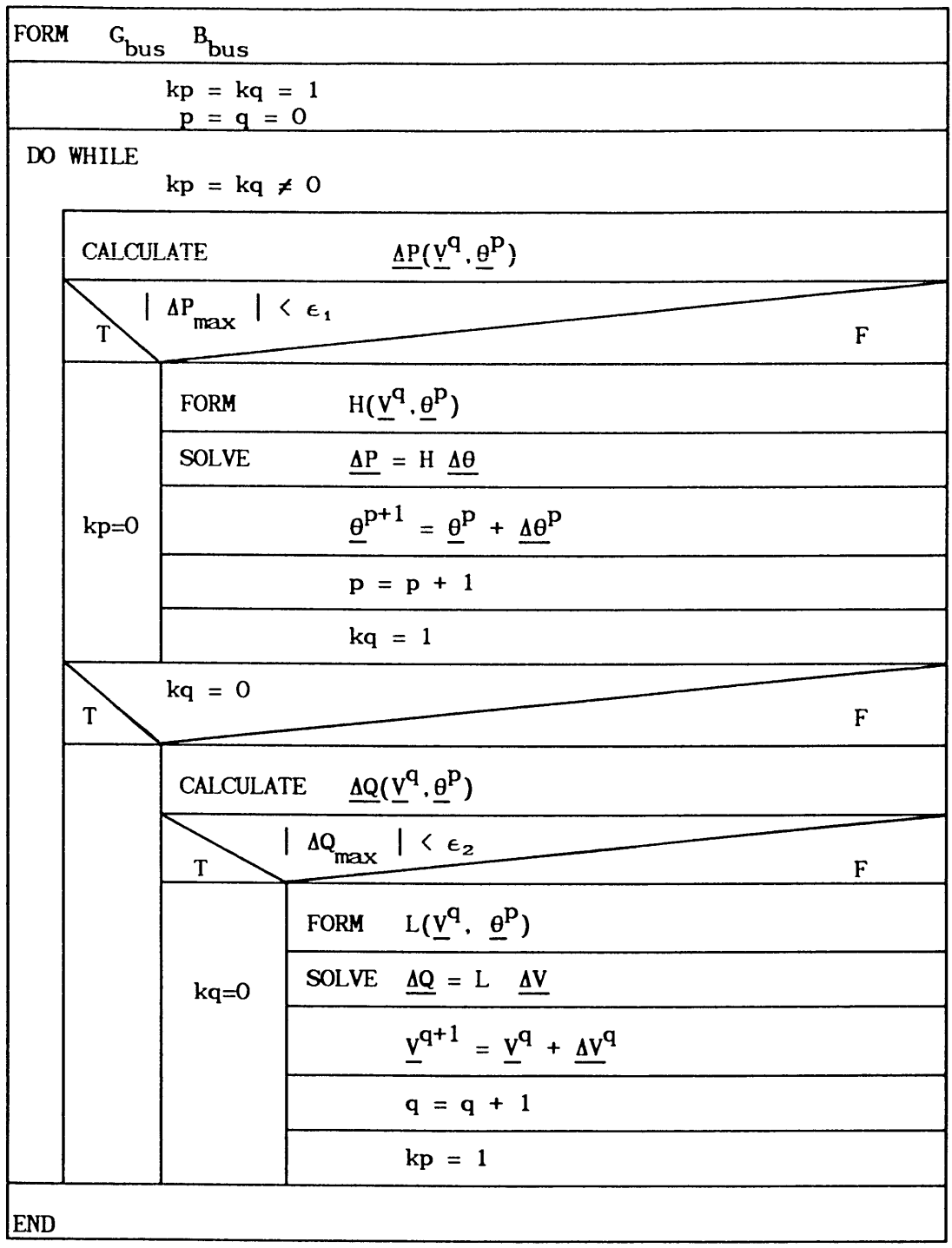


Fig. 3.5 Decoupled Load Flow Algorithm

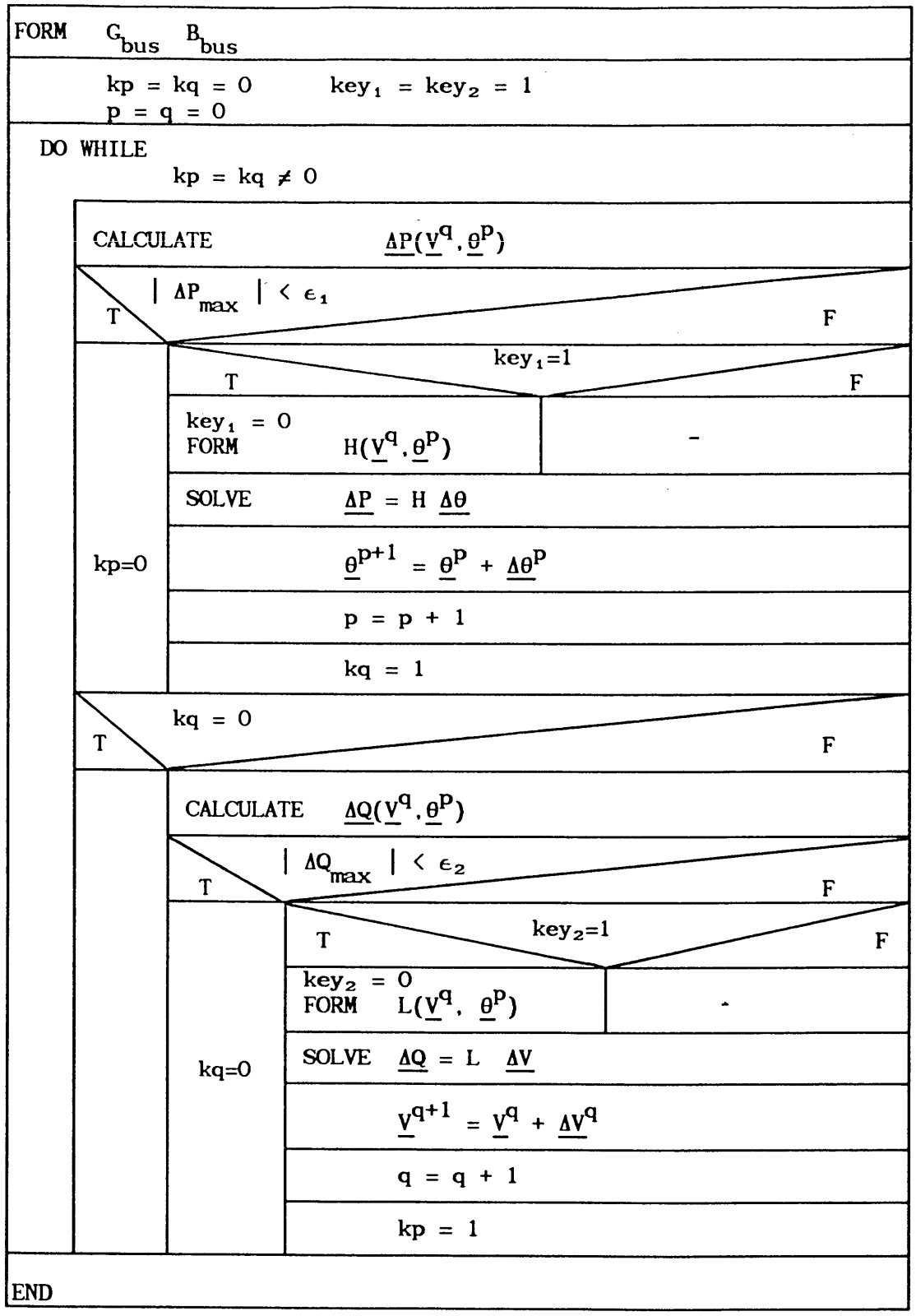


Fig. 3.6 Fast Decoupled Load Flow Algorithm

Scope of the testing

The main point investigated was the ability of the various load flow implementations to converge, with a high precision, for both normal and ill-conditioned networks.

Three test systems were used: Ward-Hale 6 bus system (WH6), IEEE 14 bus test system (IEEE14), and an actual 32 bus hard-to-solve Brazilian transmission subsystem (CEMIG32). In order to make the systems work near their static stability limits (i) the branch resistances were increased until all algorithms failed to converge, and (ii) the load was increased until all algorithms failed to converge. Note that the increase of a branch resistance corresponds to a decrease in the static stability limit and to an increase in the loss angle of this branch. The maximum number of iterations allowed was fixed at 20 for the decoupled versions and 10 for the complete Newton/Raphson method. The maximum tolerances were set up by fixing the maximum acceptable active and reactive bus power mismatches to less than 10^{-5} per unit.

Discussion of the results

Test #1 The Ward-Hale 6 bus test system was used (largest Ro/X=.69). The ratio R/Ro was increased from 0 (lossless system) to 4 (corresponding to every branch resistance equal to 4 times the original value). Table 3.1 shows the effects of increasing branch resistances on the convergence. Both CRIC and NR converged for all cases up to $R=3.5R_o$, whereas the DLF took 18 iterations to converge for a branch resistance equal to twice the original resistance and failed to converge for the larger resistances. The FD took 16p/15q

iterations to converge for R/R_o=3.0 against 6p/6q iterations for the CRIC. For all cases the number of iterations is much larger for both DLF and FD than for CRIC. The number of iterations increases significantly for the FD and DLF as the branch resistances increase, whereas it remains practically independent of increasing resistance for CRIC. Tables 3.2 and 3.3 show the load flow output for the base case and for the (R/R_o=3.5) case. It can be seen from Table 3.4 that the maximum mismatch drops rapidly and steadily even in the case of very low voltages: the (R/R_o=3.5) case produces voltage magnitudes as low as 0.59 pu.

Table 3.1 Test #1 - Ward Hale 6 Bus Test System
Effect of the Branch Resistance on the Iteration Rate

R/R_o	Number of Iterations to Converge						
	CRIC		FAST DECOUPLED		DECOUPLED		COMPLETE NEWTON
	NP	NQ	NP	NQ	NP	NQ	IT
0.0	4	4	9	8	5	5	4
0.5	4	4	8	7	5	4	3
1.0	4	4	8	7	6	5	4
1.5	5	4	7	7	6	6	4
2.0	5	5	9	9	18	18	4
2.5	6	5	11	11	f	f	4
3.0	6	6	16	15			4
3.5	10	9	f	f			6
4.0	f	f					f

Notes: 1) R_o: original branch resistance
2) NP, NQ: half iteration; IT: one Newton/Raphson iteration
3) f = fail to converge

Table 3.2a Ward Hale 6 Bus System - Base Case Results
Busbar Status

Busbar Number	Type	Voltage Magnitude p.u.	Angle degree	Power Injections Active p.u.	Reactive p.u.	Shunt +(C)/-(R) p.u.
1	SW	1.0500	.000	.952	.436	.037
2	PV	1.1000	-3.359	.500	.185	.000
3	PQ	1.0005	-12.787	-.550	-.130	.000
4	PQ	.9296	-9.837	.000	.000	.025
5	PQ	.9193	-12.338	-.300	-.180	.000
6	PQ	.9191	-12.241	-.500	-.050	.030

Table 3.2b Ward Hale 6 Bus System - Base Case Results
Branch Flows and Losses

Branch From Bus	To Bus	P (p.u.)	Q (p.u.)	P-loss (p.u.)	Q-loss (p.u.)
1	6	.443	.203		
6	1	-.417	-.091	.026	.112
1	4	.509	.270		
4	1	-.485	-.159	.024	.112
4	6	.089	.005		
6	4	-.088	-.001	.001	.004
6	5	.005	.072		
5	6	-.005	.070	.000	.002
5	2	-.295	-.110		
2	5	.328	.185	.033	.075
3	2	-.154	.026		
2	3	.172	.000	.018	.026
4	3	.396	.180		
3	4	-.396	-.156	.000	.024

Total Losses: Active: .102233 p.u. Reactive: .353331 p.u.

Table 3.3a Ward Hale 6 Bus System - (R/R_o = 3.5) Case Results
Busbar Status

Busbar Number	Type	Voltage Magnitude p.u.	Angle degree	Power Injections Active p.u.	Reactive p.u.	Shunt +(C)/-(R) p.u.
1	SW	1.0500	.000	1.619	.801	.037
2	PV	1.1000	-29.674	.500	.376	.000
3	PQ	.7365	-21.941	-.550	-.130	.000
4	PQ	.6834	-15.355	.000	.000	.014
5	PQ	.5978	-26.509	-.300	-.180	.000
6	PQ	.5930	-21.613	-.500	-.050	.012

Table 3.3b Ward Hale 6 Bus System - (R/R_o=3.5) Case
Branch Flows and Losses

Branch From Bus	To Bus	P (p.u.)	Q (p.u.)	P-loss (p.u.)	Q-loss (p.u.)
1	6	.759	.380		
6	1	-.478	-.042	.281	.339
1	4	.861	.459		
4	1	-.619	-.139	.242	.319
4	6	.142	.040		
6	4	-.126	-.021	.016	.019
6	5	.103	.025		
5	6	-.103	-.016	.000	.009
5	2	-.197	-.164		
2	5	.378	.282	.182	.118
3	2	-.073	-.073		
2	3	.122	.094	.050	.021
4	3	.478	.114		
3	4	-.478	-.057	.000	.057

Total Losses: Active: .7696 p.u. Reactive: 0.8806 p.u.

Table 3.4 Ward Hale 6 Bus System
Rate of Convergence for the (R/R_o=3.5) Case

Iteration Number	Maximum Bus Power Mismatch (p.u.) Active	Reactive
0	.516287	1.036340
1	.304603	.296559
2	.102640	.124016
3	.412624E-01	.407921E-01
4	.183145E-01	.127479E-01
5	.971645E-02	.409312E-01
6	.477621E-02	.124735E-02
7	.196929E-02	.303156E-03
8	.571222E-03	.453661E-04
9	.909817E-04	.307834E-05
10	.207603E-07	

Test #2 This test involves the IEEE14 bus test system (largest Ro/X=1.1). The branch resistances were increased from 0 to 4.5 times the original values. The quadratic convergence characteristic of the CRIC was even more noticeable in this test, as can be seen in Table 3.8. Figure 3.7 illustrates the development of the mismatch reduction with the number of iterations for the FD and for the CRIC. Both active and reactive power mismatches dropped rapidly and reached 10^{-5} in four CRIC iterations whereas it took more than 14 FD iterations to reduce the power mismatches to around 10^{-3}. Furthermore Table 3.5 shows that when the FD method was used, even after 21 FD iterations, the tolerance of 10^{-5} had not been reached. It can also be seen that the DLF method requires 20p/19q iterations to meet the tolerance criterion against 4p/4q CRIC iterations. Note also that the method of [46] always takes more iterations than the CRIC. Additionally, Table 3.5 shows that, for the CRIC, the number of iterations is insensitive to the increase in the branch resistances whereas the other decoupled algorithms fail for any increased branch resistance.

Table 3.5 Test #2 - IEEE14 Bus Test System
Effect of the Branch Resistance on the Iteration Rate

R/R_o	Number of Iterations to Converge							
	CRIC		FAST DECOUPLED		DECOUPLED		NR	RAJICIC/BOSE
	NP	NQ	NP	NQ	NP	NQ	IT	RB*
0.0	4	3	6	5	4	4	3	
0.5	4	4	7	7	6	6	3	9
1.0	4	4	21f	21f	20	19	3	9
1.5	4	4			f	f	3	
2.0	4	4					3	11
2.5	5	4					3	
3.0	6	5					4	13
3.5	6	6					4	
4.0	6	6					5	21f
4.5	f	f					f	

Notes: 1) R_o: original branch resistance 2) f=fail to converge
3) NP, NQ: half iteration; IT: one Newton/Raphson iteration
4) RB*: Results taken from [46] for a convergence tolerance of 0.01 MW/MVAr.(Tolerance=0.00001 pu for the other results)

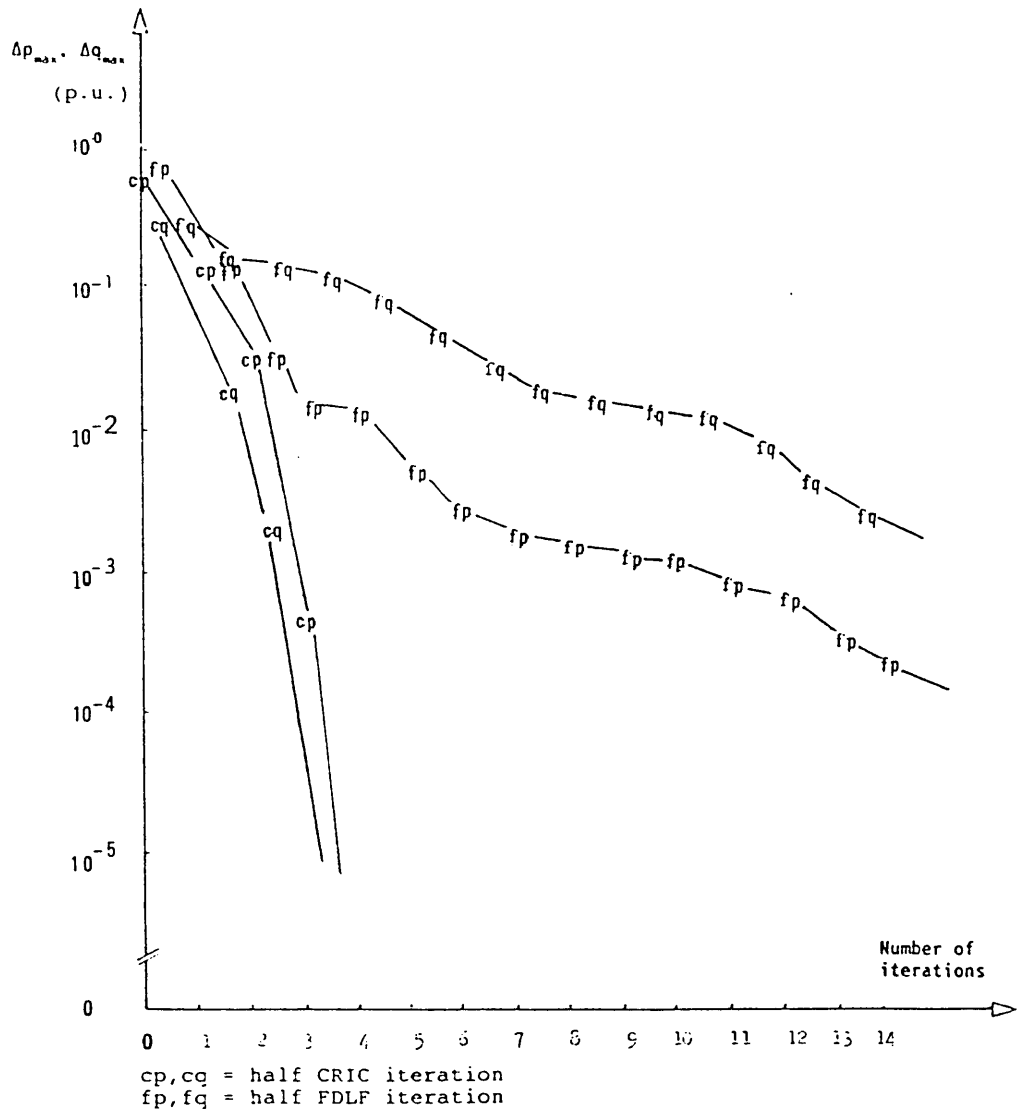


Fig. 3.7 Maximum mismatch reduction rates
IEEE 14-bus test system - base case

Table 3.6 and 3.7 show the load flow results for the base case and for the (R/R_o=4) case.

Table 3.6a IEEE14 Bus System - Base Case Results
Busbar Status

Busbar Number	Type	Voltage Magnitude p.u.	Angle degree	Power Injections Active p.u.	Reactive p.u.	Shunt +(C)/-(R) p.u.
1	SW	1.0600	.000	2.752	-.170	.000
2	PV	1.0450	-6.194	-.217	.647	.000
3	PV	1.0100	-13.895	-.942	.134	.000
6	PV	1.0300	-15.013	-.112	-.130	.000
8	PV	1.0900	-14.398	.000	.247	.000
4	PQ	1.0070	-11.174	-.478	-.039	.000
5	PQ	1.0080	-9.483	-.076	-.016	.000
7	PQ	1.0501	-14.398	.000	-.000	.000
9	PQ	1.0373	-16.081	-.295	-.166	.204
10	PQ	1.0284	-16.206	-.090	-.058	.000
11	PQ	1.0257	-15.767	-.035	-.018	.000
12	PQ	1.0162	-15.940	-.061	-.016	.000
13	PQ	1.0128	-16.069	-.135	-.058	.000
14	PQ	1.0081	-17.135	-.149	-.050	.000

Table 3.6b IEEE14 Bus Test System - Base Case Results
Branch Flows and Losses

Branch From Bus	To Bus	P (p.u.)	Q (p.u.)	P-loss (p.u.)	Q-loss (p.u.)
1	2	1.935	-.271		
2	1	-1.869	-.443	.066	.171
1	5	.817	.101		
5	1	-.784	.008	.033	.109
2	3	.729	.048		
3	2	-.706	.026	.023	.074
2	4	.541	.059		
4	2	-.525	-.031	.016	.028
2	5	.382	.097		
5	2	-.374	-.090	.008	.007
3	4	-.236	.108		
4	3	.241	-.114	.005	-.006
4	5	-.650	.189		
5	4	.657	-.176	.006	.013
4	7	.291	-.093		
7	4	-.291	.111	.000	.018
4	9	.166	.011		
9	4	-.166	.004	.000	.014

Continue...

Table 3.6b (Continuation)

5	6	.426	.242		
6	5	-.426	-.190	.000	.052
6	11	.066	-.009		
11	6	-.065	.009	.000	.001
6	12	.076	.020		
12	6	-.075	-.018	.001	.001
6	13	.173	.050		
13	6	-.171	-.046	.002	.004
7	8	.000	-.238		
8	7	.000	.247	.000	.009
7	9	.291	.127		
9	7	-.291	-.117	.000	.010
9	10	.060	.087		
10	9	-.060	-.086	.000	.001
9	14	.102	.065		
14	9	-.100	-.061	.002	.004
10	11	-.030	.028		
11	10	.030	-.027	.000	.000
12	13	.014	.002		
13	12	-.014	-.002	.000	.000
13	14	.050	-.010		
14	13	-.049	.011	.000	.001

Total Losses: Active: .161964 p.u. Reactive: .511641 p.u.

Table 3.7a IEEE14 Bus System - (R/R_o = 4.0) Case Results
Busbar Status

Busbar Number	Busbar Type	Voltage Magnitude p.u.	Voltage Angle degree	Power Injections Active p.u.	Power Injections Reactive p.u.	Shunt +(C)/-(R) p.u.
1	SW	1.0600	.000	5.254	-3.499	.000
2	PV	1.0450	-24.365	-.217	3.740	.000
3	PV	1.0100	-42.741	-.942	1.583	.000
6	PV	1.0300	-32.086	-.112	.156	.000
8	PV	1.0900	-33.298	.000	.478	.000
4	PQ	.9399	-29.985	-.478	-.039	.000
5	PQ	.9461	-25.354	-.076	-.016	.000
7	PQ	1.0127	-33.298	.000	.000	.000
9	PQ	.9929	-34.985	-.295	-.166	.187
10	PQ	.9813	-34.504	-.090	-.058	.000
11	PQ	.9955	-33.320	-.035	-.018	.000
12	PQ	.9871	-32.682	-.061	-.016	.000
13	PQ	.9727	-32.746	-.135	-.058	.000
14	PQ	.9289	-34.549	-.149	-.050	.000

Table 3.7b IEEE14 Bus Test System - (R/R_0=4) Case Results
Branch Flows and Losses

Branch From Bus	To Bus	P (p.u.)	Q (p.u.)	P-loss (p.u.)	Q-loss (p.u.)
1	2	3.774	-3.026		
2	1	-2.164	4.225	1.610	1.199
1	5	1.481	-.473		
5	1	-1.019	.925	.462	.452
2	3	1.112	-.611		
3	2	-.837	.877	.275	.266
2	4	.512	-.035		
4	2	-.456	.059	.056	.024
2	5	.323	.163		
5	2	-.295	-.158	.028	.005
3	4	-.105	.707		
4	3	.242	-.636	.137	.071
4	5	-.684	.800		
5	4	.751	-.753	.068	.047
4	7	.269	-.229		
7	4	-.269	.258	.000	.028
4	9	.151	-.033		
9	4	-.151	.047	.000	.014
5	6	.486	-.032		
6	5	-.486	.090	.000	.058
6	11	.098	-.007		
11	6	-.094	.009	.003	.002
6	12	.080	.020		
12	6	-.077	-.018	.003	.002
6	13	.197	.053		
13	6	-.187	-.048	.010	.005
7	8	.000	-.444		
8	7	.000	.478	.000	.034
7	9	.269	.187		
9	7	-.269	-.175	.000	.012
9	10	.033	.086		
10	9	-.032	-.085	.001	.001
9	14	.092	.063		
14	9	-.085	-.059	.006	.003
10	11	-.058	.028		
11	10	.059	-.027	.001	.001
12	13	.016	.002		
13	12	-.015	-.002	.000	.000
13	14	.067	-.007		
14	13	-.064	.009	.003	.002

Total Losses: Active:2.665 p.u. Reactive:2.225 p.u.

Table 3.8 IEEE14 Bus System
Rate of Convergence for the (R/R_0=4.0) Case

Iteration Number	Maximum Bus Power Mismatch (p.u.) Active	Reactive
0	.879635	1.06137
1	.539958	.296519
2	.173639	.123726
3	.541898E-01	.158130E-01
4	.678710E-02	.177908E-02
5	.792037E-03	.199633E-04
6	.883936E-05	.853282E-05

Test #3 The IEEE14 bus test system. This test involved raising the load on every busbar from 100% to 400% of the initial loading, in steps of 50%. The DLF algorithm failed to meet the tolerances from the 200% loading upwards, as shown in Table 3.9. The FD method failed to meet the test tolerance criterion for loads equal to 100%, 150%, and 350% upwards. Note also that the method of [45] always takes more iterations than the CRIC. Both the CRIC and NR methods converged for all cases up to 350% of the initial loading. The 350% loading case was a very good test for the ability of the CRIC method to deal with heavy-load conditions. It can be seen from Table 3.10a that the 350% loading case presented 9 bus voltage magnitudes below 0.9581 per unit; 4 below 0.8329 p.u., and one as low as 0.7854 p.u.. It can also be seen that the voltage angles were abnormally high, the majority of them being in the range of 70-80 degrees. Even for this special power system condition the CRIC algorithm shows that the number of iterations is practically insensitive to the system loading. It is interesting to note from Table 3.10b that the huge variations in the var flows here are strongly influenced by the

variations in angles. For instance, comparing Table 3.6b and Table 3.10b one sees that the reactive line flow 3-2 varies from .026 pu, in the base case, to 1.461, in the 350% loading case, corresponding to a 5519% rise. It is also worth noting that the terminal busbars connecting line 2-3 are both PV type, therefore there were no variations in the busbar voltage magnitudes. These observations show the importance of considering the angle variations in further var developments. For example, a power system model based on a complete decoupled method used for monitoring voltage magnitudes alone, would not be able to detect similar problems. Contingency analysis and calculations of sensitivity are other areas where the effect of the angle should be taken into account.

Table 3.9 Test #3 - IEEE14 Bus Test System
Effect of the Loading on the Iteration Rate

S/S_o	Number of Iterations to Converge							
	CRIC		FAST DECOUPLED		DECOUPLED		NR	HALEY/AYRES
	NP	NQ	NP	NQ	NP	NQ	IT	HA*
1.0	4	4	21f	21f	20	19	3	8
1.5	4	4	21f	20f	20	20	3	
2.0	4	4	18	18	f	f	4	12
2.5	5	5	15	15			4	
3.0	5	5	13	13			4	18
3.5	6	5	f	f			5	
4.0	f	f					f	

Notes: 1) $S_o=P_o+jQ_o$: original busbar load
2) NP, NQ: half iteration; IT: one Newton/Raphson iteration
3) HA*: Results taken from [45] for 0.01 MW/MVAr tolerance. (0.00001 pu tolerance for the other results)
4) f=fail to converge.

Table 3.10a IEEE14 Bus System - (S/S_o = 3.5) Case Results
Busbar Status

Busbar Number	Busbar Type	Voltage Magnitude p.u.	Voltage Angle degree	Power Injections Active p.u.	Power Injections Reactive p.u.	Shunt +(C)/-(R) p.u.
1	SW	1.0600	.000	12.464	1.219	.000
2	PV	1.0450	-30.089	-.760	7.054	.000
3	PV	1.0100	-65.703	-3.297	2.839	.000
6	PV	1.0300	-74.442	-.392	2.087	.000
8	PV	1.0900	-67.953	.000	1.176	.000
4	PQ	.8319	-52.940	-1.673	-.137	.000
5	PQ	.8286	-45.367	-.266	-.056	.000
7	PQ	.8998	-67.953	.000	.000	.000
9	PQ	.8304	-75.977	-1.033	-.581	.131
10	PQ	.8329	-77.093	-.315	-.203	.000
11	PQ	.9154	-76.156	-.123	-.063	.000
12	PQ	.9581	-77.998	-.214	-.056	.000
13	PQ	.9257	-78.166	-.473	-.203	.000
14	PQ	.7854	-82.543	-.522	-.175	.000

Table 3.10b IEEE14 Bus Test System - (S/S_o=3.5) Case Results
Branch Flows and Losses

Branch From Bus	Branch To Bus	P (p.u.)	Q (p.u.)	P-loss (p.u.)	Q-loss (p.u.)
1	2	9.297	-.271		
2	1	-7.803	4.799	1.493	4.528
1	5	3.167	1.491		
5	1	-2.576	.927	.591	2.418
2	3	3.204	.409		
3	2	-2.755	1.461	.449	1.870
2	4	2.218	.909		
4	2	-1.911	.005	.307	.914
2	5	1.622	.935		
5	2	-1.438	-.390	.184	.546
3	4	-.542	1.377		
4	3	.688	-1.021	.146	.357
4	5	-1.899	.809		
5	4	1.982	-.554	.083	.255
4	7	.948	-.075		
7	4	-.948	.337	.000	.261
4	9	.502	.146		
9	4	-.502	.060	.000	.206
5	6	1.766	-.039		
6	5	-1.766	1.034	.000	.995
6	11	.347	.430		
11	6	-.320	-.372	.027	.057
6	12	.310	.148		
12	6	-.297	-.119	.014	.028

Continue...

Table 3.10b (Continuation)

6	13	.717	.475		
13	6	-.671	-.385	.046	.091
7	8	.000	-.971		
8	7	.000	1.176	.000	.205
7	9	.948	.634		
9	7	-.948	-.457	.000	.177
9	10	.132	-.073		
10	9	-.131	.076	.001	.003
9	14	.285	.020		
14	9	-.270	.012	.015	.032
10	11	-.184	-.279		
11	10	.197	.309	.013	.031
12	13	.083	.063		
13	12	-.080	-.061	.003	.002
13	14	.279	.243		
14	13	-.251	-.187	.027	.055

Total Losses: Active:3.398663 p.u. Reactive:13.031573 p.u.

Table 3.11 IEEE14 Bus System
Rate of Convergence for the (S/S_0=3.5) Case

Iteration Number	Maximum Bus Power Mismatch (p.u.) Active	Reactive
0	3.28	1.59
1	.704	.866
2	.269	.165
3	.710E-01	.886E-02
4	.483E-02	.323E-03
5	.167E-03	.190E-05
6	.122E-08	

Test #4 An actual 138/69/34.5 kV transmission system was used (largest Ro/X=3.4). This electric network is the south-northern subsystem of the transmission system of a Brazilian utility: Centrais Eletricas de Minas Gerais (CEMIG). The loading condition is the heavy-load condition of 1981. Unlike the previous test networks the CEMIG32 has a radial configuration. Unusually high r/x ratios, low voltage, high load, and radial network topology make the CEMIG32 a hard-to-solve system. Table 3.12 shows that both DLF and FD methods fail even if every branch resistance is reduced to half (R/R_o=0.5). The CRIC method was successful in solving the load flow problem for this network. Table 3.15 shows the maximum mismatch reduction rate. In Table 3.13 it can be seen that the voltage profile is very low: one busbar with voltage magnitude as low as 0.7986 p.u.; 18 busbars with voltage between 0.80 and 0.95 per unit.

Table 3.12 Test #4 - CEMIG32 Bus Test System
Effect of the Branch Resistance on the Iteration Rate

R/R_o	Number of Iterations to Converge						
	CRIC		FAST DECOUPLED		DECOUPLED		COMPLETE NEWTON
	NP	NQ	NP	NQ	NP	NQ	IT
0.0	4	4	8	7	5	5	3
0.5	6	6	f	f	f	f	3
1.0	11	10					4
1.5	f	f					f

Notes: 1) R_o: original branch resistance
2) NP, NQ: half iteration; IT: one Newton/Raphson iteration
3) f=fail to converge.

Table 3.13 CEMIG32 Bus System - Busbar Status

Busbar Number	Busbar Type	Voltage Magnitude p.u.	Voltage Angle degree	Power Injections Active p.u.	Power Injections Reactive p.u.	Shunt +(C)/-(R) p.u.
1	SW	1.0000	.000	.749	.169	.000
2	PV	1.0000	-18.368	.035	.085	.000
3	PQ	.9184	-7.142	.000	.000	.000
4	PQ	.9859	-5.764	.000	.000	.000
5	PQ	.8274	-7.057	.000	.000	.000
6	PQ	.9439	-10.953	.000	.000	.000
7	PQ	.9575	-10.815	.000	.000	.000
8	PQ	.9478	-14.403	.000	.000	.000
9	PQ	.9230	-12.732	.000	.000	.000
10	PQ	.9407	-16.846	.000	.000	.000
11	PQ	.9664	-17.969	.000	.000	.000
12	PQ	.9607	-2.962	.000	.000	.000
13	PQ	.9638	-12.255	.000	.000	.000
14	PQ	.8791	-13.727	.000	.000	.000
15	PQ	.8117	-14.463	.000	.000	.000
16	PQ	.8408	-14.890	.000	.000	.000
17	PQ	.7986	-16.254	.000	.000	.000
18	PQ	.9286	-6.661	-.105	-.051	.000
19	PQ	.8649	-9.560	-.051	-.025	.018
20	PQ	.9685	-13.148	-.040	-.016	.023
21	PQ	.8901	-15.949	-.016	-.005	.000
22	PQ	.8507	-18.847	-.031	-.010	.009
23	PQ	.8662	-18.255	-.009	-.003	.000
24	PQ	.8399	-20.051	-.024	-.008	.008
25	PQ	.9463	-12.411	-.138	-.054	.032
26	PQ	.9494	-11.791	-.061	-.030	.000
27	PQ	.9788	-17.730	-.019	-.008	.011
28	PQ	.9723	-20.369	-.086	-.034	.011
29	PQ	.9995	-20.765	-.036	-.012	.000
30	PQ	.9303	-16.950	-.092	-.039	.021
31	PQ	.9681	-10.953	.000	.000	.000
32	PQ	.9232	-12.744	.000	.000	.000

Table 3.14 CEMIG32 Bus Test System - Branch Flows and Losses

Branch From Bus	To Bus	P (p.u.)	Q (p.u.)	P-loss (p.u.)	Q-loss (p.u.)
1	12	.749	.169		
12	1	-.728	-.155	.021	.014
12	3	.449	.093		
3	12	-.436	-.089	.013	.004
12	4	.173	.002		
4	12	-.173	.006	.000	.008
4	5	.061	.008		
5	4	-.051	-.009	.010	-.001
4	6	.113	-.015		
6	4	-.107	.015	.006	.001
6	7	-.026	-.030		
7	6	.027	.027	.000	-.003
7	8	.116	-.046		
8	7	-.112	.048	.004	.002
8	10	.093	-.046		
10	8	-.090	.046	.002	.000
10	11	.004	-.074		
11	10	-.003	.072	.001	-.002
11	2	-.033	-.086		
2	11	.035	.085	.002	-.001
3	7	.298	.054		
7	3	-.298	-.035	.000	.020
7	9	.095	.023		
9	7	-.092	-.023	.003	-.001
6	13	.093	.020		
13	6	-.093	-.018	.000	.002
13	14	.054	.011		
14	13	-.049	-.010	.004	.002
14	15	.033	.004		
15	14	-.031	-.003	.002	.001
13	16	.039	.006		
16	13	-.034	-.005	.005	.001
16	17	.025	.001		
17	16	-.024	-.001	.001	.000
12	18	.105	.060		
18	12	-.105	-.051	.000	.009
5	19	.051	.009		
19	5	-.051	-.007	.000	.002
14	21	.016	.006		
21	14	-.016	-.005	.000	.001
15	22	.031	.003		
22	15	-.031	-.001	.000	.002
16	23	.009	.004		
23	16	-.009	-.003	.000	.001
17	24	.024	.001		
24	17	-.024	.000	.000	.002
6	20	.040	-.005		
20	6	-.040	.007	.000	.002
7	26	.061	.031		
26	7	-.061	-.030	.000	.001
9	30	.092	.025		

Continue...

Table 3.14 (Continuation)

30	9	-.092	-.018	.000	.007
8	27	.019	-.002		
27	8	-.019	.003	.000	.001
10	28	.086	.028		
28	10	-.086	-.023	.000	.006
11	29	.036	.014		
29	11	-.036	-.012	.000	.002
25	3	-.138	-.022		
3	25	.138	.035	.000	.013
6	31	.000	.000		
31	6	.000	.000	.000	.000
9	32	.000	-.002		
32	9	.000	.000	.000	-.002

Total Losses: Active=0.07592 pu, Reactive=0.09178 pu

Table 3.15 CEMIG32 Bus System - Rate of Convergence

Iteration Number	Maximum Bus Power Mismatch (p.u.) Active	Reactive
0	.138000	.527872
1	.978724E-01	.167938
2	.440720E-01	.576067E-01
3	.592067E-01	.803069E-01
4	.480786E-01	.301509E-01
5	.467986E-02	.323634E-01
6	.791189E-02	.549862E-03
7	.138409E-02	.531843E-02
8	.210280E-02	.864743E-04
9	.778226E-04	.157493E-03
10	.655356E-04	.244052E-07
11	.385159E-07	

Concluding Comments: These comments are made with regard to the above numerical results: (i) The FD and DLF methods show failure in the majority of the cases. (ii) The CRIC implementation shows the same convergence characteristic as the complete NR. (iii) The number of CRIC iterations required for a solution is practically insensitive to both system loading and modifications of network parameters. It converges to a small tolerance within a few iterations and it is able

to handle ill-conditioned networks. Additionally, it is worth observing: (iv) It is a mistake to attempt to solve a heavy-loaded system in terms of FD and DLF. Similarly, it is wrong to concentrate on the effects of busbar voltage variations alone if unknown system conditions are to be analyzed. (For example: contingency analysis, var security assessment and enhancement and var emergency control.) (v) It is clear that the representation of the voltage angle cannot be neglected in solving var-related problems. (vi) On the other hand, a power system model with decoupling between the active and reactive power can be allowed if the var problem is to be solved as a second step. (vii) The implicit representation of the voltage angle is the answer to these two previous, apparently conflicting, conditions. Thereby, it becomes possible to adopt the evolutionary approach, i.e., after starting with an active power solution analyze the var/voltage problems.

3.5 THE PHYSICAL INTERPRETATION OF THE CRIC

A physical interpretation of the CRIC method allows for the calculation of a very close approximation of the matrix L'. To get a clear understanding of the principles involved a lossless system is analyzed step by step, then the general formulae for the approximation of L' are derived.

Consider the two bus system in Fig. 3.8, where active and reactive power injections P and Q are both known quantities.

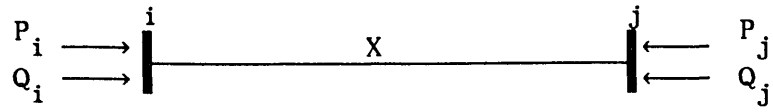


Fig. 3.8 Two-Busbar System

In this case, the load flow equations are

$$P_i - \frac{V_i V_j}{X} \sin \theta_{ij} = 0$$
$$P_j - \frac{V_j V_i}{X} \sin \theta_{ji} = 0 \qquad (3.39)$$

$$Q_i - \frac{V_i^2}{X} + \frac{V_i V_j}{X} \cos \theta_{ij} = 0$$
$$Q_j - \frac{V_j^2}{X} + \frac{V_j V_i}{X} \cos \theta_{ij} = 0 \qquad (3.40)$$

Let us apply the CRIC algorithm to solve the load flow problem for this system.

Step p: Keep the voltage magnitudes constant and find the voltage angles.

Make the initial guesses $V_i=V_i^o$ and $V_j=V_j^o$, and consider that $P_i=-P_j=P_o$ are given values. The solution in this particular case can then be obtained directly from (3.39) as

$$\sin \theta_{ij}^o = \frac{P_o X}{V_i^o V_j^o} \qquad \theta_{ij}^o = \sin^{-1}\left[\frac{P_o X}{V_i^o V_j^o}\right] \qquad \theta_{ji}^o = -\theta_{ij}^o$$

Step q: Keep the active injections constant and find the voltage magnitudes. As the reactive power injections have already been specified, the problem is now to solve the set of equations (3.40) subject to the constraints:

$$\sin \theta_{ij} = \frac{P_o X}{V_i V_j}$$

$$\sin \theta_{ji} = -\frac{P_o X}{V_j V_i}$$

These constraints are then used to eliminate the angles in (3.40) yielding a new model as a function of V only.

$$Q_i^o - \frac{V_i^2}{X} + \frac{V_i V_j}{X} - \frac{X P_o^2}{V_i V_j} = 0$$

$$Q_j^o - \frac{V_j^2}{X} + \frac{V_j V_i}{X} - \frac{X P_o^2}{V_j V_i} = 0 \qquad (3.41)$$

It is worthwhile to investigate the range of variation of the voltage magnitudes in this new formulation. Thus, the first equation of (3.39) is depicted in Fig.3.9.

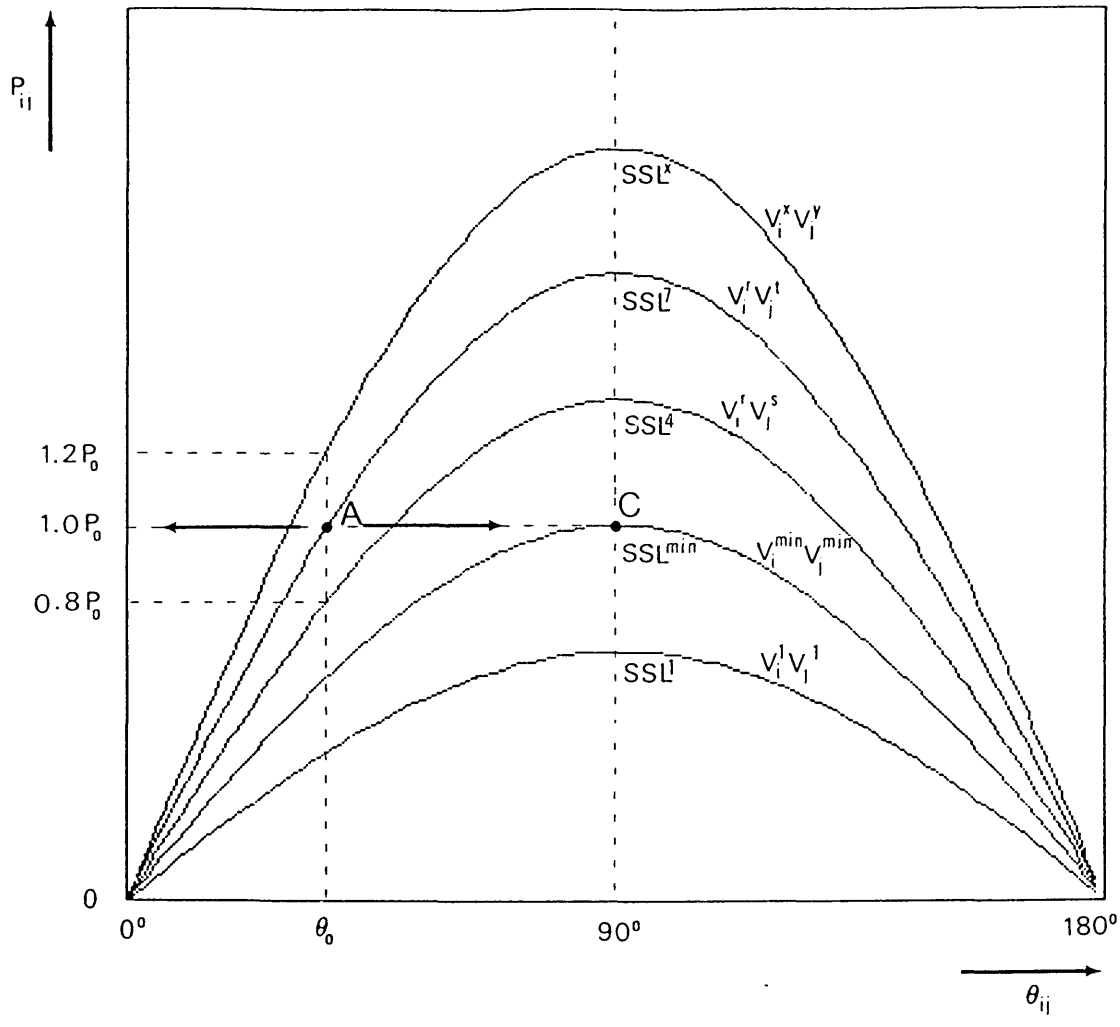


Fig 3.9 Two Bus System - Active Power Versus Angle

Point $A(\theta_o, P_o)$, in Fig. 3.9, represents the initial solution for the active power load flow step. The amplitude of the sinusoidal represents the static transmission limit ($SSL=V_iV_j/X$) of the line i-j. The variation of V_i V_j affects the SSL and describes a family of sinusoids. For increasing values of V_iV_j the point $A(\theta, P_o)$ moves to the left and a new stable solution can be reached. On the other hand, for decreasing values of V_i V_j the point $A(\theta, P_o)$ moves to the right,

and a stable solution can be reached until $V_i V_j = X\ P_o$, when the point A reaches the point $C(90^o, P_o)$. However, in general it is the equipment voltage limits which will prevail. Figure 3.10 further illustrates the range of variation of the voltage magnitudes and angles.

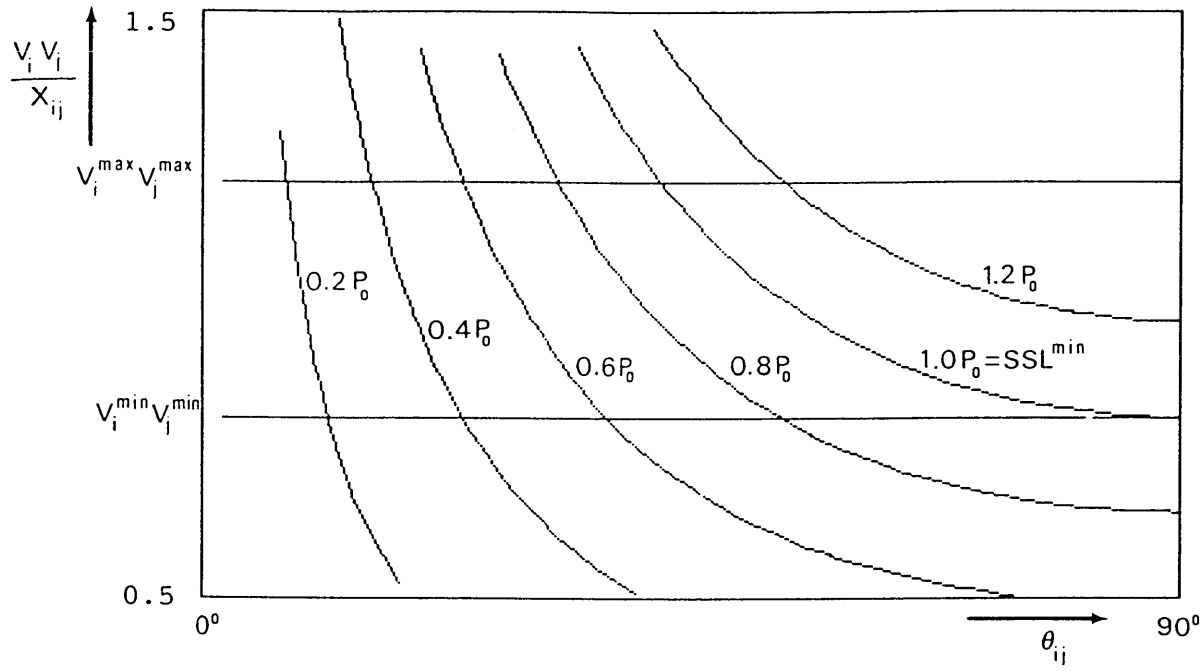


Fig 3.10 Two Bus System - V_i V_j versus θ

Using Fig. 3.10 as a basis the var-only load flow can be formulated as a completely independent non-linear problem in V alone:-

Minimise $\quad ||\underline{Q}(\underline{V})||_p$

subject to $\quad \underline{V}^{min} < \underline{V} < \underline{V}^{max}$

$$V_i\ V_j \geq P_{ij}\ X_{ij}$$

Where, p is some vector norm, the components of $\underline{Q}(\underline{V})$ are given by (3.41), P_{ij} are the active line flows calculated in the active step, and the limits are defined in Fig. 3.10. Notice that in the last set of constraints, only those constraints for which $P_{ij} > SSL(V_i^{min}, V_j^{min})$ will be active. The above formulation of the problem represents an

important achievement in as much as it allows for an exact var/voltage model. Thus further developments, such as contingency analysis and optimisation can now be carried out. Note that, this above formulation turns out to be a definition for var reserve: If a feasible solution exists then the var reserve is sufficient to meet the load conditions under consideration. Note also that it is indeed a new approach, allowing, in addition to the thermal limits, for the static stability limits to be taken into account. The constrained problem will be the subject of Chapter 5. However, the E&PSG load flow algorithm, which will be detailed later in this chapter, involves the minimization of the infinite norm and the monitoring of the stability limits.

The L' matrix derived from physical interpretation

The formulas for an actual system are now derived. Let a generalized branch be either an off-nominal tapped transformer (B=0) or a transmission line (a_i=1) as in Fig. 3.11.

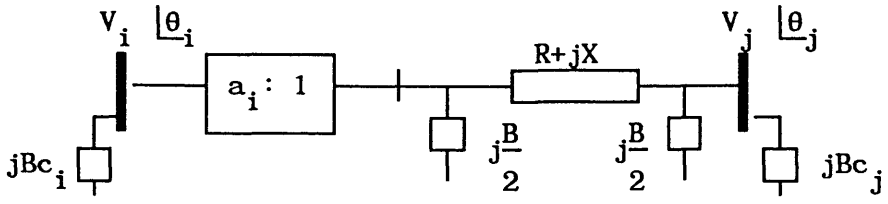


Fig. 3.11 Generalized Branch

Then the active and reactive power flows are given by

$$P_{ij} = y_{ij} \ (a_i V_i) V_j \sin(\theta_{ij} - \delta_{ij}) + (a_i V_i)^2 y_{ij} \sin(\delta_{ij}) \quad (3.42)$$

$$Q_{ij} = - y_{ij} (a_i V_i) V_j \cos(\theta_{ij} - \delta_{ij}) + (a_i V_i)^2 (y_{ij} \cos \delta_{ij} - B/2)$$

where,

$$y_{ij} = (R^2+X^2)^{-(1/2)} \qquad \text{and} \qquad \delta_{ij} = \frac{\pi}{2} - \tan^{-1}(X/R)$$

The power busbar injections are given by

$$P_i = \sum_{j\epsilon I',ij} P_{ij} \qquad \text{and} \qquad Q_i = \sum_{j\epsilon I',ij} Q_{ij} - Bc_i\, V_i^2 \tag{3.43}$$

In the same way as for the lossless system, after the active power step the active power flows for every branch of the network are calculated and then used to establish a relation between angle and voltage magnitude. From the first equation of (3.42) we obtain

$$\sin(\theta_{ij} - \delta_{ij}) = \frac{P^o_{ij}}{y_{ij}\,(a_i\,V_i)\,V_j} - \frac{(a_i\,V_i)^2\, y_{ij}\,\sin(\delta_{ij})}{y_{ij}\,(a_i\,V_i)\,V_j}$$

$$\cos(\theta_{ij}-\delta_{ij}) = \left[1 - \left[\frac{P^o_{ij}}{y_{ij}\,(a_i\,V_i)\,V_j} - \frac{(a_i\,V_i)^2 y_{ij}\,\sin(\delta_{ij})}{y_{ij}\,(a_i\,V_i)\,V_j} \right]^2 \right]^{1/2} \tag{3.44}$$

At this point it is convenient to define new parameters in order to simplify the explanation and, more importantly, to allow for an efficient computational implementation of the direct evaluation of L' subroutine. So, for a step q, let us define parameters which remain constant

$$\alpha_{ij} = P^o_{ij}/(y_{ij}\,a_i) \qquad \beta_{ij} = a_i\,\sin\delta_{ij}$$

$$\gamma_{ij} = y_{ij}\,a_i \qquad \eta_i = \sum_{j\epsilon I',i} a_i^2\,(y_{ij}\cos(\delta_{ij}) - 0.5\,B_i) - Bc_i$$

and, parameters which are voltage magnitude dependent

$$\rho_{ij} = \alpha_{ij} + \beta_{ij}\,V_i^2 \qquad s_{ij} = (\alpha_{ij} - \beta_{ij} V_i^2)/(V_i V_j) \qquad c_{ij} = (1-s_{ij}^2)^{1/2}$$

In terms of the above definitions, the reactive power flow equation of (3.43) becomes

$$Q_i = V_i \left(V_i \eta_i - \sum_{j \in I', ij} \gamma_{ij} V_j c_{ij} \right) \qquad (3.45)$$

The Jacobian of (3.45) yields the approximation of matrix L'. Thus, its components are given by,

$$L'_{ii} = \frac{\partial Q_i}{\partial V_i} = 2 \eta_i V_i - \sum_{j \in I', ij} \gamma_{ij} \frac{V_j + 2 \beta_{ij} s_{ij} V_i}{c_{ij}} \qquad (3.46)$$

$$L'_{ij} = \frac{\partial Q_i}{\partial V_j} = - \frac{\gamma_{ij} V_i}{c_{ij}}$$

Note that the approximation of the L' matrix calculated using (3.46) is as sparse as the network matrix Y_{bus}.

3.6 E&PSG - A NOVEL LOAD FLOW ALGORITHM

The comparative study carried out to compare the efficacy of various load flow methods to handle ill-conditioned systems has proved to be a very useful research tool not only for selecting the best load flow method but also as a learning mechanism. A good deal of insight was gained either by analyzing the programming aspects of the various algorithm implementations or by analyzing the output results of different methods. Many particularly small details were studied, as for instance, how alternative update schemes for iterative loops work, which data structure is more advantageous [52,53], how efficient are different numerical methods for the solution of linear systems of equations [53-59], which simplifications on the physical modelling can be made and how combinations of good characteristics of each method can be implemented. Thereby, many new solutions and improvements have

emerged. These improvements have been put together to design the final load flow methodology, called E&PSG, which meet the specifications of accuracy, robustness, compactness and speed. The main features of the present implementation of the method are discussed in the following.

Optimal Numbering

The Gaussian elimination (LDU factorisation) tends to destroy the sparsity of the triangular matrices L and U by creating new elements fill-in in positions that were zero in the original matrix. However, it is possible to minimise the number of fill-in elements by adopting a convenient order of pivoting during the elimination process. Another advantage of the optimal ordering besides storage economy is the reduction in the computation time, and the minimisation of the rounding-off errors. The optimal ordering can be efficiently implemented by simulating the elimination process in the incident matrix of the network [60]. There are,at least, three well known schemes of renumbering [58]. They are, in order of complexity:- Scheme 1 Renumber the rows of the matrix (or the buses of the network) in decreasing numerical order of off-diagonal non-zero elements (or of incident branches). Scheme 2 At each step of the gaussian elimination chose as the next row to be processed the one which presents the least number of non-zero off-diagonal elements. If more than one row satisfy this criterion, chose any one of them. Scheme 3 Renumber the rows so that the next row to be processed is the one which, if processed, would create the least fill-in. If more than a row satisfy this criterion, chose any one of them. This last scheme was adopted. Although scheme 3 takes a bit more computational effort than schemes 1 and 2, it produces the best result in terms of

minimisation of fill-in and, therefore, it speeds up further repeated forward and backward solutions. Other reasons for having chosen scheme 3 are:- (i) Because in our implementation the sparsity structure for the Jacobian matrices are kept the same as for the network Y_{bus} matrix, it is possible to simulate once and for all, at the beginning of the algorithm, the optimum ordering. (ii) The load flow is to be the base for further developments (contingency analysis, sensitivity analysis and optimisation) which require a great number of repeated solutions with maximum speed of response. (iii) Use on a micro-computer requires economic storage so as to enable to run medium size and large systems.

An additional ordering scheme has also been implemented in the E&PSG consisting of giving the number one to the slack busbar, then numbering in ascending order all the PV busbars, followed by the PQ busbars. The ordering is performed during the data input by just forming an integer pointer array whose elements point to the old busbar number. Almost no time is spent in this task which is transparent to the program user. Nevertheless, this renumbering scheme yields a significant speed-up in execution time, because it allows the loops to be written directly over the set of PV or PQ busbars without the need of searching and/or testing for the busbar status. Note that many such loops are present in a load flow program, and, mainly, in the further developments involving sensitivity matrices and OPF.

E&PSG Jacobian Matrices

Structural considerations: In traditional decoupled load flow formulations the dimensions of the active Jacobian (B'or H) and reactive power Jacobian (B'' or L) are different. The former has

dimension $(N_{bus}-N_{sw})x(N_{bus}-N_{sw})$ and the latter $(N_{bus}-N_{pv}-N_{sw})x(N_{bus}-N_{pv}-N_{sw})$. This difference in dimension constitutes a real disadvantage. Therefore, a different data structure has to be built and different routines should be written to deal with these matrices. Deriving extensions from the LDU table become a very intricate task. The schemes of automatic busbar status changes (PV-PQ-PV) requires changes in the structure of the matrix, which is likely to be time consuming. Moreover, when sensitivity matrices need to be derived the computational effort can be enormous, usually requiring the building of the whole sensitivity matrix from scratch.

In the E&PSG all matrices have the same dimension as the network matrices $(N_{bus}xN_{bus})$. The result is that only one data structure is built at the start. At the beginning of the program the storage area for the sparse arrays is allocated and the pointers are built dynamically from the transmission line input data, and the optimal renumbering performed at once. The addresses of the elements of all the sparse arrays are then referenced by the same pointers. No change in structure or dimension is performed during the execution of the program. This treatment of the matrices allows for significant simplification of the routines, and, therefore, gain in execution time.

Active Power Jacobian (B_p) It was found that defining the active power Jacobian matrix (B_p) as a constant matrix H (3.9) produces an accurate linear model for the active power step. This matrix should be calculated at the initial point $(\underline{V},\underline{\theta})$, and, in the same way as used in the DC load flow, the shunt elements should be neglected. This formulation has proved to be good enough to solve problems, such as for example the CEMIG32 bus system, which could not be solved by

adopting the B' matrix, as recommended in [46]. Another very important finding was that this matrix can be kept constant throughout the computation without affecting the performance of the algorithm. This last improvement lead to a tremendous saving in computer execution time, due to the fact that the LDU factorisation of this matrix is performed only once at the beginning of the program. An extra feature, which will be discussed in the next chapter, is that the triangular factors of this matrix can be used in contingency simulation for producing very good compensation injections.

VAR Jacobian Matrix (L_q) In order to define the var Jacobian with the same dimension as the active power Jacobian we should further investigate the physical concepts involved in the specification of a busbar as PV (or SW). The specification of the voltage magnitude on the PV busbars (and on the SW busbar as well) aims to represent the local voltage control that actually exists in these busbars. In other words, the voltage magnitude is to remain in the specified value as long as there exists enough local var generation to allow this condition to be satisfied. Now, in the Jacobian linearised model of the network the concept of the PV busbar is exactly the same concept as that of the infinite busbar, namely , a busbar that maintains the voltage magnitude constant for all loading conditions. In other words, a busbar with an infinite short-circuit level or an ideal source of voltage. It follows that a busbar with an infinite short-circuit level or an ideal source of voltage has a zero internal impedance or an infinite internal admittance. With regard to the above arguments, we simulated the PV specification of a busbar by exactly connecting an infinite

admittance (numerically speaking) to it. Thus, the elements of the L_q matrix are given by (3.46) with the following modification for PV busbars.

$$L_{q_{ii}} = \frac{\partial Q_i}{\partial V_i} = 2(\eta_i + b_\infty)V_i - \sum_{j \in I', ij} \gamma_{ij} \frac{V_j + 2\,\beta_{ij}\, s_{ij}\, V_i}{c_{ij}} \qquad i \leq N_{pv} \qquad (3.47)$$

The value $b_\infty = 10^{19}$ pu has proved to be adequate for all test systems. However, matrix B_p, and L_q as well, can still be singular if the slack busbar is simply included into the linear models. Nevertheless, this inclusion of the slack busbar in the matrices B_p and L_q is fundamental because in addition to the already discussed structural uniformity of the various matrices there are developments in sensitivity analysis and optimal power flow to be considered. Note that, in OPF the voltage magnitude at the slack busbar should be considered as a control variable. Although, there were found to be several OPF implementations in the literature which did not mention this requirement. The following solution was developed to solve the above problem.

False slack busbar

To avoid problems of singularity with the matrix B_p and L_q, a false slack bus is defined as shown in Fig. 3.12. The voltage magnitude, V_{fs} , and voltage angle, θ_{fs}, are set equal to the actual swing busbar voltage magnitude, V_{sw} , and voltage angle, θ_{sw}, respectively. The reactances, $\pm X$, connecting the false slack to the power system and to ground are made equal to 1% of the smallest line reactance of the network. At the end of the study the false slack busbar is eliminated by transferring its active power injection to

the actual swing busbar, P_{sw}, and, by adding the var flow entering the swing bus through the connecting branch to the actual swing reactive power, Q_{sw}.

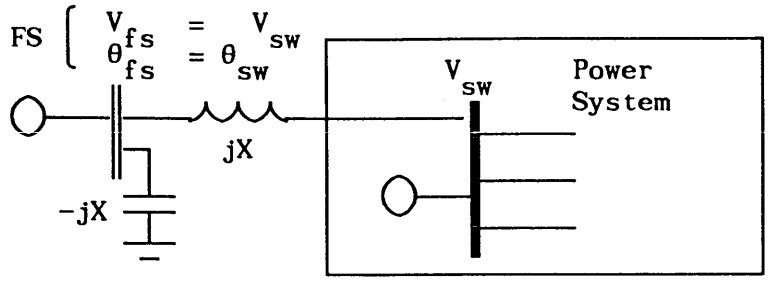


Fig. 3.12 False Slack Busbar (FS)

Enforcement of limits on var source outputs

There are two basic ways of enforcing the var limits at PV busbars in Newton/Raphson type algorithms:- (i) PV-PQ-PV type switching. Any violated PV busbar is converted to the PQ type with the var generation set at the limiting value. The voltage of the converted bus is subsequently compared to the schedule value, and the bus is reconverted to the PV-type, if the back-off conditions are satisfied.(ii) An error feedback scheme type $\Delta Q_i = s\ \Delta V_i$, where s is an estimated sensitivity coefficient. A combination of schemes (i) and (ii) have been recently suggested by Chan and Brandwajn [61].

The switching PV-PQ-PV method has been found to be the most efficient. A disadvantage of this scheme, which was resolved in our implementation, is the fact that the switching of busbar types involves insertion and deletion of equalities into/from the var Jacobian. In the E&PSG method there are no changes in the structure of the matrix; a PV busbar is transformed in PQ and vice-versa just by switching $\pm b_{\infty}$ in/off (3.47), therefore there is no structural

change of the Jacobian. During the iterative solution, the voltage magnitudes are updated only in the PQ bus set, neglecting the components of the vector ΔQ corresponding to the PV busbars. In our implementation the complete refactorisation of the matrix is performed. Although, the refactorisation as it is now, already presents very fast CPU time (0.06 sec., IEEE118, MICROVAX II), a gain of approximated 25% in CPU time may well be expected by implementing sparse factor updating [63] or partial matrix refactorisation (PR) [53,62] techniques, but at the sacrifice of the robustness of the method for ill-conditioned cases. Incidentally, from [62] it is worth quoting: "PR methods are most easily implemented for nonstructural modifications that involve changes only in value of the non-zero entries. Structural modifications caused by the addition of nonzero elements or alteration in the symmetry can be handled by PR methods, but additional logic is required to insert the new matrix factors into the LDU tables."

Update of the Jacobian Matrices

As has already been mentioned the B_p matrix is calculated and factorised only at the beginning of the program and kept constant throughout the load flow calculations. The Jacobian matrix L_q is a function of the latest voltage solution and, consequently, it should be formed and factorised anew at each iteration. During the assembling of the L_q matrix using (3.44), the SSL is monitored. Should a instable condition arise a warning message is given informing the terminal busbars involved. The updating scheme involves only the L_q matrix, therefore, it yields a considerably fast and very robust technique. This update scheme characterizes one of the two versions of the E&PSG method. Test results have shown that it is at least as robust as the complete Newton/Raphson method, and

conceptually faster than the decoupled load flow. Additionally, the E&PSG is a decoupled technique that can handle hard-to-solve and ill-conditioned systems as well as accommodating evolutionary extensions such as var-contingency analysis and var-OPF.

The next step was to investigate the variations of the L_q matrix with respect to the voltage solutions during the iterative process. It is well known that the linearised network model, whether based on the DC load flow, or on the first iteration of the FD, produces reasonable results for the voltage angle. In particular, it was observed that in general, the first p iteration produces the largest variation in the voltage angle vector, practically almost leading to the final result. It was not surprising, therefore, that the L_q matrix calculated using the angles obtained in the first active power iteration and kept constant for the other iterations has produced a good model for the var problem. The analysis of several results has confirmed the above reasoning leading eventually to the implementation of a fast version of the E&PSG. The outline of the fast E&PSG load flow update scheme is as follows.

For the first iteration do:

(i) Form and factor the B_p matrix

(ii) Solve $\underline{\Delta P} = B_p \underline{\Delta\theta}$ and $\underline{\theta} = \underline{\theta}^o + \underline{\Delta\theta}$

(iii) Calculate active branch flows $\underline{P}_{br} = \underline{P}_{br}(\underline{V}^o, \underline{\theta})$

(iv) Form and factor L_q matrix

(v) Solve $\underline{\Delta Q} = L_q \underline{\Delta V}$ and $\underline{V} = \underline{V}^o + \underline{\Delta V}$

For other iterations do only steps (ii) and (v).

Figures 3.13 and 3.14 show the complete logic of the E&PSG and the fast E&PSG load flow.

```
FORM        G_bus, B_bus
SET         k_p = k_q = 1, p = q = 0, initial values V^o, θ^o
OPTIMAL RENUMBERING
FORM AND FACTOR   B_p(V^q, θ^p)
WHILE   { k_p ≠ 0 or k_q ≠ 0 } DO
        CALCULATE  ΔP^p(V^q, θ^p)
        IF  { max_i | ΔP_i^p | > ε_p } THEN
                SOLVE  ΔP^p = B_p Δθ^p
                θ^(p+1) = θ^p + Δθ^p ;  p = p + 1 ;  k_q = 1
        ELSE
                k_p = 0
        END IF
        IF { k_q ≠ 0 } THEN
           CALCULATE  ΔQ^q(V^q, θ^p)
           IF { max_i | ΔQ_i^q | > ε_q } THEN
              CALCULATE  P_br^q(V^q, θ^p)
              FORM AND FACTOR   L_q(P_br^q, V^q)
              SOLVE  ΔQ^q = L_q ΔV^q
              V^(q+1) = V^q + ΔV^q ;   q = q + 1 ;  k_p = 1
           ELSE
              k_q = 0
           END IF
        END IF
END WHILE
CALCULATE  P_br(V^q, θ^p);  Q_br(V^q, θ^p)
END
```

Fig. 3.13 E&PSG Load Flow Algorithm

```
FORM      G_bus, B_bus
SET       k_p = k_q = 1, p = q = 0, initial values V^o, θ^o
OPTIMAL RENUMBERING
FORM AND FACTOR   B_p(V^q, θ^p)
WHILE   { k_p ≠ 0 or k_q ≠ 0 } DO
        CALCULATE  ΔP^p(V^q, θ^p)
        IF  { max_i | ΔP_i^p | > ε_p } THEN
              SOLVE  ΔP^p = B_p Δθ^p
              θ^(p+1) = θ^p + Δθ^p ;  p = p + 1 ;  k_q = 1
        ELSE
              k_p = 0
        END IF
        IF { k_q ≠ 0 } THEN
           CALCULATE  ΔQ^q(V^q,θ^p)
           IF { max_i | ΔQ_i^q | > ε_q } THEN
              IF { q = 0 } THEN
                 CALCULATE  P_br^q(V^q,θ^p)
                 FORM AND FACTOR   L_q(P_br^q,V^q)
              END IF
              SOLVE  ΔQ^q = L_q ΔV^q
              V^(q+1) = V^q + ΔV^q ;   q = q + 1 ;  k_p = 1
           ELSE
              k_q = 0
           END IF
        END IF
END WHILE
CALCULATE  P_br(V^q,θ^p);  Q_br(V^q,θ^p)
END
```

Fig. 3.14 Fast E&PSG Load Flow Algorithm

Other E&PSG features and program performance

The data structure of the E&PSG load flow program has been the object of a good deal of study and it may be considered to be particularly elaborate, fully exploiting sparsity techniques. However, the careful use of structured programming techniques has produced a self-documented program. As a result, ease of maintenance, further developments, and expansion of the program have been assured. Another development specification fully met was the portability of the software. This was achieved by deliberately using only standard FORTRAN features. Proof that this requirement is fulfilled is that the program development started on a mainframe CDC computer, then it was transferred to a VAX and finally to an IBM PC. The program runs on all these computers without any modification. There are no limitations imposed by the input data and individual representation of any number of parallel branches is allowed for, including off-nominal tapped transformers. The power system var reserve is monitored during the var generator limit checking and if all generators reach their limits a warning is given together with the best answer possible. The power mismatches are efficiently calculated by looping over the neighborhood of every busbar and minimising the number of arithmetical operations. By-products of the mismatch calculations are the bookkeeping of the busbar which presents the maximum power mismatch at a given iteration,and the best voltage results so far.

The E&PSG program has proved to meet the requirements of accuracy, robustness, compactness and speed. The first implementation has shown that the implicit representation of the angle was able to handle ill-conditioned problems while preserving decoupling between

active and var modelling. Thus, the requirements of accuracy and robustness were met. Since then the research effort has been concentrated in achieving speed and compactness whilst keeping accuracy and robustness. As a result of gradual improvements these goals have been eventually achieved. Table 3.16 shows the performance of the method in terms of computer time for several test systems. The performance of the present method has far surpassed by 419% the research goals in terms of cpu time given in Table 3.17 (The program is four times faster than the mean goal time: 7.75s x 32.5s). The program size is given in Table 3.18. Finally, it is interesting to mention that due to its ability to handle hard-to-solve problems and of converging for small tolerances, the program has been used in other research in the E&PSG group to investigate voltage collapse situations.

Table 3.16 E&PSG Load Flow Performance

Test Network Characteristics			Total Execution Time (CPU+I/O)		Number of Iterations	
System	Buses	Branches	MICRO VAX II (s)		p	q
Ward/Hale	6	7	.21		3	3
IEEE	14	20	.32		$1_1/_2$	$1_1/_2$
IEEE	24	34	.51		$2_1/_2$	$2_1/_2$
IEEE	30	41	.52		$1_1/_2$	$1_1/_2$
CEMIG	32	32	.76		4	$5_1/_2$
CEGB	34	56	.82		$3_1/_2$	4
IEEE	39	46	1.20		$2_1/_2$	$2_1/_2$
IEEE	57	80	1.96	(3.07)*	3	3
IEEE	118	179	3.91	(7.12)*	$2_1/_2$	$2_1/_2$
CEGB	729	1105	16.45		$3_1/_2$	5

* ( ) IBM-PC AT

Table 3.17 Computer Time Requirements for Modern Power System Control Centers (Basis: 500 bus , 1 MPI)

Function	CPU (sec)	I/O (sec)	Frequency of Execution (min)
State Estimator	5-10	10-20	5-30
Ext. Model	10-20	10-20	15-30
Sec. Analysis(DC)	3-16	3-5	5-30
Sec. Analysis(AC)	21-26	3-5	15-30
Volt. Scheduling	70-80	5-10	15-60
Security Dispatch	22-30	5-10	15-80
Load Flow	20-30	5-10	60-90
OPF	70-100	5-10	60-90

Source: F.F.Wu, Modern Power System Control Centers, Short Course at Helsinki University, 6 June 1988.

Table 3.18 E&PSG Load Flow Program Current Capabilities

Program Version	Max. Dimensions		Code Size	
	Buses	Branches	Source	Executable
IBM PC-AT	200	300	30 kbytes	296 kbytes
MICRO VAX II	1200	2000	63 blocks	36 blocks

CHAPTER 4

VAR/VOLTAGE CONTINGENCY ANALYSIS

4.1 INTRODUCTION

The security assessment process is composed of two functions: Security Monitoring and Contingency Analysis (Fig. 2.4). Contingency Analysis is often the most time-consuming function on an EMS [35]. The general practice is to perform contingency analysis on a list of credible contingency cases. Outages of components are simulated on the base-case model of the power system and the calculated post-contingency operating states are checked for operating limit violations. In principle, for any specific system and given set of contingencies, the current state can be estimated and post contingency system conditions calculated for all contingencies using a full AC load flow program. The results are accurate but the entire process is extremely time consuming. When super-computers are used, the process can be moderately time consuming but highly costly.

As has already been shown in the previous chapters, particularly in Tables 1.4 and 1.5, the time frames for the studies are long, medium and short term. The requirement of high speed of response makes the short time frame the most challenging one and, therefore, of special interest.

In this chapter the various aspects of contingency analysis are investigated. After a brief review of the present techniques, a new method for var/voltage contingency analysis is given.

4.2 CONTINGENCY ANALYSIS STAGES

Nowadays it is well established that contingency analysis should be divided into three main stages: contingency definition, contingency selection and contingency evaluation.

Contingency definition involves defining the list of contingencies to be studied in terms of electrical network changes. As it is impractical to study all possible contingencies because of time and the computational resources necessary, the general practice, usually called the N-1 criterion[1] , is to prepare a base case model of the network and to simulate the impacts of all single component branch/generator outages.

This common practice of using the N-1 criterion for assessing security for active power has proved to be inadequate from the var viewpoint. In addition to the traditional active power contingency list it is also necessary to take account of contingencies based on engineering judgement and experience. These may involve considering a few high probability N-2 contingencies, network and load level changes and var source outages [37,74]. In consequence, the initial list of contingencies is normally large.

Contingency selection is the process by which the initial long list of contingencies is screened to identify those producing truly

---

1 According to Carpentier [36] safety degree N-1 is met when for any state of the system occurring after the trip of one element (line or unit) from the foreseen steady state, line currents are lower or equal to a permissible limit, and voltages remain between given limits.

serious effects. The widely adopted approach is to rank the outage events according to their severity so that only the higher ranked cases are then studied in detail. Full AC studies are then applied to cases according to their listed rank order in a second stage until a non-violation case or a case with a violation less than a pre-defined tolerance is reached. The reason for this is that it is generally very difficult to set an absolute severity tolerance to detect severe cases individually, while it is easy and more accurate to rank cases according to relative severity. The reduced list containing the higher ranked cases is called the worst case list. According to reference [71] while a typical initial list involves around 50 to 1000 contingencies, the worst case list is normally reduced to a subset in the range of 5 to 25 cases.

Contingency evaluation is the detailed analysis of those contingencies considered to be severe, i.e., the worst case list. This analysis is accomplished by running full AC load flow computation.

In a recent paper [70] both the selection and analysis phases are solved in only one stage. Immediately after a severe case is detected the AC solution is carried out. One advantage of such an approach is that the full AC load flow computation can take advantage of the calculation already done in the contingency selection stage. A major difficulty is to select an absolute severity tolerance. Usually the two stage method uses a stopping criterion to choose the cases for contingency analysis but has an upper limit to the number of cases chosen. Thereby, the analysis of the higher ranked contingencies, theoretically the most severe

cases, is guaranteed. Additionally, knowing the maximum number of contingencies allows for an accurate assessment of the maximal computational requirement of the security assessment function with the two stage approach. This cannot be done for the one pass method as an upper limit may not catch the worst cases. Thus the number of AC solutions may vary widely depending on the system conditions. This makes it very difficult to predict computer loading for this function[83].

For the reasons presented above the three stage approach was preferred and adopted in this thesis. In summary, it can be said that: Contingency definition is a task typically dependent on the utility criterion and on the available computing power. The contingency evaluation stage can be solved by using the E&PSG load flow method of the previous chapter. A section describing the extensions to this program, to ease the decision making contingency evaluation stage, is included. These extensions are techniques for calculating the set of the most sensitive controls associated with each contingency. These can be incorporated very effectively inside an expert system for voltage control and var management as discussed by Cheng, Malik and Hope [93]. The contingency selection problem will be examined closely in the following sections.

4.3 CONTINGENCY SELECTION TECHNIQUES

Most of the present techniques for contingency selection are based on a simplified linear model of the network. These techniques invariably trade off accuracy for execution speed. At one extreme,

DC load flow methods are fast, but provide no voltage information. At the other extreme, full AC contingency evaluation is slow, but provides accurate voltages. Intermediate methods attempt to provide some voltage information with less computation time.

Approaches for Contingency Selection

The approaches for contingency selection are generally classified as performance index (PI) based ranking and contingency screening techniques.

Performance Index

The PI approach relies on a single-valued function whose magnitude reflects the severity of out-of-limit bus voltages, output of power sources and branch overloads for a given contingency. The decision if a contingency is critical or noncritical is based on the value of the PI and its relative value to some threshold value J_{th}.

General Form of Performance Index:- Fischl et al. [76] have shown that all performance indices have the same general form

$$J = w_i \, [f_i(z)]^p \tag{4.1}$$

where $f_i(z)$ is a linear function of z which denotes either the real power line flows $(P_{br,i}/P^{max}_{br,i})$ [66,77,78,84,85], or changes in load bus voltage magnitudes $(\Delta V_i/\Delta V_i^{lim})$ [77,85,86], or generator bus injections with respect to their ratings $(\Delta Q_i/\Delta Q_i^{lim})$ [77,85], or a composite PI based on the sum of voltage magnitude and injected

reactive power [77] respectively. The major differences between the various PI's is the choice of the weighting coefficients w_i.

Some PI-based methods

DC Load Flow:- These methods are based on the linear model of the network $P=P(\theta)$. They generally use some variation of the Woodbury-Morrison-Shermam formula for inverse matrix modification, called compensation methods [57,79]. An example of this method can be found in [66]. An alternative formulation using P-θ, Q-V decompositions and fast decoupled strategies is given in [49].

Adjoint Network Sensitivity Method:- These techniques use contingency ranking schemes based on first-order sensitivity of the PI to the occurrence of contingencies. Only one additional DC load flow is required to compute the changes of the PI with respect to changes in every line, and, consequently, the method is very fast. Ejebe and Wollenberg [77] defined two criteria functions based on active power flows and on reactive generation and voltage magnitudes. Improvement in accuracy was reported to be achieved by evaluating the exact change of the active power flow PI [78]. The ranking produced by this method was said to be identical to that ranking based on the DC load flow technique.

Local Areas:- The idea is to determine and solve only that portion of the network affected by the contingency [82]. A very interesting approach for the active power problem can be found in [81]. First, the maximum value of power flow for every branch is

expressed in terms of maximum angle changes $\Delta\theta_{ij}$. Then, sparse vector techniques are used to calculate the bus voltage angle change $\Delta\theta_{km}$ between the terminal buses k-m of the outaged branch. Finally, assuming that the rest of the network acts as a voltage divider of $\Delta\theta_{km}$ it is shown that the angle across any branch cannot be larger than $\Delta\theta_{km}$. In consequence, it is only necessary to compare $\Delta\theta_{km}$ with the pre-prepared maximum angle change for each branch, in order to detect and eliminate contingency cases with no overloads. Unfortunately, the extension of these ideas to the var/voltage problem is hampered by the lack of a stand alone linear model Q-V.

Problems with the Performance Index Approach

Problems with PI include aggregation, misclassification and masking.

1. **Aggregation**

It is significant to notice that a single performance index encompassing a mixture of generically different variables such as bus voltage magnitude, branch real and reactive power flows, or real and reactive injections, does not seem to be appropriate, since the effects of some limit violations may be masked in the process of aggregation. It is generally well agreed that instead of using a single index, several indices should be defined representing each area of contingency selection. One such index may be used to rank transmission branch and injection contingencies in terms of the severity of branch overloads. A different index can be used for ranking transmission branch contingencies on the basis of their severity in terms of the out-of-limit voltage profile. A third index

can be used to analyze transmission branch contingencies in terms of their impact on reactive power injections at the generation buses. For example, according to [75] AEP defines five areas of application for the automatic contingency selection techniques: (1) Selection of transmission branch contingencies adversely affecting the real power flow (MW) in the transmission network. (2) Selection of transmission branch contingencies adversely affecting the voltage profile of the load buses (3) Selection of transmission branch contingencies adversely affecting the reactive power injections (Mvar) at the generation buses (4) Selection of real power (MW) injection contingencies adversely affecting the real power (MW) flow in the transmission network (5) Selection of reactive power (Mvar) injection contingencies adversely affecting the reactive power flows in the transmission network or bus voltage profile.

2. Misclassification

Another problem with the PI approach is that contingencies which are active (i.e, yield out-of-limit conditions) are misclassified by the algorithm as being inactive (i.e., yield no out-of-limit conditions) or vice-versa. The capture and miss rate of a PI based algorithm is defined [76] as a function of the number of misses (i.e., classifying an active contingency as being non-active) and false alarms (classifying an inactive contingency as being critical). A method to determine the PI threshold, J_{th}, and the weighting factors, w_i, is proposed in [76]. The problem is formulated as a non-linear optimisation in J_{th} and w_i, so as to minimise the capture rate of the critical contingencies. This method

has the potential of reducing the misclassification errors in contingency ranking but with a correspondingly increased computation burden.

3. Masking Effect

Masking effect is a problem normally associated with the choice of the exponent p in (4.1). This choice is critical in order to produce enough discrimination between the various contingencies. The PI for a case with many small violations can be comparable in value to the PI for a case with one huge violation. Usually the latter case is more severe. Furthermore, situations may occur where the limit violations may not be recognized (i.e., misclassification). This inability to discriminate such cases is called the masking effect. One approach to overcome this problem is to increase the value of the exponent, p to 2 or higher. The problem with this approach is that it introduces complications in the implementation of the algorithms. Another approach for reducing the masking effect is by partitioning the network into local areas and then to perform multiple ranking.

Conclusion, Performance Index:- Contingency ranking methods, although successfully applied to contingency selection of branch MW flow violations, have not achieved the same degree of success when applied to voltage-severity ranking. The main reason is that the reactive power-voltage problem is more non-linear. Consequently no stand alone linearized var-voltage network models are adequately valid for large perturbation analysis. Hence over the past few

years, contingency screening methods for var/voltage security analysis have emerged [66-70]. In these methods, explicit contingency screening is performed on all contingency cases using approximate network solutions.

Contingency Screening

The contingency screening approach is basically either the computation of 1p-1q iterations of the FDLF load flow algorithm or a combination of the active power portion of the FDLF with the Gauss-Seidel algorithm, with or without calculating the performance index. The main difference is that in contingency screening each voltage magnitude is explicitly calculated.

Some Screening Methods

Network Impedance Matrix:- These approximations rely on the use of simplified models such as Z_{bus} and Y_{bus} matrices, from which distribution factors for the line flows and generator injections are derived [54]. These methods were used in the past for planning and operating studies which were mainly based upon thermal limits considerations. Because the voltage magnitudes are considered fixed at the nominal value they are not appropriate for var/voltage studies. An extension of the method of distribution factors to reactive power, based on a S-E (complex power x complex voltage) representation of the network, was proposed in [87]. A claimed advantage of distribution factor methods is that because they are based on the Z_{bus} network and on the nominal operating conditions, they are independent of the operating point, and, therefore,

constant as long as the network structure does not change. Thus, they can be calculated and stored once and for all and can be used as needed under changing load conditions. Paradoxically, these same features above are sometimes used to exemplify a disadvantage of the method, namely, that many distribution factors, which have to be calculated and stored, may never be used.

1p-1q Algorithm:- Attempts to apply the DC load flow approach with a pure Q-V formulation to automatic contingency selection have failed for the var/voltage problem. For instance, reference [75] recognizes that a similar course of action as in [84] was tried for the var/voltage problem. This produced unreliable rankings when checked against the results generated by the full load flow simulation of each branch outage and explicit substitution of the post-contingency voltage magnitudes into the performance index. It is now generally accepted that a better procedure would be to first update the bus phase angles due to the branch outage, and, next, to use the updated angles to compute the reactive power mismatches, and, finally, compute the changes in the bus voltage magnitudes [77,66,87,75]. This essentially implies that one full iteration of the fast decoupled load flow of [49] must be performed. The so called 1p-1q algorithm can be thus outlined:-

(1) form and factorise the coefficient matrices B' and B''

(2) for all the transmission branches in the network do

    begin

(3) update the nodal admittance matrix to reflect the branch

outage;

(4) solve for the bus angles using the real portion of FDLF equations and network compensation;

(5) solve for the voltage magnitudes using the reactive portion of the FDLF and network compensation;

(6) compute the performance index value;

end

(7) sort the performance index values in descending order.

References [66,69,70,75] are examples of methods that employ the first iteration of the FDLF.

Pre-processing:- One of the most time-consuming tasks in the 1p-1q iteration is the calculation of the reactive power mismatches. With this method the idea consists of breaking the mismatch calculation into two terms. One term involves parameters which are independent of the operating points and, therefore, it can be computed off-line and stored. Thus, only the second term, which is dependent of the post-contingency operating point, needs to be computed on-line. Following this line, reference [75] defines a reference case each time that the change in the bus angle vector exceeds a given threshold. In terms of this reference case coefficients of the reactive power mismatches are computed and kept constant until a given change in the bus angle vector indicates the need for a computation of a new reference case.

Gauss-Seidel:- The idea is to use the FDLF for the active portion of the problem and the Gauss-Seidel algorithm for evaluating the voltage magnitudes.

$$B' \underline{\Delta\theta} = \underline{\Delta P / V}$$

$$V_m = (Q_m / V_m + \sum_{\substack{n=1 \\ n \neq m}}^{N_{bus}} B_{mn} V_n \cos \theta_{mn} + G_{mn} V_n \sin \theta_{mn}) / \sum_{\substack{n=1 \\ n \neq m}}^{N_{bus}} B_{mn}$$

Reference [88] claims a speed-up of fifty-percent in relation to the FDLF. This speed-up is based on the fact that this model does not use the matrix B", thus additional speed-up is obtained when B" needs to be refactorized. Another usually claimed advantage of this model is to enable easy representation of generator var limits. Incidentally,in the context of contingency selection this can be questionable, as the generator limit enforcement may be considered at the contingency evaluation stage. During the contingency selection process it can be assumed that the reference voltages of the AVRs remain unchanged and the generators' responses to a given contingency will be primarily dependent on changes to the field currents and, consequently, changes in the output of the var sources. Thereby, severe var contingencies can always be detected by monitoring the output of var sources during the contingency selection stage. The output of the var source limits can then be enforced at the contingency evaluation phase. Experiments made with this method have shown the usual problem with Gauss-Seidel methods, i.e., unreliable convergence. Similar findings are posteriorly

reported in references [89,90].

Methods [67,68] are additional examples of Gauss-Seidel based iterative techniques.

Local Areas:- These methods rely on the assumption that a contingency has local effects and, therefore, only the local area in the vicinity of the contingency needs to be solved. There are two different local area approaches: concentric relaxation methods and sparse vector methods. The former uses the Gauss-Seidel technique and the latter uses the lp-lq algorithm.

Concentric Relaxation Methods:- The method was first presented in [67]. The idea is that the algorithm adaptively determines the area to be solved. Starting with the first tier[2] buses around the contingency, the voltages are solved by a modified Gauss-Seidel iterative technique, assuming fixed voltages at the other buses. The flows into the second tier buses are then computed and compared against their pre-contingency values. If the change is significant the second tier buses are included in the subsystem of interest, and the above process is repeated, keeping the third tier voltages fixed at their pre-contingency values. The process continues by considering more buses tier by tier, until a point is reached where the changes in the boundary flows are no longer significant. A

2 For a given bus, the first tier is defined to be the set of buses that are directly connected to it. The second tier is the set of buses that are directly connected to those in the first tier (and not already in the first or inner tiers), and so on.

simplified version of concentric relaxation [68] employs three tiers of buses around the contingency as the best compromise between speed and accuracy, but loses the inherent adaptive advantages of the method. Difficulties with the concentric relaxation methods include: (i) to know a priori whether or not a given contingency has local effects, (ii) to identify how far the contingency effects propagate in the system, (iii) the origin of the voltage disturbance may be outside of the first tier, (iv) because the method uses a Gauss-Seidel load flow with its inherent convergence problems, it will not provide the required improvement in CPU time.

Sparse Vectors:-The basic attributes of sparse vector methods are a sparse independent vector and a sparse solution vector [91]. As the reactive power mismatch vector is full (and therefore, the corresponding vector of the changes in the voltage profile as well), none of the above requirements are met, and, therefore, the application of sparse vector techniques to the var problem, in principle, would be improper. However, under the assumption that local areas can be selected, it is possible to define a simplified sparse mismatch vector. The problem is that the process of selection of such an area requires additional computation time. Unless very simplified assumptions are made, yielding even more unreliable results, the additional computational effort required in the selection process offsets the gain in computing time resulting from the use of sparse vector techniques. An example of the method can be found in [70]. It uses the first iteration of the FDLF and the P^2X criterion for the selection of a voltage sub-network. This voltage

subnetwork is determined under the assumption that the voltage changes due to a branch contingency are predominantly caused by the redistribution of the active power flow previously flowing in this branch into the alternate path formed by the branches around the contingency. Thereby, only the terminal buses connecting the branches of the alternate path of the active power flow are chosen as belonging to the voltage sensitive subnetwork.

P^2X Criterion[70,92]:- The effects of the active power flow changes on bus voltage magnitudes in terms of reactive power line flows are given by

$$q_{loss,ij} = I^2 X_{ij} = X_{ij} (P_{ij}^2+Q_{ij}^2)/V_i^2$$

or, assuming V_i=1 and $P_{ij}>>Q_{ij}$, the var loss becomes:

$$q_{loss,ij} = P_{ij}^2 X_{ij}$$

Assuming, further that $P_{ij}=b_{ij}\ \theta_{ij}$, yields the incremental change in line power loss due to change in active power flow P_{ij}

$$\Delta q_{loss,ij} = 2\ b_{ij}\ \theta_{ij}\ \Delta\theta_{ij} \qquad (4.2)$$

The changes $\Delta\theta$ can be calculated from a DC load flow [92] or from the first iteration of the FDLF [70]. Equation (4.2) is used in [70] to define those buses connected to branches whose estimated incremental var loss exceeds a pre-fixed threshold ϵ. The set of voltage sensitive buses is there defined as

$$S_v = \{\ i,j\ :\ |\ \Delta q_{loss,ij}\ |\ >\ \epsilon_q\ \}$$

A similar approximation can be derived from the var injection expression:

$$Q_i = V_i \sum_{j\epsilon I} V_j\ (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij})$$

Making the simplifying assumptions $V_i \cong V_j \cong 1$ pu and $G_{ij} \cong 0$ gives

$$Q_i \cong - \sum_{j \in I} B_{ij} \cos \theta_{ij}$$

or, adopting $\sin \theta_{ij} \cong \theta_{ij} - \theta_{ij}^3$, or even $\sin \theta_{ij} \cong \theta_{ij}$, leads to

$$\Delta Q_i = \sum_{j \in I} B_{ij} \theta_{ij} \Delta\theta \qquad (4.3)$$

There are at least four major problems with the P^2X criterion: (i) The approximations given by (4.2-3) may not be valid. Note that this is the case for highly loaded branches where θ_{ij} is large; therefore the approximation $\sin \theta_{ij} \cong \theta_{ij}$ no longer applies. Another case is when the voltage profile of the base case is adverse: very low voltage magnitudes, for example. (ii) The computational effort to evaluate (4.3) cannot be ignored. It can be approximately of the order of calculating the exact var mismatches if $\sin \theta_{ij}$ is considered. (iii) Changes in the angle θ_{ij} will cause mismatch variations in all buses of the system. Even if one could select a sparse ΔQ vector by using an arbitrary threshold, the effect in terms of voltage changes would spread all over the system. (iv) Contingencies with off-nominal tapped transformers with great impact on the var flows would be hard to detect by just considering the active power flow effects.

Expert Systems

Artificial Intelligence [73] has began to appear in the literature. In my view, the judgement dependent tasks in contingency analysis are mostly confined to the contingency definition and contingency evaluation stages. The selection of weights, threshold, the definition of the worst-case-list, and the local area approach

in the contingency selection stage also call for expertise.

There is a more radical viewpoint [72] which argues that contingency selection is a data driven, knowledge intensive task, whose nature prevents algorithmic approaches from ever performing the selection well. On the other hand, from [72], it is recognized that there are several difficulties in integrating an expert system with an EMS computer: (1) Present EMS computers generally do not support languages suitable for expert systems. In particular, none of the more sophisticated commercial tools run on EMS computers. (2) Expert systems are notorious consumers of CPU cycles. The impact on the loading of the present EMS computers would be severe, and probably unacceptable. (3) Development of the expert system would require the availability of the entire EMS CPU. This makes it difficult to install an expert system on an existing EMS. (4) Software maintenance is already a major burden on the availability of existing EMS CPUs. The additional maintenance required by expert systems would aggravate this situation.(5) There are many other possible applications of expert systems in EMSs. No single CPU currently widely adopted in EMSs has the capacity to run them all. Thus, it appears that the best approach for integration is to use distributed processing.

Concluding Remarks on Current VAR/Voltage Security Assessment

There is a definite need for accuracy in the contingency selection algorithms. Unfortunately, it seems that most of the recent developments aim to speed-up execution time at the cost of accuracy. The big problem is that the existing techniques themselves

have not proved to be accurate enough to afford simplifications which invariably lead to even less accurate results.

An attempt to summarise the problems with the var/voltage contingency selection methods follows:

There is no stand alone simplified network model for the Q-V problem similar to that used for the P-θ problem. Furthermore, there is enough evidence [75,35] to show that an extension of the active power related methods is unacceptable for accuracy reasons. Any new Q-V model should take into account the changes in the voltage angles.

The local area approaches do not seem an attractive option due to their dependency on the network structure and lack of a general principle to define a local area. The computational effort to select a voltage area must be taken into account in assessing efficiency of the method. The employment of efficient sparse vector techniques is hampered by the fullness of the reactive power mismatch and voltage correction vectors.

Neither the Gauss-Seidel Hybrid Model nor the lp-lq algorithm seem to be a satisfactory option because of problems of accuracy and convergence.

The definition of several performance indices instead of only one global performance index seems to be the most adequate alternative in order to detect both the system wide effects of the contingencies and localized problems. The enforcement of out-of-limit var sources can be done in the contingency evaluation phase, nevertheless, the contingency selection algorithm must flag these situations.

Keeping these remarks in mind a new methodology for the var/voltage contingency selection was developed and will be detailed in the next section.

4.4 E&PSG CONTINGENCY SELECTION TECHNIQUE - THE BASIC MODEL

Network Model

The most important point in var contingency selection is to establish the model of the network. As has already been shown, the var step of the E&PSG Load Flow is a good linear model of the network because the effects of the voltage angles are implicitly represented in the decoupling. So it is the basis of the contingency selection methodology. Having obtained an accurate base case solution, the Jacobian matrix L_q, to be used in the contingency selection process, is formed and factorised once and for all. The active power model uses the same constant matrix B_p as for the base case. In summary, the linear models used are given by

$$B_p \, \underline{\Delta\theta} = \underline{\Delta P} \tag{4.4}$$

$$L_q \, \underline{\Delta V} = \underline{\Delta Q} \tag{4.5}$$

Iterative Scheme

The solution procedure consists of two independent iterative loops. First, the contingency effects are simulated in the active power mismatch vector and then the active power model (4.4) is solved for the voltage angles. Next, these angles are used to calculate the reactive power mismatches and then the reactive power

model (4.5) is solved for the voltage magnitudes. As in the DC load flow solution, only one iteration for the active power problem was found to be necessary to produce fairly good results for the voltage angles. However better accuracy is obtained by iterating with both active and reactive power problems sequentially. Experiments have shown that three P-θ iterations followed by three Q-V iterations, in general, produce good results. However, there are cases where convergence cannot be reached in three iterations. Several strategies were studied for such cases. The first strategy chosen consisted of adopting the voltage results of the first iteration and then computing a separate PI for the var injections, taking into account the reactive power mismatches of all busbars. The algorithm in this case becomes practically equivalent to the 1p-1q algorithm, but still presents better results than the traditional 1p-1q algorithm, because of the better modelling provided by the matrices B_p and L_q. Later, it was observed that a more effective stop criteria was to choose the best voltage result possible within the specified number of iterations. This best voltage result is found by monitoring the least maximum reactive power mismatch during the iterative Q-V process. The assurance of capturing all critical contingencies is guaranteed by the way the PI's were designed. Before detailing the design of the PI's it is worth noting that contingencies such as shunt capacitor/reactor switching, generation and load level modifications, which involve changes only in the injections vector do not cause convergence problems. Therefore attention is focused on branch contingencies.

Performance Index

A severe contingency is one which either causes a bus voltage or var source output violation greater than a predefined tolerance, or produces a large value for the summation of all bus voltage magnitudes or var source output violations in the system.

As has already been shown, a system wide performance index defined as a single valued function type of index, which penalizes violations of the bus voltage profile or/and reactive power injection limits, cannot detect local problems. Usually a single large violation is more severe than several minor kV or Mvar violations spread over all buses of the system. Such cases can easily be missed or ranked as of low severity if a system-wide PI is used alone.

In order to overcome this problem two PI's need to be used: one to detect the system-wide effects of the contingency and another to account for the local effects. In addition, the violations to be monitored involve different quantities, namely, voltage, and var outputs. To completely avoid the problems of aggregation, masking, and misclassification these quantities must be computed separately. Therefore, two extra indices are needed. Finally, it is also important to count the number of violations. Thus, to describe completely the effects of a contingency four PI's should be defined. These are defined as

$$J_{1v} = || \underline{\Delta V}_c ||_1 \tag{4.6}$$

$$J_{\infty v} = || \underline{\Delta V}_c ||_\infty \tag{4.7}$$

$$J_{1q} = || \underline{\Delta Q}_c ||_1 \tag{4.8}$$

$$J_{\infty q} = || \underline{\Delta Q}_c ||_\infty \tag{4.9}$$

where,

$$\Delta V_{ci} = w_{vi} |V_i - V_i^{lim}|$$

$$\Delta Q_{ci} = \begin{cases} w_{qi} \; |(Q_{gi} - Q_{gi}^{lim})/Q_{gi}^{lim}| & \text{iff } Q_{gi}^{lim} \neq 0 \\ w_{qi} \; | \; Q_{gi} | & \text{otherwise} \end{cases}$$

with,

$$w_{vi} = \begin{cases} 0 & \text{iff } V_i^{min} \leq V_i \leq V_i^{max} \\ 1 & \text{otherwise} \end{cases}$$

$$w_{gi} = \begin{cases} 0 & \text{iff } Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \\ 1 & \text{otherwise} \end{cases}$$

Note that the norms involve out-of-limit quantities only. If Q_{gi}^{lim} is equal to zero, the absolute value of Q_{gi} is taken into the norm instead of the relative value. Note also that the norms in (4.8-9) correspond to the relative value of the var source limit violations. Thus, each var source violation is accounted for with the same importance, independent of the size of the source. In other words, both large and small sources contribute with the same relative value to the index. Table 4.1 gives typical output of the performance indices for the IEEE 30 bus test system system. All of the four severity indicators in this table are equally important for a reliable contingency selection. Rather than an unexpressive number, the PI's so calculated provide all information necessary for a safe security assessment. The highly ranked contingency set, which is obtained by sorting the columns of Table 4.1, forms the worst case list.

Although sort processes can be computationally fast (usually

proportional to N log N, where N is the size of the list [57,52]), a better alternative for quickly finding the critical contingencies is to display the PI's graphically. This can be seen by considering, for example, Fig. 4.1, where the critical contingencies are clearly visible.

E&PSG Contingency Selection - The Basic Algorithm

The simplified outline of the basic algorithm is given in the following; more computational details can be found in Fig. 4.2.

(1) converge a base-case load flow.

(2) form and factorise the var Jacobian matrices B_p and L_q.

(3) for all transmission branches in the network do

begin

(4) update the nodal admittance matrix to reflect the branch outage;

(5) perform active power-only iterations for the angles using the voltage magnitudes of the base case.

(6) perform var-only iterations using the angles calculated in step (5) to calculate the reactive power mismatches. Record the best result so far.

(7) compute the performance index values and record the number of violations;

end

(8) sort in descending order (or plot) the performance index values and the number of violations.

Table 4.1 **Typical Performance Index Output**
E&PSG Contingency Selection Algorithm
IEEE 30 bus test system

Contingency	Buses		Performance Index				Number of Violations	
			Voltage		var output			
No.	from	to	J_{v1}	$J_{v\infty}$	J_{q1}	$J_{q\infty}$	V	var
base case			.472E+00	.390E-01	.000E+00	.000E+00	18	0
1	1	2	.509E+00	.410E-01	.000E+00	.000E+00	19	0
2	1	3	.482E+00	.395E-01	.000E+00	.000E+00	18	0
3	2	4	.478E+00	.393E-01	.000E+00	.000E+00	18	0
4	3	4	.474E+00	.390E-01	.000E+00	.000E+00	18	0
5	2	5	.499E+00	.404E-01	.000E+00	.000E+00	19	0
6	2	6	.489E+00	.399E-01	.000E+00	.000E+00	19	0
7	4	6	.510E+00	.413E-01	.000E+00	.000E+00	19	0
8	5	7	.502E+00	.403E-01	.000E+00	.000E+00	20	0
9	6	7	.455E+00	.381E-01	.000E+00	.000E+00	18	0
10	6	8	.529E+00	.417E-01	.000E+00	.000E+00	19	0
11	6	9	.478E+00	.403E-01	.000E+00	.000E+00	18	0
12	6	10	.462E+00	.383E-01	.000E+00	.000E+00	18	0
*13	9	11	-.111E+01	-.111E+01	-.111E+01	-.111E+01		
14	9	10	.847E+00	.683E-01	.000E+00	.000E+00	18	0
15	4	12	.350E+00	.313E-01	.000E+00	.000E+00	17	0
*16	12	13	-.111E+01	-.111E+01	-.111E+01	-.111E+01		
17	12	14	.521E+00	.560E-01	.000E+00	.000E+00	18	0
18	12	15	.635E+00	.591E-01	.000E+00	.000E+00	19	0
19	12	16	.474E+00	.392E-01	.000E+00	.000E+00	18	0
20	14	15	.471E+00	.388E-01	.000E+00	.000E+00	18	0
21	16	17	.462E+00	.381E-01	.000E+00	.000E+00	18	0
22	15	18	.472E+00	.394E-01	.000E+00	.000E+00	18	0
23	18	19	.464E+00	.408E-01	.000E+00	.000E+00	18	0
24	19	20	.509E+00	.627E-01	.000E+00	.000E+00	18	0
25	10	20	.583E+00	.734E-01	.000E+00	.000E+00	17	0
26	10	17	.498E+00	.577E-01	.000E+00	.000E+00	17	0
27	10	21	.550E+00	.460E-01	.000E+00	.000E+00	19	0
28	10	22	.491E+00	.390E-01	.000E+00	.000E+00	19	0
29	21	22	.471E+00	.390E-01	.000E+00	.000E+00	18	0
30	15	23	.461E+00	.390E-01	.000E+00	.000E+00	18	0
31	22	24	.476E+00	.394E-01	.000E+00	.000E+00	18	0
32	23	24	.466E+00	.393E-01	.000E+00	.000E+00	18	0
33	24	25	.454E+00	.403E-01	.000E+00	.000E+00	18	0
*34	25	26	-.111E+01	-.111E+01	-.111E+01	-.111E+01		
35	25	27	.568E+00	.718E-01	.000E+00	.000E+00	17	0
36	27	28	.164E+01	.223E+00	.000E+00	.000E+00	19	0
37	27	29	.509E+00	.453E-01	.000E+00	.000E+00	18	0
38	27	30	.507E+00	.529E-01	.000E+00	.000E+00	18	0
39	29	30	.472E+00	.390E-01	.000E+00	.000E+00	18	0
40	8	28	.502E+00	.399E-01	.000E+00	.000E+00	19	0
41	6	28	.535E+00	.460E-01	.000E+00	.000E+00	20	0

* Negative values = Network splitting

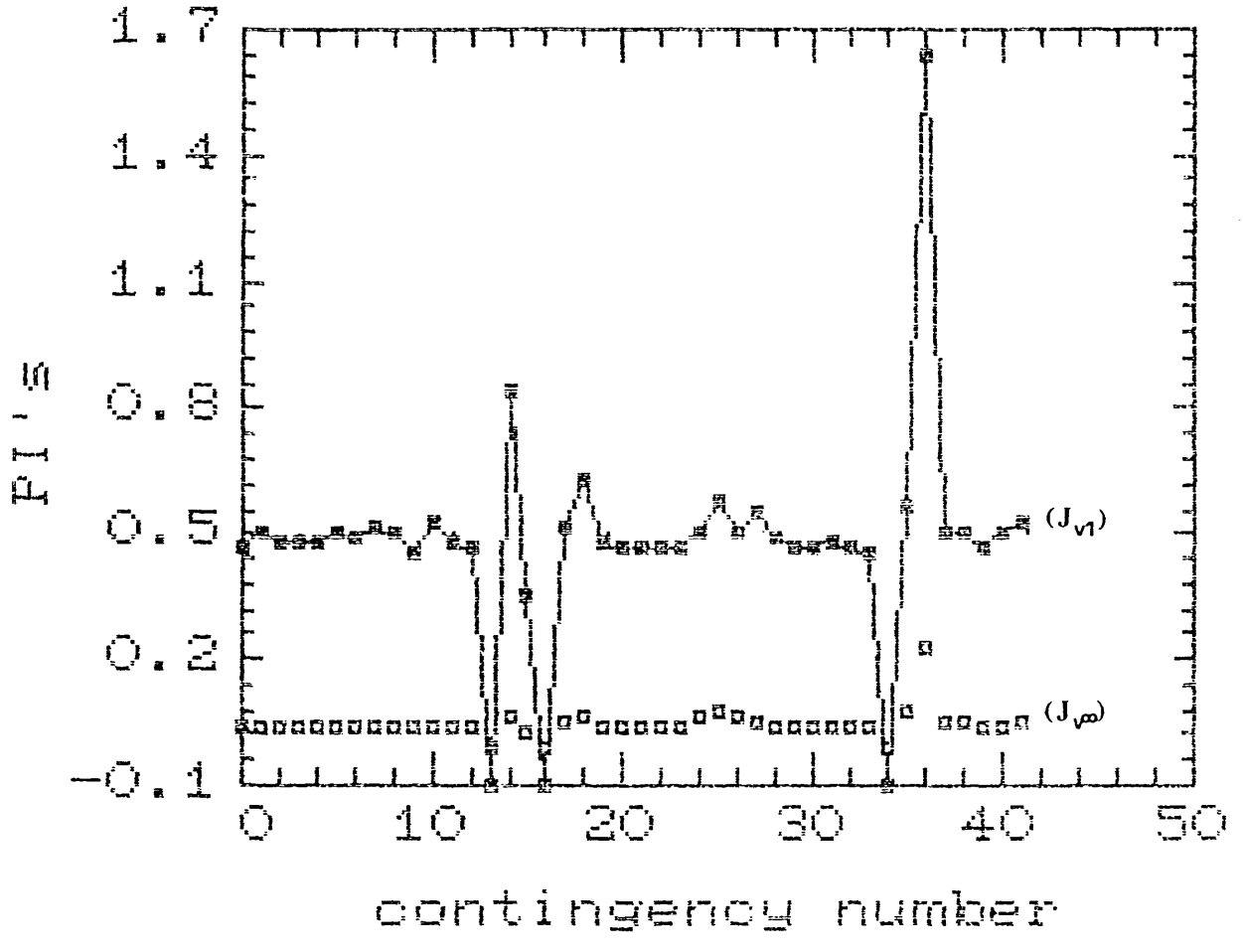


Fig. 4.1 **Performance Indices**
IEEE 30 bus test system

```
SET  p_max, q_max, ε_p, ε_q, p = 0, q = 0
FOR  { i = 1, 2, ..... nc }   DO
     CALCULATE  ΔP^p(V^q, θ^p)
     WHILE  { max_i | ΔP_i^p | > ε_p }  DO
          Δθ^p = B_p^-1 ΔP^p
          θ^p+1 = θ^p + Δθ^p
          p = p + 1
          IF { p > p_max } THEN
               Δθ^p = B_p^-1 ΔP^o
               θ^p+1 = θ^o + Δθ^p
               ABANDON WHILE LOOP
          END IF
          CALCULATE  ΔP^p(V^q, θ^p)
     END WHILE
     CALCULATE  ΔQ^q(V^q, θ^p)
     WHILE { max_i | ΔQ_i^q | > ε_q }  DO
          ΔV^q = L_q^-1 ΔQ^q
          V^q+1 = V^q + ΔV^q
          q = q + 1
          CALCULATE  ΔQ^q(V^q, θ^p)
     END WHILE
     CALCULATE PI's
END FOR
END
```

Fig. 4.2 **E&PSG Contingency Selection - Basic Algorithm**

Experiments have shown the accuracy of this algorithm to be encouraging. For example, the results of 41 branch contingencies in the IEEE 30 busbar test system, summarised in Tables 4.2a to 4.2c and Figs. 4.3a to 4.3d, illustrate the accuracy of the method. This test involved comparison with the exact results obtained from a converged load flow running for each contingency case, as shown in Table 4.2a. The post-contingency voltage magnitude minimum and maximum limits were set at 0.95 pu and 1.05, respectively. Columns 3 and 4 show voltage magnitude performance indices calculated from a converged load flow. These are the exact results. Columns 1 and 2 show performance indices calculated by the algorithm. These are the approximations. Columns 5 and 6 show the absolute value of the difference between columns 1 and 3, and between columns 2 and 4, in percent of columns 3 and 4 respectively. These are the percent errors.

For the unit norm, which represents the system-wide effects of the contingencies, the mean error is 1.77% with standard deviation of 2.19% and median of 0.93%. The localized effects of the contingencies, which is represented by the infinite norm, presents a mean error of 4.71% with standard deviation of 8.06%, and median of 1.18%. Tables 4.2b and 4.2c show the frequency distribution of the errors for the unit and infinite norms, respectively. The plots of the cumulative relative frequencies are shown in Fig. 4.3a and Fig. 4.3b. It can be seen from Fig. 4.3a that, for the unit norm, more than 90% of the cases present errors below 5%. Fig. 4.3b shows that in more than 90% of the cases, the errors for the infinite norm are at or below 10%. The histograms in Fig. 4.3c and 4.3d further illustrate these results.

Table 4.2a Voltage Magnitude PI Accuracies, IEEE 30 bus test system
E&PSG Contingency Selection Basic Algorithm

Branch Number	From Bus	To Bus	Approximation J_{v1}	Approximation $J_{v\infty}$	Exact J_{v1}	Exact $J_{v\infty}$	Error e_{v1}%	Error $e_{v\infty}$%
(a)	(b)	(c)	(1)	(2)	(3)	(4)	(5)	(6)
0	(base	case)	.472	.039	.472	.039	.000	.000
1	1	2	.496	.040	.525	.042	5.524	3.589
2	1	3	.482	.040	.484	.040	.413	.253
3	2	4	.478	.039	.480	.039	.417	.254
4	3	4	.466	.039	.479	.039	2.714	1.781
5	2	5	.504	.041	.509	.041	.982	.733
6	2	6	.489	.040	.492	.040	.610	.499
7	4	6	.498	.040	.513	.041	2.924	1.942
8	5	7	.496	.040	.493	.040	.609	.250
9	6	7	.458	.038	.450	.038	1.778	1.058
10	6	8	.541	.042	.540	.042	.185	.236
11	6	9	.484	.041	.487	.041	.616	.732
12	6	10	.485	.040	.492	.041	1.423	1.463
13	9	11	-.111	-.011	-.111	-.011	.000	.000
14	9	10	.795	.064	.881	.070	9.762	8.535
15	4	12	.361	.032	.354	.032	1.977	1.582
16	12	13	-.111	-.011	-.111	-.011	.000	.000
17	12	14	.547	.070	.527	.054	3.795	28.413
18	12	15	.683	.067	.667	.063	2.399	7.189
19	12	16	.494	.040	.502	.040	1.594	.743
20	14	15	.472	.039	.472	.039	.000	.000
21	16	17	.472	.039	.470	.039	.426	.257
22	15	18	.496	.049	.506	.053	1.976	6.464
23	18	19	.472	.039	.472	.039	.000	.000
24	19	20	.492	.052	.530	.078	7.170	33.205
25	10	20	.619	.084	.633	.090	2.212	7.412
26	10	17	.492	.049	.506	.070	2.767	30.057
27	10	21	.576	.052	.571	.050	.876	3.800
28	10	22	.498	.039	.498	.039	.000	.508
29	21	22	.468	.039	.464	.039	.862	.256
30	15	23	.488	.043	.500	.048	2.400	9.751
31	22	24	.507	.046	.509	.046	.393	1.293
32	23	24	.470	.039	.469	.039	.213	.000
33	24	25	.447	.043	.445	.044	.449	2.036
34	25	26	-.111	-.011	-.111	-.011	.000	.000
35	25	27	.589	.078	.631	.090	6.656	12.918
36	27	28	1.560	.210	1.640	.232	4.878	9.483
37	27	29	.571	.074	.578	.078	1.211	5.754
38	27	30	.575	.088	.574	.089	.174	1.017
39	29	30	.479	.044	.484	.050	1.033	10.685
40	8	28	.505	.040	.508	.041	.591	.739
41	6	28	.538	.046	.551	.048	2.359	2.725

$e_{v1}\% = |[(3)-(1)]/(3)| * 100\%$; $e_{v\infty}\% = |[(4)-(2)]/(4)| * 100\%$; $J_v < 0$=Network splitting.

Table 4.2b Frequency Distribution of the Unit Norm Percent Error (e_1%)
E&PSG Contingency Selection - Basic Algorithm

CLASS	LOWER LIMIT	UPPER LIMIT	MIDPOINT	FREQUENCY	RELATIVE FREQUENCY	CUMULATIVE FREQUENCY	CUM. REL FREQUENC
AT OR BELOW		.00		7	.1667	7	.16
1	.00	1.09	.544	16	.3810	23	.54
2	1.09	2.18	1.633	6	.1429	29	.69
3	2.18	3.27	2.722	7	.1667	36	.85
4	3.27	4.36	3.811	1	.0238	37	.88
5	4.36	5.44	4.900	1	.0238	38	.90
6	5.44	6.53	5.989	1	.0238	39	.92
7	6.53	7.62	7.078	2	.0476	41	.97
8	7.62	8.71	8.167	0	.0000	41	.97
9	8.71	9.80	9.256	1	.0238	42	1.00
ABOVE	9.80			0	.0000	42	1.00

MEAN = 1.7707 STANDARD DEVIATION = 2.1898 MEDIAN = 0.929

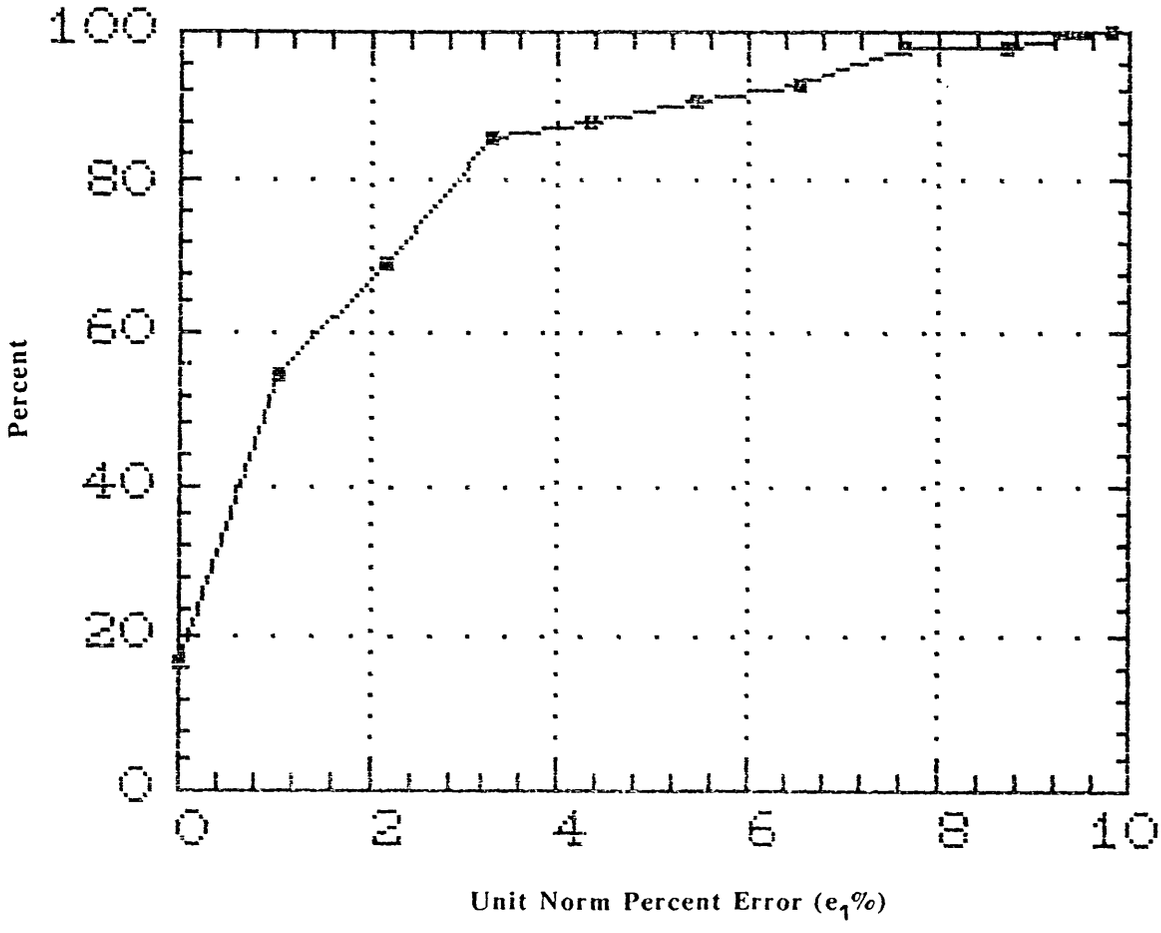


Fig. 4.3a Cumulative Relative Frequency (e_1%)
E&PSG Contingency Selection - Basic Algorithm

Table 4.2c Frequency Distribution of the Infinite Norm Percent Error ($e_{\infty\%}$)
E&PSG Contingency Selection - Basic Algorithm

CLASS	LOWER LIMIT	UPPER LIMIT	MIDPOINT	FREQUENCY	RELATIVE FREQUENCY	CUMULATIVE FREQUENCY	CUM. REL FREQUENC
AT OR BELOW		.00		7	.1667	7	.16
1	.00	3.78	1.89	22	.5238	29	.69
2	3.78	7.56	5.67	5	.1190	34	.81
3	7.56	11.33	9.44	4	.0952	38	.90
4	11.33	15.11	13.22	1	.0238	39	.92
5	15.11	18.89	17.00	0	.0000	39	.92
6	18.89	22.67	20.78	0	.0000	39	.92
7	22.67	26.44	24.56	0	.0000	39	.92
8	26.44	30.22	28.33	2	.0476	41	.97
9	30.22	34.00	32.11	1	.0238	42	1.00
ABOVE	34.00			0	.0000	42	1.00

MEAN = 4.705 STANDARD DEVIATION = 8.0566 MEDIAN = 1.1755

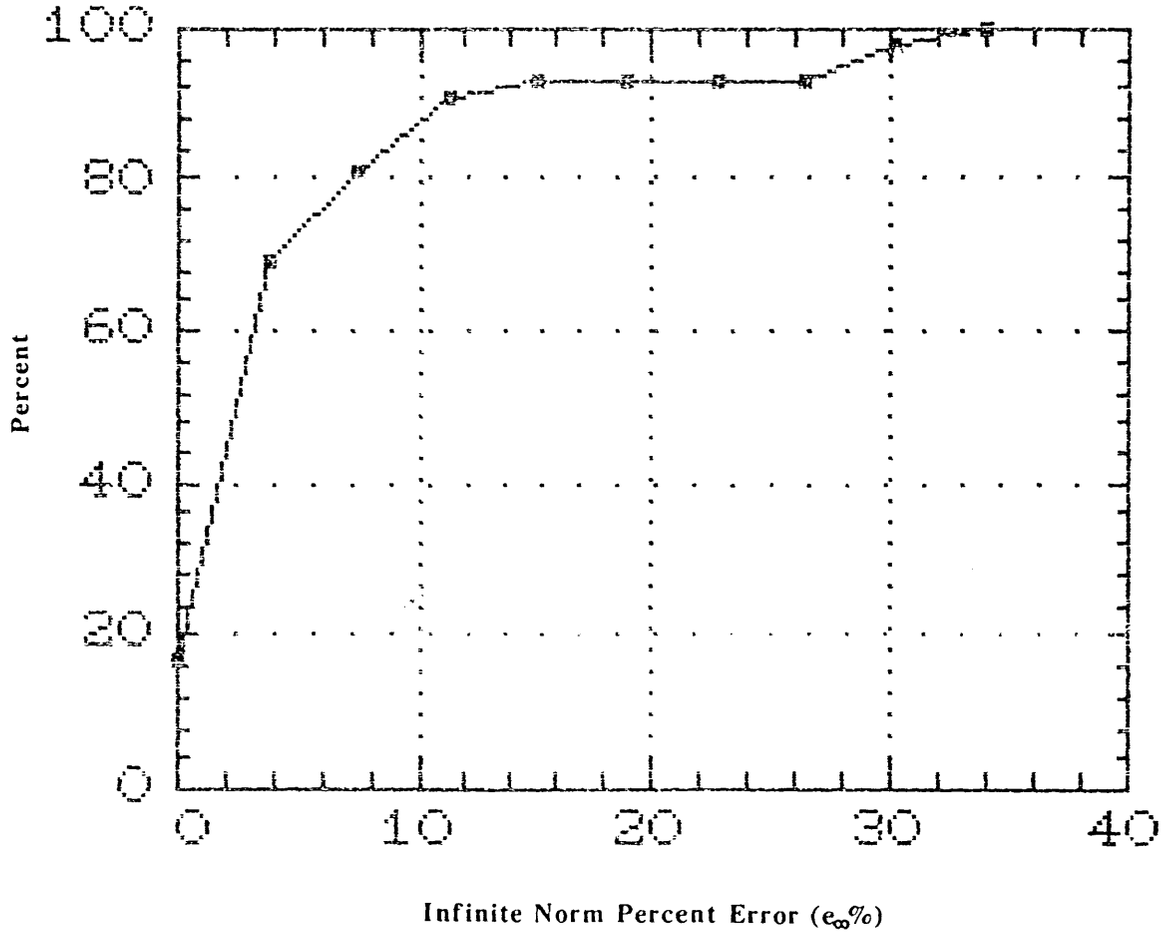


Fig. 4.3b Cumulative Relative Frequency (e_{∞}%)
E&PSG Contingency Selection - Basic Algorithm

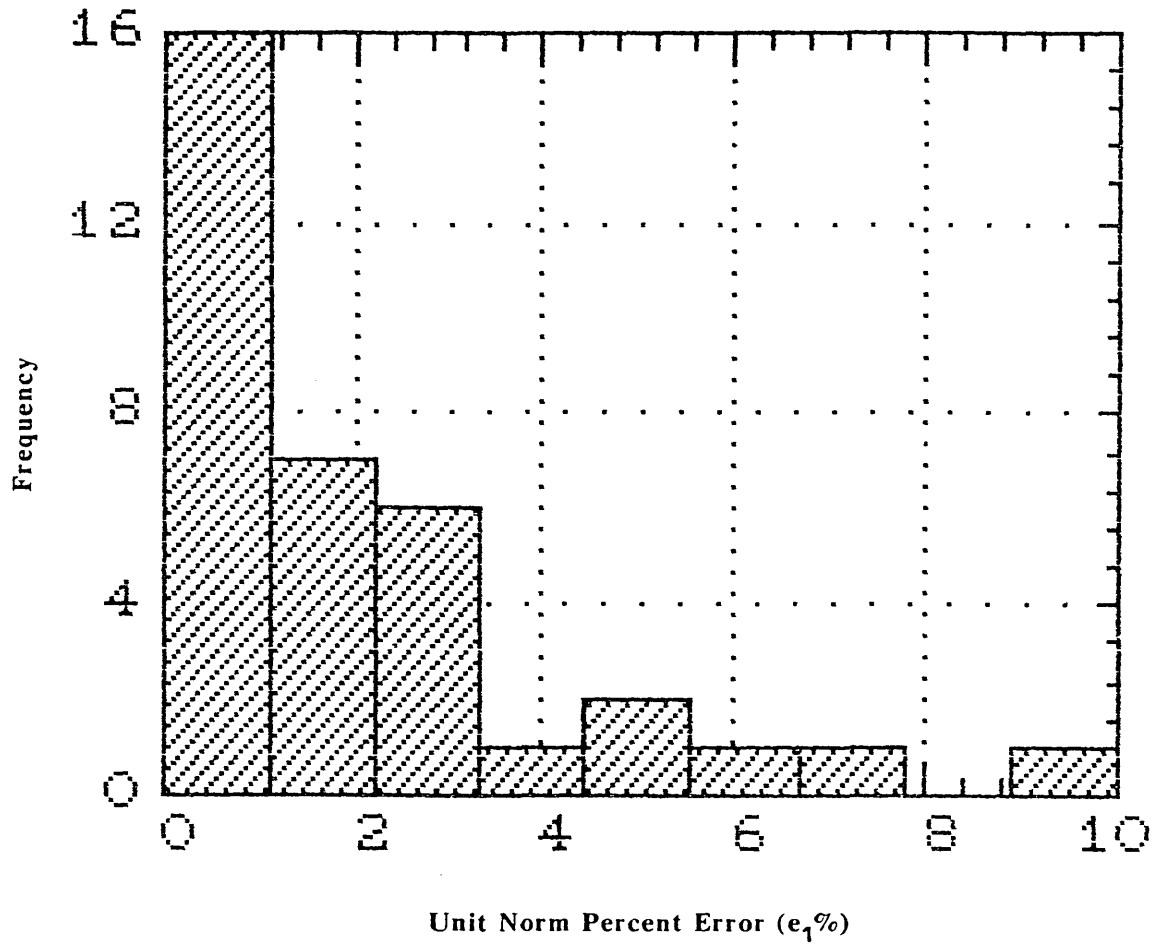


Fig. 4.3c Frequency Histogram (e_1%)
E&PSG Contingency Selection - Basic Algorithm

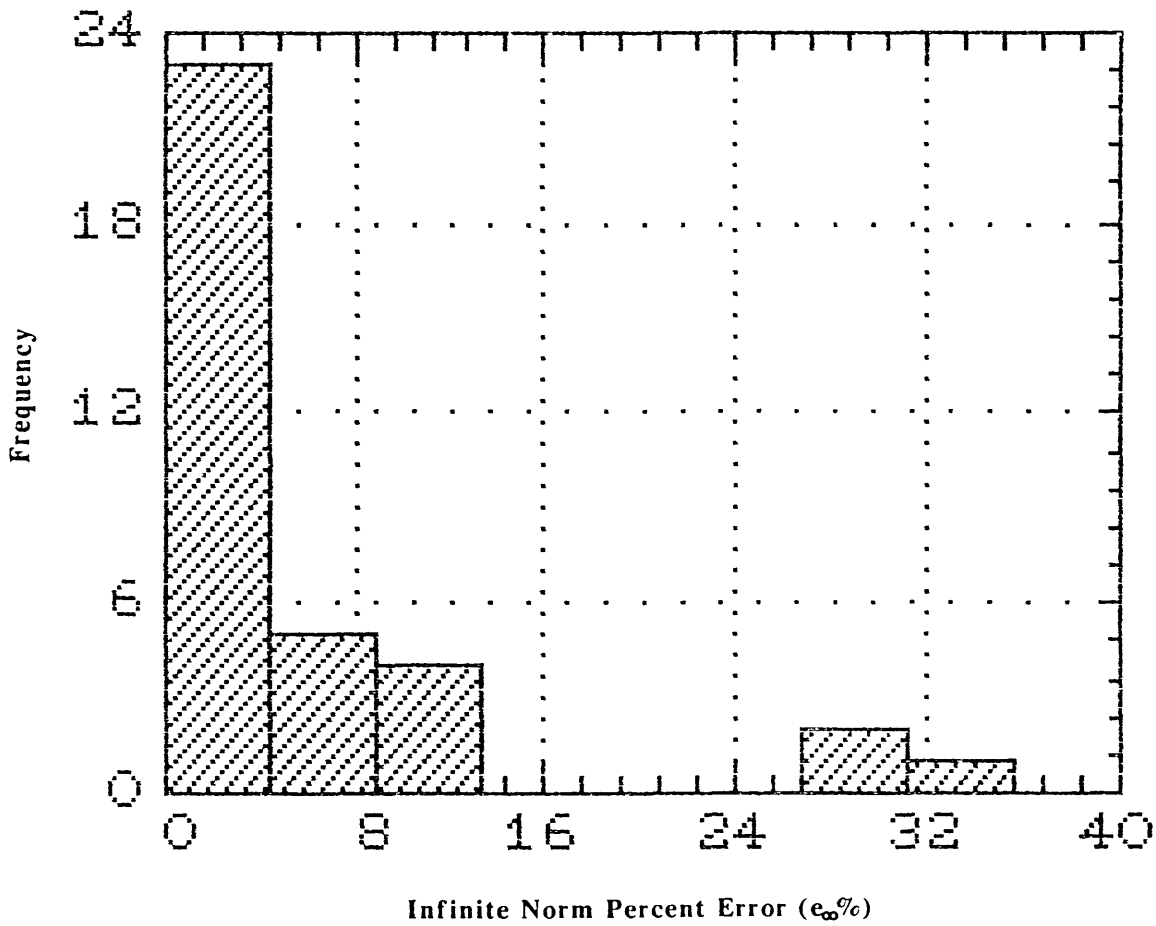


Fig. 4.3d Frequency Histogram (e_∞%)
E&PSG Contingency Selection - Basic Algorithm

Having found the accuracy of the algorithm to be satisfactory the next step was to obtain a reduction in computing time without sacrificing accuracy. An analysis of the computational effort of the algorithm showed that steps (1,2,4 and 8) do not represent a significant computational burden, step (3) is inevitable, therefore, the major problems reside in steps (5) and (6). These problems will be dealt with in the next two sections, one at a time.

4.5 E&PSG CONTINGENCY SELECTION - IMPROVEMENTS ON THE BASIC MODEL

The first modification of the basic algorithm involved simplification of step (5) by adopting network compensation techniques [79,80]. Two alternative approaches are possible to efficiently introduce this modification.

The first alternative consists of calculating and storing the explicit inverse of matrix B_p. Once the matrix inverse has been obtained, the Inverse Matrix Modification Lemma (IMML) permits the rapid calculation of the changes in the base case angle vector , $\underline{\Delta\theta}$, due to a single (or multiple) branch outage. For instance, the outage of a branch between buses i and j requires no more than the subtraction of columns i and j of the inverse. The equivalent impedance between the nodes i and j is given by

$$Z_{ij}^{eq} = Z_{ii}+Z_{jj}-2\,Z_{ij}$$

To calculate Z_{ij}^{eq}, first obtain the vector $\underline{w}_{ij}$,

$$\underline{w}_{ij} = \underline{z}_i^o - \underline{z}_j^o$$

where $\underline{z}_i^o$ and $\underline{z}_j^o$ are the columns i and j, and finally,

$$Z_{ij}^{eq} = w_{ij}^i - w_{ij}^j$$

where w_{ij}^{i} and w_{ij}^{j} are the i^{th} and j^{th} component of the vector $\underline{w}_{ij}$. The non-null entries i and j of the sparse compensation vector are given by

$$-\Delta P_i = \Delta P_j = \Delta\theta_{ij}^{o}/(b_{ij}^{-1} + Z_{ij}^{eq}) \qquad (4.10)$$

A null denominator in (4.10) indicates that the equivalent impedance Z_{ij}^{eq} is equal to the impedance of the single branch connecting busbars i and j, b_{ij}^{-1}. Therefore, the outage of this branch disconnects the network. The strategy in our implementation to handle this condition consists of emitting a warning that the current contingency splits the network. The processing is then rapidly shifted to the next contingency. It is worth saying that reference [80] **provides** a good analysis of network islanding problems. I felt tempted to pursue this way further, but it was realized that this would mean my research moving towards active contingency analysis, which was not the point. Therefore, the treatment of island cases was abandoned. This point has been made here as a suggestion for a basis of further developments in the future.

The second alternative consists of calculating the compensation for each contingency directly from the table of LDU factors of B_p. This alternative is completely similar to the first one as far as the exact precision in the linear model and computing effort are concerned. The only difference is that there is no need to allocate extra area for the storage of the inverted matrix B_p, since it is not calculated explicitly. In adopting the second alternative, the non-zero components of the injection vector given by (4.10) are

obtained by first solving the linear system

$$B_p \, \underline{w}_{ij} = \underline{e}_{ij}$$

where, $\underline{e}_{ij} = [\ 0 \quad 0 \quad \underset{i}{1} \quad 0 \quad 0 \quad \underset{j}{-1} \quad 0\ ]^t$, and then calculating the equivalent impedance Z_{ij}^{eq}

$$Z_{ij}^{eq} = w_{ij}^{i} - w_{ij}^{j}$$

As both alternatives lead to the same results the choice between them was dictated by the storage availability for the explicit inverse. Thus, the second alternative was preferred and implemented in the improved version of the basic algorithm. For reference purposes we called this algorithm of E&PSG Contingency Selection version 1. This encompasses two improvements in relation to the basic version: computing time and system splitting detection. It can be observed that version 1 can automatically handle all single branch contingencies, including those that split the system, whereas the basic algorithm is unable to recognize system splitting and, therefore, requires a list of contingencies as input data.

The accuracy of E&PSG version 1 is practically the same as that of the basic version and the reduction in the execution time for step (5) is of about 8,000% (79.4 : 1 time units - for 6p iterations of the basic algorithm against the compensation method in version 1).

The same test conditions used for the basic algorithm in Table 4.2a are adopted to illustrate the effects of the above modifications on the accuracy of the method. Thus, in Table 4.3a those columns corresponding to the results obtained from the basic algorithm are

Table 4.3a Voltage Magnitude PI Accuracies, IEEE 30 bus test system
E&PSG Contingency Selection Version 1 Algorithm

Branch Number	From Bus	To Bus	Approximation J_{v1}	Approximation $J_{v\infty}$	Exact J_{v1}	Exact $J_{v\infty}$	Error e_{v1}%	Error $e_{v\infty}$%
(a)	(b)	(c)	(1)	(2)	(3)	(4)	(5)	(6)
0	(base	case)	.472	.039	.472	.039	.000	.000
1	1	2	.509	.041	.525	.042	3.048	1.914
2	1	3	.482	.040	.484	.040	.413	.253
3	2	4	.478	.039	.480	.039	.417	.254
4	3	4	.456	.038	.479	.039	4.802	3.053
5	2	5	.499	.040	.509	.041	1.965	1.222
6	2	6	.489	.040	.492	.040	.610	.499
7	4	6	.510	.041	.513	.041	.585	.243
8	5	7	.502	.040	.493	.040	1.826	.750
9	6	7	.465	.039	.450	.038	3.333	2.116
10	6	8	.529	.042	.540	.042	2.037	1.418
11	6	9	.478	.040	.487	.041	1.848	1.707
12	6	10	.462	.038	.492	.041	6.098	6.585
13	9	11	-.111	-.111	-.111	-.111	.000	.000
14	9	10	.770	.063	.881	.070	12.599	10.669
15	4	12	.350	.031	.354	.032	1.130	.949
16	12	13	-.111	-.111	-.111	-.111	.000	.000
17	12	14	.513	.052	.527	.054	2.657	3.506
18	12	15	.585	.052	.667	.063	12.294	16.294
19	12	16	.474	.039	.502	.040	5.578	2.970
20	14	15	.471	.039	.472	.039	.212	.513
21	16	17	.462	.038	.470	.039	1.702	2.057
22	15	18	.472	.039	.506	.053	6.719	25.095
23	18	19	.464	.041	.472	.039	1.695	4.615
24	19	20	.483	.042	.530	.078	8.868	45.769
25	10	20	.557	.065	.633	.090	12.006	27.876
26	10	17	.484	.039	.506	.070	4.348	44.729
27	10	21	.535	.043	.571	.050	6.305	15.000
28	10	22	.491	.039	.498	.039	1.406	1.015
29	21	22	.471	.039	.464	.039	1.509	.256
30	15	23	.461	.039	.500	.048	7.800	19.087
31	22	24	.476	.039	.509	.046	6.483	15.086
32	23	24	.466	.039	.469	.039	.640	.512
33	24	25	.454	.040	.445	.044	2.022	8.824
34	25	26	-.111	-.111	-.111	-.111	.000	.000
35	25	27	.538	.061	.631	.090	14.739	31.626
36	27	28	1.350	.178	1.640	.232	17.683	23.276
37	27	29	.509	.045	.578	.078	11.938	42.072
38	27	30	.507	.053	.574	.089	11.672	40.226
39	29	30	.472	.039	.484	.050	2.479	21.371
40	8	28	.502	.040	.508	.041	1.181	1.724
41	6	28	.518	.044	.551	.048	5.989	7.966

$e_{v1}\% = |[(3)-(1)]/(3)| * 100\%$; $e_{v\infty}\% = |[(4)-(2)]/(4)| * 100\%$; $J_v < 0$=Network splitting.

Table 4.3b Frequency Distribution of the Unit Norm Percent Error (e_1%)
E&PSG Contingency Selection - Version 1

CLASS	LOWER LIMIT	UPPER LIMIT	MIDPOINT	FREQUENCY	RELATIVE FREQUENCY	CUMULATIVE FREQUENCY	CUM. REL FREQUENC
AT OR BELOW		.00		4	.0952	4	.095
1	.00	2.11	1.06	17	.4048	21	.500
2	2.11	4.22	3.17	4	.0952	25	.595
3	4.22	6.33	5.28	6	.1429	31	.738
4	6.33	8.44	7.39	3	.0714	34	.809
5	8.44	10.56	9.50	1	.0238	35	.833
6	10.56	12.67	11.61	5	.1190	40	.952
7	12.67	14.78	13.72	1	.0238	41	.976
8	14.78	16.89	15.83	0	.0000	41	.976
9	16.89	19.00	17.94	1	.0238	42	1.000
ABOVE	19.00			0	.0000	42	1.000

MEAN = 4.4913 STANDARD DEVIATION = 4.6713 MEDIAN = 2.258

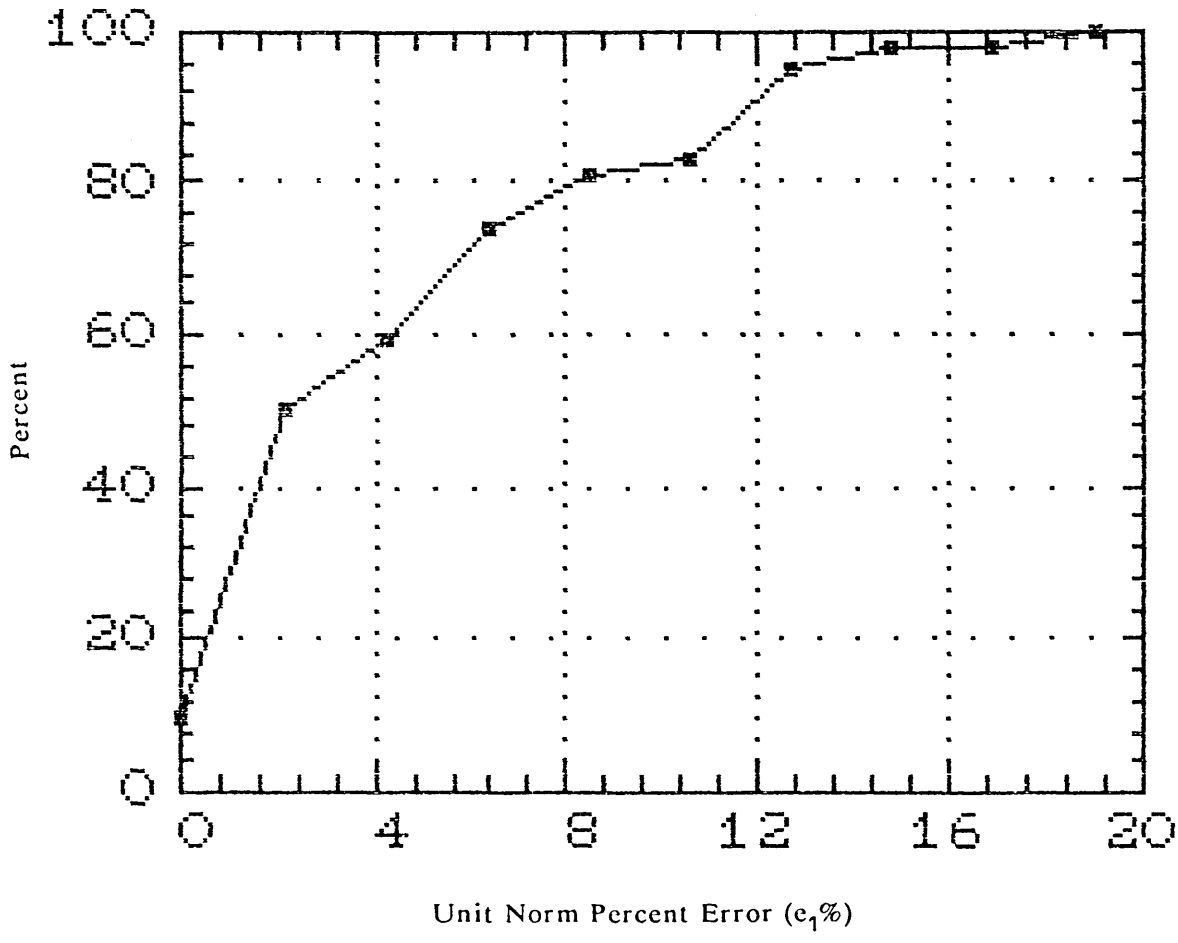


Fig. 4.4a Cumulative Relative Frequency (e_1%)
E&PSG Contingency Selection - Version 1

Table 4.3c **Frequency Distribution of the Infinite Norm Percent Error ($e_{\infty\chi}$)**
E&PSG Contingency Selection - Version 1

CLASS	LOWER LIMIT	UPPER LIMIT	MIDPOINT	FREQUENCY	RELATIVE FREQUENCY	CUMULATIVE FREQUENCY	CUM. REL FREQUENC
AT OR BELOW		.00		4	.0952	4	.095
1	.00	5.11	2.56	21	.5000	25	.595
2	5.11	10.22	7.67	3	.0714	28	.666
3	10.22	15.33	12.78	3	.0714	31	.738
4	15.33	20.44	17.89	2	.0476	33	.785
5	20.44	25.56	23.00	3	.0714	36	.857
6	25.56	30.67	28.11	1	.0238	37	.881
7	30.67	35.78	33.22	1	.0238	38	.904
8	35.78	40.89	38.33	1	.0238	39	.928
9	40.89	46.00	43.44	3	.0714	42	1.000
ABOVE	46.00			0	.0000	42	1.000

MEAN = 10.312 STANDARD DEVIATION = 13.864 MEDIAN = 2.543

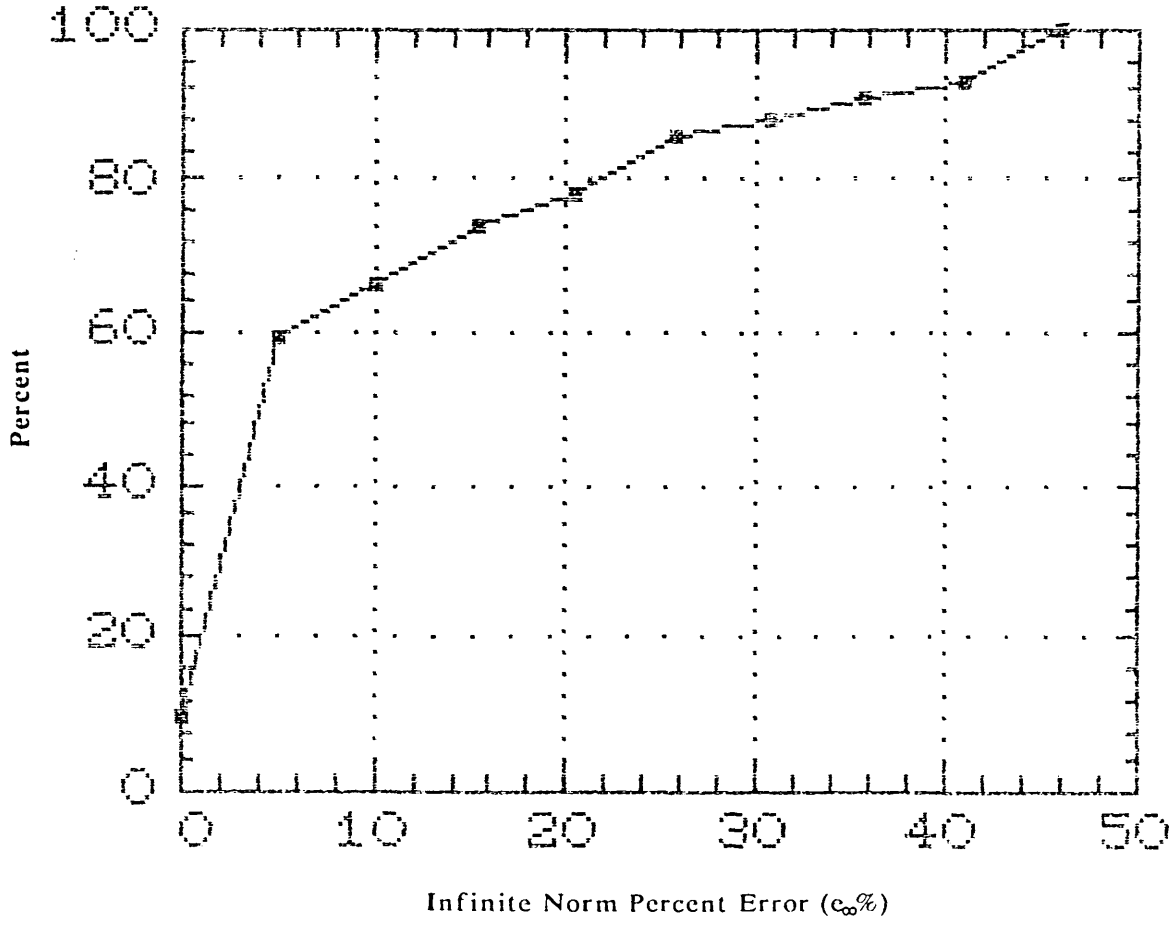


Fig. 4.4b Cumulative Relative Frequency (e_{∞}%)
E&PSG Contingency Selection - Version 1

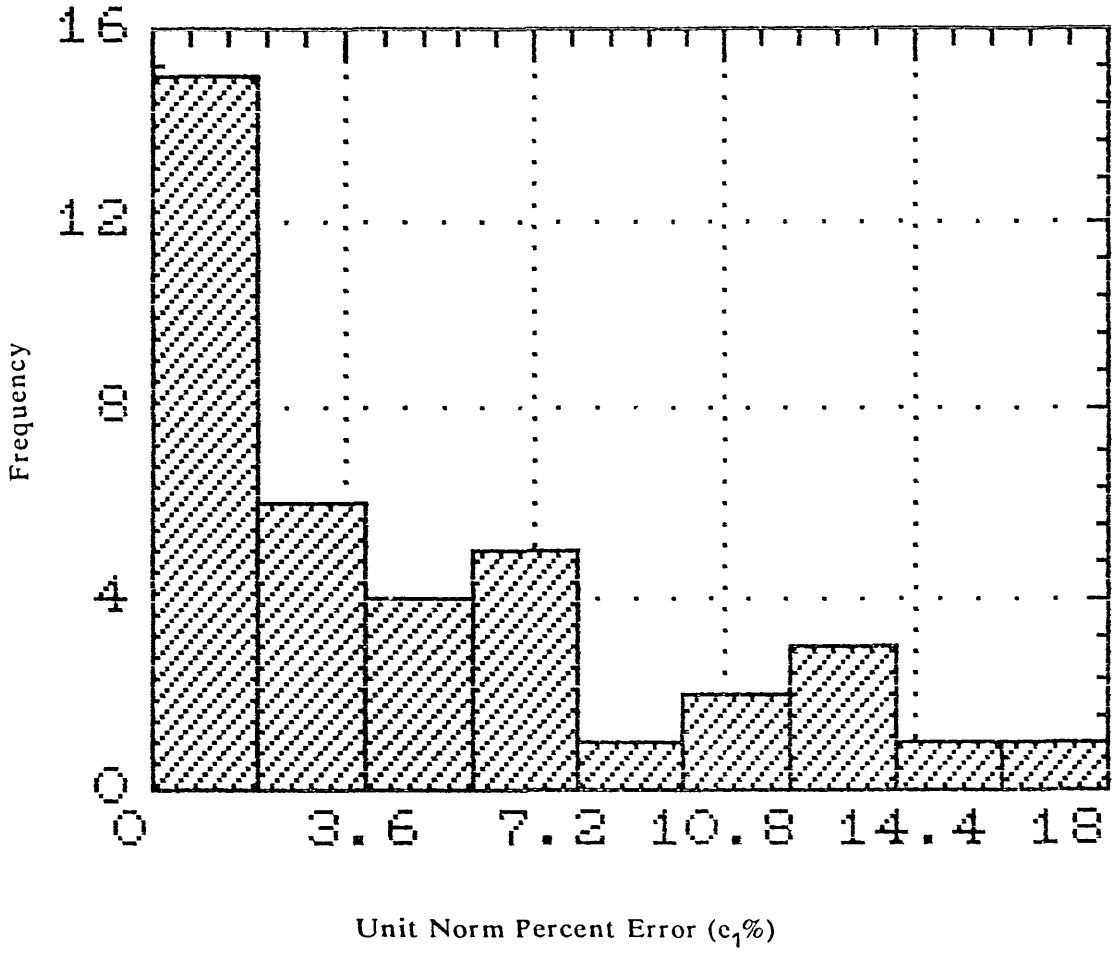


Fig. 4.4c Frequency Histogram (e_1%)
E&PSG Contingency Selection - Version 1

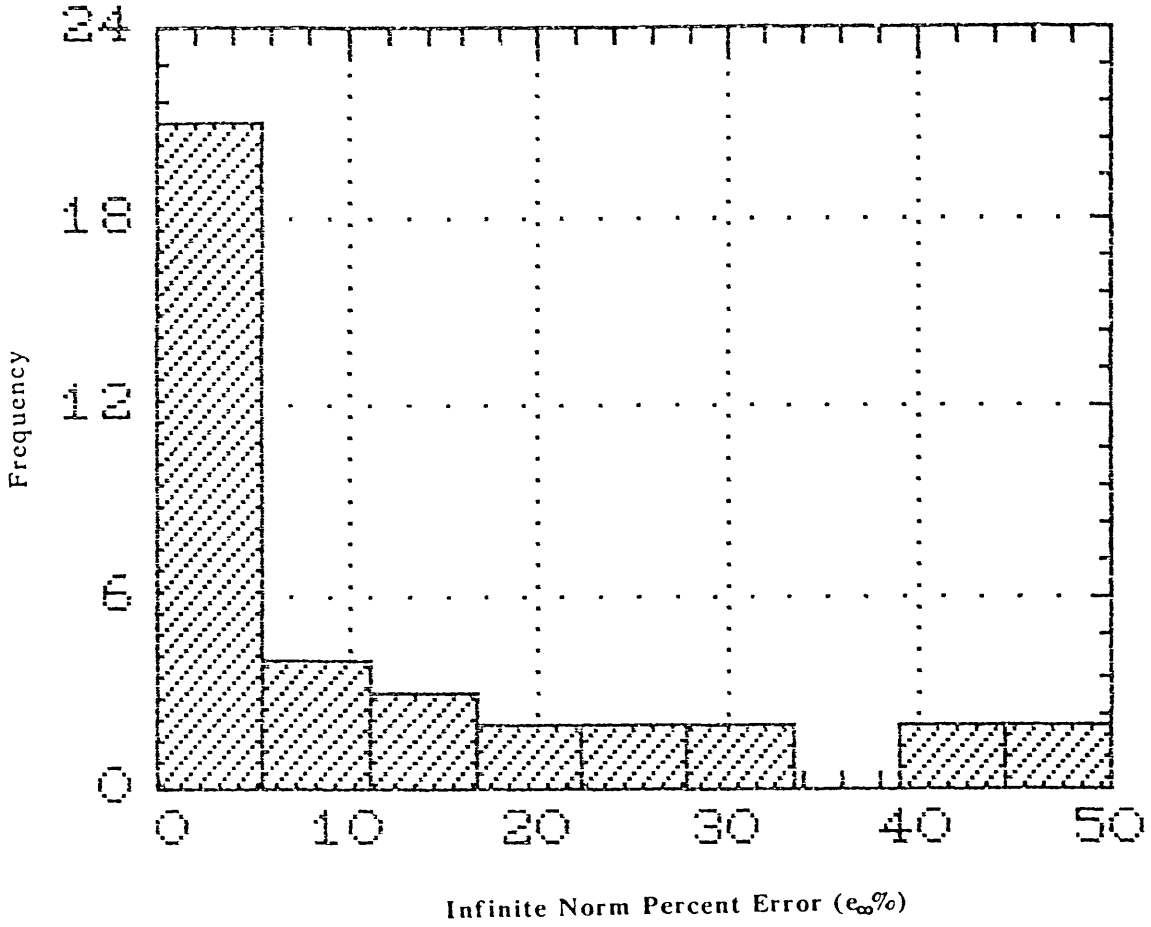


Fig. 4.4d Frequency Histogram (e_∞%)
E&PSG Contingency Selection - Version 1

replaced by the results obtained from version 1 and, then, checked against the exact results. For the unit norm the mean performance index error is 4.49% with standard deviation of 4.67% and median of 2.26%. For the infinite norm the mean performance index error is 10.31% with standard deviation of 13.86% and median of 2.54%. Similarly, the test of the basic algorithm, Tables 4.3b and 4.3c gives the frequency tabulation of the errors which are further illustrated in Figs. 4.4a through 4.4d. In Table 4.4 a comparison of the statistical parameters of this test with those corresponding to the basic algorithm shows the effects of the approximation on the performance of the method as far as accuracy is concerned. In conclusion: considering the gain in execution time, the small decrease in the accuracy of the method was considered to be acceptable.

Table 4.4 Accuracy Comparison between E&PSG Contingency Selection Algorithms

PI's	Parameter	Basic Algorithm	Version 1
J_{v1}	Mean	1.771 %	4.491 %
	Standard Deviation	2.190 %	4.671 %
	Median	0.929 %	2.258 %
$J_{v\infty}$	Mean	4.705 %	10.312 %
	Standard Deviation	8.057 %	13.864 %
	Median	1.176 %	2.543 %

4.6 E&PSG CONTINGENCY SELECTION - FURTHER DEVELOPMENTS

Having optimized the active power portion of the basic procedure (step 5) we shall now concentrate on the optimisation of

step 6, which corresponds to the reactive power portion of the basic algorithm.

To better analyse the computational effort involved in the calculation of step 6, it is convenient to break it up into basic tasks. Hence, step 6 is rewritten as follows:-

6.a) Input from step 5 of the E&PSG algorithm version 1:

$$\underline{\theta}^{p} \quad , \underline{V}^{o}$$

(Note that the angles were updated in the active power step)

6.b) Set iteration counter and initial values; (for example:)

$$\upsilon = 0 \ , \quad \Delta Q^{best} = 1E19 \ , \ \upsilon^{max} = 6$$

6.c) Calculate the reactive power mismatches

$$\Delta Q^{max} = 0$$

FOR $i=1,N_{bus}$ DO

$$\Delta Q_i^{\upsilon} = Q_i^{sp} - V_i^{\upsilon} \sum_{j \in I} V_j^{\upsilon} \left(G_{ij} \sin \theta_{ij}^{p} - B_{ij} \cos \theta_{ij}^{p}\right)$$

IF $(|\Delta Q_i| > \Delta Q^{max})$ THEN $\Delta Q^{max} = |\Delta Q_i|$

END DO

6.d) Record the best result so far (brsf)

IF $(\Delta Q^{max} < \Delta Q^{best})$ THEN

$$\Delta Q^{best} = \Delta Q^{max}$$

$$\underline{\Delta Q}^{brsf} = \underline{\Delta Q}^{\upsilon}$$

$$\underline{V}^{brsf} = \underline{V}^{\upsilon}$$

END IF

6.e) Test for convergence and maximum number of iterations

IF $(\Delta Q^{max} < \epsilon_q$ OR $\upsilon > \upsilon^{max})$ THEN output $\underline{\Delta Q}^{brsf}$, $\underline{V}^{brsf}$ stop.

6.f) Solve

$$\underline{\Delta V}^{\upsilon} = L_q^{-1} \, \underline{\Delta Q}^{\upsilon}$$

6.g) Update

$$\underline{V}^{\upsilon+1} = \underline{V}^{\upsilon} + \underline{\Delta V}^{\upsilon}$$

$$\upsilon = \upsilon + 1$$

go to step (6.c)

The computational effort is now analysed. Steps (6.a), (6.b), (6.e) and (6.g) are trivial, and, therefore require almost no computation time. The most time consuming steps are step (6.c) followed by step (6.f). For instance, for the CEGB 729 bus, 1105 branch test system, the computing times are 0.30 seconds for step (6.c) and 0.06 seconds for step (6.f).

The possibilities for reducing the cpu time for each step are now examined:

Step (6.f)

The technique used to solve the linear system of equations is forward and backward substitution. The potential for improvements rely upon the use of sparse vectors of [91]. Let us look further at this possibility.

To fully exploit sparse vector techniques, that is, to use fast-forward and fast-backward substitution it is necessary to fulfill two requirements, namely, (i) have a sparse injection vector $\underline{\Delta Q}$, and (ii) have a sparse solution vector $\underline{\Delta V}$.

Assume, in a first approach, that it is possible to obtain the sparse vector $\underline{\Delta Q}$. Assume further, in an extreme simplification, that

the reactive power mismatch vector could be a singleton[3] . Even under this extremely simplified hypotheses, one has to examine the effects of this injection in every busbar of the system. There is no general rule that allows for knowing a priori the impact of this injection, and how far in the system the effects of such injection will spread, or even where is the location of the biggest effect. Approximations based on the superposition principle, using the transfer impedances of the base case intact system, are frequently used. But, these approximations are computationally equivalent to solving the linear system of step 6.f.

As there is no way to know how far into the system the effects of $\underline{\Delta Q}$ will spread one has to evaluate the whole unknown vector $\underline{\Delta V}$. In terms of sparse vector techniques, this makes mandatory the adoption of a full back substitution.

The other possibility offered by sparse vectors involves the use of the fast-forward substitution followed by a full backward substitution. This alternative would allow a gain of approximately 50% in the total number of multiplications-additions in relation to the full forward substitution. In this case the only requirement is a sparse reactive power mismatch vector $\underline{\Delta Q}$.

Suppose one can estimate the effects of the active power angle in a sub-network. For instance, by using the $P^2 X$ criterion or selecting an small area around the contingency. Thereby, a sparse reactive power mismatch can be defined for the first iteration. (Incidentally, note that the assumption of $\underline{\Delta Q}$ being a singleton was

---

[3] A singleton is a vector with only one nonzero element; the nonzero is in location k.

of course unrealistic, it was just used for analysis with an extremely exaggerated condition). Therefore, during the first iteration the linear system is used to calculate the first iteration, yielding a full vector $\underline{\Delta V}$. These adjustments into the voltage magnitude profile cause var mismatches into all buses of the system. As a consequence, for the subsequent iterations, the reactive power mismatch vector is bound to be full and therefore, the fast-forward substitution can no longer be applied.

Numerical experiments confirmed the reasoning above. For instance, Table 4.5 shows the reactive power mismatches, $\underline{\Delta Q}$, and the voltage adjustments, $\underline{\Delta V}$, for two first iterations corresponding to the outage of branches 1 and 14 of the IEEE 30 bus test system. Branch 1 is between two PV buses and branch 14 between two PQ buses. It can be seen that the effects of the contingencies spread all over the system. It is interesting to note that the effects of branch 1 outage is due to the change in the angles (this outage involves two PV buses). In particular, note that the largest voltage magnitude adjustment in the second iteration affects strongly bus 30 (largest ΔV) which is far away from the contingency, as illustrated in Fig. 4.5. Note also that other buses in the neighborhood of bus 30 are also subject to large voltage corrections. In spite of these results, and even expecting a marginal gain in computing time, different heuristic approaches were tried. These included concentric relaxation techniques, such as, considering adaptive choice of the tier around the contingency, adaptive choice of the tier around the origin of the two largest mismatches, adaptive choice of the tier around the three largest mismatches, tracking of the largest mismatch at each iteration, etc. The results turned out to be discouraging. The idea of defining a local area and applying sparse

vector techniques was thus abandoned. The attention was then focused into further optimising step (6.c)

Table 4.5 Effects of Branch Outages on the Bus Reactive Power Mismatch and Voltage Variation Vectors
IEEE 30 bus test system

	Branch 1 outage from bus 1 to bus 2				Branch 14 outage from bus 9 to bus 10			
	$\lvert\Delta Q_i/\Delta Q_i^{max}\rvert$%		$\lvert\Delta V_i/\Delta V_i^{max}\rvert$%		$\lvert\Delta Q_i/\Delta Q_i^{max}\rvert$%		$\lvert\Delta V_i/\Delta V_i^{max}\rvert$%	
iter. bus	1st	2nd	1st	2nd	1st	2nd	1st	2nd
3	100.0	100.0	100.0	42.3	.1	.1	11.8	2.3
4	88.9	51.6	75.2	6.5	27.6	1.2	14.3	2.7
6	9.4	50.1	28.4	11.3	18.2	5.0	6.5	1.0
7	.2	3.1	17.2	5.0	.0	.0	3.9	.6
9	.6	1.6	25.4	26.4	56.9	100.0	13.3	54.7
10	12.2	25.7	38.2	46.3	100.0	96.0	100.0	100.0
12	22.4	66.2	13.9	30.7	26.6	.9	11.4	27.5
14	2.7	5.1	16.1	19.8	3.3	1.0	19.1	34.6
15	4.3	9.5	24.6	1.7	5.5	1.3	33.7	44.2
16	1.7	3.9	27.0	7.6	3.4	.6	54.5	59.6
18	.2	.5	30.2	18.1	.6	.2	59.1	65.9
19	.1	.2	33.2	27.1	.1	.1	73.1	78.2
20	.3	.0	34.6	31.9	.6	.4	80.2	84.1
21	.1	.0	39.5	51.9	.3	.2	95.6	95.8
22	.1	2.4	39.8	53.5	5.0	1.6	93.6	93.9
23	.4	1.0	33.6	36.1	.3	.1	45.4	54.1
24	3.4	21.0	44.1	78.9	2.2	1.3	59.8	66.7
25	.3	.3	48.1	89.4	.1	.5	22.0	37.2
26	.1	.0	48.8	91.4	.0	.0	22.3	37.9
27	5.3	17.5	49.5	95.8	11.1	1.9	1.3	20.5
28	1.4	2.3	24.0	18.6	11.3	.5	10.1	1.8
29	.0	.0	50.6	98.4	.0	.0	1.4	21.0
30	.0	.1	51.2	100.0	.0	.0	1.5	21.3

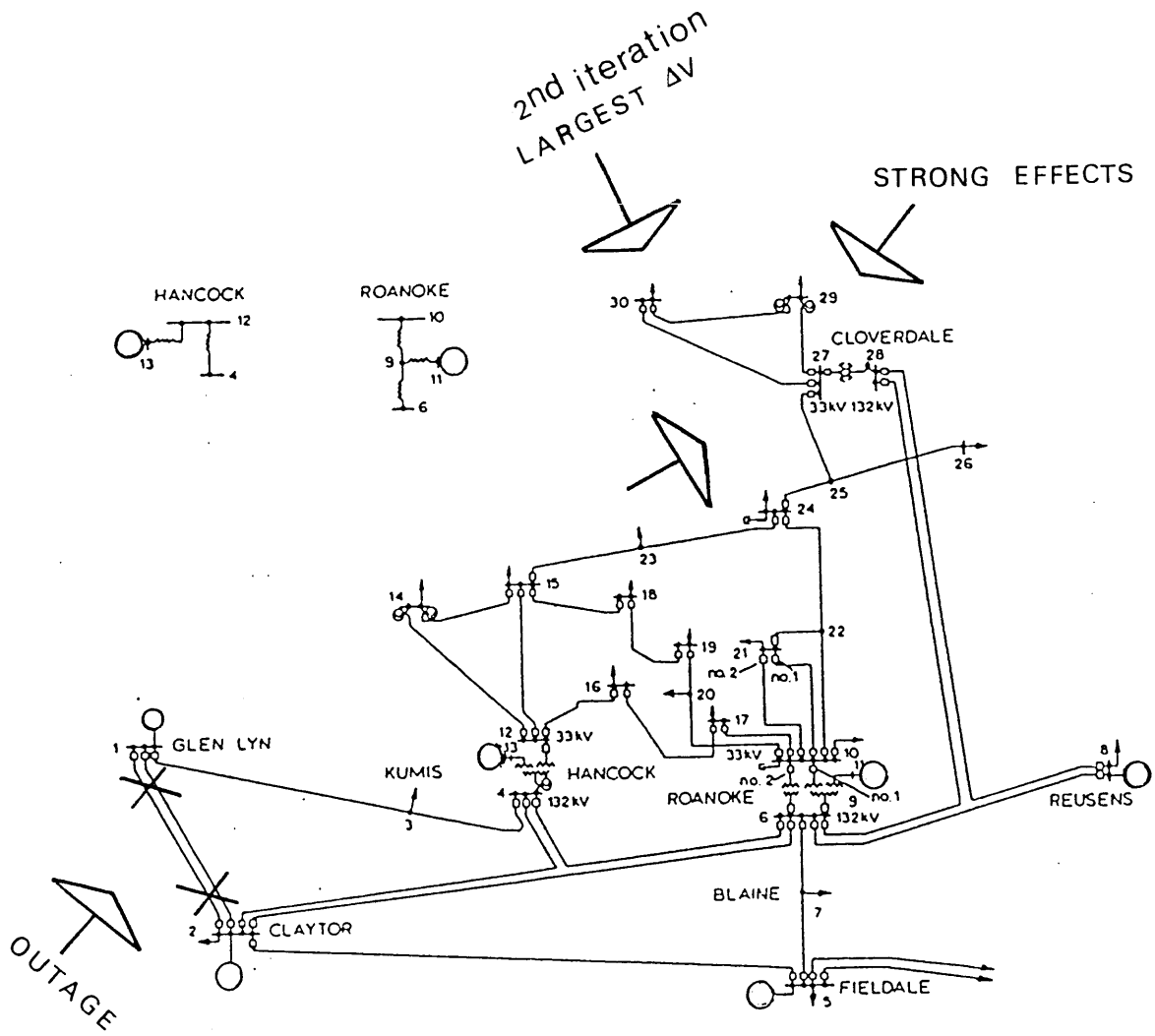


Fig. 4.5 IEEE 30 bus test system
System-wide effects of branch 1 outage

Step (6.c)

The time-consuming operation in step (6.c) is the reactive power mismatch calculation. This operation involves two loops: one loop over all buses of the system and, for each busbar i in this loop, another loop over the neighborhood I of i. Step (6.c) is expanded further, so as to highlight these operations.

6.c) Calculate the reactive power mismatches

$\Delta Q^{max} = 0$

FOR i=1,N_{bus} DO

$\Delta Q^{aux} = 0$

FOR $j \epsilon I$ DO

$$\Delta Q^{aux} = \Delta Q^{aux} + V_j^{\upsilon} \, (G_{ij} \sin \theta_{ij}^{p} - B_{ij} \cos \theta_{ij}^{p})$$

END DO

$\Delta Q_i^{\upsilon} = Q_i^{sp} - V_i^{\upsilon} \, \Delta Q^{aux}$

IF ($|\Delta Q_i^{\upsilon}| > \Delta Q^{max}$) THEN $\Delta Q^{max} = |\Delta Q_i^{\upsilon}|$

END DO

Incidentally, note that the computational effort for this procedure is equivalent to that for determining the voltage sensitive sub-network of [70]. The bracketed term $(G_{ij}\sin\theta_{ij}^{p} - B_{ij}\cos\theta_{ij}^{p})$ is responsible for the major portion of the computational burden at each iteration υ. However, for the reactive power portion of the algorithm this term needs to be calculated only once at the first iteration, because the angle remains constant for the other iterations. Consequently, a gain in cpu time is obtained by storing the results of the first iteration in a sparse array A.

$$A_{ij} = (G_{ij} \sin \theta_{ij}^{p} - B_{ij} \cos \theta_{ij}^{p}) \qquad (4.11)$$

Note that, the data structure already provides for the storage and retrieval of the elements of this array in sparse form, once the matrix A has the same sparsity pattern as the Y_{bus}, and, therefore, the same Y_{bus} pointers are used to manipulate A. Further economy in cpu time can be obtained by adopting the relations $\sin(x)=x-x^3/6$ and $\cos(x)=1-x^2/2+x^4/24$. These modifications allow for a reduction in CPU time for the other iterations in relation to the first one. For instance, for the CEGB 729 bus 1105 branch system the times are 0.30 seconds for the first iteration and 0.06 seconds for higher iterations. As the other iterations became less expensive in terms of CPU time it becomes worthwhile to increase the number of iterations in return for accuracy. Thus, new strategies were developed and will be detailed in the following sections.

4.7 A NEW COMPENSATION TECHNIQUE

Compensating (for) the effects of ΔV

According to step (4) of the basic algorithm the outage of a generalized branch is taken into account by updating the network matrix $Y_{bus}=G_{bus}+jB_{bus}$. Then the admittance for the generalized branch between nodes i and j, y_{ij}, is added to Y_{ij} and Y_{ji} and subtracted from Y_{ii} and Y_{jj}. The generalized branch admittance between node i and ground, y_{io}, and between node j and ground, y_{jo}, are subtracted from Y_{ii} and Y_{jj}, respectively. In matrix notation these modifications can be expressed as:

$$Y'_{bus} = Y_{bus} - M\ y\ M^t$$

where, y is a (3x3) diagonal matrix representing the primitive

admittance of the generalized branch and M is a $(3xN_{bus})$ matrix, with all entries equal zero, but +1 and -1 into the positions i and j of the first column, +1 into the positions i of the second column, and +1 into the position j of the third column.

$$M\,y\,M^{t} = \begin{array}{c} \\ i \\ j \end{array}\begin{bmatrix} & & \\ +1 & +1 & 0 \\ & & \\ -1 & 0 & +1 \end{bmatrix}\begin{bmatrix} y_{ij} & & \\ & y_{io} & \\ & & y_{jo} \end{bmatrix}\begin{array}{c} \begin{matrix} i & & j \end{matrix} \\ \begin{bmatrix} +1 & -1 \\ +1 & 0 \\ 0 & +1 \end{bmatrix} \end{array}$$

These modifications affect the reactive power portion of the version 1 algorithm, more specifically, the reactive power mismatches. The variations on the voltage angle vector $\underline{\theta}$ and the network change cause all the components of the vector $\underline{\Delta Q}$ to be nonzero at the first iteration (and in the subsequent iterations as well). Although, this strategy has been found to present a satisfactory overall accuracy, some problems of convergence, and even some oscillations, have been observed when the number of iterations were augmented in order to try a more accurate solution. In such cases, the best results, in general, were among the first iterations. To investigate this problem several cases involving different networks were analysed. Two main facts emerged from this analysis: (i) The majority of the problematic cases involved branch outage between two PQ nodes. (ii) There were hardly any problems when one of the terminal nodes connecting the outaged branch was a PV type and, (iii) there were no problems at all when both terminal nodes were PV type. Let us leave these observations for the time being, to concentrate in the numeric aspects of the reactive power

portion of the algorithm. Thus, this portion of the algorithm consists of solving the non-linear system

$$\underline{\Delta Q}(\underline{V}) = 0$$

using an approximated fixed Jacobian matrix L_q (which is equivalent to use an approximated tangent method for a scalar function).

$$\underline{V}^{\upsilon+1} = \underline{V}^{\upsilon} + L_q^{-1}\ \underline{\Delta Q}^{\upsilon}$$

A first impression as to the cause of the convergence problems may be the fact that the approximation of the Jacobian given by L_q is not valid. However recalling the fact that the method works well for outages involving PV busbars leads to the following reasoning:

The mismatches elements are given by

$$\Delta Q_i = Q_i^{sp} - Q_i(\underline{V})$$

When an outage of a branch between buses k and m is simulated, in fact, what one wants to find is the compensation for the outaged branch var flows Q_{km} and Q_{mk} in terms of the compensating injections ΔQ_k^c and ΔQ_m^c. From the algorithm viewpoint, the only busbars in the system that "see" the network changes are busbars k and m. Therefore, during the iterative process these injections depend only on the voltage magnitude of the terminal buses, V_k and V_m. If these terminal buses are both PV type, then ΔQ_k^k and ΔQ_m^c are fixed throughout the iterations, υ, and, therefore, the compensation injections are exact. If only one busbar, say k, is PV type, ΔQ_k^c and ΔQ_m^c depend mostly on V_m, and the corrections on ΔQ_k^c and ΔQ_m^c at each iteration, υ, are bound to be less accentuated than when both terminal nodes are PQ type. To sum up, there are three possibilities as represented in Fig. 4.6 :

(i) Both of the terminal buses are PV type.

$$\underline{\Delta Q} = \underline{Q}^{sp} - \underline{\Delta Q}^{c} - \underline{Q}(\underline{V})$$

Then the compensation vector is constant. The nonzero entries

in locations k and m are equal to the var branch flows Q_{km} and Q_{mk}.

(ii) One busbar is PV type, say k, and another is PQ type, say m.

$$\underline{\Delta Q} = \underline{Q}^{sp} - \underline{\Delta Q}^{c}(V_m) - \underline{Q}(\underline{V})$$

Then the compensation vector is dependent on V_m. The nonzero entries in locations k and m are equal to the var branch flows $Q_{km}(V_m)$ and $Q_{mk}(V_m)$, which vary at each iteration υ.

(iii) Both of the terminal buses are PQ type.

$$\underline{\Delta Q} = \underline{Q}^{sp} - \underline{\Delta Q}^{c}(V_k, V_m) - \underline{Q}(\underline{V})$$

Then the compensation vector is dependent on V_m and V_k. The nonzero entries in locations k and m are equal to the var flows $Q_{km}(V_k, V_m)$ and $Q_{mk}(V_k, V_m)$, which vary at each iteration υ.

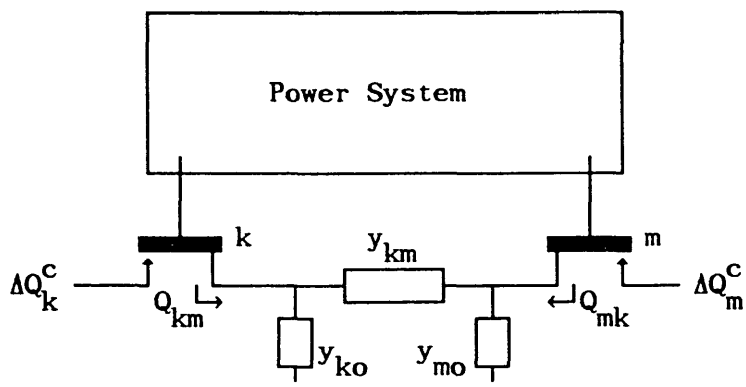


Fig. 4.6 VAR Compensation Scheme

Now, observe that if the compensation injections were fixed known values, as in the case involving both PV nodes, then the approximation would be valid for all cases and, numerically, the procedure would present the good convergence characteristics of the tangent's method.

$$L_q \underline{\Delta V} = \underline{\Delta Q(V)} + \underline{\Delta Q}^c$$

The problem is the same as that of obtaining adjusted solutions in load flows, namely, when the control variables are adjusted during the iterative process these adjustments cause the algorithm to oscillate. The solution, which is sometimes reported in the literature as a practical rule, is to wait some (frequently three) iterations before enforcing the controls. Well, "wait 3 iterations and then apply the adjustment on the control variables" in terms of NR type algorithms means convergence, or partial convergence of the iterative process has already been obtained. This strategy is indeed very efficient, because from the point of view of the iterative process, it corresponds to solve an entirely new problem each time the controls are readjusted. Consequently, if the method presents a good convergence in general, then solving one adjusted problem, for the method, acts as though it has solved several uncontrolled cases in series.

The above observations lead to the design of a new iterative strategy which consists of two iterative loops. The procedure starts by making the compensation injections at nodes k and m equal to the

reactive power flows into the generalized branch. Keeping these values constant a new solution is obtained for the voltage magnitude vector. If the contingency involves two PV nodes these compensation values are exact and the iterative solution is the final solution. If not, the adjustments in the compensation injections are performed and a new iterative solution is calculated. The process continues until the maximum adjustment in the compensation injections are less than a prefixed tolerance. As a result of this new procedure, the modification on the network matrices in step 4 of the version 1 algorithm is no longer needed. With the above modifications the var procedure to solve a branch contingency between nodes k and m can now be expressed as

step p:

Update the voltage angle using IMML.

$$\underline{\theta}^{p} = \underline{\theta}^{o} + \underline{\Delta\theta}$$

step q:

i. Initialize outer loop iteration counter and set the var flow tolerance:

$$\mu = 0 \; ; \; \epsilon_f = \epsilon_{fo}$$

ii. Calculate the initial var compensations

$$\Delta Q_k^{\mu} = Q_{km}(V_k^{\mu}, V_m^{\mu}, \theta_k^{p}, \theta_m^{p}) \qquad \Delta Q_m^{\mu} = Q_{mk}(V_k^{\mu}, V_m^{\mu}, \theta_k^{p}, \theta_m^{p})$$

iii. Solve (inner iteration, $\upsilon = 0, 1..\upsilon^{max}$)

$$\underline{V}^{\upsilon+1} = \underline{V}^{\upsilon} + L_q^{-1} \left[\underline{\Delta Q}(\underline{V}^{\upsilon}) + \underline{\Delta Q}^{c(\mu)}\right]$$

iv. IF (k,m ϵ PV) THEN stop

v. Update the var compensation injections

$$\Delta Q_k^{\mu+1} = Q_{km}(V_k^{\upsilon}, V_m^{\upsilon}, \theta_k^{p}, \theta_m^{p})$$
$$\Delta Q_m^{\mu+1} = Q_{mk}(V_k^{\upsilon}, V_m^{\upsilon}, \theta_k^{p}, \theta_m^{p})$$
$$\Delta q_{max} = \max_{k,m} \{ |\Delta Q_k^{\mu+1} - \Delta Q_k^{\mu}|, |\Delta Q_m^{\mu+1} - \Delta Q_m^{\mu}| \}$$

vi. Test for convergence

IF ($\Delta q_{max} < \epsilon_f$) THEN stop ELSE $\mu = \mu+1$ and go to step (iii).

The above procedure, in general, converges in three outer loop iterations. The computing effort required for the outer loop is very small, because at most only two var flows have to be updated at each outer loop iteration. Remember that the inner loop is also very fast; after the first iteration, only voltage magnitude dependent terms of the mismatch vector have to be updated.

$$\Delta Q_i = Q_i^{sp} - V_i^{\upsilon} \sum_{j \in I} V_j^{\upsilon} A_{ij}$$

The success of the above approach motivated further investigations in order to allow for the prespecification of the number of iterations for all cases. The following facts emerged: (i) the largest var injections and therefore the major perturbations generally correspond to the first overall iteration; (ii) after the first outer loop iteration the adjustments in the compensating injections are marginal. As a consequence, the physical and mathematical details of the first iteration were thoroughly investigated and eventually lead to a better model for the first iteration being developed. It was found that a local solution for

the voltage changes at the terminal buses of the outaged branch can be calculated analytically. This solution allows for the determination of better estimates of the voltages magnitudes and consequently, better initial values for the var compensating injections. Proof and details for this calculation follow.

Consider the outage of the generalized branch between buses k and m. As mentioned before, at the first iteration, the terminal buses k-m are the only buses in the system that "feel" the change in the network structure. The reactive power injections are given by

$$Q_i = V_i \sum_{j \in I} V_j \, (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij})$$

Then, the effects of the network change in structure can be expressed as

$$\frac{\partial Q_i}{\partial b_{ij}} = V_i^2 - V_i V_j \cos\theta_{ij} \; ; \qquad \frac{\partial Q_i}{\partial b_{io}} = -V_i^2$$
$$\frac{\partial Q_i}{\partial g_{ij}} = - V_i V_j \sin\theta_{ij} \tag{4.12}$$

The changes in the injected reactive power are given by

$$\Delta Q_k = \frac{\partial Q_k}{\partial b_{km}} \Delta b_{km} + \frac{\partial Q_k}{\partial b_{ko}} \Delta b_{ko} + \frac{\partial Q_k}{\partial g_{km}} \Delta g_{km} + \frac{\partial Q_k}{\partial V_k} \Delta V_k + \frac{\partial Q_k}{\partial V_m} \Delta V_m$$
$$\Delta Q_m = \frac{\partial Q_m}{\partial b_{mk}} \Delta b_{mk} + \frac{\partial Q_m}{\partial b_{mo}} \Delta b_{mo} + \frac{\partial Q_m}{\partial g_{mk}} \Delta g_{mk} + \frac{\partial Q_m}{\partial V_k} \Delta V_k + \frac{\partial Q_m}{\partial V_m} \Delta V_m \tag{4.13}$$

To calculate corresponding changes in the terminal voltage

magnitudes, ΔV_k and ΔV_m, three different cases must be considered.

1) The terminal buses k and m are both PQ type. Then, $\Delta Q_k=\Delta Q_m=0$ and (4.13) becomes a (2x2) linear system in ΔV_k and ΔV_m,

$$\begin{bmatrix} \partial Q_k/\partial V_k & \partial Q_k/\partial V_m \\ \partial Q_m/\partial V_k & \partial Q_m/\partial V_m \end{bmatrix} \begin{bmatrix} \Delta V_k \\ \Delta V_m \end{bmatrix} = - \begin{bmatrix} (\partial Q_k/\partial b_{km})\Delta b_{km} + (\partial Q_k/\partial b_{ko})\Delta b_{ko} + \\ (\partial Q_m/\partial b_{mk})\Delta b_{mk} + (\partial Q_m/\partial b_{mo})\Delta b_{mo} + \\ + (\partial Q_k/\partial g_{km})\Delta g_{km} \\ + (\partial Q_m/\partial g_{mk})\Delta g_{mk} \end{bmatrix} \quad (4.14)$$

The coefficients $\partial Q_i/\partial V_j$ are taken from the matrix L_q, $g_{km}, g_{mk}, b_{km}, b_{mk}, b_{ko}$ and b_{mo} are primitive conductances and susceptances of the generalized branch k-m, respectively, and $\partial Q_i/\partial b_{ij}$, $\partial Q_i/\partial b_{io}$ and $\partial Q_i/\partial g_{ij}$ are given by (4.12).

Upon substituting $\Delta g_{km}= -g_{km}$, $\Delta b_{km}=-b_{km}$, $\Delta g_{mk}= -g_{mk}$, $\Delta b_{mk}=-b_{mk}$, $\Delta b_{ko}=b_{ko}$, $\Delta b_{mo}= b_{mo}$ and the partial derivatives into (4.14) we obtain

$$\begin{bmatrix} L_{q_{kk}} & L_{q_{km}} \\ L_{q_{mk}} & L_{q_{mm}} \end{bmatrix} \begin{bmatrix} \Delta V_k \\ \Delta V_m \end{bmatrix} = - \begin{bmatrix} V_k^2(b_{km}+b_{ko}) - V_k V_m b_{km}\cos\theta_{km} + V_k V_m g_{km}\sin\theta_{km} \\ V_m^2(b_{mk}+b_{mo}) - V_m V_k b_{mk}\cos\theta_{mk} + V_m V_k g_{mk}\sin\theta_{mk} \end{bmatrix} \quad (4.15)$$

Where, the expressions on the right hand side are promptly recognized as the var flows entering the generalized branch k-m, the solution of (4.15) yields

$$\Delta V_k = \left[Q_{km} L_{q_{mm}} - Q_{mk} L_{q_{km}} \right] / \left[L_{q_{kk}} L_{q_{mm}} - L_{q_{km}} L_{q_{mk}} \right]$$

$$\Delta V_m = \left[Q_{mk} L_{q_{kk}} - Q_{km} L_{q_{mk}} \right] / \left[L_{q_{kk}} L_{q_{mm}} - L_{q_{km}} L_{q_{mk}} \right]$$

2) One terminal bus, say k, is PQ type and the other, say m, is PV

type. Then, $\Delta Q_k=0$ and $\Delta V_m=0$, the first equation of (4.13) yields

$$\Delta V_k = Q_{km}/L_{q_{kk}}$$

3) The terminal buses k and m are both PV type. Then $\Delta V_k=\Delta V_m=0$.

Therefore, better estimates $\tilde{V}_k$ and $\tilde{V}_m$ for V_k and V_m can be calculated before the first iteration,

$$\tilde{V}_k^o = V_k^o + \Delta V_k$$
$$\tilde{V}_m^o = V_m^o + \Delta V_m$$

In consequence the initial values for the var compensating injections are now expressed as

$$\Delta Q_k^{c(\mu=0)} = Q_{km}(\tilde{V}_k, \tilde{V}_m, \theta_k^p, \theta_m^p)$$
$$\Delta Q_k^{c(\mu=0)} = Q_{mk}(\tilde{V}_k, \tilde{V}_m, \theta_k^p, \theta_m^p)$$

With improved initial conditions the adjustments in the var compensating injections become even less accentuated. Therefore, it is no longer necessary to converge the inner loop before applying the adjustments in the var injections for the second and higher outer loop iterations. In view of the above argument and because the inner loop usually takes three iterations to converge, the number of inner loop iterations was fixed to three for the first outer loop iteration, and to one iteration (i.e, direct solution for the voltage magnitudes) for the second and higher outer loop iterations. In the final implementation of the method (called E&PSG Contingency Selection Version 2), the program user is prompted for the maximum number of iterations. Although, after the first overall iteration, the computing cost of each iteration is very low, it is found to be sufficient to set the maximum number of iterations to three. This is

the maximum number of iterations adopted for the computing times and accuracies reported for version 2. Of course, one can set just one iteration, and in this case, the method becomes a pure compensation approach. In this case, the results are bound to be fairly accurate in the majority of the cases. However, such practice is to be discouraged for two main reasons: (i) the abnormal system conditions such as high load and unusual topological network structure for which a pure compensation is prone to produce low accuracy are likely to be the most important contingencies to be flagged by a contingency selection algorithm; (ii) the computational cost of higher iterations is very low in comparison with the first one. The outline of the final E&PSG Contingency selection (version 2) algorithm follows,

step p:

Update the voltage angle using IMML.

$$\underline{\theta}^{p} = \underline{\theta}^{o} + \underline{\Delta\theta}$$

step q:

i. Initialize outer loop iteration counter, set the var flow tolerance, and maximum number of iterations:

$$\mu = 0 \; ; \; \epsilon_f = \epsilon_{fo} \; ; \; \mu_{max} = \mu^{o}_{max} \; ; \; \upsilon_{max} = \upsilon^{o}_{max}$$

IF (k,m ϵ PV) THEN go to step iii

ii. Calculate the initial voltage estimates and the var compensations

$$\tilde{V}^{o}_{k} = V^{o}_{k} + \Delta V_{k}$$

$$\tilde{V}^{o}_{m} = V^{o}_{m} + \Delta V_{m}$$

$$\Delta Q^{\mu}_{k} = Q_{km}(\tilde{V}^{o}_{k}, \tilde{V}^{o}_{m}, \theta^{p}_{k}, \theta^{p}_{m})$$

$$\Delta Q^{\mu}_{m} = Q_{mk}(\tilde{V}^{o}_{k}, \tilde{V}^{o}_{m}, \theta^{p}_{k}, \theta^{p}_{m})$$

iii. Solve

IF μ=0 THEN (inner iteration, υ=0,1..υ_{max}) ELSE υ=μ (i.e., do only once)

$$\underline{V}^{\upsilon+1} = \underline{V}^{\upsilon} + L_q^{-1} \left[\underline{\Delta Q}(\underline{V}^{\upsilon}) + \underline{\Delta Q}^{c(\mu)}\right]$$

iv. IF (k,m ϵ PV) THEN stop

v. Update the var compensation injections

$$\Delta Q_k^{\mu+1} = Q_{km}(V_k^{\upsilon}, V_m^{\upsilon}, \theta_k^{p}, \theta_m^{p})$$

$$\Delta Q_m^{\mu+1} = Q_{mk}(V_k^{\upsilon}, V_m^{\upsilon}, \theta_k^{p}, \theta_m^{p})$$

$$\Delta q_{max} = \max_{k,m} \{|\Delta Q_k^{\mu+1} - \Delta Q_k^{\mu}|, |\Delta Q_m^{\mu+1} - \Delta Q_m^{\mu}|\}$$

vi. Test for convergence and maximum number of iterations

IF ($\Delta q_{max} < \epsilon_f$ OR $\mu \geq \mu_{max}$) THEN stop

ELSE $\mu = \mu+1$ and go to step (iii).

The IEEE 30 bus test system was used to compare the results of the E&PSG Contingency Selection Algorithm Version 2 with the exact results obtained from a full AC load flow, in a similar way as the basic algorithm and version 1 had been compared before. Thus, Tables 4.6a through 4.6c and Figs. 4.7a through 4.7d show the statistics for the normalized percent PI errors. The mean error is 2.98% with standard deviation of 3.18% and median of 1.76% for the unit norm whilst for the infinite norm the mean error is 7.29% with standard deviation of 10.60% and median of 1.99%. The cumulative relative frequencies show that more than 90% of the percent unit norm errors are below 7.33% and, more than 90% of the percent infinite norm errors are below 21.5%.

Table 4.6a Voltage Magnitude PI Accuracies, IEEE 30 bus test system
E&PSG Contingency Selection Version 2

Branch Number	From Bus	To Bus	Approximation J_{v1}	Approximation $J_{v\infty}$	Exact J_{v1}	Exact $J_{v\infty}$	Error e_{v1}%	Error $e_{v\infty}$%
(a)	(b)	(c)	(1)	(2)	(3)	(4)	(5)	(6)
0	(base	case)	.472	.039	.472	.039	.000	.000
1	1	2	.509	.041	.525	.042	3.048	1.914
2	1	3	.482	.040	.484	.040	.413	.253
3	2	4	.478	.039	.480	.039	.417	.254
4	3	4	.474	.039	.479	.039	1.044	.763
5	2	5	.499	.040	.509	.041	1.965	1.222
6	2	6	.489	.040	.492	.040	.610	.499
7	4	6	.510	.041	.513	.041	.585	.243
8	5	7	.502	.040	.493	.040	1.826	.750
9	6	7	.455	.038	.450	.038	1.111	.794
10	6	8	.529	.042	.540	.042	2.037	1.418
11	6	9	.478	.040	.487	.041	1.848	1.707
12	6	10	.462	.038	.492	.041	6.098	6.585
13	9	11	-.111	-.111	-.111	-.011	.000	.000
14	9	10	.847	.068	.881	.070	3.859	2.845
15	4	12	.350	.031	.354	.032	1.130	.949
16	12	13	-.111	-.111	-.111	-.011	.000	.000
17	12	14	.521	.056	.527	.054	1.139	3.321
18	12	15	.635	.059	.667	.063	4.798	5.591
19	12	16	.474	.039	.502	.040	5.578	2.970
20	14	15	.471	.039	.472	.039	.212	.513
21	16	17	.462	.038	.470	.039	1.702	2.057
22	15	18	.472	.039	.506	.053	6.719	25.095
23	18	19	.464	.041	.472	.039	1.695	4.615
24	19	20	.509	.063	.530	.078	3.962	19.615
25	10	20	.583	.073	.633	.090	7.899	18.805
26	10	17	.498	.058	.506	.070	1.581	17.806
27	10	21	.550	.046	.571	.050	3.678	8.000
28	10	22	.491	.039	.498	.039	1.406	1.015
29	21	22	.471	.039	.464	.039	1.509	.256
30	15	23	.461	.039	.500	.048	7.800	19.087
31	22	24	.476	.039	.509	.046	6.483	15.086
32	23	24	.466	.039	.469	.039	.640	.512
33	24	25	.454	.040	.445	.044	2.022	8.824
34	25	26	-.111	-.111	-.111	-.011	.000	.000
35	25	27	.568	.072	.631	.090	9.984	20.045
36	27	28	1.640	.223	1.640	.232	.000	3.879
37	27	29	.509	.045	.578	.078	11.938	42.072
38	27	30	.507	.053	.574	.089	11.672	40.226
39	29	30	.472	.039	.484	.050	2.479	21.371
40	8	28	.502	.040	.508	.041	1.181	1.724
41	6	28	.535	.046	.551	.048	2.904	3.564

e_{v1}%=|[(3)-(1)]/(3)|*100%; $e_{v\infty}$%=|[(4)-(2)]/(4)|*100%; J_v<0=Network splitting.

Table 4.6b Frequency Distribution of the Unit Norm Percent Error (e_1%)
E&PSG Contingency Selection - Version 2

CLASS	LOWER LIMIT	UPPER LIMIT	MIDPOINT	FREQUENCY	RELATIVE FREQUENCY	CUMULATIVE FREQUENCY	CUM. REL FREQUENC
AT OR BELOW		.00		5	.1190	5	.11
1	.00	1.33	.667	11	.2619	16	.38
2	1.33	2.67	2.000	11	.2619	27	.64
3	2.67	4.00	3.333	5	.1190	32	.76
4	4.00	5.33	4.667	1	.0238	33	.78
5	5.33	6.67	6.000	3	.0714	36	.85
6	6.67	8.00	7.333	3	.0714	39	.92
7	8.00	9.33	8.667	0	.0000	39	.92
8	9.33	10.67	10.000	1	.0238	40	.95
9	10.67	12.00	11.333	2	.0476	42	1.00
ABOVE	12.00			0	.0000	42	1.00

MEAN = 2.9755 STANDARD DEVIATION = 3.1833 MEDIAN = 1.764

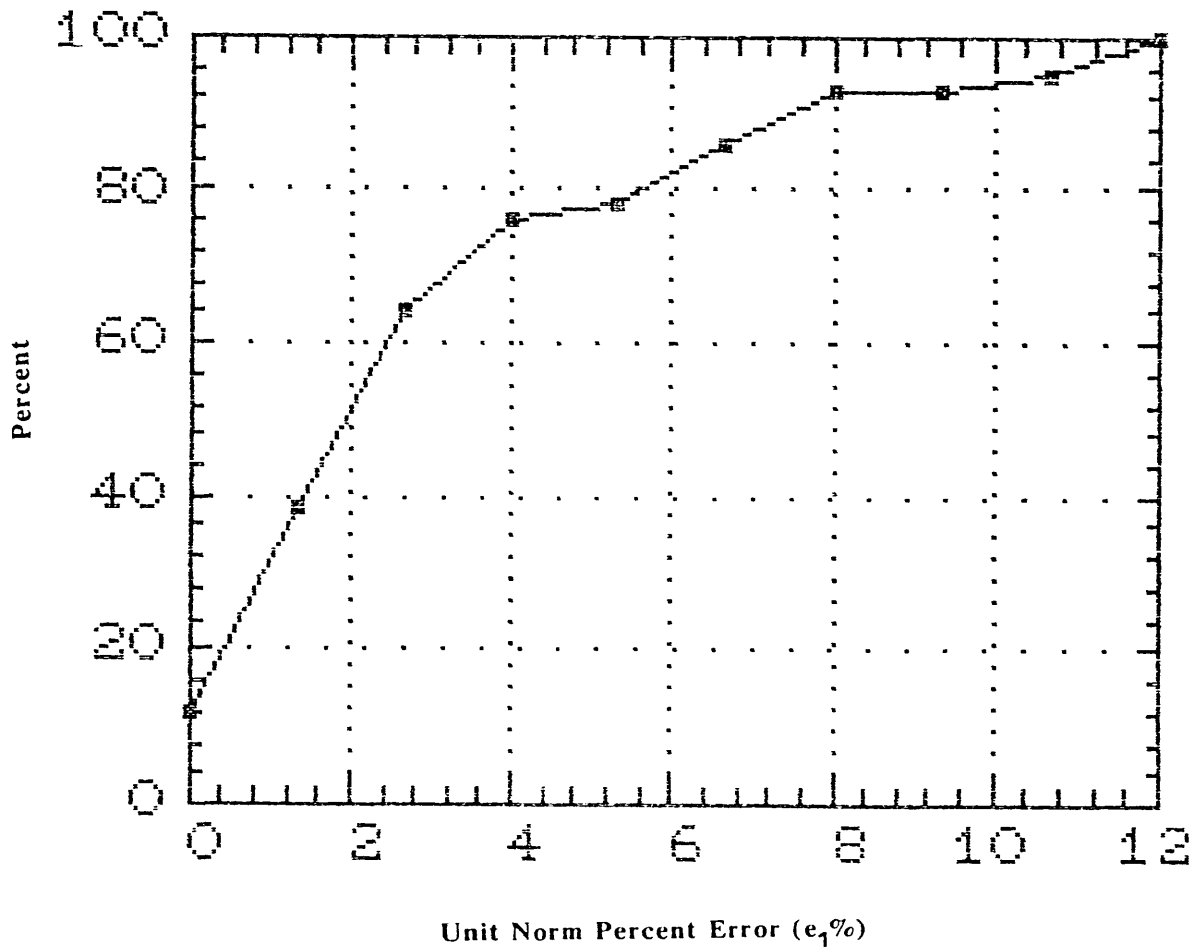


Fig. 4.7a Cumulative Relative Frequency (e_1%)
E&PSG Contingency Selection - Version 2

Table 4.6c **Frequency Distribution of the Infinite Norm Percent Error ($e_{\infty\chi}$)**
E&PSG Contingency Selection - Version 2

CLASS	LOWER LIMIT	UPPER LIMIT	MIDPOINT	FREQUENCY	RELATIVE FREQUENCY	CUMULATIVE FREQUENCY	CUM. REL FREQUENC
AT OR BELOW		.00		4	.0952	4	.095
1	.00	4.78	2.39	24	.5714	28	.666
2	4.78	9.56	7.17	4	.0952	32	.761
3	9.56	14.33	11.94	0	.0000	32	.761
4	14.33	19.11	16.72	4	.0952	36	.857
5	19.11	23.89	21.50	3	.0714	39	.928
6	23.89	28.67	26.28	1	.0238	40	.952
7	28.67	33.44	31.06	0	.0000	40	.952
8	33.44	38.22	35.83	0	.0000	40	.952
9	38.22	43.00	40.61	2	.0476	42	1.000
ABOVE	43.00			0	.0000	42	1.000

MEAN = 7.2915 STANDARD DEVIATION = 10.599 MEDIAN = 1.9855

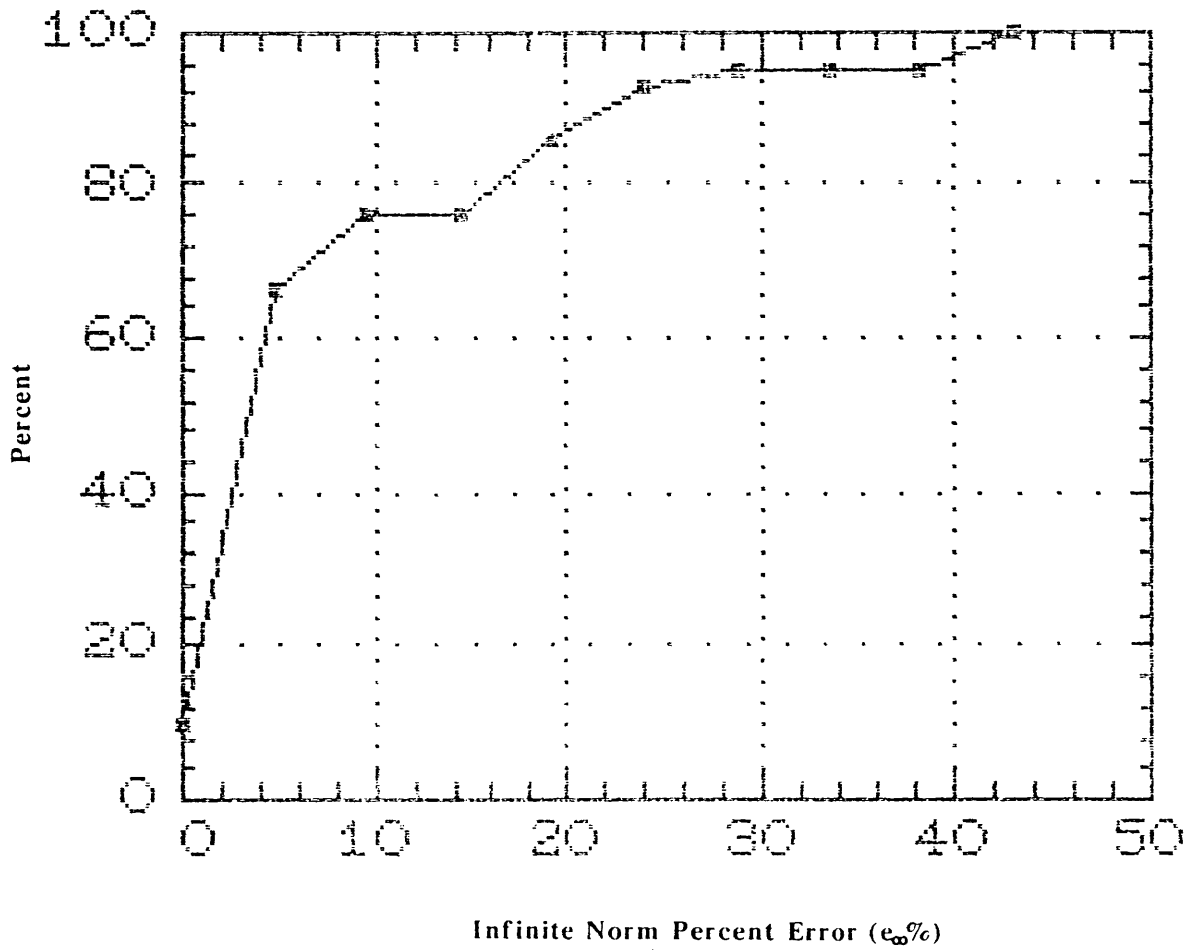


Fig. 4.7b **Cumulative Relative Frequency (e_{∞}%)**
E&PSG Contingency Selection - Version 2

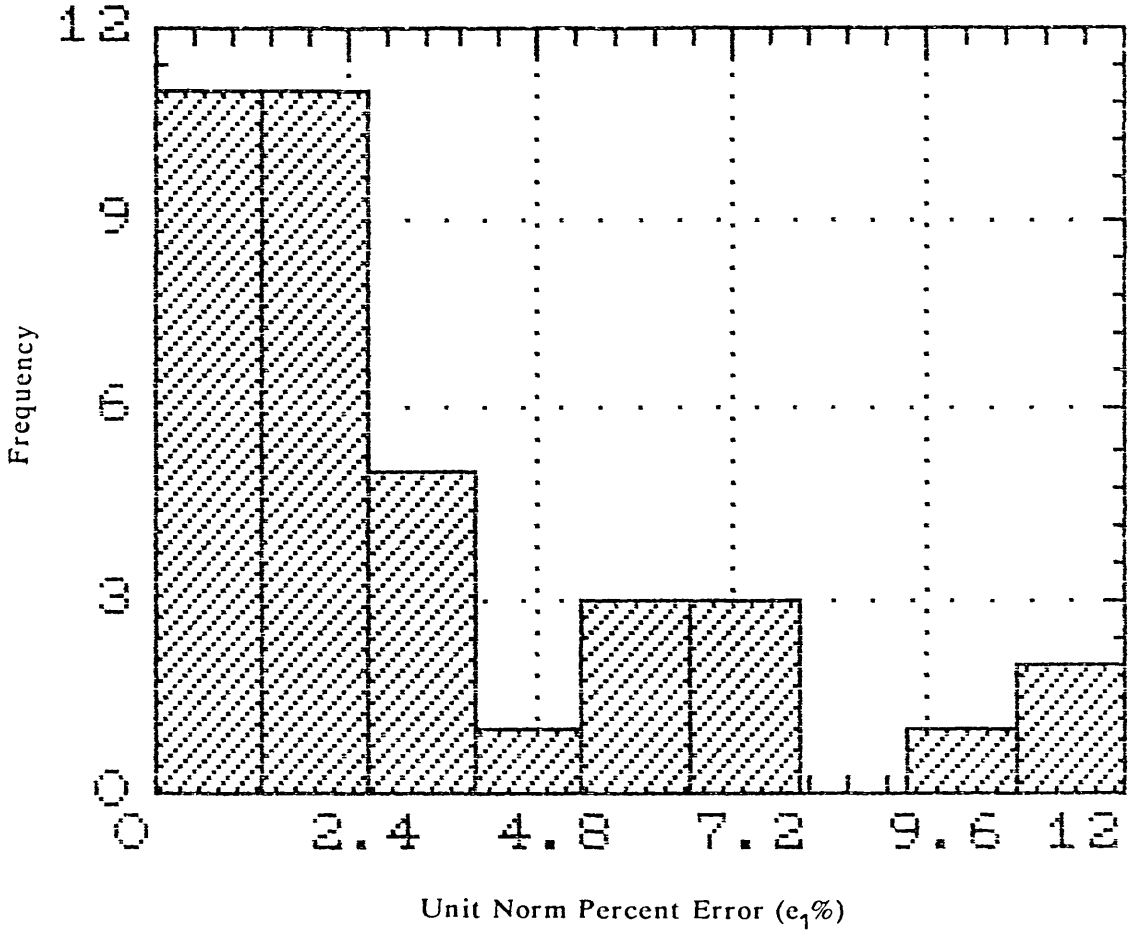


Fig. 4.7c **Frequency Histogram (e_1%)**
E&PSG Contingency Selection - Version 2

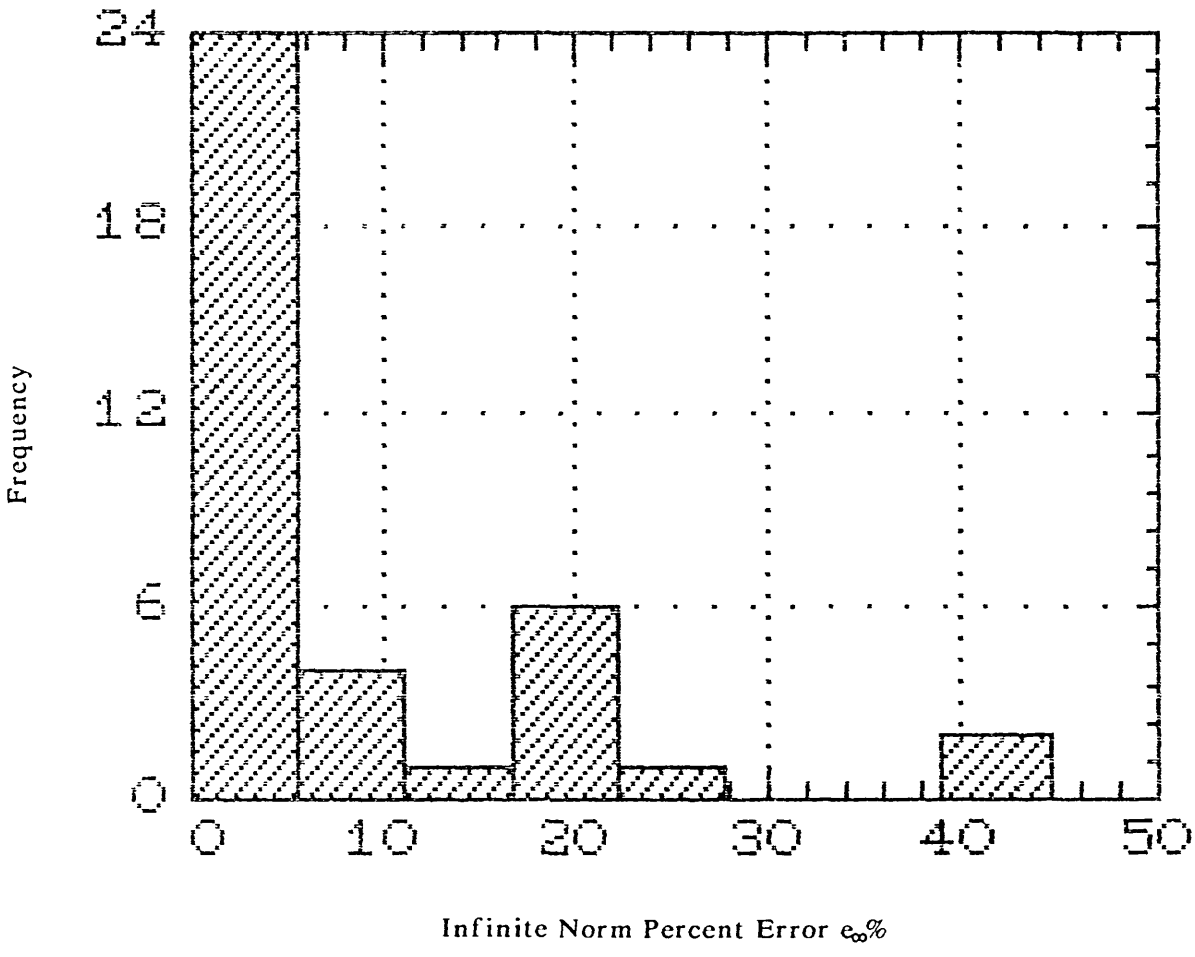


Fig. 4.7d Frequency Histogram (e_∞%)
E&PSG Contingency Selection - Version 2

4.8 FINAL EVALUATION OF THE NEW METHODOLOGY

Pairwise comparison of the different E&PSG Contingency Selection versions

Figure 4.8a and Fig. 4.8b show a multiple Box-and-Whisker plot of the percent unit norm errors and percent infinite norm errors for the different versions of the E&PSG Contingency Selection Algorithm. The box-and-whisker plot is an effective way to display summary statistics graphically. The central box covers the middle 50% of the data values, between the lower and upper quartiles. The "whiskers" extend out to the extremes (minimum and maximum values), while the central line is at the median. When unusual values occur far way from the bulk of the data, they are plotted as separate points.

Percent unit norm errors (Fig. 4.8a):- Note that the medians for all the three algorithms are very close, and that the median for version 2 is below version 1. The plot for version 1 shows two extreme values, well above the bulk values. Note that the errors for version 1 appear to vary somewhat more than the two other versions, with a larger central box and longer whiskers. The accuracies of the basic algorithm are very close to the accuracies of version 2.

Percent infinite norm errors (Fig. 4.8b):- The relative results are very similar to those for the percent unit norm errors. The medians for all the three algorithms are very close, and the median for version 2 is below version 1. The plot for version 1 shows extreme values, well above the bulk values. Again, the errors for version 1 appear to vary somewhat more than the two other versions, with a larger central box and longer whiskers. The interquatile range of the errors for both the basic algorithm and version 2 are

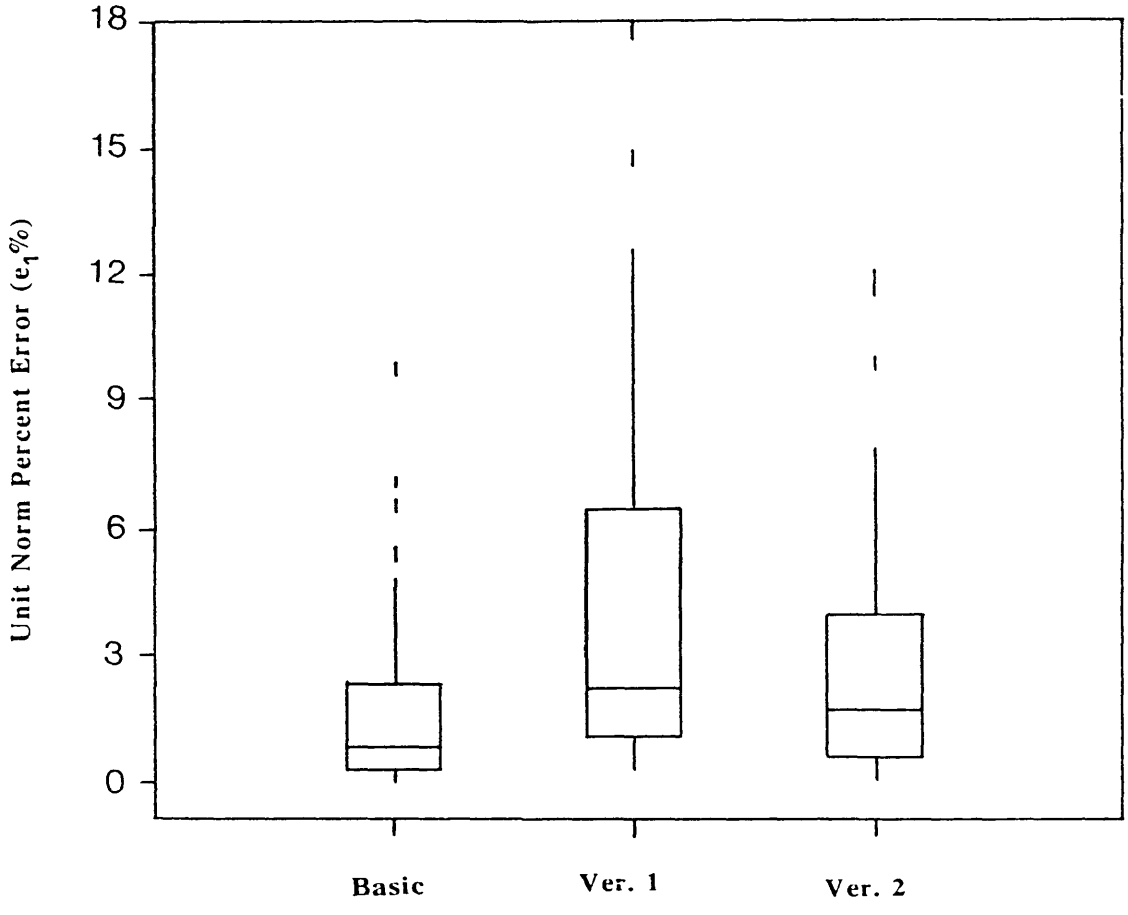


Fig. 4.8a Box-and-Whisker Plot of the Unit Norm Percent Error e_1%

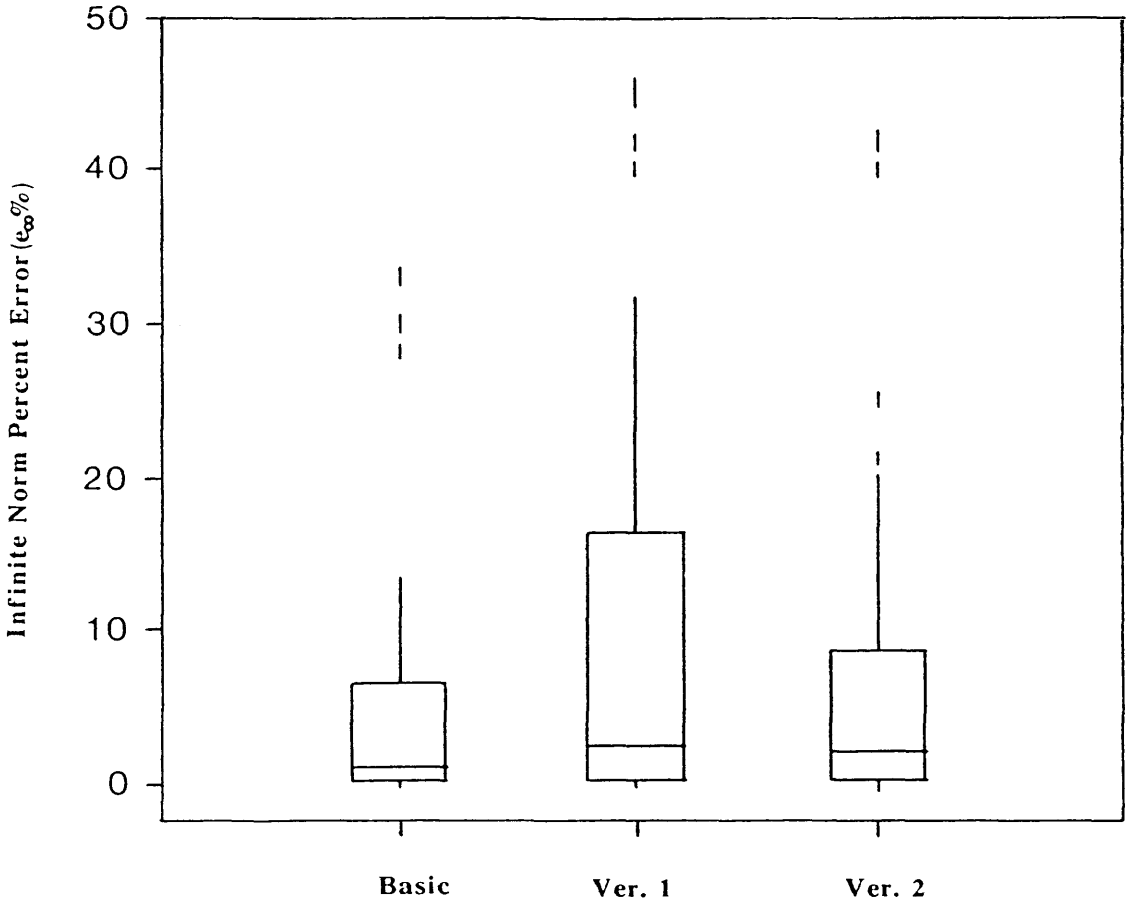


Fig. 4.8b Box-and-Whisker Plot of the Infinite Norm Percent Error e_∞%

below 10%, which is considered a very high accuracy, since the infinite norm represents the largest voltage violation, therefore usually the most stringent condition.

Other Numerical Results

In view of the above results version 2 was chosen as the final method, and from now on it will be called E&PSG Contingency Selection. Further results are reported in the following to provide additional illustration of the performance of the method.

The IEEE 57 bus test system:- A base case with 33 voltages below .95 pu was chosen in order to create hard-to-solve contingency cases. Thirty branch contingencies, corresponding to branches number 1 to 30 (See Appendix B), were then evaluated by running the E&PSG contingency selection algorithm and a full load flow program. The error was defined as the absolute value of the difference between each PQ bus voltage calculated by the load flow (V_i^{lf}) and by the E&PSG program ($V_i^{E\&PSG}$):-

$$e_i = | V_i^{lf} - V_i^{E\&PSG} |$$

Table 4.7 Frequency Distribution of e_i - IEEE 57 bus test system

Class	Lower Limit	Upper Limit	Midpoint	Freq.	Relative Freq.	Cum. Freq.	Cum. Rel. Freq.
at or below		.00000		184	.116382	184	.116
1	.00000	.00500	.00250	1246	.788109	1430	.904
2	.00500	.01000	.00750	81	.051233	1511	.956
3	.01000	.01500	.01250	42	.026565	1553	.982
4	.01500	.02000	.01750	12	.007590	1565	.990
5	.02000	.02500	.02250	6	.003795	1571	.994
6	.02500	.03000	.02750	2	.001265	1573	.995
7	.03000	.03500	.03250	3	.001898	1576	.997
8	.03500	.04000	.03750	2	.001265	1578	.998
9	.04000	.04500	.04250	1	.000633	1579	.999
10	.04500	.05000	.04750	2	.001265	1581	1.000
above	.05000			0	.000000	1581	1.000

Mean = 0.0019 Standard Deviation = 0.0042 Median = 0.0005

Note that 1430 bus voltage magnitudes or 90.4% percent of the values show error at or below 0.005 pu.

The IEEE 118 bus test system:- The E&PSG contingency selection program covered the 179 branch contingencies. The base case run from the flat start presented 8 voltage violations, with the lowest voltage magnitude equal to 0.9286 pu. The minimum and maximum pre-contingency voltage magnitude limits were set at 0.95 and 1.05 pu., respectively. The post-contingency limits were set at .910 and 1.05 pu. Therefore, those contingencies whose infinite norm PI (largest voltage violation) exceeded 0.0400 pu were selected to form the worst-case-list. Having obtained the worst-case-list, the PI's were recalculated using a full AC load flow. The comparison results are summarised in Table 4.8.

Table 4.8 IEEE 118 bus test system The Wort-Case-List

a) E&PSG Contingency Selection Results

Contingency	From	To	J_{v1}	$J_{v\infty}$	No. of Violations
112	68	81	.129	.0491	9
140	84	85	.135	.0487	8
103	63	64	.127	.0478	9
155	94	95	.143	.0449	8

b) E&PSG Load Flow Results

Contingency	From	To	J_{v1}	$J_{v\infty}$	No. of Violations
112	68	81	.129	.0497	9
140	84	85	.123	.0389	8
103	63	64	.129	.0497	9
155	94	95	.143	.0449	8

c) Absolute Errors

Contingency	$J_{v1}^{(a)} - J_{v1}^{(b)}$	$J_{v\infty}^{(a)} - J_{v\infty}^{(b)}$	No.of Viol. (a)-(b)
112	0.000	-0.0006	0
140	0.012	0.0098	0
103	-0.002	-0.0019	0
155	0.000	0.0000	0

Computing Time:- The total computing times (cpu+i/o) are shown in Table 4.9 for six test systems: the IEEE 30, 57 and 118 bus test systems, the CEMIG 32 bus system, and the CEGB 34 and 729 bus systems. The flat start voltage profile was adopted as initial conditions for all test systems. This produced low voltage base cases for all tested system, and therefore, hard-to-solve contingency cases. The E&PSG contingency selection program running covered every single branch outage. The test were performed using an IBM AT and a MICROVAX II computers. The IBM AT version of the program was dimensioned for 200 buses and 300 branches. Therefore the results for the CEGB 729 bus system was obtained only with the

MICROVAX II version of the program.

Table 4.9 E&PSG Contingency Selection Computing Time

Test System Characteristic			Computing Time(sec)	
Network Name	No.of buses	No.of branches	MICROVAX II	IBM AT
IEEE30	30	41	2.11	9.45
CEMIG	32	32	0.73	4.07
CEGB-SW	34	56	3.61	15.93
IEEE57	57	80	7.56	30.97
IEEE118	118	179	28.55	117.43
CEGB-729	729	1105	1238.15	-

4.9 CONTINGENCY EVALUATION

Even though in the contingency selection phase the voltages in every bus of the system for each contingency are explicitly evaluated there is little interest in recording these voltages, due to the large amount of data. For example, the 179 branch contingencies of the IEEE 118 bus test system would generate a data set with 42244 items (2 x 118 x 179). Moreover, most of the cases would have a voltage profile within the permissible range therefore requiring no further analysis. So, even adopting a screening technique the results should be summarised in the form of PI's, and in terms of these PI's the worst-case-list should be formed. Then, for the worst-case list a detailed analysis is carried out. However, it is convenient to pre-fix both the maximum number of cases in the worst-case-list and a threshold for the largest violation. Thereby, only the voltage results for those contingencies with a violation larger than the pre-fixed threshold need to be stored. These results can then be used as a starting point for the contingency evaluation phase. With a good starting point the contingency evaluation

process becomes extremely fast, since only a polishing of the approximate initial solution is needed.

In the contingency evaluation phase all individual voltage results including the sensitivity coefficients with respect to the control variables should be recorded, since they are likely to be the input data for calculations of measurements for enhancement of the system security. Techniques were developed as an extension to the E&PSG load flow method to allow for the efficient calculation and handling of these sensitivity coefficients. These techniques are described in this section, and the effective tool for the general problem of removal of violations, which is the optimal power flow, is dealt with in the next chapter.

Sensitivity Matrix Techniques

When a contingency is evaluated, it is important for control purposes (i) to determine the control action which has the greatest effect over the voltage magnitude of every busbar in the system, and (ii) to determine which busbar has its voltage magnitude most affected by one particular control action among those control actions which can be commanded by the operator, e.g., voltage magnitude at PV buses, transformer taps, capacitor/reactor switching.

The major relationship between the control actions and their effects can be approximated by the first order sensitivity matrix. Since this matrix is dependent on the system operating conditions and the system structure, it should be calculated anew for each contingency. A useful representation of the relationship between the N_{pq} system PQ bus voltages and the M control measures, taken from Cheng et al.[93], is shown in Fig. 4.9. It can be seen that for each

bus voltage, several control measures can be used. It can be also seen that changes in each control measure results in changes to several bus voltages. For a certain bus voltage violation, it is possible to calculate, by using the sensitivity technique, the control action needed to overcome this voltage violation. Two facts limit the control action. First, the control action should not exceed the control constraints. Second the control action used to overcome the voltage violation should not produce new bus voltage violations.

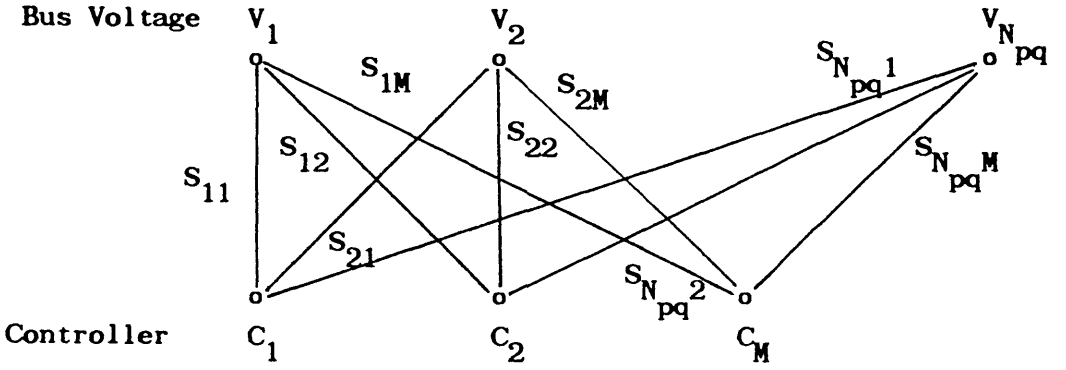


Fig. 4.9 Representation of the Voltage Control
(Adapted from Cheng et al.[93])

Calculation of the Sensitivity Matrix S_u:- From a converged load flow solution, the relationship between changes in the power injections and voltage angles and magnitudes can be expressed as

$$\begin{bmatrix} \Delta P_{sw} \\ \Delta P_{pv} \\ \Delta P_{pq} \\ \hline \Delta Q_{sw} \\ \Delta Q_{pv} \\ \Delta Q_{pq} \end{bmatrix} = \left[\begin{array}{c:c} & \\ [\partial P/\partial\theta] & [\partial P/\partial V] \\ & \\ \hdashline & \\ [\partial Q/\partial\theta] & [\partial Q/\partial V] \\ & \end{array}\right] \begin{bmatrix} \Delta\theta \\ \hline \Delta V_{sw} \\ \Delta V_{pv} \\ \Delta V_{pq} \end{bmatrix}$$

As $\Delta P=0$ and $\Delta\theta\neq 0$, the elimination of $\Delta\theta$ in the above equation yields

$$\begin{bmatrix} \Delta Q_{sw} \\ \Delta Q_{pv} \\ \Delta Q_{pq} \end{bmatrix} = \left[[\partial Q/\partial V]-[\partial Q/\partial\theta][\partial P/\partial\theta]^{-1}[\partial P/\partial V] \right] \begin{bmatrix} \Delta V_{sw} \\ \Delta V_{pv} \\ \Delta V_{pq} \end{bmatrix}$$

Which is the linearised reactive load flow equation of the E&PSG Load Flow; where

$$L_q = [\partial Q/\partial V]-[\partial Q/\partial\theta][\partial P/\partial\theta]^{-1}[\partial P/\partial V]$$

Since the injection changes at the PQ busbar $\Delta Q=0$, it can be written

$$[\,0\,] = [\,[\,L_1\,] \vdots [\,L_2\,]\,] \left[\begin{array}{c} \Delta V_{sw} \\ \Delta V_{pv} \\ \hline \Delta V_{pq} \end{array}\right]$$

where, L_1 and L_2 are submatrices given by partitioning L_q accordingly. The effects of tculs are now included

$$[\,0\,] = [\,[\,L_1\,] \vdots [\,L_a\,] \vdots [\,L_2\,]\,] \left[\begin{array}{c} \Delta V_{sw} \\ \Delta V_{pv} \\ \hline \Delta a \\ \hline \Delta V_{pq} \end{array}\right] \qquad (4.16)$$

The elements $L_{a,ij}$ of matrix L_a are calculated by expressing the reactive power injection as a function of the reactive power flows entering the generalized branch i-j.

$$Q_i = Q_{io} + \sum_{j\epsilon I'} Q_{ij} = Q_{io} + \sum_{j\epsilon I'} -(a_i V_i)^2 (b_{ij}+b_{io}) + (a_i V_i) V_j b_{ij} \cos\theta_{ij} - (a_i V_i) V_j g_{ij} \sin\theta_{ij}$$

Hence,

$$L_{a,ii}=\frac{\partial Q_i}{\partial a_i}=\sum_{j\epsilon I'} -2a_i V_i^2(b_{ij}+b_{io})+V_i V_j b_{ij}\cos\theta_{ij}-V_i V_j g_{ij}\sin\theta_{ij} \tag{4.17}$$

$$L_{a,ij}=\frac{\partial Q_i}{\partial a_j}=\sum_{j\epsilon I'} V_j V_i b_{ji}\cos\theta_{ji}-V_j V_i g_{ji}\sin\theta_{ji}$$

At this point it is convenient to adopt the notation used in optimal power flows and to define the vector of the independent or control variables

$$[\ \Delta u\ ] = [\ [\ \Delta V_{sw}\ ]\ [\ \Delta V_{pv}\ ]\ [\ \Delta a\ ]\ ]^t \tag{4.18}$$

and the vector of the dependent variables

$$[\ \Delta x\ ] = [\ \Delta V_{pq}\ ] \tag{4.19}$$

In terms of which, (4.16) can be written as

$$[\ 0\ ] = [\ G_u\ ]\ [\ \Delta u\ ] + [\ G_x\ ]\ [\ \Delta x\ ] \tag{4.20}$$

where,

$[\ G(u,x)\ ] = [\ Q(V,a)\ ]$

$[\ G_u\ ] = [\ \partial Q/\partial u\ ] = [\ [L_1] : [\ L_a\ ]\ ]$

$[\ G_x\ ] = [\ \partial Q/\partial x\ ] = [\ L_2\ ]$

From (4.20), we write the sensitivity of dependent variables with respect to control variables,

$$[\ \Delta x\ ] = [\ S_u\ ]\ [\ \Delta u\ ] \tag{4.21}$$

where,

$$[\ S_u\ ] = -\ [\ G_x\ ]^{-1}\ [\ G_u\ ] \tag{4.22}$$

The sensitivity of the voltage magnitude at a bus i (PQ) with respect to a shunt capacitor/reactor switching at bus j (PQ) is calculated by modelling the shunt element as a var injection ΔQ_j^{sh}.

$$\Delta V_i = L_{q_{ij}}^{-1}\ \Delta Q_j^{sh} \tag{4.23}$$

The control vector and the sensitivity matrix should be modified to include this sort of control.Thus,

$$\Delta u = [\ [\ \Delta V_{sw}\ ]\ [\ \Delta V_{pv}\ ]\ [\ \Delta a\ ]\ [\ \Delta Q^{sh}\ ]\ ]^t$$

$$[\ G_u\ ] = [\ [\ L_1\ ] : [\ L_a\ ] : [\ L_{sh}\ ]\ ]$$

where, L_{sh} is a (N_{pq} x N_{sh}) matrix with all elements equal zero, but -1 in position ji corresponding to the j^{th} bus where the i^{th} shunt element control is to be switched.

Efficient Computation of S_u:- Even though G_x and G_u are sparse the sensitivity matrix S_u is full. Therefore, the direct calculation and storage of one sensitivity matrix for each contingency may not be convenient, because of storage reasons. Instead the LDU table of factors of L_q and the few elements of the sparse L_a matrix are stored for each contingency. Using the LDU decomposition routine of the E&PSG load flow program, it is extremely fast to obtain the matrix S_u (or just the needed elements of S_u) column by column. Thus, to obtain the i^{th} column of S_u. First, set up the vector

$$\underline{w} = -\ G_{u,ki} \qquad k = 1, \ldots, N_{pq}$$

Then solve the linear system,

$$G_x\ \underline{s} = \underline{w}$$

In the solution the vector $\underline{s}$ contains the i^{th} column of S_u.

Selection of the Effective Control Variables

Sensitivity based techniques for selection of the most sensitivity control variables have been widely used in var/voltage control problems. Examples of these can be found in [93-101]. Some very simplified approaches rely on the constant network Z_{bus} matrix

[101,96]. Others [96] select the control devices based on their geographical location. The existing approaches have at least four major difficulties:

1) Geographical considerations for selection of sensitive areas can be unrealistic. Cases are now known where the most effective control is far from the busbar needing correction.

2) For large network disturbances, as in the case of contingencies, some sensitivities calculated for the base case will change completely and should be recalculated.

3) Sensitivities calculated using the B'' matrix of the fast decoupled load flow are bound to be totally wrong.

4) The set of control variables in the outage cases is different in value from that in the base case: for example when tcul transformers, shunt elements or generators are outaged. Outage of these elements is not generally considered.

Procedures for the Selection of the most Sensitive Control Variable:- Two procedures for selection of the most sensitive control variable were developed and implemented as menu options in the E&PSG Load Flow for contingency evaluation. The first procedure consists of the straightforward selection of the sensitive set, Ω_k, of control variables available for removing voltage violation in bus i at contingency k.

$$\Omega_k = \{ i : |S_{u,ij}/S^{max}_{u,ij}| > \tau \}$$

The second procedure aims to qualify the effectiveness of a particular control variable in eliminating out-of-limit voltage in a given contingency. Thus, a table of indices , I_{kj}, was organized,

where the rows, k, correspond to the contingencies, and the columns, j, to the control variables. The numerical values of the I_{kj}'s are obtained by computing the effects of a unit increase in every control variable over the set, χ, of buses that present limit violation problems:

$$I_{kj} = \left| \sum_{i} S_{u,ij} \, du_j \right| \qquad (4.24)$$

$$i \in \chi, \; j \in \Omega_k, \; k \in \Psi$$

where, Ψ is the set of contingencies. Finally, to provide better relative values each row of the table is expressed as a percent of the maximum value in this row. More details of this procedure are given as part of a numerical case example developed in Chapter 7.

CHAPTER 5

VAR OPTIMAL POWER FLOW

5.1 INTRODUCTION

The problem of improving the system state by removing the violations caused by both load variations and contingencies requires a reactive power control model. The tool for this is a var optimal power flow. As pointed out earlier, the var optimal power flow can be used in conjunction with the state estimator to periodically adjust significant out-of-optimum controls in order to maintain feasible voltages and reactive power output of sources. It can also be used to study, in advance, the requirements of reactive resources for contingencies and scheduled maintenance. Both the reactive power control model and the associated optimal power flow have been developed and are presented in this chapter.

A robust optimal reactive power flow has been produced by improvements in the mathematical model, careful programming implementation, full use of sparse matrix techniques, as well as by innovative techniques for enforcement of functional inequalities and by analytic determination of the step in the minimum seeking descending direction. Fast execution times, high convergence rates and efficient and compact program code allowed for the solution of large scale networks using low cost personal microcomputers. Applications of the methodology include both the optimisation of intact networks and the solution of the var expansion and var dispatch problems. The optimisation of intact networks is dealt with in this chapter while the var expansion and var dispatch problems are

the subjects of Chapter 6 and Chapter 7 respectively. Numerical testing results on several test networks and comparisons with existing methods are also presented.

5.2 PRELIMINARY CONSIDERATIONS

Statement of the Problem

All OPF approaches are based on optimisation techniques. The mathematical description of the problem of concern is:

$$\begin{aligned} &\text{Minimize} && f(y) \\ &\quad y\epsilon\mathbb{R}^n \\ &\text{subject to} && c_i(y)\geq 0 \qquad i=1,2,....m \end{aligned}$$

where the objective function $f(y)$ and the constraint functions $\{c_i(y)\}$ are twice continuous differentiable.

In power system applications the choice of the objective function $f(y)$ determines the type of control OPF will provide. If $f(y)$ is chosen to reflect cost or losses OPF becomes an economic dispatch (See [102,103]). If the system is insecure or in an emergency state (See Table 2.2), $f(y)$ can be chosen to minimise violations or to return the system to a secure state, and the OPF becomes a preventive dispatch or emergency control. If loads have been lost, but the system is no longer in an emergency state, $f(y)$ can be selected to restore loads with minimum control action and the OPF becomes a restorative control (See Fig. 2.3). The constraint set $\{c_i(y)\}$ includes both the physical Kirchhoff laws represented by the load flow equations and the operational constraints associated with the problem the OPF is solving. These operating constraints are often translated into upper and lower limits on system quantities. The limits are sometimes classified as soft or hard depending on their nature. Thus, limits associated with the range of physical equipment

are naturally seen as hard, whilst the following limits are usually seen as soft limits: branch flows, spinning reserves, area interchanges, bus voltage angle separation, bus voltage angles, MW wheeling, etc. Therefore, the choice of the objective function as well as the type of constraints imposed will determine the type of control action being aimed for and the type of problem the OPF is solving.

Decision, Dependent and Specified Variables

In order to establish the cause-effect relationship of the system it is useful to adopt the nomenclature used in control theory [104]. The variables of the system are divided into three groups, namely, (i) decision, independent or control variables (u), (ii) dependent or state variables (x), (iii) specified or disturbance variables (p). In addition to the variables there are the fixed network parameters and the output functions.

The decision variables are those that can be directly controlled in real-time operations: (1) the voltage magnitude and power output of all generation sources, except for the power output at least one generator (slack), which is considered a dependent power source with its output being the value necessary to maintain an energy balance for the network; (2) the real power flows through DC lines; (3) the phase angles across phase-shift transformers; (4) the tap settings of tculs; (5) the admittance of variable reactors and switched capacitor banks; (6) breaker positions by which the network can be reconfigured. Variables (1) and (2) are continuous. Variables (3) through (5) change in small steps, and therefore, can be thought of as continuous. Variables (6) produce large discrete changes in the power flows and, therefore, are not seen as part of the problem as

defined here.

The dependent or state variables are those which are physically controlled by the decision variables: bus voltage magnitudes, phase angles at load buses and phase angles at generation buses.

The specified or disturbance[1] variables are the active and reactive power components of load. These are completely beyond direct power system control, since they are determined by the power user [33]. Of course, if some form of load management is to be used, then those corresponding active and reactive components of the bus loads under management become control variables.

The fixed network parameters are represented by the admittance matrix Y_{bus}. The output functions are power output of the slack bus, reactive power output of generation sources, branch currents, power flows and losses.

Decomposition

The OPF formulations and their corresponding solution approaches are strongly influenced by the natural decomposition of the control variables according to their effects on the active and reactive power flows. Some of the control variables primarily affect reactive power flows and others the active power flows. In many cases it is difficult, undesirable, or impossible to change a large number of system controls. Likewise it is inappropriate to reschedule active-power controls simultaneously with reactive power controls.

For instance, Stott, Olsac and Monticelli [35] give, as an example of a badly posed problem, trying to minimise losses by using

1 According to Elgerd,(chapter 7, pp. 233,[33]) the name disturbance refers to the fact that the unpredictable changes in these variables cause the system to deviate from its nominal state.

generator powers as control variables. Another bad example is the imposition of limits on MW reserves with only voltages and taps as controls. They also state that the active- and the reactive-power subproblems should, in any case, be solved separately.

This thesis addresses the reactive-power subproblem only.

Objective Function

It was assumed that the results of loss minimisation are only marginal and that the primary objective is considered to be the assurance of a level of security in terms of meeting var constraints under a set of predefined contingencies [105,106,123,124]. Furthermore, as the var dispatch is to be performed as a second step (See Tables 1.1-2 and Fig.1.1), i.e.,after the optimisation of the active power dispatch, the former produces results near the optimal loss minimisation anyway, irrespective of the objective function used for the var dispatch [107-110]. For example, the optimisation results of the IEEE 30-bus test system given in Table 5.5aII (at the end of the chapter) use the sum of the squares of the deviations from the flat voltage profile as objective function. The results show final active power losses of 7.11 MW. D.T. Sun and R. Shoults [152] use a composite objective function which includes loss minimisation to solve the same problem. Their results show final losses of 9.283, therefore 30.6% greater. Another problem with loss minimisation occurs in interconnected systems. The solution sometimes decreases the internal system losses in one area at the expense of higher losses in the neighbouring areas. Finally, it is worth stressing that var/voltage problems may limit the transmission capacity and cause system breakdown [111].

5.3 THE BACKGROUND OF PREVIOUS WORK

The methodology in this thesis benefits in various ways from the vast literature on optimal power flow [112]. Extensive reviews can be found in references [50,113-115]. The general optimisation principles on which all OPF methods are based are reviewed in reference [116]. Additional basic mathematical literature can be found in references [117-121].

The State of the Art

No practically usable methods guarantee to solve feasible problems or to find global Optima [152]. The Minos 5.0 Code[2] seems to be the state of the art in non-linear optimisation techniques. According to Murtagh and Saunders [122] about 150 academic and research institutions and 30 private industries have installed it. Example of its applications to the OPF problem can be found in references [123-131]. The code consists of developments of particular algorithms (the simplex method, a quasi-Newton method, the reduced gradient method, and a projected Lagrangian method) into a single program. Therefore, it permits the solution of both small and large problems in the four main areas of smooth optimisation: linear programming, unconstrained optimization, linearly constrained optimisation, and nonlinearly constrained optimisation. With reference to the difficulty of solving general optimisation problems Murtagh and Saunders [122] recognized, "...many users have been able to develop substantial nonlinear models and have come to be fairly

---

2 Minos stands for Modular In-core Nonlinear Optimisation System, Systems Optimization Laboratory, Department of Operations Research, Stanford University, Stanford, California 94305 (1983).

confident that the Optimal Solution message actually means what it says. Certainly, other less joyful exit messages will often have greeted eager eyes. These serve to emphasize that model building remains an art, and that nonlinear problems can be difficult to solve."

Optimisation: Ready-to-use package versus customised program

The first decision to be made was to choose between using an optimisation package or developing a customised optimisation program. Investigations with the Minos 5.0 code presented the following difficulties:-

1) The Minos 5.0 is a parameter-driven system. There are 80 parameters to be set for each case.
2) The various modules cannot be called upon in any arbitrary order.
3) In the quasi-Newton algorithm a dense triangular matrix of the approximation of the second derivatives, i.e., the Hessian, has to be stored and requires about 2,000 words of storage.
4) The amount of workspace required is roughly 800m bytes (m is the number of constraints). A further 300 kbytes, approximately, are needed for the program itself, along with buffer space for several files.
5) The computing time is of the order of several minutes. (See, for example references [123,124]).

Consequently, it was concluded that the Minos 5.0 code was not adequate for the real-time interactive applications aimed for in the developments of this thesis. Moreover, the use of microcomputers would not be possible, if this alternative were adopted.

Following this, some effort was spent on the adaptation of other ready-to-use optimisation packages. These involved implementations of

OPFs using the NAG library [55], and the method of reference [121]. Both cases showed convergence problems, inadequate computing times and code sizes. Another problem was the inflexibility of the ready-to-use routines with regard to modifications,i.e. , rather than adapting the optimisation software to the physical OPF problem, the physical model had to adapt to the requirements of the optimisation routine. Therefore, the development from scratch of an optimal power flow, with full exploitation of the structure of the var/voltage problem was found to be necessary and was finally adopted.

As a user of Minos I found that considerable time needed to be spent (i.e., several months) to gain familiarity with its use. Having then encountered the many handicaps outlined above I decided to abandon use of Minos and develop an OPF from scratch. The next logical step was to choose the most suitable mathematical method of solution.

Main Mathematical Methods of Solution

There are four mathematical methods of solution largely applied to the OPF problem: Linear Programming (LP), Kuhn-Tucker (KT), Gradient (GR) and Variable Metric (VM).

Linear Programming is not an attractive choice, because of the high nonlinearity of the reactive power problem. Nevertheless, there are several reported attempts to use LP in the literature [132-143]. A good example of an LP formulation for improving the voltage profile and to optimise losses can be found in [142]. A very similar formulation appears later in [143]. Nowadays it is recognised that LP can only be successfully applied to remove slight violations around the operational point and is unable to represent a real alternative for solving the reactive optimal power flow.

Kuhn-Tucker techniques attempt to solve the problem by

satisfying the KT optimality conditions directly. These techniques seem to be the first methods to be proposed for the optimum control of reactive power flow [109]. The Kuhn-Tucker techniques have not received much success, lacking reliability and speed [12].

Gradient techniques are perhaps the most used optimisation method in OPF. The method consists of generating a series of estimates $\{y_\upsilon\}$ of the optimal y^* by calculating the gradient of the objective function $\nabla f(y_\upsilon)$ and a step length β_υ such that

$$y_{\upsilon+1}=y_\upsilon + \beta_\upsilon \nabla f(y_\upsilon) \text{ and } f(y_{\upsilon+1}) \leq f(y_\upsilon).$$

In OPF applications, it is common to divide the GR techniques into two approaches according to the treatment of the independent variables set: The Dommel-Tinney approach [144] and the Generalized Reduced Gradient (GRG) approach [36,145-147]. In the Dommel-Tinney approach the set of decision variables is fixed and a penalty term in the objective function provides for the enforcement of the functional inequalities. In the GRG approach the sets of control and dependent variables are chosen to facilitate the handling of the inequality constraints. The set of control variables change from one iteration to the next, whenever a functional quantity violates a limit. The main practical difficulties usually associated with the gradient methods are the handling of the functional inequalities constraints and the determination of the step length. In the Dommel-Tinney approach the penalty function requires careful tuning while in the GRG approach the variable switching introduces a logical burden that complicates algorithms and code, besides making it difficult to use a load flow program. Slow convergence is another problem with GR approaches.

Variable metric methods, which are sometimes called quasi-Newton methods, use an approximation, A, of the Hessian matrix, H, to

calculate the descent direction. For example, at the minimum we have

$$H\, y^{*} = b$$

At a current point y_{υ}, whatever it is, we have,

$$H\, y_{\upsilon} = \nabla f(y_{\upsilon}) + b$$

Subtracting these two equations and multiplying by the inverse matrix H^{-1}, yields

$$y^{*} - y_{\upsilon} = - H^{-1}\, \nabla f(y_{\upsilon})$$

Subtracting the above equation at $y_{\upsilon+1}$ from that same equation at y_{υ} gives the recurrence equation

$$y_{\upsilon+1} = y_{\upsilon} - H^{-1}\, [\nabla f(y_{\upsilon+1}) - \nabla f(y_{\upsilon})]$$

If the exact Hessian is used, the correction is called the Newton correction [148]. If the approximation, A, is used the correction is called quasi-Newton [125]. Usually, A is initially made equal to the unit matrix and then updated at each iteration using the Davidon-Fletcher-Powell or the Broyden-Fletcher-Goldfarb-Shanno updating formula (See [57]). The difficulties with the VM approaches are: 1) H is difficult and costly to evaluate, 2) Round-off errors can cause the matrix A to become nearly singular or non-positive definite. If A is non-positive definite the direction is inappropriate to follow. If A is nearly singular the updating formulae tend to give subsequent A's which are also nearly singular. 3) The VM approaches require the storage of a NxN matrix.

Choice of the Mathematical Method of Solution

A Dommel-Tinney type approach, with the use of the Fletcher and Reeves conjugate directions, was the mathematical approach preferred for the development of the new reactive-only power flow of this thesis. The disadvantages of the approach (slow convergence, determination of the step length and treatment of the inequalities

constraints) were expected to be solved in the course of the developments of the new OPF. The details of the solutions developed will be the subject of the rest of this chapter.

The main factors which led to choice of this method are listed as follows.

1) The approach presents the best potential for economy of memory space used, which is fundamental with regard to the use of personal microcomputers.
2) The Dommel-Tinney method is probably the most coded algorithm. Many production programs exist (see [2]).
3) The interfaces between OPF, other programs and the operator can be made more effective when the optimisation is over the variables which the operator can directly and independently control.
4) Simplicity.

Finally, with regard to the above decision, it is useful to quote here some authorities either in the power system optimisation field, or in the pure optimisation field:-

J.L. Carpentier [12]: "For active-reactive or reactive-only OPF, gradient compact and quadratic sparse techniques appear to be equivalent in performance, as long as security under contingency is not concerned. When it is, gradient compact techniques seem better for real-time use."

P.E.Gill, W.Murray, M.A.Saunders and M.Wright [116]: " Conjugate-gradient methods require the storage of only a few n-vectors.....if the approximate Hessian matrix can be stored, the Fletcher-Reeves algorithm is generally inferior to the BFGS quasi-Newton algorithm in terms of the number of times that F is evaluated. However, recent research on conjugate-gradient-type methods has considerably increased their robustness and efficiency."

W.H.Press, B.P.Flannery, S.A.Teukolsky, W.T.Vetterling [57]: " The variable metric approach differs from the gradient in the way it stores and updates the information that is accumulated. Instead of requiring intermediate storage of the order of N, the number of dimensions, it requires a matrix of size NxN.....there is not, as far as we know, any overwhelming advantage that the variable metric holds over the conjugate gradient techniques, except perhaps an historical one..... We tend to use variable metric rather than conjugate gradient, but we have no reason to urge this habit on you."

R.C.Burchett, H.H.Happ, K.A.Wirgau [125]: " ...the conjugate gradient method has been shown to be a possible alternative to the quasi-Newton method for very large problems that could have large reduced Hessians."

B.Stott,O.Alsac,A.J.Monticelli [35]: " The most "powerful" methods that solve smooth classical formulations with quadratic convergence appear to be at a disadvantage particularly for real time application. Each iteration is very time-consuming, providing the un-needed accuracy overkill characteristic of these methods."

5.4 THE MODEL OF THIS THESIS

Problem Formulation

The Mathematical Problem:- The optimal var-only load flow is formulated as an non-linear optimisation problem.

Minimise	$F(u, x)$	(5.1)
Subject to	$G(u, x) = 0$	(5.2)
	$H(u, x) \geq 0$	(5.3)

Control Variables

In this formulation u represents the vector of independent

variables and x is the vector of dependent or state variables. The voltage magnitudes at swing, var generation and load buses, and the tap settings of in-phase tcul transformers are represented by V_{sw}, V_{pv}, V_{pq} and T, respectively

$$[\ u\ ] = [V_{sw}\quad V_{pv}\quad T\ ]^t \qquad (5.4)$$
$$[\ x\ ] = [\ V_{pq}\ ]$$

Objective Function

The objective function F(.) is the minimisation of the summation of the squares of the deviations from a given voltage magnitude and var source output targets (for example, the base case intact system voltage profile and var generation limits, or an optimum operating point $z^*=(u^*,x^*)^t$, assumed to be taken from some previous optimal real power schedule.)

$$F(u,x) = \frac{w_v}{2}\sum_{i\epsilon N} \rho_{vi}(V_i - V_i^o)^2 + \frac{w_g}{2}\sum_{j\epsilon G} \rho_{gj}(Q_{gj} - Q_{gj}^{lim})^2 \qquad (5.5)$$

where, G is the set of var sources, (generator/compensators), N is the set of buses, w_v and w_g are weights, Q_{gj} and Q_{gj}^{lim} are output and limits of var sources, respectively, and ρ_{gj} and ρ_{vi}

$$\rho_{gj}\begin{cases} = 0 & \text{iff} \quad Q_{gj}^{min} \le Q_{gj} \le Q_{gj}^{max} \\ = 1 & \text{otherwise} \end{cases}$$
$$\rho_{vi}\begin{cases} = 0 & \text{iff} \quad V_i^{min} \le V_i \le V_i^{max} \\ = 1 & \text{otherwise} \end{cases} \qquad (5.6)$$

The output of the var sources are computed in per unit of the violated limits as in (4.8-9).

Constraints

Equality Constraints:- G(.) are the n_{pq} reactive power load flow equations (3.45) (where the voltage angles are implicitly considered).

$$Q_i^{sp} - Q_i(V) = 0 \qquad i=1,2,.....n_{pq} \qquad (5.7a)$$

Inequality Constraints:- H(.) represent the system operating constraints: limits on n_{bus} voltage magnitudes, tap settings of n_t tcul transformers and bounds on n_g var generations.

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad i=1,2,.....n_{bus} \qquad (5.7b)$$

$$a_i^{min} \leq a_i \leq a_i^{max} \qquad i=1,2,.....n_t \qquad (5.7c)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \qquad i=1,2,.....n_g \qquad (5.7d)$$

Method of Solution

In the Reduced Gradient (RG) method, equations (5.1) and (5.2) are combined to form the Lagrangian function,

$$\mathcal{L}(u,x,\lambda) = F(u,x) + [\ \lambda\ ]^t\ [\ G(u,x)\ ] \qquad (5.8)$$

The necessary conditions for an optimum solution require that (5.9) through (5.11) be satisfied,

$$[\ \mathcal{L}_u\ ] = [\ \partial\mathcal{L}/\partial u\ ] = [\ F_u\ ] + [\ G_u\ ]^t\ [\ \lambda\ ] = 0 \qquad (5.9)$$

$$[\ \mathcal{L}_x\ ] = [\ \partial\mathcal{L}/\partial x\ ] = [\ F_x\ ] + [\ G_x\ ]^t\ [\ \lambda\ ] = 0 \qquad (5.10)$$

$$[\ \mathcal{L}_\lambda\ ] = [\ \partial\mathcal{L}/\partial \lambda\ ] = [\ G(u,x)\ ] = 0 \qquad (5.11)$$

For a feasible Load Flow solution G(u,x)=0. From (5.10) we have,

$$[\ \lambda\ ] = -\ [\ G_x\ ]^{t^{-1}}\ [\ F_x\ ] \qquad (5.12)$$

Replacing (5.12) in (5.9) yields,

$$[\ \nabla F\ ] = [\ F_u\ ] - [\ G_u\ ]^t\ [\ G_x\ ]^{t^{-1}}\ [\ F_x\ ] \qquad (5.13)$$

or, rewriting (5.13) in terms of the sensitivity matrix of (4.22) gives,

$$[\ \nabla F\ ] = [\ F_u\ ] + [\ S_u\ ]^t\ [\ F_x\ ] \qquad (5.14)$$

Expression (5.14) is called the reduced or projected gradient.

Steepest Descent Algorithm:- The reduced gradient is projected on the set of feasible controls and the search direction is taken as the negative of this projected value. The feasible direction is taken as

$$r_i = \begin{cases} 0 & \text{if} \quad \delta F/\delta u_i < 0 \quad \text{and} \quad u_i = u_i^{max} \\ 0 & \text{if} \quad \delta F/\delta u_i > 0 \quad \text{and} \quad u_i = u_i^{min} \\ -\ \delta F/\delta u_i & \text{otherwise} \end{cases} \qquad (5.15)$$

In fact, at a given iteration a better direction can be constructed to be conjugated to the old gradient, and in so far as possible, to all previous directions traversed. Methods which accomplish this construction are called conjugate gradient methods. This will be dealt with in the next section.

The increments in the control variables are calculated by expressing all voltage magnitudes as a function of the step length, β

$$\begin{bmatrix} \begin{bmatrix} \Delta V_{sw} \\ \Delta V_{pv} \end{bmatrix} \\ \begin{bmatrix} \Delta V_{pq} \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} 1 \end{bmatrix} \begin{bmatrix} 0 \end{bmatrix} \\ \begin{bmatrix} S_u \end{bmatrix} \end{bmatrix} \beta \begin{bmatrix} r \end{bmatrix} \qquad (5.15)$$

The objective function is then written as a function of β, and the optimum step length, β^*, is given by

$$\frac{dF(\beta)}{d\beta} = 0 \qquad \text{and} \qquad \frac{d^2F(\beta)}{d\beta^2} > 0 \qquad (5.16)$$

The analytic determination of the optimum step length will be the subject of Section 5.5.

The control variables are then updated according to

$$u_i^{new} = \begin{cases} u_i^{max} & \text{if} \quad u_i + \beta^* r_i > u_i^{max} \\ u_i^{min} & \text{if} \quad u_i + \beta^* r_i < u_i^{min} \\ u_i + \beta^* r_i & \text{otherwise} \end{cases} \qquad (5.17)$$

With these new values of the control variables a new var-only load flow solution is performed. The iterative process continues until no more significant reductions in the objective function are obtained or until the maximum gradient component is less than a predefined tolerance. Having reached convergence, the false slack busbar is eliminated, as already explained in Chapter 3. Fig. 5.1 shows a flow chart of the optimisation procedure.

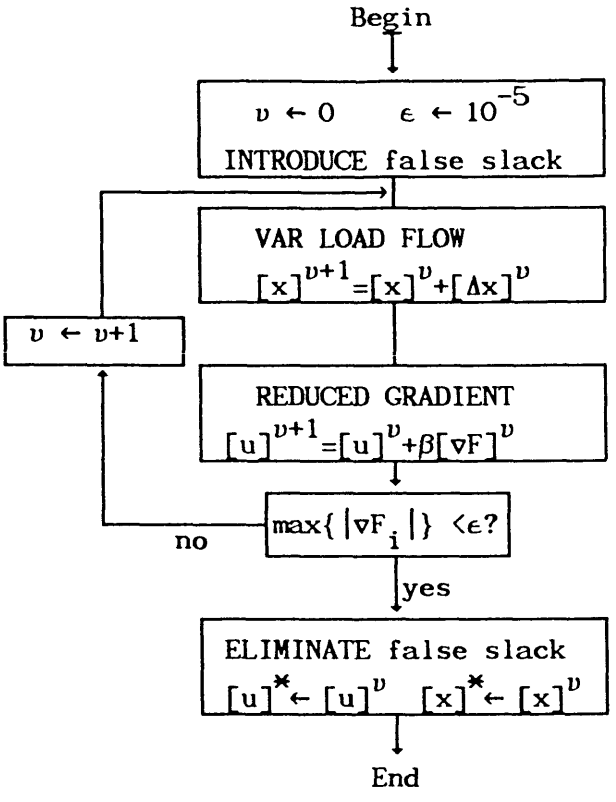


Fig. 5.1 Steepest Descent Algorithm

Conjugate Gradient Direction

The steepest descent algorithm converges linearly, and in some cases converges slowly. The direction of the steepest descent, $-\nabla F$, can be greatly improved for most objective functions by linearly combining the descent directions at adjacent points in a recursive manner. Consider the descent direction as,

$$r_{\upsilon+1} = -\nabla F + \alpha_{\upsilon} r_{\upsilon}$$

$$\alpha_{o} = 0$$

where, υ is the current iteration. The change in the control variable, Δu, is,

$$\Delta u_{\upsilon+1} = \beta r_{\upsilon+1}$$

This formulation is called the conjugate directions algorithm. The scalar value, α_{υ}, is defined depending on the conjugate directions

technique used. The most popular technique is the Fletcher-Reeves method (See [57,116,149])

$$\alpha_{\upsilon} = \frac{|| \nabla F^{\upsilon+1} ||^2}{|| \nabla F^{\upsilon} ||^2}$$

The conjugate directions algorithm is quadratically convergent for quadratic forms of the objective function and superlinearly convergent for most power system applications. The strategy described in Burchet, Happ, Vierath and Wirgau [149] was adopted: the conjugate gradient algorithm is the primary technique, but convergence is improved by periodically switching to steepest descent for one optimal iteration.

Computation of the Derivatives (F_u, F_x)

In order to calculate the derivatives of the objective function with respect to the control and state variables it is convenient to rewrite (5.5) as

$$F(x,u)=\frac{w_{pq}}{2}\sum_{i=1}^{n_{pq}}\rho_{xi}(x_i-x_{oi})^2+\frac{w_{pv}}{2}\sum_{j=1}^{n_u}\rho_{uj}(u_j-u_{oj})^2+\frac{w_g}{2}\sum_{k=1}^{n_g}\rho_{gk}(Q_{gk}(u,x)-Q_{gk}^{lim})^2$$

where the weights w_v and ρ_v were dismembered into w_{pq} and w_{pv}, and ρ_{xi} and ρ_{uj}, respectively.

It follows that

$$F_{u_i} = \frac{\partial F}{\partial u_i} = w_{pv}\,\rho_{ui}\,(u_i-u_{oi}) + w_g \sum_{k=1}^{n_g}\rho_{gk}(Q_{gk}(u,x)-Q_{gk}^{lim})\,\frac{\partial Q_{gk}}{\partial u_i}$$

$$F_{x_i} = \frac{\partial F}{\partial x_i} = w_{pq}\,\rho_{xi}\,(x_i-x_{oi}) + w_g \sum_{k=1}^{n_g}\rho_{gk}(Q_{gk}(u,x)-Q_{gk}^{lim})\,\frac{\partial Q_{gk}}{\partial x_i}$$

For $u = V_{pv}$ and $x = V_{pq}$, i.e. voltage magnitudes, the partial

derivatives $\partial Q_{gk}/\partial u_m$ and $\partial Q_{gk}/\partial x_m$ are given by the corresponding elements $L_{q,km}$ of the matrix L_q. For u = T, i.e. tculs, the partial derivatives $\partial Q_{gk}/\partial u_m$ are given by (4.17).

5.5 OPTIMAL STEP LENGTH (β)

Introduction

"It must be emphasized that the robustness of an optimisation method will depend upon the method used to compute the step length." Gill et. al. [116]. A measure of the efficiency of the method for calculating β is the number of times that the objective function has to be evaluated. An analytic method of calculating β was developed and will be described in this section. Thereby, the objective function does not need to be evaluated at all. The generalisation of the method for other objective functions of interest in var optimal power flow was also derived and is presented.

Development of the Method

The var output of a source k is given by

$$Q_{g_k} = V_k \sum_{m \epsilon K} V_m \, (G_{km} \sin \theta_{km} - B_{km} \cos \theta_{km}) + Q_{d_k} \qquad (5.18)$$

In terms of matrix A of (4.11)

$$A_{km} = G_{km} \sin \theta_{km} - B_{km} \cos \theta_{km} \qquad (5.19)$$

it can be written

$$Q_{g_k} = V_k \sum_{m \epsilon K} V_m \, A_{km} + Q_{d_k} \qquad (5.20)$$

where, K is the set of busbars directly connected to bus k, including

the busbar k.

Through the linear sensitivity between control and state variable, we have

$$[\ \Delta x\ ] = S_u\ [\ \Delta u\ ] \tag{5.21}$$

Let $\Delta u(\beta)$ be the displacement towards the optimum value of the objective function. Thus

$$[\ \Delta u(\beta)\ ] = \beta\ [\ r_u\ ] \tag{5.22}$$

where β is a positive real number which gives the step length in the negative direction of the conjugate gradient vector, and

$$[\ r_u\ ] = \frac{[\ r\ ]}{\| r \|_2} \tag{5.23}$$

In terms of the dependent variables, we can write

$$[\ \Delta x(\beta)\ ] = S_u\ \beta\ [\ r_u\ ] \tag{5.24}$$

or, for all SW, PV and PQ busbars

$$\begin{bmatrix} \Delta V_{1sw} \\ \Delta V_{1pv} \\ \vdots \\ \Delta V_{npv} \\ \Delta V_{1pq} \\ \Delta V_{2pq} \\ \vdots \\ \Delta V_{npq} \end{bmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 \cdots & 0 & 0 & \cdots & 0 \\ \vdots & 0 & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & 0 & \cdots & 0 \\ S_{11} & S_{12} & \cdots & S_{1npv} & \cdots & & S_{1nt} \\ S_{21} & S_{22} & \cdots & S_{2npv} & \cdots & & S_{2nt} \\ \vdots & \vdots & \ddots & \vdots & & & \vdots \\ S_{npq1} & S_{npq2} & \cdots & S_{npqnpv} & \cdots & & S_{npqnt} \end{bmatrix} \beta \begin{bmatrix} r_{u1sw} \\ r_{u1pv} \\ \vdots \\ r_{unpv} \\ r_{u1t} \\ \vdots \\ r_{unt} \end{bmatrix} \tag{5.25}$$

or, schematically,

$$\begin{bmatrix} \begin{bmatrix} \Delta V_{sw} \\ \Delta V_{pv} \end{bmatrix} \\ \begin{bmatrix} \Delta V_{pq} \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \boxed{1} & \boxed{0} \\ \multicolumn{2}{c}{\boxed{S_u}} \end{bmatrix} \beta\ [\ r_u\ ] \tag{5.26}$$

The i^{th} component of (5.26) reads

$$\Delta V_i(\beta) = \beta \sum_{j\epsilon\Omega} S'_{u_{ij}} r_{u_j} \tag{5.27}$$

where Ω is the set of all control variables.

Voltage magnitudes and output of var sources can then be written as functions of β

$$V_i(\beta) = V_i + \Delta V_i(\beta) \tag{5.28}$$

$$Q_{g_k}(\beta) = (V_k + \Delta V_k(\beta)) \sum_{m\epsilon K} (V_m + \Delta V_m(\beta)) A_{km} + Q_{d_k} \tag{5.29}$$

or,

$$Q_{g_k}(\beta) = (V_k + \beta \sum_{j\epsilon\Omega} S'_{u_{kj}} r_{u_j}) \sum_{m\epsilon K} (V_m + \beta \sum_{j\epsilon\Omega} S'_{u_{mj}} r_{u_j}) A_{km} + Q_{d_k} \tag{5.30}$$

The objective function becomes a function of β as well

$$F(\beta) = F_1(\beta) + F_2(\beta) \tag{5.31}$$

where,

$$F_1(\beta) = \frac{w_v}{2} \sum_{m\epsilon N} \rho_{v_m} (V_m(\beta) - V_m^o)^2 \tag{5.32}$$

$$F_2(\beta) = \frac{w_g}{2} \sum_{k\epsilon G} \rho_{g_k} (Q_{g_k}(\beta) - Q_{g_k}^{lim})^2 \tag{5.33}$$

where N and G are the sets of busbars and var sources, respectively, w_v and w_g are weights, and

$$\rho_{v_m} (\rho_{v_m} - 1) = 0 \qquad \rho_{g_k} (\rho_{g_k} - 1) = 0 \tag{5.34}$$

The point β^* yields an optimum value for (5.31) when its first derivative with respect to β becomes zero.

$$\frac{dF(\beta^*)}{d\beta} = \frac{dF_1(\beta^*)}{d\beta} + \frac{dF_2(\beta^*)}{d\beta} = 0 \qquad (5.35)$$

Computation of the derivatives

1) Derivative of $F_1(\beta)$

$$\frac{dF_1(\beta)}{d\beta} = w_v \sum_{m\epsilon N} \rho_{v_m} (V_m(\beta) - V_m^o) \frac{dV_m(\beta)}{d\beta} \qquad (5.36)$$

Considering (5.27) and (5.28) we find

$$\frac{dV_m(\beta)}{d\beta} = \sum_{j\epsilon\Omega} S'_{u_{mj}} r_{u_j} \qquad (5.37)$$

Making

$$C_i = \sum_{j\epsilon\Omega} S'_{u_{ij}} r_{u_j} \qquad (5.38)$$

and,

$$\Delta V_i^o = V_i - V_i^o \qquad (5.39)$$

and substituting (5.37) through (5.39) into (5.36), we have

$$\frac{dF_1(\beta)}{d\beta} = w_v \sum_{m\epsilon N} \rho_{v_m} (\Delta V_m^o C_m + \beta C_m^2) \qquad (5.40)$$

Hence, if the objective function is only $F_1(\beta)$, then according to (5.35), we have

$$\beta^* = \frac{-\sum_{m\epsilon N} \rho_{v_m} \Delta V_m^o C_m}{\sum_{m\epsilon N} \rho_{v_m} C_m^2} \tag{5.41}$$

Indeed, β^* is a point of minimum for $F_1(\beta)$, since

Proof:-

$$\frac{d^2F_1(\beta^*)}{d\beta^2} = w_v \sum_{m\epsilon N} \rho_{v_m} C_m^2 > 0 \tag{5.42}$$

2) Derivative of $F_2(\beta)$

$$\frac{dF_2(\beta)}{d\beta} = w_g \sum_{k\epsilon G} \rho_{g_k} (Q_{g_k}(\beta) - Q_{g_k}^{lim}) \frac{dQ_{g_k}(\beta)}{d\beta} \tag{5.43}$$

Considering (5.30), we find

$$\frac{dQ_{g_k}(\beta)}{d\beta} = \frac{C_k Q_k + D_k}{V_k} + 2 C_k D_k \beta \tag{5.44}$$

where,

$$D_k = \sum_{m\epsilon K} C_m A_{km} \tag{5.45}$$

Making,

$$\Delta Q_{g_k}^o = Q_{g_k} - Q_{g_k}^{lim} \tag{5.46}$$

and,

$$E_k = \frac{C_k Q_k + D_k}{V_k} \tag{5.47}$$

and, taking (5.44) into (5.43) yields a third degree polynomial in β of the form

$$\frac{dF_2(\beta)}{d\beta} = w_g \left(a + b\,\beta + c\,\beta^2 + d\,\beta^3 \right) \tag{5.48}$$

whose coefficients are given by

$$a = \sum_{k \epsilon G} \rho_{g_k} E_k \Delta Q^o_{g_k} \tag{5.49}$$

$$b = \sum_{k \epsilon G} \rho_{g_k} \left(E_k^2 + 2\, C_k\, D_k\, \Delta Q^o_{g_k} \right) \tag{5.50}$$

$$c = 3 \sum_{k \epsilon G} \rho_{g_k} C_k\, E_k\, D_k \tag{5.51}$$

$$d = 2 \sum_{k \epsilon G} \rho_{g_k} C_k^2\, D_k^2 \tag{5.52}$$

Hence, if the objective function is only $F_2(\beta)$, then according to (5.35), the roots of the equation below give the optimum values for (5.31)

$$a + b\,\beta + c\,\beta^2 + d\,\beta^3 = 0 \tag{5.53}$$

This equation is solved using the analytical formulas given in Chapter VI of Francois Viete's treatise "De emendatione," published in 1615, as presented in Press and others [57].

Write (5.53) in the form

$$\beta^3 + a_1\beta^2 + a_2\beta + a_3 = 0 \tag{5.54}$$

then compute

$$Q = \frac{a_1^2 - 3a_2}{9} \quad \text{and} \quad R = \frac{2a_1^3 - 9a_1a_2 + 27a_3}{54} \tag{5.55}$$

Next, check that $R^2-Q^3>0$. If this holds, then the cubic equation has only one real root, given by

$$\beta_1 = -\text{sgn}(R)\left[(\sqrt{R^2-Q^3}+|R|)^{1/3} + \frac{Q}{(\sqrt{R^2-Q^3}+|R|)^{1/3}}\right] - \frac{a_1}{3} \tag{5.56}$$

If, on the other hand, $Q^3-R^2 \geq 0$, then the cubic equation has three real roots. To find them, compute

$$\theta = \arccos\left(\frac{R}{\sqrt{Q^3}}\right) \tag{5.57}$$

the three roots are

$$\begin{aligned}
\beta_1 &= -2\sqrt{Q}\cos\left(\frac{\theta}{3}\right) - \frac{a_1}{3} \\
\beta_2 &= -2\sqrt{Q}\cos\left(\frac{\theta+2\pi}{3}\right) - \frac{a_1}{3} \\
\beta_3 &= -2\sqrt{Q}\cos\left(\frac{\theta+4\pi}{3}\right) - \frac{a_1}{3}
\end{aligned} \tag{5.58}$$

These roots are points of optimum values for (5.31). A positive value for the second derivative shows which one of the three is a point of minimum, β^*.

$$\frac{d^2F_2(\beta)}{d\beta^2} = w_g\,(\,b + 2\,c\,\beta + 3\,d\,\beta^2\,) > 0 \tag{5.59}$$

An alternative way to find out β^* numerically has been developed

using the tangent's method. The algorithm is as follow:-

1. Initialize the iteration counter: $\upsilon = 0$.
2. Make an initial guess: e.g., $\beta_\upsilon = 0$.
3. Set the tolerance: e.g., $\epsilon = 0.000001$
4. Calculate:

$$f_\upsilon = f(\beta_\upsilon) = a + b\,\beta_\upsilon + c\,\beta_\upsilon^2 + d\,\beta_\upsilon^3$$

$$f'_\upsilon = \frac{df(\beta_\upsilon)}{d\beta} = b + 2\,c\,\beta_\upsilon + 3\,d\,\beta_\upsilon^2$$

5. If $|\,f_\upsilon\,| < \epsilon$ then $\beta_1^* = \beta_\upsilon$ and go to step 9.
6. Update β:

$$\beta_{\upsilon+1} = \beta_\upsilon - \frac{f_\upsilon}{f'_\upsilon}$$

7. Update the iteration counter: $\upsilon = \upsilon+1$
8. Go to step 4.
9. If $w_g\, f'(\beta_1^*) = \dfrac{d^2F_2(\beta_1^*)}{d\beta^2} > 0$ then $\beta^* = \beta_1^*$ stop otherwise go to step 10.
10. Reduce the degree of the equation dividing it by $(\beta - \beta_1^*)$, i.e., calculate:

$$e = d\,\beta_1^{*2} + \beta_1^*\,c + b$$

$$g = d\,\beta_1^{*2} + c$$

11. Solve $h(\beta) = e + g\,\beta + d\,\beta^2 = 0$:-

$$\delta = -\frac{1}{2}\left[\, g + \mathrm{sgn}(g)\,\sqrt{g^2 - 4\,e\,d}\,\right]$$

$$\beta^* = \begin{cases} \beta_2^* = \delta/d & \text{if} \quad f'(\beta_2^*) > 0 \\ \text{or, exclusive,} & \\ \beta_3^* = e/\delta & \text{if} \quad f'(\beta_3^*) > 0 \end{cases}$$

12. End.

3) Derivative of F(β)

$$\frac{dF(\beta)}{d\beta} = \frac{dF_1(\beta)}{d\beta} + \frac{dF_2(\beta)}{d\beta} \qquad (5.60)$$

Performing the sum above, i.e., adding (5.40) to (5.48) yields a third degree polynomial equation of the form

$$\frac{dF(\beta)}{d\beta} = a' + b'\,\beta + c'\,\beta^2 + d'\,\beta^3 \qquad (5.61)$$

where,

$$\begin{aligned} a' &= w_g\, a + w_v \sum_{m\epsilon N} \rho_{v_m}\, \Delta V_m^o\, C_m \\ b' &= w_g\, b + w_v \sum_{m\epsilon N} \rho_{v_m}\, C_m^2 \\ c' &= w_g\, c \qquad \text{and} \qquad d' = w_g\, d \end{aligned} \qquad (5.62)$$

Whose solution β^*, is found in the same way as described in item 2) above.

Generalization of the Objective Function

This subsection shows how to extend the method to cover the various objective functions of interest in var optimisation.

Equation (5.31) can be seen as a general form for several different objective functions used in var optimisation, namely:-

a) Minimum deviation of an economic operational point [V^{opt}].

$$V_m^o = V_m^{opt} \quad m\epsilon N, \quad \rho_v = 1, \quad w_g = 0.$$

b) Minimisation of the reactive output of var sources, trying to distribute them in proportion to the generator ratings.

$$Q_k^{lim}=0, \quad \rho_{g_k}^{1/2}=\frac{1}{\sqrt{S_{g_k}^2 - P_{g_k}^2}}, \quad w_v=0$$

where, S_{g_k} and P_{g_k} are the ratings of the var source k and active power of the generator k, respectively.

This function tends to avoid the rotor limitation of the smaller units.

c) Minimisation of active transmission losses.

$$A_{km} = G_{km} \cos \theta_{km} + B_{km} \sin \theta_{km}$$
$$w_v=0 \qquad Q_{g_k}^{lim} = Q_{d_k} = 0 \qquad k \epsilon G$$

d) Minimisation of the sum of the reactive injections from var sources.

$$Q_{g_k}^{lim} = 0 \quad k \epsilon G, \qquad w_v=0$$

This objective tends to maximise the overall var margin, without taking into account its distribution in the different generating areas.

e) Minimisation of the deviation of the voltages from pre-selected values, e.g.: rated values.

$$V_m^o = V_m^{rated} \qquad m \epsilon N, \qquad w_g=0$$

f) Minimisation of the total investment cost of additional var sources (capacitor/reactor).

$$Q_{g_k}^{lim} = 0 \quad k\epsilon G', \quad w_v=0, \quad \rho_{g_k}^{1/2} = c_k$$

where, G' is the set of candidate buses for addition of capacitor/reactor, and c_k is the unit cost of the var source at busbar k.

5.6 APPLICATION OF THE METHODOLOGY

Table 5.1 shows results of the optimisation of three test systems. The initial conditions involved 3 violating quantities for the 6 bus WDHL test system, 5 for the IEEE 14 bus test system and 18 for the IEEE 30 bus test system. At solution there were no violations. It can be seen that the method converges rapidly for all cases. Two results are presented for the IEEE 14 bus test system. In the first case limits were imposed in all var outputs while in the second case the var sources were unlimited. These two test conditions were set up so as to demonstrate the effects of the weighting in the composite objective function and in the number of iterations taken. Whilst in the first case 5 iterations were needed for convergence, the second case, which corresponded only to enforcement of voltage violations, took just one iteration. Complete results for the first case are given in Table 5.2. It can be seen from there that the convergence process was fast and steady, with all components of the gradient vector becoming zero at the minimum point.

Table 5.1 Optimisation Results
Number of Iterations and Weights

Test System Characteristics			Weight Factors			Number of iterations
Name	Buses	Branches	w_{pv}	w_{pq}	w_g	
WDHL	6	7	1.	20.	.1	1
IEEE	14	20	1.	20.	.1	5
IEEE*	14	20	1.	20.	.1	1
IEEE	30	41	1.	20.	.1	2
* Unlimited var source outputs						

The method provides very good performance and fast convergence. However, since the objective function encompasses a composite objective involving summation of dissimilar quantities, there is the problem of tuning the weights for the optimisation of each particular system. It does not constitute a great disadvantage if the method is to be used with a fixed network. Of course, for a given utility network, the weights can be tuned once and for all. This problem is characteristic of all optimisation involving multi-objective function. It is similar to the aggregation problem with the performance index studied in the previous chapter. Whenever an objective function involves different quantities one has to define the relative priority of the goals to be achieved and to weight properly. For instance, a decision should be made if it is more important to remove a certain percentage of voltage magnitude violations or to enforce rigidly the limits on var sources. Adopting an equal weighting is not, of course, a satisfactory solution. Furthermore, the control variables have different sensitivities with respect to each different objective. For instance, the optimisation program can move all the controls to remove a minor var violation and cause new voltage violations all over the system, and vice versa. Both cases may lead to instability of the optimisation process.

Table 5.2 **Optimisation Results for the IEEE 14 Bus Test System**

a) Gradient Vector versus Iteration Number

	iteration number					
GR	0	1	2	3	4	5
(1)	-.3543	-.2565	-.1361	-.1004E-01	-.7454E-02	.0000
(2)	.9781	-.6625	2.154	-.3242E-01	.1151	.0000
(3)	-.2401	.9458E-02	-.1615	.1346	-.8849E-02	.0000
(4)	-.8877	-.6691	-.1611	-.1395E-01	-.8808E-02	.0000
(5)	-.3334	-.2538	-.7179E-01	-.8588E-02	-.3935E-02	.0000
(6)	.9652E-01	.6699E-01	.7544E-01	.9015E-02	.4007E-02	.0000
(7)	-.5152E-02	-.7256E-02	.3118E-01	.3766E-02	.1661E-02	.0000
(8)	.3426	.2420	.1266	.9106E-02	.6739E-02	.0000

b) Control Variable versus Iteration Number

iteration	control variable							
number	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0	1.005	.9861	1.003	1.013	1.005	1.021	1.032	1.068
1	1.020	1.026	1.003	1.053	1.020	1.017	1.033	1.054
2	1.022	.9989	1.005	1.054	1.021	1.016	1.032	1.052
3	1.023	1.002	.9919	1.056	1.022	1.015	1.032	1.051
4	1.023	1.001	.9920	1.056	1.022	1.015	1.032	1.051

c) Objective Function Values

Iter.No.	Objective Function Value
0	.36845E-01
1	.30686E-01
2	.25757E-02
3	.93397E-04
4	.81165E-05
5	.00000

Continue...

Table 5.2 Continuation

d) Busbar Status

d.1 Initial Values (pu)

u/x	Bus	Type	Voltage	Angle	P-gen	Q-gen.	P-load	Q-load
u1	1	SW	1.0000	.00	2.350	-.427	.000	.000
u2	2	PV	1.0000	-5.91	.400	.658**	.217	.127
u3	3	PV	1.0000	-14.88	.000	.683**	.942	.190
u4	6	PV	1.0000	-16.06	.000	.086	.112	.075
u5	8	PV	1.0000	-15.07	.000	.058	.000	.000
x1	4	PQ	.9683**	-11.64	.000	.000	.478	-.039
x2	5	PQ	.9665**	-9.90	.000	.000	.076	.016
x3	7	PQ	.9898	-15.07	.000	.000	.000	.000
x4	9	PQ	.9847	-16.88	.000	.000	.295	.166
x5	10	PQ	.9794	-17.07	.000	.000	.090	.058
x6	11	PQ	.9858	-16.71	.000	.000	.035	.018
x7	12	PQ	.9841	-17.04	.000	.000	.061	.016
x8	13	PQ	.9789	-17.14	.000	.000	.135	.058
x9	14	PQ	.9628**	-18.15	.000	.000	.149	.050

d.2 Final Values (pu)

Voltage	Angle	P-gen.	Q-gen.
1.0231	.00	2.337	-.039
1.0005	-5.27	.400	.096
.9920	-13.99	.000	.495
1.0559	-15.65	.000	.395
1.0216	-14.36	.000	.051
.9844	-11.18	.000	.000
.9877	-9.60	.000	.000
1.0129	-14.36	.000	.000
1.0157	-16.02	.000	.000
1.0151	-16.24	.000	.000
1.0317	-16.06	.000	.000
1.0390	-16.52	.000	.000
1.0322	-16.55	.000	.000
1.0044	-17.31	.000	.000

(**) Violating Quantity

Continue...

Table 5.2 Continuation

e) Tcul Tap Settings

u	Tcul No.	From	To	Tap (% of nominal) Initial	Final
u6	8	4	7	102.25	101.53
u7	9	4	9	103.20	103.17
u8	10	5	6	107.30	105.12

f) Total System Losses

Iteration No.	MW	Mvar
0	15.97	50.81
1	15.93	50.56
2	14.91	45.49
3	15.02	46.68
4	14.71	45.70
5	14.75	45.86

g) Step Length

Iteration	Step Length (beta)
0	.0210
1	.0619
2	.0269
3	.0135
4	.00147

h) Mismatch Logging

Iteration Number Loop: Outer	Inner	Maximum Mismatches p	q
0	0	.942000	.518872
	1	.124407	.350325E-01
	2	.798763E-02	.246676E-03
	3	.879169E-06	
1	0	.167242	.954531E-01
	1	.740845E-01	.135439E-02
	2	.107814E-02	.720633E-04
	3	.373675E-06	
2	0	.291517	.499176
	1	.294192	.266923E-01
	2	.140373E-01	.936105E-03
	3	.119849E-05	
3	0	.269707	.138699
	1	.300271E-01	.148666E-02
	2	.328385E-03	.929668E-04
4	0	.334390E-01	.504628E-01
	1	.126075E-01	.706447E-04
	2	.778266E-06	
5	0	.147905E-01	.755680E-02
	1	.165640E-02	.590090E-05
	2	.388518E-06	

==========

Therefore, a real improvement in the method would be to adopt a unique goal objective function. The benefits would be greater still if the objective function could be a pure quadratic form. In this case the method theoretically would converge in only one iteration. This can be noted from Table 5.1: when unlimited var bounds were set for the IEEE 14 bus test system it took just one iteration to converge, since the objective was made a pure quadratic form (only summation of the squared voltage violations.)

A new method for enforcing the var limits was developed thus enabling a unique goal objective function to be defined. This will be described in the next section.

5.7 ADAPTIVE LIMIT ENFORCEMENT-AN INNOVATIVE FEATURE

As has already been discussed in this chapter, one major obstacle to the success of GR techniques in OPF problems is the handling of functional inequalities constraints. An efficient technique for this was developed and will be detailed in the following.

Let the phases of the optimisation process be represented as in Fig. 5.2 below

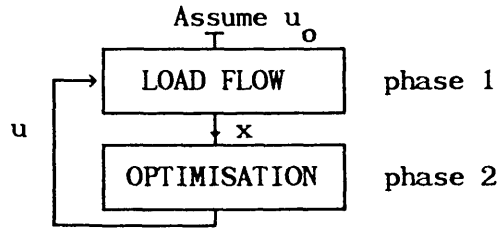


Fig. 5.2 Main Phases of the Optimisation Process

It can be seen that the opportunities of enforcement of the var

generation limits are either at the load flow phase or at the optimisation phase. The first idea was to automatically enforce the limits at the load flow phase. Then, the optimisation phase would only involve the rescheduling of the control variables to remove voltage violations. This alternative was thoroughly analysed, with several cases being studied. The scheme of changing bus status PV-PQ-PV was adopted to enforce the var generation limits at the load flow phase. The results showed the existence of a positive feedback loop between the load flow and the optimisation phase. A conflicting situation exists when, following the rules of the PV-PQ-PV switching scheme, the var limits were enforced and new voltage magnitudes calculated at the load flow phase. Then, the optimisation process tends to reschedule the control variables to new values which, in general, lead to new var generation violations. The result of these conflicting adjustments produces oscillation in almost all cases.

However, a detailed analysis of the mechanisms of this conflicting situation made it clear that a co-ordination of the adjustment process was not only possible but also necessary. Hierarchical levels were then attributed to the several adjustment tasks. The load flow phase was attributed high priority to enforce the var limits and to establish adaptively the range in the control variables. This range should be fixed in such a way that the var outputs would remain within the limits for new values of the control variables within the range. The optimisation phase could then completely ignore the problem of var enforcement. The assumed relations for determining the adaptive fixation of the limits are represented in Fig. 5.3.

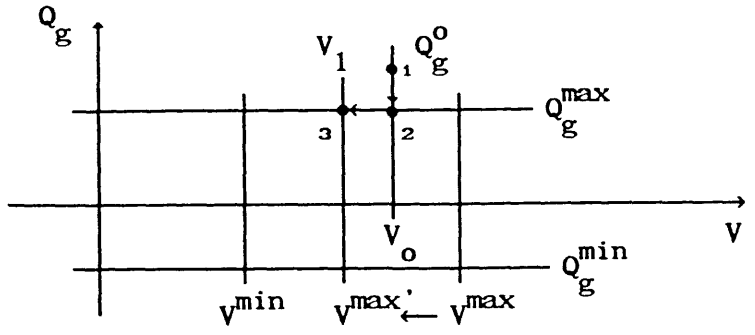


Fig. 5.3 VAR Output and Voltage Limits at PV buses

At the load flow step the voltage is specified (V_o) and the load flow solution gives Q_g. Should Q_g be found out of bounds (say, Q_g^o, point 1) then Q_g is fixed at the violating limit ($Q_g=Q_g^{max}$, point 2) and a new load flow solution is carried out giving a new value V_1 for V (point 3). The arrows shows that when Q_g tends to Q_g^{max}, V tends to V_1. Therefore, it is only to be expected that $Q_g < Q^{max}$ for $V<V_1$ whereas for $V>V_1$ then $Q_g>Q_g^{max}$, V_1 being the voltage value required to put the var output in the limit. Of course, there could be a better value for the voltage between V_1 and V^{min}, which keeping the var output within the permissible range, allows for a global gain in the objective function. In consequence, V_1 must be the maximum voltage limit, $V^{max'}$. The range of freedom for the optimisation phase is then between V^{min} and $V^{max'}$.

The optimisation phase can now be carried out with a unique goal objective function without inequality function constraints or penalty terms. Moreover, the rescheduled voltage values given by the optimisation constitutes a negative feedback for the loop load flow-optimisation and tends to keep the values of var outputs within the bounds, but not in the limit.

Having obtained a new value for V, at the optimisation phase, the

voltage limits are reestablished to the original values, since the conditions of the whole network may change and so the sensitivities between Q_g and V. The process continues with the load flow adaptively fixing new ranges of freedom for the rescheduling phase each time a var output violates its bounds.

Cases may occur when $V_1 < V^{min}$ (Fig. 5.3). In such cases the maximum limit is set equal to the minimum, and a corresponding term $(V-V_o)^2$ enters the objective function. All other controls will then try to reestablish the voltage magnitude at this bus to the scheduled value.

The above methodology was implemented in a computer program and tested with several systems. Table 5.3 and Fig. 5.4 show details of the programming organisation and the flow chart of the program.

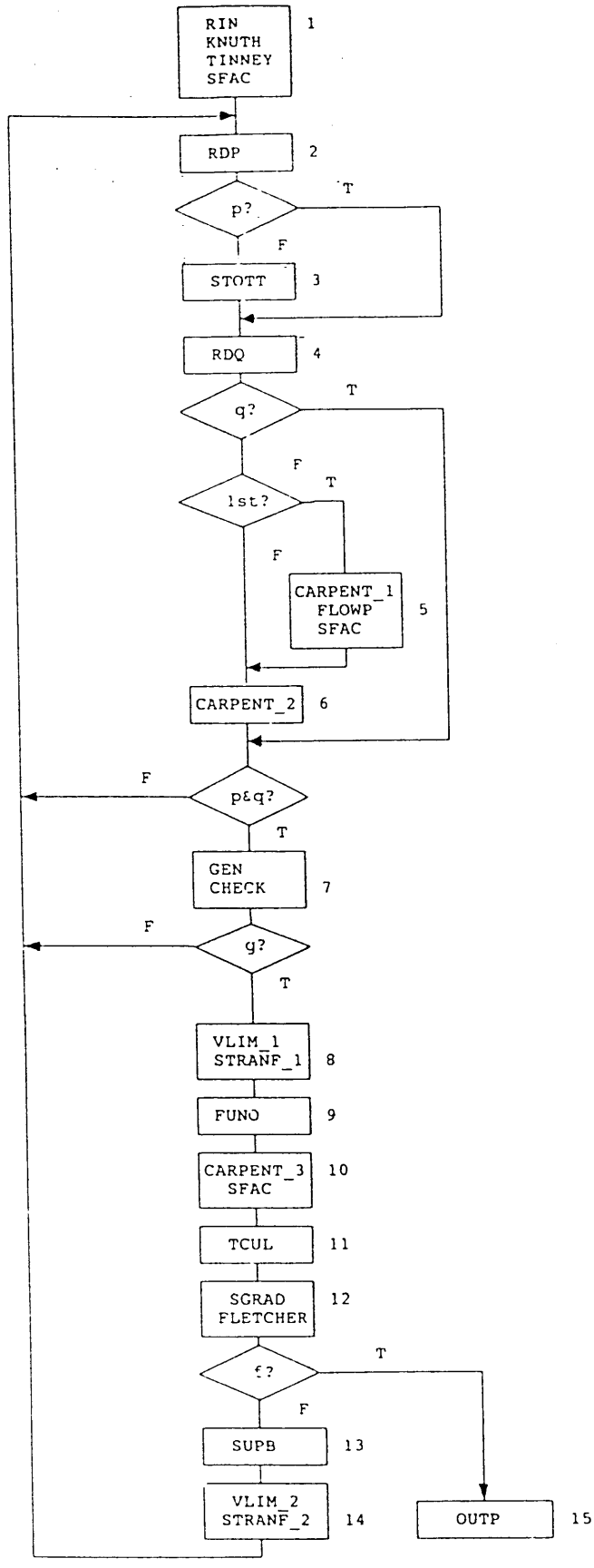
5.8 NUMERICAL RESULTS AND COMPARISONS

Numerical results

Numerical results summarised in Table 5.4 illustrate the performance of the methodology. The adaptive limit enforcement strategy resolves the problem of enforcement of functional inequalities and avoids the use of either penalties or composite objective functions. The objective function is now the pure quadratic form of (5.32). In contrast with the results presented in Table 5.1, where the number of iterations depend on the tuning of the weighting factors, the new approach requires no such tuning. The optimal point is reached in a few iterations independently of the network characteristics. It can also be seen from Table 5.4 that computing times are of the order of seconds. This makes it possible to implement the sophisticated non-linear optimisation techniques on

Table 5.3 Adaptive Limit Enforcement Optimisation Algorithm
Description of the Computing Subroutines
(See Fig. 5.4)

Step	Subroutine	Task
1	RIN	- Open data files - Set up limits (defaults) - Read in data
	KNUTH	- 1st renumbering and data consistency - Allocate memory for sparse arrays - Set up the false slack bus - Form the sparse network matrices, the Jacobian, B_p, and the structure of L_q.
	TINNEY	- 2nd renumbering: optimal ordering (3rd scheme of Tinney)
	SFAC	- Form the LDU factors of B_p.
2	RDP	- Compute the P mismatches - Bookkeep the best result so far: maximum mismatch, bus number, iteration number, voltage profile.
3	STOTT	- Solve for the voltage angles
4	RDQ	- Compute the Q mismatches - Bookkeep the best result so far: maximum mismatch, bus number, iteration number, voltage profile.
5	CARPENT_1	- Form L_q
	FLOWP	- Compute the P flows - Check for the static stability limits.
	SFAC	- Form the LDU factors of L_q
6	CARPENT_2	- Solve for the voltage magnitudes
7	GEN	- Compute the Q outputs for generators
	CHECK	- Check the Q output limits - Modify diagonal elements of L_q for violated PV buses.
8	VLIM_1	- Set up new voltage limits for violated PV buses.
	STRANF_1	- Form the control and state vectors.
9	FUNO	- Evaluate the objective function and the partial derivatives.
10	CARPENT_3	- Form L_1, L_2
	SFAC	- Form the LDU factors of L_2
11	TCUL	- Form L_*
12	SGRAD	- Solve for lambda. - Form the reduced gradient - Form the sparse sensitivity matrix. - Find the feasible direction and store it.
	FLETCHER	- Calculate the Fletcher and Reevers conjugate direction. - Calculate the optimal step length - Restart in the reduced gradient direction, if necessary. - Update the control variables, u.
13	SUPB	- Compensate the sparse network matrices for the effects of new tap settings.
14	VLIM_2	- Restore the voltage limits on PV buses.
	STRANF_2	- Update the PV bus voltages.
15	OUTP	- Eliminate the false slack bus. - Output Files.



Legend:

T = true F = false

Logical Operators:

p = max $|\Delta p_i| < \epsilon_p$, q = max$|\Delta q_i| < \epsilon_q$, f = max$|\nabla f_i| < \epsilon_f$,

1st = first iteration, g = $Q_{gi,min} < Q_{gi} < Q_{gi,max}$.

Fig. 5.4 Flow Chart of the Adaptive Limit Enforcement Optimisation Algorithm

low-cost personal computers and on EMS computers for on-line applications.

Table 5.4 Adaptive Limit Enforcement Optimisation Method
Number of iterations and Computing Times

Test System Characterisitics			No.of itera-	Computing times (sec) CPU+IO	
Name	Buses	Branches	tions	MICROVAX II	IBM-PC AT
IEEE	30	41	1	3.33	3.57
IEEE	39	46	1	4.10	4.33
IEEE	57	80	1	7.20	8.79
IEEE	118	179	3	20.64	59.81

Comparison of the result

The optimisation results for the above test systems are given in Tables 5.5a-d (at the end of the chapter). The results for the IEEE 118-bus test system are compared with other methods in Table 5.6. The new methodology was compared with two recent implementations of reactive power optimal load flow, whose test results were published in Balu et al. [123] and De la Fuente and Lumbreras [124]. The former is an EPRI research project (EPRI) and the latter a Spanish research project, Programa Investigation Electrotecnico (PIE). Both EPRI and PIE are large scale research projects which involve several different individual skills and institutions, such as industry, research centres, consultants, and universities, including specialised mathematical consultancy. Both EPRI and PIE use the Minos code for the optimisation method. Although the power system used in the PIE had 194 buses against the 118 bus network used to test the new methodology, the computing times were obtained using a much more powerful computer than the computer used to test the new methodology. The EPRI project also used a faster computer. In all cases, the bus voltage magnitudes were constrained between 0.95 and 1.05 pu. The flat voltage profile (1.0 pu, 0 degree) was adopted by PIE and also

in testing of the new methodology. The EPRI project recognized that run times are a function of the goodness of the starting point. The EPRI starting point was obtained by running the Philadelphia Electric Co. power flow program (PECO). It is also worth reproducing here an observation made in the EPRI report when establishing the scope of their testing: "...the use of this tool, and the proper interpretation of the results (even for a refined, production-grade model) requires the careful judgment of an engineer who is knowledgeable both in power system analysis and the specific system under study. For instance, within a reasonable solution tolerance, there is often not a unique answer. ... There may be several sets of coordinated settings of generator reactive outputs and transformer tap ratios that can satisfy voltage constraints, especially if loss minimization is not required.... Therefore the proper interpretation of merits of different possible solutions is necessary in using this program."

Table 5.6 Comparison of the New Methodology

Methodology/ Test Network	Computer/ MIPS	Starting Point	No.of Parameters	Core Code Size	Computing time (sec)
New Method IEEE 118 bus test system	MICROVAX II 0.9 MIPS	Flat	0	296 kbytes	20
EPRI Project IEEE 118 bus test system	VAX 11/780	Converged Load Flow Solution	80	2 Mbytes	90 600*
PIE Project 194 bus network.	SIEMENS 7570 5 MIPS	Flat	80	> 2 Mbytes (estimate)	115
*) Time for 5 iteration of active/reactive mode.					

As can be seen from Table 5.6, both the EPRI and PIE methods require the setting of at least 80 parameters whereas no parameters

need to be set in the new methodology. Both the EPRI and PIE implementations require considerably more user-interaction, core and computing times than the new method. Therefore EPRI and PIE are more suitable for an off-line batch environment whilst the new methodology can be used in an on-line interactive environment. Incidentally, the EPRI project recognised the need for the incorporation of a fast load flow program in order to streamline the solution process and to improve the portability of their package. Additionally, the PIE method required evaluation of 410 functions and 410 Jacobians (not reported for EPRI) against just 3 function and 9 Jacobian evaluations of the new methodology. Furthermore, the size of the Jacobian in the new methodology is presumably 4 times less than the Jacobian in both EPRI and PIE, since they use the PECO load flow (complete NR).

Concluding Comments

Whereas existing OPF techniques are suitable for off-line batch-oriented jobs, requiring large main frame computers, involving large programs, and experienced and trained users, the new approach is robust, compact, fast, and portable, being suitable for on-line applications. Even for off-line planning purposes, the existing methodology is expensive and non-portable. Therefore, it is only available to medium- or large-size organizations. On the other hand, the proposed methodology is portable and cheap, since it can be implemented in low cost microcomputers, including personal computers. Implemented in a control center computer, it can be either executed periodically or against operator's supplied data files.

Executed periodically the new methodology can:-

. assist the operator to detect significant out-of-optimum -control with regard to

- voltage profile
- management of var resources

. calculate the optimal setting of controls

. control the adequacy of var production margins

. indicate where additional var resources are more desirable in order to increase security and economy.

Executed against operator supplied data files:-

. to study in advance the requirements of var resources for contingencies and maintenance scheduling

. to planning the target voltage and var reserve.

Table 5.5a Optimisation Results for the IEEE 30-bus test System

I. BEFORE OPTIMISATION

	VOLTAGE			GENERATION		DEMAND	
No./TY	Mag.	Angle	Cap/Reat	MW	Mvar	MW	Mvar
1SW	1.0000	.00	.00	139.68	-37.08	.00	.00
2PV	1.0000	-3.33	.00	57.56	18.88	21.70	12.70
3PQ	.9956	-5.31	.00	.00	.00	2.40	1.20
4PQ	.9942	-6.38	.00	.00	.00	7.60	1.60
5PV	1.0000	-10.37	.00	24.56	50.77	94.20	19.00
6PQ	.9929	-7.39	.00	.00	.00	.00	.00
7PQ	.9874	-9.14	.00	.00	.00	22.80	10.90
8PV	1.0000	-7.49	.00	35.00	50.48	30.00	30.00
9PQ	.9732*	-9.30	.00	.00	.00	.00	.00
10PQ	.9616*	-11.52	17.57	.00	.00	5.80	2.00
11PV	1.0000	-7.10	.00	17.93	13.22	.00	.00
12PQ	.9604*	-10.53	.00	.00	.00	11.20	7.50
13PV	1.0000	-9.12	.00	16.91	28.52	.00	.00
14PQ	.9465*	-11.62	.00	.00	.00	6.20	1.60
15PQ	.9439*	-11.78	.00	.00	.00	8.20	2.50
16PQ	.9530*	-11.29	.00	.00	.00	3.50	1.80
17PQ	.9532*	-11.71	.00	.00	.00	9.00	5.80
18PQ	.9368*	-12.53	.00	.00	.00	3.20	.90
19PQ	.9360*	-12.74	.00	.00	.00	9.50	3.40
20PQ	.9416*	-12.51	.00	.00	.00	2.20	.70
21PQ	.9491*	-12.08	.00	.00	.00	17.50	11.20
22PQ	.9500*	-12.07	.00	.00	.00	.00	.00
23PQ	.9388*	-12.34	.00	.00	.00	3.20	1.60
24PQ	.9412*	-12.67	3.81	.00	.00	8.70	6.70
25PQ	.9569*	-12.70	.00	.00	.00	.00	.00
26PQ	.9380*	-13.18	.00	.00	.00	3.50	2.30
27PQ	.9759	-12.41	.00	.00	.00	.00	.00
28PQ	.9873	-7.84	.00	.00	.00	.00	.00
29PQ	.9550*	-13.76	.00	.00	.00	2.40	.90
30PQ	.9429*	-14.74	.00	.00	.00	10.60	1.90

SYSTEM GENERATION: 291.64 MW 146.16 Mvar

SYSTEM LOAD: 283.40 MW 126.20 Mvar

TAP SETTINGS:

NUMBER	TAP
11	97.80
12	96.90
15	93.20
36	96.80

(*) out-of-limit quantity

Table 5.5a Optimisation Results for the IEEE 30-bus test System

II. AFTER OPTIMISATION

	VOLTAGE			GENERATION		DEMAND	
No./TY	Mag.	Angle	Cap/Reat	MW	Mvar	MW	Mvar
1SW	1.0805	.00	.00	138.55	19.46	.00	.00
2PV	1.0581	-2.49	.00	57.56	15.14	21.70	12.70
3PQ	1.0486	-4.27	.00	.00	.00	2.40	1.20
4PQ	1.0413	-5.12	.00	.00	.00	7.60	1.60
5PV	1.0100	-8.26	.00	24.56	7.24	94.20	19.00
6PQ	1.0377	-5.99	.00	.00	.00	.00	.00
7PQ	1.0183	-7.43	.00	.00	.00	22.80	10.90
8PV	1.0482	-6.13	.00	35.00	60.00	30.00	30.00
9PQ	1.0298	-7.64	.00	.00	.00	.00	.00
10PQ	1.0253	-9.60	19.98	.00	.00	5.80	2.00
11PV	1.0277	-5.62	.00	17.93	-.75	.00	.00
12PQ	1.0300	-8.74	.00	.00	.00	11.20	7.50
13PV	1.0465	-7.48	.00	16.91	12.53	.00	.00
14PQ	1.0160	-9.69	.00	.00	.00	6.20	1.60
15PQ	1.0124	-9.82	.00	.00	.00	8.20	2.50
16PQ	1.0206	-9.39	.00	.00	.00	3.50	1.80
17PQ	1.0185	-9.75	.00	.00	.00	9.00	5.80
18PQ	1.0045	-10.47	.00	.00	.00	3.20	.90
19PQ	1.0031	-10.65	.00	.00	.00	9.50	3.40
20PQ	1.0079	-10.45	.00	.00	.00	2.20	.70
21PQ	1.0130	-10.08	.00	.00	.00	17.50	11.20
22PQ	1.0136	-10.08	.00	.00	.00	.00	.00
23PQ	1.0045	-10.30	.00	.00	.00	3.20	1.60
24PQ	1.0027	-10.58	4.32	.00	.00	8.70	6.70
25PQ	1.0055	-10.52	.00	.00	.00	.00	.00
26PQ	.9876	-10.95	.00	.00	.00	3.50	2.30
27PQ	1.0159	-10.21	.00	.00	.00	.00	.00
28PQ	1.0351	-6.40	.00	.00	.00	.00	.00
29PQ	.9959	-11.45	.00	.00	.00	2.40	.90
30PQ	.9844	-12.35	.00	.00	.00	10.60	1.90

SYSTEM GENERATION: 290.51 MW 137.92 MVAR

SYSTEM LOAD: 283.40 MW 126.20 MVAR

FINAL TAP SETTINGS:

No.	TAP
11	100.47
12	100.42
15	100.46
36	98.15

Table 5.5b

Optimisation Results for the IEEE 39-bus test System
I. BEFORE OPTIMISATION

	VOLTAGE		GENERATION		DEMAND	
No./TY	Magnitude	Angle	MW	Mvar	MW	Mvar
1PQ	1.0031	-9.61	.00	.00	.00	.00
2PQ	.9826	-6.62	.00	.00	.00	.00
3PQ	.9596*	-9.87	.00	.00	322.00	2.40
4PQ	.9380*	-10.77	.00	.00	500.00	184.00
5PQ	.9461*	-9.41	.00	.00	.00	.00
6PQ	.9495*	-8.62	.00	.00	.00	.00
7PQ	.9390*	-11.10	.00	.00	233.80	84.00
8PQ	.9386*	-11.68	.00	.00	522.00	176.00
9PQ	.9865	-11.51	.00	.00	.00	.00
10PQ	.9583*	-5.93	.00	.00	.00	.00
11PQ	.9539*	-6.85	.00	.00	.00	.00
12PQ	.9333*	-6.87	.00	.00	8.50	86.00
13PQ	.9529*	-6.73	.00	.00	.00	.00
14PQ	.9445*	-8.61	.00	.00	.00	.00
15PQ	.9343*	-9.06	.00	.00	320.00	153.00
16PQ	.9464*	-7.38	.00	.00	329.40	32.30
17PQ	.9537*	-8.59	.00	.00	.00	.00
18PQ	.9544*	-9.58	.00	.00	158.00	30.00
19PQ	.9744*	-1.99	.00	.00	.00	.00
20PQ	.9725*	-3.45	.00	.00	680.00	103.00
21PQ	.9474*	-4.52	.00	.00	274.00	115.00
22PQ	.9696*	.72	.00	.00	.00	.00
23PQ	.9645*	.50	.00	.00	247.50	84.60
24PQ	.9428*	-7.21	.00	.00	308.60	92.20
25PQ	.9935	-5.15	.00	.00	224.00	47.20
26PQ	.9816	-6.51	.00	.00	139.00	17.00
27PQ	.9621*	-8.80	.00	.00	281.00	75.50
28PQ	.9864	-2.54	.00	.00	206.00	27.60
29PQ	.9896	.56	.00	.00	283.00	26.90
30PV	1.0000	-3.98	250.00	102.04	.00	.00
31SW	1.0000	.00	578.27	249.67	9.20	4.60
32PV	1.0000	1.86	650.00	252.99	.00	.00
33PV	1.0000	3.22	632.00	177.44	.00	.00
34PV	1.0000	1.87	508.00	150.86	.00	.00
35PV	1.0000	6.22	650.00	243.68	.00	.00
36PV	1.0000	9.53	560.00	164.25	.00	.00
37PV	1.0000	2.08	540.00	48.09	.00	.00
38PV	1.0000	8.04	830.00	78.09	.00	.00
39PV	1.0000	-11.32	1000.00	200.00	1104.00	250.00
SYSTEM GENERATION:			6198.27 MW		1667.11 Mvar	
SYSTEM LOAD:			6150.00 MW		1591.30 Mvar	

TAP SETTINGS	No.	TAP	No.	TAP	No.	TAP
	5	100.00	22	100.00	37	100.00
	14	100.00	32	100.00	39	100.00
	20	100.00	33	100.00	41	100.00
	21	100.00	34	100.00	46	100.00

Table 5.5b

Optimisation Results for the IEEE 39-bus test System

II. AFTER OPTIMISATION

No./TY	VOLTAGE Magnitude	Angle	GENERATION MW	Mvar	DEMAND MW	Mvar
1PQ	1.0611	-7.75	.00	.00	.00	.00
2PQ	1.0509	-5.20	.00	.00	.00	.00
3PQ	1.0455	-8.05	.00	.00	322.00	2.40
4PQ	1.0460	-8.88	.00	.00	500.00	184.00
5PQ	1.0604	-7.84	.00	.00	.00	.00
6PQ	1.0655	-7.22	.00	.00	.00	.00
7PQ	1.0526	-9.19	.00	.00	233.80	84.00
8PQ	1.0501	-9.64	.00	.00	522.00	176.00
9PQ	1.0627	-9.44	.00	.00	.00	.00
10PQ	1.0803	-5.12	.00	.00	.00	.00
11PQ	1.0741	-5.83	.00	.00	.00	.00
12PQ	1.0615	-5.85	.00	.00	8.50	86.00
13PQ	1.0721	-5.72	.00	.00	.00	.00
14PQ	1.0558	-7.15	.00	.00	.00	.00
15PQ	1.0326	-7.41	.00	.00	320.00	153.00
16PQ	1.0369	-5.96	.00	.00	329.40	32.30
17PQ	1.0401	-6.94	.00	.00	.00	.00
18PQ	1.0408	-7.79	.00	.00	158.00	30.00
19PQ	1.0519	-1.35	.00	.00	.00	.00
20PQ	1.0314	-2.57	.00	.00	680.00	103.00
21PQ	1.0399	-3.58	.00	.00	274.00	115.00
22PQ	1.0608	.80	.00	.00	.00	.00
23PQ	1.0490	.64	.00	.00	247.50	84.60
24PQ	1.0334	-5.82	.00	.00	308.60	92.20
25PQ	1.0557	-3.70	.00	.00	224.00	47.20
26PQ	1.0498	-4.99	.00	.00	139.00	17.00
27PQ	1.0395	-7.04	.00	.00	281.00	75.50
28PQ	1.0414	-1.41	.00	.00	206.00	27.60
29PQ	1.0393	1.41	.00	.00	283.00	26.90
30PV	1.0427	-2.79	250.00	65.39	.00	.00
31SW	1.0890	.00	572.71	302.50	9.20	4.60
32PV	1.1000	1.44	650.00	394.46	.00	.00
33PV	1.0550	3.39	632.00	192.37	.00	.00
34PV	1.0302	2.43	508.00	62.07	.00	.00
35PV	1.0693	5.64	650.00	313.67	.00	.00
36PV	1.0390	8.80	560.00	53.60	.00	.00
37PV	1.0295	3.04	540.00	-40.26	.00	.00
38PV	1.0264	8.49	830.00	-1.17	.00	.00
39PV	1.0504	-9.24	1000.00	50.94	1104.00	250.00
SYSTEM GENERATION:			6192.71 MW		1393.56 Mvar	
SYSTEM LOAD:			6150.00 MW		1591.30 Mvar	

FINAL TAP SETTINGS:	No.	TAP	No.	TAP	No.	TAP
	5	98.22	22	99.45	37	97.19
	14	96.55	32	97.76	39	98.44
	20	95.81	33	99.28	41	98.75
	21	99.38	34	98.78	46	98.90

Table 5.5c

Optimisation Results for the IEEE 57-bus test System

I. BEFORE OPTIMISATION

No./TY	VOLTAGE Magnitude	Angle	Cap/Reat	GENERATION MW	Mvar	DEMAND MW	Mvar
1SW	1.0000	.00	.00	479.97	2.24	55.00	17.00
2PV	.9914	-1.66	.00	.00	50.00	3.00	88.00
3PV	.9908	-7.09	.00	40.00	59.99	41.00	21.00
4PQ	.9873	-8.47	.00	.00	.00	.00	.00
5PQ	.9854	-9.73	.00	.00	.00	13.00	4.00
6PV	.9900	-9.89	.00	.00	25.00	75.00	2.00
7PQ	.9824	-8.75	.00	.00	.00	.00	.00
8PV	1.0000	-5.51	.00	450.00	52.35	150.00	22.00
9PV	.9731	-10.61	.00	.00	9.00	121.00	26.00
10PQ	.9717	-12.46	.00	.00	.00	5.00	2.00
11PQ	.9634	-11.15	.00	.00	.00	.00	.00
12PV	1.0000	-11.34	.00	310.00	133.36	377.00	24.00
13PQ	.9699	-10.69	.00	.00	.00	18.00	2.30
14PQ	.9621	-10.17	.00	.00	.00	10.50	5.30
15PQ	.9758	-7.97	.00	.00	.00	22.00	5.00
16PQ	.9906	-9.60	.00	.00	.00	43.00	3.00
17PQ	.9858	-5.88	.00	.00	.00	42.00	8.00
18PQ	.9768	-13.14	9.54	.00	.00	27.20	9.80
19PQ	.9336*	-14.65	.00	.00	.00	3.30	.60
20PQ	.9197*	-14.84	.00	.00	.00	2.30	1.00
21PQ	.9132*	-14.57	.00	.00	.00	.00	.00
22PQ	.9126*	-14.50	.00	.00	.00	.00	.00
23PQ	.9111*	-14.57	.00	.00	.00	6.30	2.10
24PQ	.9020*	-14.93	.00	.00	.00	.00	.00
25PQ	.8712*	-21.14	4.48	.00	.00	6.30	3.20
26PQ	.9040*	-14.55	.00	.00	.00	.00	.00
27PQ	.9357*	-13.02	.00	.00	.00	9.30	.50
28PQ	.9545	-11.93	.00	.00	.00	4.60	2.30
29PQ	.9705	-11.18	.00	.00	.00	17.00	2.60
30PQ	.8475*	-21.85	.00	.00	.00	3.60	1.80
31PQ	.8145*	-22.76	.00	.00	.00	5.80	2.90
32PQ	.8272*	-21.66	.00	.00	.00	1.60	.80
33PQ	.8245*	-21.72	.00	.00	.00	3.80	1.90
34PQ	.8644*	-16.16	.00	.00	.00	.00	.00
35PQ	.8720*	-15.88	.00	.00	.00	6.00	3.00
36PQ	.8826*	-15.55	.00	.00	.00	.00	.00
37PQ	.8909*	-15.28	.00	.00	.00	.00	.00
38PQ	.9154*	-14.33	.00	.00	.00	14.00	7.00
39PQ	.8893*	-15.34	.00	.00	.00	.00	.00
40PQ	.8813*	-15.63	.00	.00	.00	.00	.00
41PQ	.9230*	-15.95	.00	.00	.00	6.30	3.00
42PQ	.8806*	-17.48	.00	.00	.00	7.10	4.40
43PQ	.9507	-12.56	.00	.00	.00	2.00	1.00
44PQ	.9274*	-13.37	.00	.00	.00	12.00	1.80
45PQ	.9647	-10.53	.00	.00	.00	.00	.00
46PQ	.9482*	-12.17	.00	.00	.00	.00	.00
47PQ	.9257*	-13.84	.00	.00	.00	29.70	11.60
48PQ	.9220*	-13.99	.00	.00	.00	.00	.00
49PQ	.9286*	-14.27	.00	.00	.00	18.00	8.50
50PQ	.9194*	-14.87	.00	.00	.00	21.00	10.50
51PQ	.9604	-13.83	.00	.00	.00	18.00	5.30
52PQ	.9310*	-12.95	.00	.00	.00	4.90	2.20
53PQ	.9168*	-13.72	5.30	.00	.00	20.00	10.00
54PQ	.9352*	-13.01	.00	.00	.00	4.10	1.40
55PQ	.9638	-11.91	.00	.00	.00	6.80	3.40
56PQ	.8725*	-17.91	.00	.00	.00	7.60	2.20
57PQ	.8640*	-18.53	.00	.00	.00	6.70	2.00

SYSTEM GENERATION: 1279.97 MW 351.26 Mvar

SYSTEM LOAD: 1250.80 MW 336.40 Mvar

TAP SETTINGS:

No.	TAP	No.	TAP	No.	TAP
19	100.00	41	100.00	66	100.00
20	100.00	46	100.00	71	100.00
31	100.00	54	100.00	73	100.00
35	100.00	58	100.00	76	100.00
36	100.00	59	100.00	80	100.00
37	100.00	65	100.00		

(*) out-of-limit quantity

Table 5.5c

Optimisation Results for the IEEE 57-bus test System
II. AFTER OPTIMISATION

	VOLTAGE			GENERATION		DEMAND	
No./TY	Magnitude	Angle	Cap/Reat	MW	Mvar	MW	Mvar
1SW	1.0230	.00	.00	478.92	44.26	55.00	17.00
2PV	.9995	-1.33	.00	.00	-17.00	3.00	88.00
3PV	1.0099	-6.74	.00	40.00	59.84	41.00	21.00
4PQ	1.0072	-8.07	.00	.00	.00	.00	.00
5PQ	1.0042	-9.28	.00	.00	.00	13.00	4.00
6PV	1.0081	-9.44	.00	.00	20.03	75.00	2.00
7PQ	1.0009	-8.41	.00	.00	.00	.00	.00
8PV	1.0218	-5.23	.00	450.00	43.87	150.00	22.00
9PV	1.0032	-10.06	.00	.00	8.79	121.00	26.00
10PQ	1.0093	-11.79	.00	.00	.00	5.00	2.00
11PQ	.9957	-10.62	.00	.00	.00	.00	.00
12PV	1.0364	-10.88	.00	310.00	155.00	377.00	24.00
13PQ	1.0010	-10.22	.00	.00	.00	18.00	2.30
14PQ	.9898	-9.74	.00	.00	.00	10.50	5.30
15PQ	1.0010	-7.63	.00	.00	.00	22.00	5.00
16PQ	1.0237	-9.21	.00	.00	.00	43.00	3.00
17PQ	1.0145	-5.65	.00	.00	.00	42.00	8.00
18PQ	1.0230	-12.24	10.47	.00	.00	27.20	9.80
19PQ	.9996	-13.74	.00	.00	.00	3.30	.60
20PQ	.9974	-13.98	.00	.00	.00	2.30	1.00
21PQ	1.0079	-13.38	.00	.00	.00	.00	.00
22PQ	1.0102	-13.34	.00	.00	.00	.00	.00
23PQ	1.0094	-13.41	.00	.00	.00	6.30	2.10
24PQ	1.0114	-13.87	.00	.00	.00	.00	.00
25PQ	1.0410	-18.49	6.39	.00	.00	6.30	3.20
26PQ	.9782	-13.50	.00	.00	.00	.00	.00
27PQ	1.0153	-12.18	.00	.00	.00	9.30	.50
28PQ	1.0356	-11.24	.00	.00	.00	4.60	2.30
29PQ	1.0522	-10.60	.00	.00	.00	17.00	2.60
30PQ	1.0180	-18.96	.00	.00	.00	3.60	1.80
31PQ	.9825	-19.52	.00	.00	.00	5.80	2.90
32PQ	.9804	-18.65	.00	.00	.00	1.60	.80
33PQ	.9782	-18.69	.00	.00	.00	3.80	1.90
34PQ	.9691	-14.72	.00	.00	.00	.00	.00
35PQ	.9743	-14.47	.00	.00	.00	6.00	3.00
36PQ	.9825	-14.19	.00	.00	.00	.00	.00
37PQ	.9897	-13.96	.00	.00	.00	.00	.00
38PQ	1.0122	-13.19	.00	.00	.00	14.00	7.00
39PQ	.9877	-14.00	.00	.00	.00	.00	.00
40PQ	.9807	-14.24	.00	.00	.00	.00	.00
41PQ	.9923	-14.63	.00	.00	.00	6.30	3.00
42PQ	.9581	-16.01	.00	.00	.00	7.10	4.40
43PQ	1.0143	-11.80	.00	.00	.00	2.00	1.00
44PQ	1.0230	-12.33	.00	.00	.00	12.00	1.80
45PQ	1.0566	-9.85	.00	.00	.00	.00	.00
46PQ	1.0472	-11.45	.00	.00	.00	.00	.00
47PQ	1.0235	-12.82	.00	.00	.00	29.70	11.60
48PQ	1.0188	-12.92	.00	.00	.00	.00	.00
49PQ	1.0191	-13.15	.00	.00	.00	18.00	8.50
50PQ	1.0048	-13.70	.00	.00	.00	21.00	10.50
51PQ	1.0322	-12.88	.00	.00	.00	18.00	5.30
52PQ	1.0090	-12.14	.00	.00	.00	4.90	2.20
53PQ	.9923	-12.81	6.20	.00	.00	20.00	10.00
54PQ	.9986	-12.13	.00	.00	.00	4.10	1.40
55PQ	1.0148	-11.09	.00	.00	.00	6.80	3.40
56PQ	.9555	-16.45	.00	.00	.00	7.60	2.20
57PQ	.9513	-17.01	.00	.00	.00	6.70	2.00

SYSTEM GENERATION: 1278.92 MW 337.85 Mvar
SYSTEM LOAD: 1250.80 MW 336.40 Mvar

FINAL TAP SETTINGS

No.	TAP	No.	TAP	No.	TAP
19	101.84	41	106.48	66	105.05
20	101.84	46	96.98	71	102.89
31	100.23	54	102.15	73	99.68
35	104.95	58	106.39	76	100.07
36	104.95	59	107.30	80	101.64
37	96.47	65	103.03		

Table 5.5d Optimisation Results for the IEEE 118-bus test System

	I. BEFORE OPTIMISATION							II. AFTER OPTIMISATION						
	VOLTAGE			GENERATION		DEMAND		VOLTAGE			GENERATION		DEMAND	
No./TY	Magnitude	Angle	Cap/Reat	MW	Mvar	MW	Mvar	Magnitude	Angle	Cap/Reat	MW	Mvar	MW	Mvar
1PV	.9370	-10.85	.00	.00	-.00	51.00	27.00	.9508	-10.91	.00	.00	7.98	51.00	27.00
2PQ	.9513	-10.15	.00	.00	.00	20.00	9.00	.9616	-10.18	.00	.00	.00	20.00	9.00
3PQ	.9496*	-9.97	.00	.00	.00	39.00	10.00	.9610	-10.01	.00	.00	.00	39.00	10.00
4PV	.9772	-5.79	.00	100.00	-100.00	39.00	12.00	.9849	-5.85	.00	100.00	-100.00	39.00	12.00
5PQ	.9861	-5.90	-38.90	.00	.00	.00	.00	.9938	-5.96	-39.50	.00	.00	.00	.00
6PV	.9659	-8.32	.00	5.00	-5.00	52.00	22.00	.9738	-8.34	.00	5.00	-4.99	52.00	22.00
7PQ	.9664	-8.74	.00	.00	.00	19.00	2.00	.9743	-8.76	.00	.00	.00	19.00	2.00
8PV	1.0000	-2.44	.00	100.00	147.16	28.00	.00	1.0058	-2.53	.00	100.00	143.73	28.00	.00
9PQ	1.0278	-.86	.00	.00	.00	.00	.00	1.0342	-.97	.00	.00	.00	.00	.00
10PV	1.0185	.95	.00	100.00	-100.00	.00	.00	1.0252	.82	.00	100.00	-100.00	.00	.00
11PQ	.9661	-8.45	.00	.00	.00	70.00	23.00	.9738	-8.47	.00	.00	.00	70.00	23.00
12PV	.9689	-9.05	.00	30.00	75.00	47.00	10.00	.9769	-9.07	.00	30.00	75.00	47.00	10.00
13PQ	.9558	-9.00	.00	.00	.00	34.00	16.00	.9624	-9.01	.00	.00	.00	34.00	16.00
14PQ	.9707	-8.77	.00	.00	.00	14.00	1.00	.9771	-8.79	.00	.00	.00	14.00	1.00
15PV	.9806	-5.29	.00	5.00	-5.00	90.00	30.00	.9828	-6.30	.00	5.00	-5.00	90.00	30.00
16PQ	.9723	-7.88	.00	.00	.00	25.00	10.00	.9786	-7.90	.00	.00	.00	25.00	10.00
17PQ	1.0079	-2.98	.00	.00	.00	11.00	3.00	1.0103	-3.03	.00	.00	.00	11.00	3.00
18PV	.9883	-5.33	.00	5.00	23.00	60.00	34.00	.9894	-5.33	.00	5.00	22.55	60.00	34.00
19PV	.9819	-6.14	.00	5.00	15.00	45.00	25.00	.9819	-6.13	.00	5.00	5.04	45.00	25.00
20PQ	.9721	-4.03	.00	.00	.00	18.00	3.00	.9723	-4.03	.00	.00	.00	18.00	3.00
21PQ	.9702	-1.56	.00	.00	.00	14.00	8.00	.9706	-1.56	.00	.00	.00	14.00	8.00
22PQ	.9799	1.99	.00	.00	.00	10.00	5.00	.9804	1.97	.00	.00	.00	10.00	5.00
23PQ	1.0118	8.46	.00	.00	.00	7.00	3.00	1.0123	8.42	.00	.00	.00	7.00	3.00
24PV	1.0000	10.91	.00	100.00	-46.79	13.00	.00	1.0000	10.90	.00	100.00	-49.15	13.00	.00
25PV	1.0550	11.25	.00	100.00	-100.00	.00	.00	1.0567	11.16	.00	100.00	-100.00	.00	.00
26PV	1.0000	12.07	.00	300.00	172.78	.00	.00	1.0025	11.97	.00	300.00	173.87	.00	.00
27PV	1.0000	5.44	.00	100.00	-22.65	71.00	13.00	1.0000	5.40	.00	100.00	-23.95	71.00	13.00
28PQ	.9943	3.84	.00	.00	.00	17.00	7.00	.9944	3.80	.00	.00	.00	17.00	7.00
29PQ	.9962	2.93	.00	.00	.00	24.00	4.00	.9965	2.89	.00	.00	.00	24.00	4.00
30PQ	.9575	-.96	.00	.00	.00	.00	.00	.9617	-1.03	.00	.00	.00	.00	.00
31PV	1.0000	3.04	.00	100.00	17.11	43.00	27.00	1.0003	3.01	.00	100.00	16.33	43.00	27.00
32PV	.9988	3.89	.00	5.00	23.00	59.00	23.00	.9988	3.86	.00	5.00	21.34	59.00	23.00
33PQ	.9887	-7.78	.00	.00	.00	23.00	9.00	.9922	-7.81	.00	.00	.00	23.00	9.00
34PV	1.0111	-8.12	14.31	5.00	-5.00	59.00	26.00	1.0168	-8.19	14.48	5.00	23.00	59.00	26.00
35PQ	1.0085	-8.53	.00	.00	.00	33.00	9.00	1.0108	-8.53	.00	.00	.00	33.00	9.00
36PV	1.0085	-8.52	.00	5.00	15.00	31.00	17.00	1.0103	-8.52	.00	5.00	-5.00	31.00	17.00
37PQ	1.0165	-7.68	-25.83	.00	.00	.00	.00	1.0213	-7.74	-26.07	.00	.00	.00	.00
38PQ	.9494*	-4.71	.00	.00	.00	.00	.00	.9553	-4.78	.00	.00	.00	.00	.00
39PQ	.9994	-8.26	.00	.00	.00	27.00	11.00	1.0022	-8.29	.00	.00	.00	27.00	11.00
40PV	1.0000	-7.75	.00	101.70	12.23	66.00	23.00	1.0017	-7.77	.00	101.70	10.31	66.00	23.00
41PQ	.9932	-8.45	.00	.00	.00	37.00	10.00	.9944	-8.45	.00	.00	.00	37.00	10.00
42PV	1.0000	-7.66	.00	106.60	12.20	96.00	23.00	1.0000	-7.66	.00	106.60	10.36	96.00	23.00
43PQ	.9945	-9.99	.00	.00	.00	18.00	7.00	.9987	-10.03	.00	.00	.00	18.00	7.00

Continue...

Table 5.5d Continuation

	I. BEFORE OPTIMISATION							II. AFTER OPTIMISATION						
	VOLTAGE			GENERATION		DEMAND		VOLTAGE			GENERATION		DEMAND	
No./TY	Magnitude	Angle	Cap/Reat	MW	Mvar	MW	Mvar	Magnitude	Angle	Cap/Reat	MW	Mvar	MW	Mvar
44PQ	.9867	-10.27	9.74	.00	.00	16.00	8.00	.9885	-10.30	9.77	.00	.00	16.00	8.00
45PQ	.9823	-9.44	9.65	.00	.00	53.00	22.00	.9831	-9.47	9.67	.00	.00	53.00	22.00
46PV	1.0000	-5.54	10.00	111.10	-13.29	28.00	10.00	1.0000	-5.55	10.00	111.10	-14.30	28.00	10.00
47PQ	.9974	-6.75	.00	.00	.00	34.00	.00	.9979	-6.77	.00	.00	.00	34.00	.00
48PQ	1.0001	-7.65	15.00	.00	.00	20.00	11.00	1.0001	-7.68	15.00	.00	.00	20.00	11.00
49PV	1.0000	-7.58	.00	100.00	30.61	87.00	30.00	1.0000	-7.61	.00	100.00	28.27	87.00	30.00
50PQ	.9926	-9.55	.00	.00	.00	17.00	4.00	.9926	-9.59	.00	.00	.00	17.00	4.00
51PQ	.9801	-11.98	.00	.00	.00	17.00	8.00	.9801	-12.02	.00	.00	.00	17.00	8.00
52PQ	.9760	-12.87	.00	.00	.00	18.00	5.00	.9760	-12.90	.00	.00	.00	18.00	5.00
53PQ	.9806	-13.60	.00	.00	.00	23.00	11.00	.9806	-13.63	.00	.00	.00	23.00	11.00
54PV	1.0000	-12.59	.00	109.40	92.49	113.00	32.00	1.0000	-12.63	.00	109.40	92.50	113.00	32.00
55PV	.9943	-12.91	.00	15.00	11.00	63.00	22.00	.9943	-12.96	.00	15.00	11.00	63.00	22.00
56PV	.9957	-12.78	.00	7.20	11.00	84.00	18.00	.9957	-12.82	.00	7.20	11.00	84.00	18.00
57PQ	.9915	-11.82	.00	.00	.00	12.00	3.00	.9915	-11.86	.00	.00	.00	12.00	3.00
58PQ	.9845	-12.61	.00	.00	.00	12.00	3.00	.9845	-12.65	.00	.00	.00	12.00	3.00
59PV	1.0000	-10.05	.00	120.10	-87.97	277.00	113.00	1.0000	-10.10	.00	120.10	-93.71	277.00	113.00
60PQ	.9975	-6.61	.00	.00	.00	78.00	3.00	.9975	-6.67	.00	.00	.00	78.00	3.00
61PV	1.0000	-5.67	.00	205.00	273.09	.00	.00	1.0000	-5.73	.00	205.00	262.11	.00	.00
62PV	.9953	-6.66	.00	10.00	8.00	77.00	14.00	.9953	-6.73	.00	10.00	8.00	77.00	14.00
63PQ	.9696	-7.01	.00	.00	.00	.00	.00	.9716	-7.07	.00	.00	.00	.00	.00
64PQ	1.0158	-5.50	.00	.00	.00	.00	.00	1.0190	-5.57	.00	.00	.00	.00	.00
65PV	1.0000	-2.67	.00	100.00	-93.28	.00	.00	1.0081	-2.80	.00	100.00	-28.29	.00	.00
66PV	1.0000	-4.64	.00	100.00	-31.84	39.00	18.00	1.0000	-4.71	.00	100.00	-53.69	39.00	18.00
67PQ	.9919	-6.43	.00	.00	.00	28.00	7.00	.9919	-6.50	.00	.00	.00	28.00	7.00
68PQ	1.0040	-.92	.00	.00	.00	.00	.00	1.0079	-1.06	.00	.00	.00	.00	.00
69SW	1.0000	.00	.00	100.70	306.60	.00	.00	1.0039	.00	.00	102.30	262.98	.00	.00
70PV	.9748	3.10	.00	10.00	8.00	66.00	20.00	.9801	3.13	.00	10.00	-.01	66.00	20.00
71PQ	.9868	6.43	.00	.00	.00	.00	.00	.9895	6.47	.00	.00	.00	.00	.00
72PV	1.0000	13.50	.00	100.00	-14.50	12.00	.00	1.0000	13.52	.00	100.00	-15.96	12.00	.00
73PV	1.0000	8.84	.00	100.00	12.30	6.00	.00	1.0000	8.90	.00	100.00	6.50	6.00	.00
74PV	.9442	-.90	10.70	5.00	4.00	68.00	27.00	.9604	-.91	11.07	5.00	3.99	68.00	27.00
75PQ	.9483*	-.60	.00	.00	.00	47.00	11.00	.9674	-.66	.00	.00	.00	47.00	11.00
76PV	.9204	.15	.00	.00	7.56	68.00	36.00	.9580	.01	.00	.00	8.00	68.00	36.00
77PV	.9634	.78	.00	30.70	-9.78	61.00	28.00	1.0032	.26	.00	30.70	37.16	61.00	28.00
78PQ	.9606	.31	.00	.00	.00	71.00	26.00	1.0012	-.17	.00	.00	.00	71.00	26.00
79PQ	.9667	.38	18.69	.00	.00	39.00	32.00	1.0084	-.11	20.34	.00	.00	39.00	32.00
80PV	1.0000	2.07	.00	100.00	89.32	130.00	26.00	1.0430	1.47	.00	100.00	190.43	130.00	26.00
81PQ	.9674	.32	.00	.00	.00	.00	.00	.9854	-.01	.00	.00	.00	.00	.00
82PQ	.9376*	8.00	17.58	.00	.00	54.00	27.00	.9713	7.06	18.87	.00	.00	54.00	27.00
83PQ	.9328*	11.97	8.70	.00	.00	20.00	10.00	.9608	10.86	9.23	.00	.00	20.00	10.00
84PQ	.9409*	18.91	.00	.00	.00	11.00	7.00	.9588	17.63	.00	.00	.00	11.00	7.00

Continue...

Table 5.5d Continuation

I. BEFORE OPTIMISATION

No./TY	VOLTAGE Magnitude	Angle	Cap/Reat	GENERATION MW	Mvar	DEMAND MW	Mvar
85PV	.9572	22.53	.00	10.00	8.00	24.00	15.00
86PQ	.9582	30.58	.00	.00	.00	21.00	10.00
87PV	1.0000	45.83	.00	124.20	17.32	.00	.00
88PQ	.9732	25.34	.00	.00	.00	48.00	10.00
89PV	1.0000	29.17	.00	400.00	34.84	.00	.00
90PV	1.0000	29.58	.00	150.70	37.67	163.00	42.00
91PV	1.0000	30.77	.00	125.60	-17.69	10.00	.00
92PV	.9822	23.69	.00	10.00	8.00	65.00	10.00
93PQ	.9622	18.61	.00	.00	.00	12.00	7.00
94PQ	.9572	14.59	.00	.00	.00	30.00	16.00
95PQ	.9393*	11.47	.00	.00	.00	42.00	31.00
96PQ	.9441*	8.64	.00	.00	.00	38.00	15.00
97PQ	.9652	4.97	.00	.00	.00	15.00	9.00
98PQ	.9838	6.31	.00	.00	.00	34.00	8.00
99PV	1.0000	15.50	.00	124.90	-8.43	42.00	.00
100PV	1.0000	16.85	.00	100.00	128.50	37.00	18.00
101PQ	.9777	18.86	.00	.00	.00	22.00	15.00
102PQ	.9791	21.98	.00	.00	.00	5.00	3.00
103PV	.9949	18.83	.00	18.70	15.00	23.00	16.00
104PV	.9860	18.96	.00	20.00	15.01	38.00	25.00
105PV	.9854	19.77	19.42	20.00	5.00	31.00	26.00
106PQ	.9818	19.14	.00	.00	.00	43.00	16.00
107PV	1.0000	23.19	6.00	120.10	1.18	50.00	12.00
108PQ	.9830	21.74	.00	.00	.00	2.00	1.00
109PQ	.9824	22.58	.00	.00	.00	8.00	3.00
110PV	.9856	25.14	5.83	.00	.96	39.00	30.00
111PV	1.0000	29.61	.00	100.00	-7.12	.00	.00
112PV	1.0000	26.95	.00	118.10	13.80	68.00	13.00
113PV	1.0000	-.48	.00	100.00	-52.23	6.00	.00
114PQ	.9944	4.02	.00	.00	.00	8.00	3.00
115PQ	.9941	4.08	.00	.00	.00	22.00	7.00
116PV	1.0000	-.75	.00	250.00	-112.02	184.00	.00
117PQ	.9522	-10.66	.00	.00	.00	20.00	8.00
118PQ	.9286*	-.74	.00	.00	.00	33.00	15.00

SYSTEM GENERATION: 4389.80 MW 900.02 Mvar
SYSTEM LOAD: 4242.00 MW 1438.00 Mvar

TAP SETTINGS:

No.	TAP	No.	TAP	No.	TAP
13	95.50	62	111.11	107	101.00
42	111.11	104	111.11	111	90.50
50	111.11	106	90.90	135	111.11

II. AFTER OPTIMISATION

DEMAND MW	Mvar	VOLTAGE Magnitude	Angle	Cap/Reat	GENERATION MW	Mvar	DEMAND MW	Mvar
15.00	.9698	21.22	.00	10.00	8.00	24.00	15.00	
10.00	.9664	29.17	.00	.00	.00	21.00	10.00	
.00	1.0000	44.36	.00	124.20	13.39	.00	.00	
10.00	.9785	23.99	.00	.00	.00	48.00	10.00	
.00	1.0000	27.81	.00	400.00	-14.20	.00	.00	
42.00	1.0000	28.22	.00	150.70	37.68	163.00	42.00	
.00	1.0000	29.42	.00	125.60	-27.84	10.00	.00	
10.00	.9955	22.20	.00	10.00	8.00	65.00	10.00	
7.00	.9865	17.15	.00	.00	.00	12.00	7.00	
16.00	.9909	13.22	.00	.00	.00	30.00	16.00	
31.00	.9748	10.29	.00	.00	.00	42.00	31.00	
15.00	.9806	7.63	.00	.00	.00	38.00	15.00	
9.00	1.0052	4.18	.00	.00	.00	15.00	9.00	
8.00	1.0281	5.42	.00	.00	.00	34.00	8.00	
.00	1.0000	14.54	.00	124.90	-82.59	42.00	.00	
18.00	1.0430	15.18	.00	100.00	299.94	37.00	18.00	
15.00	1.0083	17.27	.00	.00	.00	22.00	15.00	
3.00	.9982	20.44	.00	.00	.00	5.00	3.00	
16.00	1.0152	17.40	.00	18.70	-5.00	23.00	16.00	
25.00	.9956	17.65	.00	20.00	-5.00	38.00	25.00	
26.00	.9939	18.46	19.76	20.00	-4.99	31.00	26.00	
16.00	.9941	17.79	.00	.00	.00	43.00	16.00	
12.00	1.0000	22.00	6.00	120.10	-10.00	50.00	12.00	
1.00	.9896	20.42	.00	.00	.00	2.00	1.00	
3.00	.9882	21.26	.00	.00	.00	8.00	3.00	
30.00	.9893	23.81	5.87	.00	.00	39.00	30.00	
.00	1.0000	28.33	.00	100.00	-11.95	.00	.00	
13.00	1.0000	25.69	.00	118.10	8.06	68.00	13.00	
.00	1.0018	-.52	.00	100.00	-53.51	6.00	.00	
3.00	.9944	3.98	.00	.00	.00	8.00	3.00	
7.00	.9941	4.05	.00	.00	.00	22.00	7.00	
.00	1.0000	-.87	.00	250.00	-209.47	184.00	.00	
8.00	.9604	-10.65	.00	.00	.00	20.00	8.00	
15.00	.9566	-.80	.00	.00	.00	33.00	15.00	

SYSTEM GENERATION: 4391.40 MW 872.38 Mvar
SYSTEM LOAD: 4242.00 MW 1438.00 Mvar

FINAL TAP SETTINGS:

No.	TAP	No.	TAP	No.	TAP
13	95.49	62	110.91	107	101.00
42	111.11	104	111.11	111	90.50
50	111.06	106	90.90	135	111.11

CHAPTER 6

REACTIVE POWER EXPANSION PLANNING

6.1 INTRODUCTION

The general problem of var expansion planning involves two distinct subproblems:

(i) the choice of the best locations for installing the additional var sources,

(ii) the determination of the minimum amount of the additional var sources.

The locations for the new var sources are generally given as a set of candidate buses. Having determined this set the next problem is to determine the minimum amount of the new reactive power sources to be installed in each bus. These sources are in general switched shunt reactors/capacitors. The second subproblem is sometimes referred to as capacitor/reactor allocation and addressed as an independent problem. However, such a practice can produce very conservative results, since the rescheduling capabilities of the system are neglected. In all cases the var expansion problem should only be considered after solving the var dispatch problem. Another important point, which is also frequently neglected, is the possibility of relaxation of the existing equipment limits. Possibilities of setting new tap ranges, new generator/compensator ratings and new bus voltage limits should be investigated before considering the expansion of the var sources.

This chapter addresses both of the above subproblems: the choice of the set of candidate buses and the determination of the minimum var expansion pattern. It demonstrates how to use the methodology

developed in the previous chapters in var expansion planning. The methodology presented here yields the mathematical basis and algorithmic tools for the integration of the var dispatch with the var expansion problem as described in Chapter 2 (See Fig. 2.8 and Fig. 2.9).

The material of this chapter is organized as follows. First, the formulation of the non-linear optimal load flow is modified to include the new var sources. Second, the sensitivity of the system performance with respect to the variables and parameters is derived. Third, the contextual meanings of the Lagrange multipliers and of the projected gradient vector are analysed. Fourth, based on the theoretical aspects deduced, a hierarchical methodology of solution is developed. Fifth, the methodology is applied to a scenario in the IEEE 30-bus test system in order to provide illustration and demonstration of the new approach. Finally, alternative formulations and corresponding solutions for the problem are worked out. These involve comparison between non-linear optimisation and mixed linear non-linear optimisation methods of solution.

6.2 MODELLING THE NEW VAR SOURCES TO BE ADDED TO THE SYSTEM

Development of the model

To analyse the sensitivity of the system performance with respect to the variables and parameters the var dispatch problem is modified by including a slack parameter which represents the new var sources to be added to the system. The optimisation problem is restated as

Minimise $$f(u,x) \tag{6.1a}$$

Subject to $$g(x,u,p)=0 \tag{6.1b}$$

$$u^{min} \leq u \leq u^{max} \tag{6.1c}$$

This formulation is almost identical to that for the var dispatch algorithm. The only difference is the inclusion of the parameter vector p in the load flow equations. The parameter vector [p] provides for the slack in the var load flow equations in order to represent the new reactive sources.

$$[\ p\ ] = [\ q_c\ ] \tag{6.2}$$

Hence, the var load equations continue to be written as

$$Q_i^{sp} - Q_i = Q_i(\underline{V}) \qquad i \in PQ$$

but, the specified injections, Q_i^{sp}, have now the following significance

$$Q_i^{sp} = Q_{gi} - Q_{di} + q_{ci} \qquad i \in PQ \tag{6.3}$$

If q_{ci} is specified equal to zero for all buses the problem becomes that of the var dispatch, where the objective function is the removal of voltage violations and inequality functions are enforced by using the adaptive limit enforcement approach presented in Chapter 5.

This slight modification in the var dispatch problem, however, yields the mathematical basis which enables the development of the following strategy for solving both of the two var expansion subproblems:

i) Solve the var dispatch

ii) Are all violations removed? If so end, else:

iii) Choose the set of candidate buses.

iv) Determine the minimum var expansion pattern.

For reference purposes, this sequence will be called var hierarchical strategy. Before applying the var hierarchical strategy it is necessary to investigate the sensitivities of the objective function with respect to the control variables.

6.3 SENSITIVITY OF THE SYSTEM PERFOMANCE WITH RESPECT TO THE VARIABLES AND PARAMETERS

This section extends the concepts usually applied to the economic dispatch problem, which were first explained by Carpentier in [150] and later by Peschon, Tinney and others in references [109,144,99], to the var problem in concern. Specific optimisation information can be found in references [118,120].

Expansion of Equipment Limits

The non-zero gradient components at the optimum indicate the equipment limits which prevent further reduction in the objective function.

For small variations Δx and Δu around an operating point (x^o,u^o), a first order Taylor expansion of the objective F and constraints g gives

$$\Delta F = F_x \Delta x + F_u \Delta u \tag{6.4}$$

$$0 = J_x \Delta x + J_u \Delta u \tag{6.5}$$

Substituting (6.5) into (6.4) gives

$$\Delta F = (F_u - F_x J_x^{-1} J_u)\ \Delta u \tag{6.6}$$

which reduces ΔF to a function of Δu. The expression within the parenthesis in (6.6) is immediately recognized as the reduced or projected gradient [∇F] of (5.14). The nonzero gradient components of the control variables at their limits measure the sensitivity of the objective function with respect to the limits u_i^{max} or u_i^{min} and consequently show the amount voltage violations on PQ buses being incurred for imposing rigidly the limits in the control variables or the removal of infeasibilities obtained by relaxing them. At the minimum the components $(\delta f/\delta u_i)$ of [∇f] will be

$$\delta f/\delta u_i = 0 \quad \text{iff} \quad u_i^{min} < u_i < u_i^{max}$$
$$\delta f/\delta u_i \leq 0 \quad \text{iff} \quad u_i = u_i^{max} \tag{6.7}$$
$$\delta f/\delta u_i \geq 0 \quad \text{iff} \quad u_i = u_i^{min}$$

The Khun and Tucker theorem proves that the conditions of (6.7) are necessary for a minimum, provide the functions involved are convex. To determine the sensitivity of the objective function (6.1a) with respect to the control variables the Lagrangian $\mathcal{L}(x,u,\lambda,\mu)$ is defined as

$$\mathcal{L}(x,u,\lambda,\mu)=F(x,u)+\lambda^t g(x,u,p)+\mu^{max\,t}(u-u^{max})+\mu^{min\,t}(u-u^{min}) \tag{6.8}$$

The Khun and Tucker conditions for the optimum require that the set of equations below be satisfied

$$\mathcal{L}_x=0 \tag{6.9a}$$
$$\mathcal{L}_u=0 \tag{6.9b}$$
$$\mathcal{L}_\lambda=0 \tag{6.9c}$$
$$\mu^{max\,t}(u-u^{max})=0 \tag{6.9d}$$
$$\mu^{min\,t}(u-u^{min})=0 \tag{6.9e}$$
$$\mu_i^{max} \geq 0, \quad \mu_i^{min} \geq 0 \tag{6.9f}$$

Equations (6.9d-f) are called the exclusion equations. They are satisfied either because the dual variables μ_i are zero or because the constraint has in fact been reached. If u_i reaches a limit, it will be either u_i^{max} or u_i^{min} and not both; therefore, either inequality constraint corresponding to (6.9d) or (6.9e) is active, that is μ^{max} or μ^{min} exists, but never both. Thus, the partials of the Lagrangian become

$$[\partial\mathcal{L}/\partial x]=[\partial F/\partial x]+[\partial g/\partial x]^t\,[\lambda]=0 \tag{6.10a}$$
$$[\partial\mathcal{L}/\partial u]=[\partial F/\partial u]+[\partial g/\partial u]^t\,[\lambda]+[\mu]=0 \tag{6.10b}$$

where

$$\mu_i = \mu_i^{max} \qquad \text{iff} \quad \mu_i > 0$$

$$\mu_i = \mu_i^{min} \qquad \text{iff} \quad \mu_i < 0$$

$$[\partial \mathcal{L}/\partial \lambda] = [g(x,u,p)] = 0 \tag{6.10c}$$

A solution of the var load flow equations (6.10c) gives x. Substitution of u and x in (6.10a) yields the dual vectors λ. Equation (6.10b) provides the dual vector μ. At the optimum, μ must also satisfy the exclusion equations (6.9d-f), hence

$$\begin{aligned} \mu_i &= 0 && \text{iff} && u_i^{min} < u_i < u_i^{max} \\ \mu_i &= \mu_i^{max} \geq 0 && \text{iff} && u_i = u_i^{max} \\ \mu_i &= -\mu_i^{min} \leq 0 && \text{iff} && u_i = u_i^{min} \end{aligned} \tag{6.11}$$

Making $\mu = -\nabla F$ equations (6.11) become the project gradient equations (6.7).

For any feasible load flow solution the imposed control u can be seen as restricted by both sides by pseudo limits $u^{min'}$, and $u^{max'}$, such that $u=u^{min'}=u^{max'}$. The dual variable μ, associated to this control, measures the sensitivity of F to the imposed control

$$\mu_i = -\partial F/\partial u_i \cong -\Delta F/\Delta u_i \tag{6.12}$$

Incidentally, Peschon and others [109] use this fact to develop a method where improved controls u are tried until the actual constraints u^{max} and u^{min} are in fact reached, or until the dual variable μ becomes zero at which point no further improvements remain possible.

Hence, the meaning of a positive μ_i at the optimum is

$$\mu_i = -\Delta F/\Delta u_i^{max} \tag{6.13}$$

while a negative μ_i means

$$\mu_i = \Delta F/\Delta u_i^{min} \tag{6.14}$$

In the var dispatch problem, as formulated here, the dual variables μ_i thus measure the sensitivities $\Delta F/\Delta a_i^{max}$, $\Delta F/\Delta a_i^{min}$, $\Delta F/\Delta V_i^{max}$ and $\Delta F/V_i^{min}$ for all control variables u_i. The dual vector μ is fundamental to var expansion planning studies, since it points out

the equipment constraints which prevent reductions in the sum of the infeasibilities.

Expansion of var sources

The dual variables λ gives the location for installation of additional var sources.

For fixed u, small changes Δp of the parameter p lead to small changes Δx, such that

$$\Delta \mathcal{L} = 0 = F_x \Delta x + \lambda^t g_x \Delta x \tag{6.15}$$

The variation Δx caused by the variation Δp furthermore satisfies the condition

$$g_x \Delta x + g_p \Delta p = 0 \tag{6.16}$$

Noting that

$$\Delta F \cong - F_x \Delta x \tag{6.17}$$

and substituting (6.17) into (6.15), gives

$$\Delta F \cong - \lambda^t g_x \Delta x = \lambda^t g_p \Delta p \tag{6.18}$$

Hence, equation (6.19) relates variations in the objective function ΔF to variations in the parameter vector Δp and to the Lagrange vector λ. As the parameter p_i only enters into the ith equality constraint $g_i = 0$, then the matrix g_p has all its nonzero terms along the diagonal and (6.18) can be simplified as

$$\Delta F = \sum_{i \epsilon \{PQ\}} \lambda_i \, (\partial g_i / \partial p_i) \, \Delta p_i \tag{6.19}$$

Consequently, the meaning of the dual variable λ_i is

$$\lambda_i = \frac{\Delta F}{(\partial g_i / \partial p_i) \, \Delta p_i} \tag{6.20}$$

As the var source q_{ci} only enters into the ith var load flow equation (6.1b), then the partial $\partial g_i / \partial p_i = 1$. Thus, the dual variable λ_i has the meaning

$$\lambda_i = \frac{\Delta F}{\Delta q_{ci}} \tag{6.21}$$

The Lagrange multipliers thus measure the incremental variation in the objective function ΔF due to incremental reactive power injections Δq_{ci} in the various load buses. Since any imposed control u can be seen as an optimal solution in the presence of the fictitious constraint $u^{max'}=u=u^{min'}$ with the result that $\Delta\mathcal{L}=0$, the Lagrange vector λ not only measures the sensitivity of F with respect to Δp at the true optimum but also for any feasible solution (u,x).

6.4 HIERARCHICAL METHODOLOGY OF SOLUTION

Methodology of solution

The values of μ provide the marginal reduction of F per unit of limit relaxation on control variables, and λ provide the marginal reduction of F per unit expansion of the reactive resource of each bus at an optimal solution of the var dispatch problem (u^*,x^*).
The exploitation of this information allows for the integration of the var dispatch and the var expansion problems. Hence, the var hierarchical strategy of Section 6.3 can be restated in more detail as a three level procedure.

Assume u^o
↓
First level — Solve the var dispatch
↓
gives μ , λ , (u^*,x^*), $S_u(u^*,x^*)$, $L_q^{-1}(u^*,x^*)$
↓
Second level — Analyse μ and λ
↓
Third level — Determine the minimum var expansion pattern
↓
gives u_{new}^{lim} , p^*

The first level program is the var optimal load flow program presented in Chapter 5. It gives the optimal operational point (x^*,u^*) and the dual variables μ and λ and the sensitivity matrices S_u and L_q^{-1}. In the second level this information is used to formulate the third level problem. The third level program assumes that the operating state $(x,u)^*$ is given, and minimizes the var expansion q_c. Two main families of continuous formulations were investigated for the third level program: Linear Programming and Non-linear. The former is solved using an ordinary LP routine[1] [55], the latter uses the same var optimal load flow program as used for the first level problem.

Linear Programming Formulation:- The LP formulation of the third level problem is stated as

$$\text{Minimise} \qquad C(q) = c^t\, q \tag{6.22}$$

$$\text{Subject to} \qquad \Delta V^{min} \leq L_q^{-1}\, \Gamma\, q \leq \Delta V^{max} \tag{6.23a}$$

$$q_i \geq 0 \tag{6.23b}$$

$$i \in \{PQ\}$$

$$q_c = \Gamma\, q$$

where, $C(q)$ is the investment cost for the expansion q_c, c is the vector of the unit cost of the var source at each bus of the system, and Γ a diagonal matrix which carries the information about the set of candidate buses for receiving the new var source. The definition of the elements of Γ also provides the nature of the reactive sources (capacitor/reactor) to be considered for expansion.

---

1 E04MBF - NAG FORTRAN Library

Thus,

$$\Gamma_{ii} = \begin{cases} -\lambda_i / |\lambda_i| & \text{iff} \quad \lambda_i \neq 0 \\ \lambda_i & \text{otherwise} \end{cases}$$

The components of the vectors ΔV^{min} and ΔV^{max} of the limits on voltage magnitudes are defined as

$$\Delta V_i^{max} = V_i - V_i^{max}$$
$$\Delta V_i^{min} = V_i - V_i^{min}$$

Local LP solution:- The size of the LP problem is reduced by dropping from the constrained set (6.23) those constraints corresponding to $V_i^{min}+\delta V<V_i<V_i^{max}-\delta V$, where $\delta V \geq 0$ is a small decrement on the voltage bounds. Furthermore, the maximum size of the LP formulation can be made fixed by pre-specifying, for a particular network, the size of the candidate set. In this case the second level problem becomes the calculation of a threshold τ for the Lagrange multipliers λ, such that the buses with $|\lambda_i| > \tau$ are selected as belonging to the candidate set. Hence, given the size of the candidate set Ω, the selection of those buses belonging to this set is straightforward

$$\Omega = \{ \, i : |\lambda_i / \lambda_i^{max}| \geq \tau \, \}$$

If the maximum size of the candidate set is fixed in the unit, then the linear problem becomes the trivial evaluation of:

Minimise $\quad C(q_k) = c_k \, q_k$

Subject to $\quad \Delta V_k^{min} \leq L_{q,kk}^{-1} \, \Gamma_{kk} \, q_k \leq \Delta V_k^{max}$

with $\tau = 1$ and $\lambda_k = \lambda_i^{max}$.

The solution of the third level problem, q_c, which specifies the new limits on the reactive power availabilities, is then fed into the first level program which determines the best operating state under these new conditions. Iterations between the three levels continue until it is found that no further reactive expansion can result in a

reduction of F, i.e., λ_i=0. Note that the linearized formulations and solutions discussed above are always carried out around one new operational point calculated by the var dispatch program (non-linear optimisation, all load flow equations satisfied), with all sensitivity coefficients being calculated anew at each cycle NLP-LP.

Non-Linear Optimisation Formulation:- It was found that a satisfactory general approach consists of the following steps:

1) relax the constraint corresponding to the largest λ_i's;

2) solve level 3 by using the var optimal load flow again;

3) continue iterating from level 1.

The above approaches are investigated in the next section.

Remarks:- However the alternatives presented here cover most of the applications, the best alternative for solving the second level problem (i.e., formulation of the third level problem) is strongly dependent on the particular power system conditions (such as budget resources, legal regulations, short time overload capability of sources, nature of the bounds on control variables, etc) and on the problem being solved (e.g., study of new generator ratings, new tap settings, new voltage limits, maintenance plans, corrective contingency strategies, capacitor/reactor switching schedules, load shedding, load management, limit on power factor of load buses, liberation of transmission capabilities, etc). The second level constitutes a typical knowledge data driven problem. Therefore, it offers a good possibility for applications of expert systems.

6.6 DEMONSTRATIVE EXAMPLES

The IEEE 30-bus system was selected for demonstrating the methodology. Four examples were designed to demonstrate the

capability and effectiveness of the proposed methodology to optimally allocate reactive sources. Example number 4, which is in fact a counter-example, shows the kind of conservative results that may occur, if the candidate set of buses is selected arbitrarily, i.e., ignoring the information provided by the Lagrange multipliers.

Scenario:- The following conditions have been imposed on the IEEE 30 bus test system in order to create strenuous test conditions:
1) Branch 36 corresponding to the transformer connecting buses 27-28 is considered out-of-service for all alternatives studied. As can be seen in Table 4.1-2a, or in Fig. 4.1, this condition represents the worst single contingency in the base case system (19 infeasibilities, summation of infeasibilities=1.64 pu, largest violation=.232 pu). Moreover, the outage of this transformer involves the only control in the nearby area.
2) The flat start voltage profile is adopted. The lower voltage magnitude limit is fixed at 0.975 and the higher limit at 1.1 pu. Other operating limits, loading and generation are as given in Appendix B.
4) The unit cost for capacitor/reactor allocation is assumed fixed as 1.0 monetary unit per Mvar. The system already has two fixed capacitor banks: 19 Mvar at bus 10 and 4.30 Mvar at bus 24. The assumed cost is 0.01 monetary units per Mvar (e.g.: to cover cost with the equipment of manoeuvre and protection) in the event of a scheduling involving switching operations with these capacitor banks.
5) The var expansion studies performed can be thought of as covering specific problems such as:

. Determination of a corrective contingency plan.

. Scheduling of capacitor/reactor switching.

. Determination of the location for capacitor/reactor

allocation.

. Determination of the potential control for the contingency (See Fig. 2.4 and 2.9).

. Minimum var load shedding (See Fig. 2.4).

. Planning of the system operation considering transformer number 36 out of service for maintenance.

Example #1 - Non-Linear plus Linear Optimisation

This example involves the use of the Linear Programming formulation for the third level program. The three level solution is detailed in the following.

Iteration 0

First level: var dispatch solution[2]

The number of violations is reduced from 19 to 4. The largest violation drops from 0.232 to 0.032 per unit, and the summation of the violations from 1.64 to 0.09.

The non-zero Lagrange multipliers are

$$\lambda_9 = 0.1277$$

$$\lambda_{10} = 0.1104$$

$$\lambda_{29} = -0.0345$$

$$\lambda_{30} = -0.0465$$

Second level: Choice of the location for the new var sources.

A negative λ_i indicates the need for capacitor while a positive λ_i shows the need for reactors. Hence, the potential sites for capacitor allocation are buses 29 and 30 while buses 9 and 10 are

---

2 The var optimal power flow output files can optionally include intermediary results such as complete load flow solution, mismatch logging, objective function values, sensitivity matrices, etc. See Appendix A for details of the various output file options.

potential candidates for reactor allocation. However, bus 9 cannot be considered, since it is a fictitious bus corresponding to the central point of a star equivalent circuit for a three winding auto-transformer. Then, the candidate set, Ω, is

$$\Omega = \{10, 29, 30\}$$

Third level: var expansion (Linear Programming Formulation)

Using the information provided by the first and second levels the LP problem is assembled as

Minimise $0.01\ q_{10} + 1.0\ q_{29} + 1.0\ q_{30}$

Subject to

$$\begin{bmatrix} -.1354 \\ .0199 \\ .0320 \end{bmatrix} \leq \begin{bmatrix} .107 & .108 & .108 \\ .106 & 1.230 & 1.100 \\ .108 & 1.120 & 1.320 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} q_{10} \\ q_{29} \\ q_{30} \end{bmatrix} \leq \begin{bmatrix} -.0104 \\ .1449 \\ .1570 \end{bmatrix}$$

$q_{29}, q_{30} \geq 0$

$0 \leq q_{10} \leq 0.19$

The LP solution yields the following values

$q_{10} = .1326$ pu $\qquad q_{29} = 0 \qquad q_{30} = .0351$ pu

which correspond to the incremental bus var injections

$$\begin{bmatrix} q_{c10} \\ q_{c29} \\ q_{c30} \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} .1326 \\ .0 \\ .0351 \end{bmatrix}$$

The switched capacitor/reactor at each bus is then calculated

$$\text{Mvar}_{10} = \frac{q_{c10}}{V_{10}^2}\ 100 = \frac{-.1326}{1.1104^2} = -10.75 \text{ Mvar}$$

$$\text{Mvar}_{29} = 0 \text{ Mvar}$$

$$\text{Mvar}_{30} = \frac{.0351}{.943^2}\ 100 = 3.95 \text{ Mvar}$$

Thus, 10.75 Mvar of the capacitor bank must be switched-off at bus 10 and 3.95 Mvar 3.95 must be added to bus 30 (Although, recognized as an important practical consideration, discrete unit

sizes are, of course, not considered here).

Iteration 1

First level: var dispatch solution

With the new var sources, the number of violations is reduced from 4 to 1. The largest violation drops from 0.032 to 0.001 per unit, and the summation of the violations from 0.09 to 0.001.

The only non-zero Lagrange multiplier is

$$\lambda_{30} = -0.0261$$

Second level: Choice of the location for the new var sources.

With only one $\lambda_i \neq 0$ the set of candidate buses becomes the unit set

$$\Omega = \{ 30 \}$$

Third level: var expansion (Linear Programming Formulation)

The LP problem becomes

Minimise $1.0\ q_{30}$

Subject to

$$[.0011] \leq [1.330][1][q_{30}] \leq [.1261]$$

$$q_{30} \geq 0$$

The straightforward solution gives the var injection

$$q_{c30} = .000872 \text{ pu}$$

Which corresponds to switch-on 0.09 Mvar to bus 30.

Iteration 2

First level: var dispatch solution

The var expansion allows for the removal of all violations and the problem ends with all $\lambda_i = 0$.

Example #2 - Non-Linear plus Non-Linear Optimisation

This example involves the use of the non-linear formulation for both the first and the third level programs. The three level solution

is detailed in the following.

Iteration 0

First level: var dispatch solution

The solution for the first level is the same as in example #1.

Second level: Choice of the location for the new var sources.

In this example the bank of capacitors at bus 10 was considered fixed. Thus, the set of candidate buses was reduced to

$$\Omega = \{ 29,30 \}$$

Third level: var expansion (Non-Linear Programming Formulation)

The var optimal load flow is used for the solution of the var expansion problem. The buses in the candidate set are respecified as PV, with the corresponding var limits relaxed. The program results show the following incremental injections

$$q_{c29} = 1.22 \text{ Mvar}$$

$$q_{c30} = 4.40 \text{ Mvar}$$

which correspond to switch-on the following capacitor banks

$$\text{Mvar}_{29} = \frac{1.22}{.9897^2} = 1.25 \text{ Mvar}$$

$$\text{Mvar}_{30} = \frac{4.40}{.9848^2} = 4.54 \text{ Mvar}$$

With these additional var capabilities in the system all Lagrange multipliers λ_i become zero, and all violations are removed.

Example #3:- Non-Linear plus Non-Linear Optimisation

This example consists of repeating example #2, with the choice of the candidate set involving the bus 10 also.

$$\Omega = \{ 10,29,30 \}$$

All violations are also removed at iteration 0. The results are

$$q_{c10} = 14.86 \text{ Mvar} \quad \text{or} \quad 6.23 \text{ Mvar switched off}$$

$$q_{c29} = 2.82 \text{ Mvar} \quad \text{or} \quad 2.83 \text{ Mvar installed}$$

$$q_{c30} = 4.75 \text{ Mvar} \quad \text{or} \quad 4.82 \text{ Mvar installed}$$

Example #4 - Non-Linear plus Linear Optimisation

As in example #1 the Linear Programming formulation is used for the third level program. This is a counter-example which shows the importance of solving the second level problem by analysing the Lagrange multipliers.

The first level solution is the same as before. In the second level, instead of using the information provided by the Lagrange multipliers as before, let us choose the candidate set Ω, using topological considerations.

$$\Omega = \{ 29, 30, 17 \}$$

Buses 29 and 30 present violations, and bus 17 was chosen because it is the first neighbour of two other violated buses.

The LP solution for this candidate set gives

q_{c17} = - 64.54 Mvar or - 53.49 Mvar reactor switched on.

q_{c29} = .83 Mvar or .91 Mvar capacitor switched on.

q_{c30} = 6.60 Mvar or 7.42 Mvar capacitor switched on.

To investigate the sensitivity of the above expansion pattern with respect to the unit cost of expansion at bus 17, the unit cost of installation in the bus 17 was made equal to 2, 4, 10 and 1000 monetary units per Mvar. The var expansion pattern remains constant for all different unit costs.

The LP results for var source expansion when fed to the first level program allow for the elimination of all violations.

Comments on the results

Table 6.1 shows voltage profiles and output of var sources values before and after the optimisation. Table 6.2 shows a summary of the transmission losses and the control variables and var outputs

Table 6.1 Optimisation Results-Voltage Profile/VAR Output

Case		BEFORE	AFTER OPTIMISATION #1	#2	#3	#4
		Bus Voltage Magnitude (pu)				
1	SW	1.0000	1.0800	1.0799	1.0799	1.0795
2	PV	1.0000	1.0728	1.0363	1.0424	1.0605
3	PQ	.9940	1.0315	1.0120	1.0111	1.0253
4	PQ	.9922	1.0207	.9973	.9961	1.0133
5	PV	1.0000	1.0172	1.0008	1.0021	1.0112
6	PQ	.9924	1.0184	.9855	.9834	1.0083
7	PQ	.9871	1.0098	.9833	.9826	1.0012
8	PV	1.0000	1.0208	.9748	.9754	1.0200
9	PQ	.9644*	1.0969	1.0984	1.0893	1.0963
10	PQ	.9446*	1.0905	1.0879	1.0787	1.0588
11	PV	1.0000	1.0963	1.1000	1.0693	1.1000
12	PQ	.9523*	1.0997	1.0820	1.0782	1.0726
13	PV	1.0000	1.0828	1.0800	1.0759	1.0784
14	PQ	.9337*	1.0846	1.0687	1.0644	1.0569
15	PQ	.9255*	1.0781	1.0642	1.0595	1.0503
16	PQ	.9409*	1.0888	1.0774	1.0713	1.0402
17	PQ	.9375*	1.0848	1.0795	1.0713	1.0157
18	PQ	.9186*	1.0708	1.0608	1.0544	1.0413
19	PQ	.9181*	1.0695	1.0618	1.0545	1.0391
20	PQ	.9238*	1.0740	1.0676	1.0598	1.0432
21	PQ	.9242*	1.0754	1.0725	1.0641	1.0446
22	PQ	.9226*	1.0749	1.0719	1.0637	1.0445
23	PQ	.9015*	1.0615	1.0517	1.0468	1.0344
24	PQ	.8795*	1.0480	1.0438	1.0387	1.0221
25	PQ	.8099*	1.0077	1.0090	1.0099	.9941
26	PQ	.7875*	.9899	.9912	.9921	.9760
27	PQ	.7806*	.9939	.9988	1.0036	.9886
28	PQ	.9948	1.0196	.9836	.9821	1.0116
29	PQ	.7537*	.9802	.9897	.9999	.9831
30	PQ	.7383*	.9759	.9848	.9937	.9838
		Output of var sources (Mvar)				
1	G	-36.87	.29	1.49	67.85	25.10
2	G	20.47	89.97	78.56	24.19	59.79
5	G	51.02	16.80	36.50	35.68	22.49
8	G	47.95	33.53	-1.63	5.54	60.00
11	G	17.47	-.06	1.13	-10.00	2.21
13	G	34.31	-12.91	-1.41	-1.55	4.67
10	C	16.95	9.75	22.49	14.86	21.30
17	R					-55.18
24	C	3.33	4.72	4.69	4.64	4.49
29	C			1.22	2.82	.88
30	C		3.91	4.40	4.75	7.18
		Tap settings (%)				
11	T	97.80	109.22	113.61	115.15	115.69
12	T	96.90	113.84	111.46	112.78	112.76
15	T	93.20	115.33	111.34	112.26	112.24

which are at the limits for all cases. Apart from one control variable in examples #2 and #4, and one var output at their limits in example #4, all other control variables and var outputs remained within the permissible range, for all cases. This is a characteristic feature of the adaptive limit enforcement strategy of the var optimal load flow program.

Table 6.2 Variables at their Limits and Transmission Losses

Case	Variable at the limit		Losses	
	u	Q_g	(MW)	(%)*
Example #1	none	none	9.18	81.24
Example #2	V_{11}	none	10.09	89.29
Example #3	none	none	10.11	89.47
Example #4	V_{11}	Q_{g8}	10.48	92.74
* Percent of the initial losses 11.30 MW.				

Keeping the control variables and var outputs within the allowed range is a very desirable feature in var optimisation, in as much as it provides the so called "reserve of control action" to cope with unexpected events in the system. Table 6.3 summarises the var expansion together with the scheduled switching of existing capacitor as well as the total cost of the expansion for each case.

Table 6.3 VAR Expansion Results

Case Example	Capacitor/Reactor (Mvar)			Total Expansion Cost
	Added (a)	Existing (b)	Total (c)=(a)+(b)	(d)
#1	4.15	10.75	14.80	4.15
#2	5.79	-	5.79	5.79
#3	7.71	6.23	13.94	7.71
#4	61.82	-	61.82	61.82

Example #1, which uses the LP formulation, shows the most attractive results. They involve the least cost, the least amount of

var additions, the reduction of the transmission losses to 81.24% and no control variable is put at the limit. In spite of these good results for example #1, the alternative of using the NLP formulations cannot be completely discarded, since the outer loop iteration for the NLP iteration is faster and simpler. Furthermore, the results obtained in examples #2 and #3 cannot be considered much inferior to those of example #1. For instance, Example #2 results are very similar to those of example #1 in respect to the total var added and total cost of the expansion while Example #3 shows that the NLP formulation leads to similar results as far as the total amount of rescheduling is concerning. Therefore, the NLP alternative can be used in on-line applications or planning of the switching operations.

Example #4 is aimed at drawing attention to the importance of the right choice of the location for adding new var sources. It shows how very conservative results are likely to be arrived at should the choice of the candidate set be made using heuristics rules, such as peaking up buses around the disturbance, selecting first neighbour buses, etc. For instance, in example #4, the optimal solution recommends 53.19 Mvar switching at bus 17, which is found to be completely unnecessary in the other examples. Therefore, to choose the right locations to install the extra capacitor/reactor banks is of paramount importance.

Finally, it is pertinent to point out that the amount of the var expansion does not seem strongly dependent on weighting through unit costs, although the total expansion cost, of course, is.

Concluding comments

A new methodology has been developed to solve the var expansion problem. The examples above, at the same time, demonstrate the

efficacy of the proposed methodology and show how to use the various load flow tools developed in the previous chapters. Two alternative formulations involving combinations of NLP plus LP and NLP plus NLP techniques have also been investigated. Both of them have been found to be equally efficient in solving the var expansion problem. Local LP solutions are fast and produce good results. Similar results can be obtained by using the optimal load flow in both first and third level as in examples #2 and #3 above. The whole three level procedure can be made completely automatic, e.g. by adopting an upper limit to the number of buses in the candidate set, or by relaxing the limit corresponding to the largest λ_i at each iteration, or even by using an expert system to analyse the λ's and formulate the third level problem. On the other hand, it is desirable to allow a high degree of interaction for the program user. The information available on level 2 is too important to be withheld from the program user (power system operator). The three level procedure constitutes a invaluable tool for the operator of the system. It provides for the rapid checking of various operating strategies, yields guidance and, therefore, eases and improves the decision-making process. Operational plans, such as capacitor/reactor switching schedules, can be fast established and thoroughly examined. The system short term capabilities, such as overload ratings, under/overvoltage, can be exploited by determining the new limits for particular network configurations, such as contingencies, out-of-service equipment for maintenance, or high loading conditions.

Many other applications for the proposed methodology are certainly possible. The problem of discretisation of the switching capacitor/reactor can be resolved either by rounding the third level results to the closest discrete value, or by using an integer

programming algorithm. However, the more important point is to choose the best candidates set of buses for a given optimal operating point. Having done that, any optimisation programs can be used in the third level to determine the minimum amount of var sources.

CHAPTER 7

SECURITY-CONSTRAINED REACTIVE POWER DISPATCH

7.1 INTRODUCTION

The preventive security-constrained reactive power dispatch is considered an unsolved problem [12]. In this chapter original theoretical advances are reported in the formulation of the problem as well as in the methodology of solution. The new methodology benefits from the theoretical background and computational procedures reported in the previous chapters. A decomposition-coordination scheme is conceived in order to take advantage of the special structure of the problem. Instead of tearing the network, the problem itself is decomposed into smaller sub-problems. The techniques described in Chapter 4 are used for contingency simulation and for the handling of these contingencies in the optimisation process. The computing procedure is given for the step-by-step solution for on-line implementation. A small numerical example illustrates the application of the methodology. Results of numerical testing on the IEEE 30 bus test system are also presented.

7.2 BACKGROUND

The preventive security-constrained var dispatch problem consists of the scheduling of the var control variables, available in terms of the output of generators and compensation devices and the tap settings of transformers, such that some performance specification of the system operation is optimised and no limit violations occur after any defined contingencies. The use of the

transmission losses as such a performance index has been used for the past 20 years. As discussed before in Chapter 5, nowadays it is well accepted that the results of loss minimisation are only marginal and the primary objective is considered to be the assurance of a level of security in terms of meeting var constraints under a set of pre-defined disturbances (See, for instance, Fig. 2.1).

However, the inclusion of the contingencies in the optimisation problem poses such a large non-linear problem that a direct solution cannot be found because of time and/or storage limitations.

Several attempts to simplify and solve the problem have been reported in the literature. Fernandes et al. [128] utilized the hypothesis that, for each contingency, geographically independent var-voltage areas on the network can be selected to solve the var planning problem. An interesting idea can be found in Mansour [96]. In solving a var dispatch problem, subsystems are selected by grouping var control devices based on their geographical location and performing sensitivity tests based on the Zbus matrix. The var dispatch problem is then solved without considering contingencies. Zaborszky [94,95] presents algorithms based on sensitivity concepts to select problem buses and the most sensitive set of controls that can be used in var dispatch problems.

The optimal power flow (OPF) method, as first introduced by Carpentier [150] and Dommel and Tinney [144], has since been widely extended to take into account the effect of contingencies [36,151,152]. The general approach is to carry out the intact system optimisation as normal, to test the contingencies inequalities at intervals, and to add to the problem some chosen critical ones [36,108,114,151,152].

In the new method presented here the set of control variables is

partitioned in such a way that the most effective subset of controls is associated with each of the N contingencies.Thus N independent optimisation problems are defined and solved. The scheduling algorithm is basically the var optimal load flow of Chapter 5. A linear programming technique is used to coordinate the whole process, verifying the feasibility of implementing the adjustments on the control variables of the intact system to alleviate voltage violations in both normal and contingency cases. The contingency simulation is based on the reliable implementation of the novel fast decoupled load flow technique presented in Chapter 3, including the E&PSG model for contingency screening. The procedure at each time step is given in Fig. 7.1. When implemented in a control centre it may run cyclically, for instance each time the state estimator produces a result, or when given data by the operator to study in advance the var requirements to cover contingencies and scheduled maintenance.

7.3 FORMULATION OF THE PROBLEM

The preventive security-constrained var dispatch problem of concern is formulated as the optimisation problem

$$\text{Minimise} \qquad F(u_o, x_o) \tag{7.1}$$

$$\text{Subject to} \qquad G(u_o, x_o) = 0 \tag{7.2}$$

$$H(u_o, x_o) \geq 0 \tag{7.3}$$

$$G_k(u_k, x_k) = 0 \tag{7.4}$$

$$H_k(u_k, x_k) \geq 0 \tag{7.5}$$

$$k = 1 , 2 , \ldots . . nc$$

In this formulation u represents the vector of independent or controllable variables in the system and x is the vector of dependent

or state variables. The index o represents the intact system base case and $\underline{k}$ the nc contingency cases.

As before, the voltage magnitudes at swing, var generation and load buses and the tap settings of in-phase tap-changing-under-load (tcul) transformers are represented by V_{sw}, V_{pv}, V_{pq} and T, respectively.

$$[\ u\ ] = [\ V_{sw}\ \ V_{pv}\ \ T\ ]^t \qquad [\ x\ ] = [\ V_{pq}\ ]$$

The objective function F(.) is the summation of the squares of the deviations from an optimal operating point $\underline{z}^*=(\ u^*,\ x^*\ )^t$, assumed to be taken from some previous optimal real power schedule (ORPS):-

$$F(z) = \sum_{k=1}^{n_c} \sum_{i=1}^{n_{bus}} (\ z_i^k - z_i^*\ )^2 \qquad (7.6)$$

G(.) are the n_{pq} reactive power load flow equations (where the voltage angles are implicitly considered) and H(.) represent the system operating constraints: limits on n_{bus} voltage magnitudes, tap settings of n_t tcul transformers and bounds on n_g var generations.

$$Q_i^{sp} - Q_i(\ V\ ) = 0 \qquad i = 1,\ 2,\ldots,n_{pq} \qquad (7.7)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad i = 1,\ 2,\ldots,n_{bus} \qquad (7.8)$$

$$T_i^{min} \leq T_i \leq T_i^{max} \qquad i = 1,\ 2,\ldots,n_t \qquad (7.9)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \qquad i = 1,\ 2,\ldots,n_g \qquad (7.10)$$

To sum up: given a list of nc disturbances, represented by branch/generator outages, the ultimate objective is to find u_o such that (7.2 -7.5) are satisfied with the minimum deviation from the economic operating point.

Even for small systems this formulation poses such an enormous problem that any attempt at finding a direct solution is bound to fail. For instance, considering a 100 bus system and 10 disturbances would involve around 1000 non-linear equations for G and more than 1000 inequalities for H. Therefore a simplified approach is not only computationally justified but it is also mandatory. Figure 7.1 depicts the strategy adopted.

7.4 METHODOLOGY OF SOLUTION

Contingency Simulation

The starting point to reduce the size of the problem is to use the automatic screening load flow program to identify the contingencies which are most severe: the worst-case-list. A severe contingency is one which either causes a bus voltage magnitude violation greater than a pre-defined tolerance, ($J_{v\infty}$), or produces a large value for the summation of all bus voltage magnitude violations in the system , (J_{v1}): the performance indices. Thereby, as well as system-wide effects, localized problems are detected. The operator may manually add any other contingencies to the worst case list. As pointed-out in Chapter 4, an approach that reduces masking effects is to perform the ranking by zones. In adopting such an approach, the worst-case-list is formed by taking the highly ranked contingency of each zone.

Decomposition

Further simplification is achieved by decomposing the problem into smaller sub-problems which are easier to solve. As has already been mentioned, Zaborszky [94,95] has presented the idea of identifying subsystems, based on sensitivity concepts, consisting of

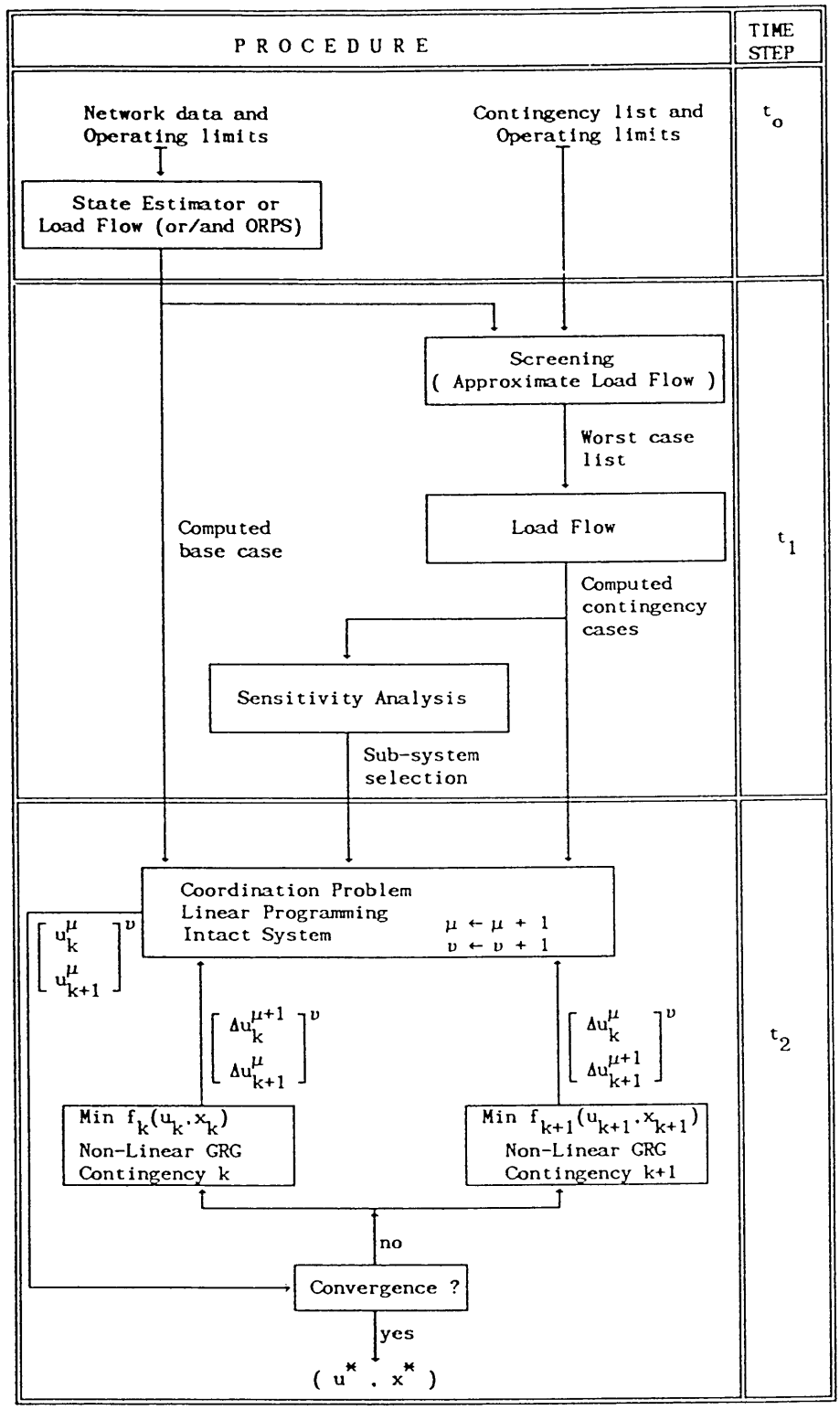


Fig. 7.1 Security-Constrained VAR Dispatch Strategy

problem buses and the highest priority set of controls which are effective on them, plus normal buses which are sensitive to controls in the cluster. In [96] Mansour used a similar technique to select subsystems based on grouping var control devices using a sensitivity criterion test.

In adopting the decomposition into sub-system approach, the following observations are pertinent:

1. Rather than causing system-wide effects, a disturbance usually causes localized problems in the system, characterized by voltage magnitudes out-of-limits within a nearby area.
2. Reactive power has a local effect, and the flow of reactive power over long distances is undesirable. The control to correct the above violations should be near to the bus needing correction, although, sometimes it has to be far away.
3. It is a good practice to avoid essentially ineffective scheduling of control variables (e.g.: a large change in a particular control variable for a minimal improvement in some inequality violation or in the objective function) [114].
4. For var generation and tcul transformer outages, the set of controls available in the contingent case is different from that in the base case. Whilst, in corrective scheduling, action is taken directly on the contingent state to quickly relieve the constraint violation, in preventive scheduling, action must be taken on the normal system. Therefore, within existing approaches, an expression is needed relating the contingent state constraint-violating quantity to the normal state vector.
5. The optimal load flow problem is sensitive to scaling [144].

Incidentally, [149] is well worth quoting: "For many problems, a group of control variables, u_1 have a stronger effect on the objective function than another group of control variables, u_2, and tend to move quickly to their optimal values, while u_2 variables lag behind. In view of this characteristic, two methodologies were developed: (i.) Scale u_2 gradients to the same relative strength as u_1, (ii.) Perform an optimal iteration on u_2 while holding u_1 variables fixed, then compute an optimal iteration on u_1 holding u_2 variables fixed; continue alternating."

6. The equivalent network techniques used in solving load flow problems produce huge errors when used in OPF [115].
7. Preventive control is expensive. For all practical purposes, the enforcement of a preventive scheduling is only considered for a few high risk contingencies. A good degree of security can be achieved by adopting the contingency selection by zone and enforcing preventive control only for the highly ranked contingency of each zone and determine a corrective contingency plan for the other contingencies.

Unlike the usual approach of tearing the network, which requires calculating equivalent networks and/or introducing approximations in the modelling, the new approach decomposes the problem itself. This provides exact modelling for each contingency, avoids the need to relate the control variable set in the contingent case to the set for the base case intact system, and automatically leads to the minimisation of the control action when only the effective control variables are considered in the optimisation. In addition, the new approach enables different objective functions to be adopted for each sub-system.

Sub-system Selection

Each contingency forms a sub-optimisation problem. For each contingency the n_p problem buses and the effective var control variables are identified. The problem buses are those which present limit violations, ($J_{vl} \neq 0$), and the var control devices are selected according to their effectiveness in eliminating those violations [37]. The var control devices to be included in each one of the sub-systems are those which present the greatest increment in an index I_{kj} of the problem buses, defined as

$$I_{kj} = \left| \sum_{i} S_{u,ij} \, du_j \right| \qquad (7.11)$$

$$i \in \chi, \; j \in \Omega, \quad k \in \psi$$

where,

S_u - sensitivity matrix

u_j - control variable, e.g.: voltage magnitude at PV or slack bus, tap setting on tcul transformer, var injection of shunt capacitor or reactor.

χ - set of out-of-limit PQ bus for contingency k.

Ω - set of var control devices available for contingency k

ψ - set of contingencies.

Alternatively, instead of calculating I_{kj} as defined in (7.11), the project gradient vector calculated at the solution of the load flow phase (See block labelled Load Flow in Fig. 7.1) yields each row of I_{kj}. The idea of using the gradient components to form I_{kj} allows for a more rigorous selection of the control vector, since the component of the project gradient vector, $\delta F/\delta u_i$, represents the maximum variation in the objective function, ΔF, in respect to the

control variable, u_i. Note, however, that at this stage of the procedure, the main interest is only in finding out which control is more effective for removing all violation in a particular contingency and not in determining the amount of control needed. The re-scheduling of the control variable is to be decided later by the non-linear optimisation algorithm.

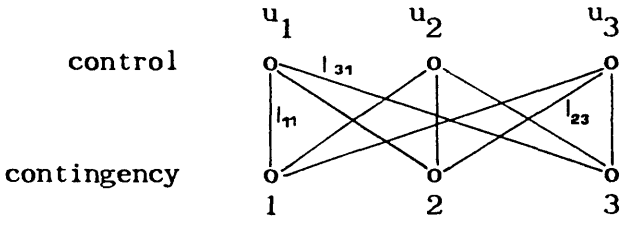
Partitioning of the control vector:- Given the indices , I_{kj}, and the harmful contingency set, ψ , the control vector is partitioned according to one of the following criteria:

1) The membership of every control variable u_j in a sub-system k is decided by singly taking the contingencies in descending numerical order of their PI, (J_{vl}), and selecting the control u_j corresponding to the greatest I_{kj}; continuing until all the control variables are distributed among the nc sub-systems. See example in Section 7.5

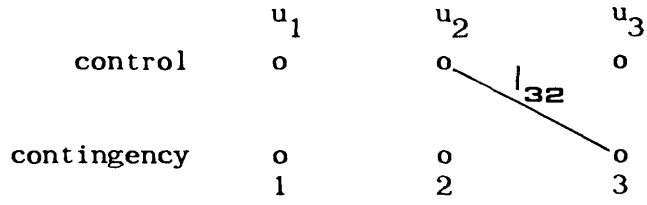
2) The membership of every control variable u_j in a sub-system k is decided by choosing a threshold $\tau > I_{kj}$, for the index I_{kj}, in such a way that the control u_j is associated with one and only one contingency k. For example, take the problem where the control vector is $[u_1\ u_2\ u_3]$ and the worst-case-list $\psi = \{1, 2, 3\}$. Then, the application of this criteria can be illustrated as follows:-

iteration 1

$\tau = \tau_o$



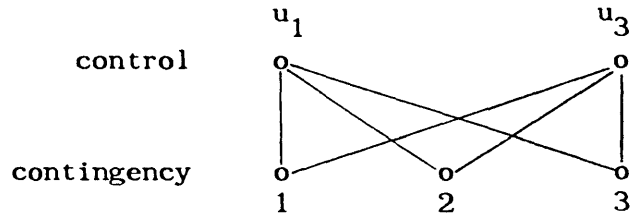
$\tau = \tau_1$



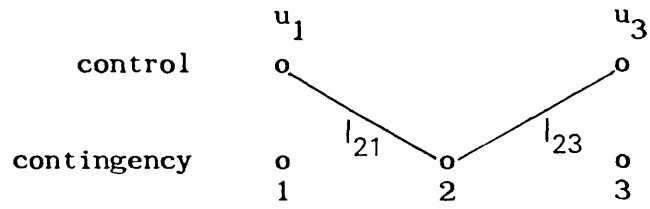
$$[\ u\ ]^3 = [\ u_2\ ]$$

iteration 2

$\tau = \tau_o$



$\tau = \tau_1$



$$[\ u\ ]^2 = [\ u_1\ ,\ u_3\ ]$$

$$[\ u\ ]^3 = [\ u_2\ ]$$

Thus, the partitioning of the control vector produces two sub-system optimisation.

$$[\ u\ ] = [\ [\ u\ ]^2\ [\ u\ ]^3\ ]$$

The results tell us that contingency 1 has no effective control in the context of the algorithm, i.e., compared with contingencies 2 and 3. This condition may occur when the number of control is small compared to the number of contingencies. Of course, it always occurs when the number of controls is less than the number of contingencies.

Two alternatives are possible in such a case: 1) to drop contingency 1 and try to solve it in a corrective mode, and 2) to include contingency 1 as pseudo-subsystem, since there is a chance that the global adjustment in the control variables may remove the violations in this contingency. The pseudo-subsystem does not carry out any optimisation, but its objective function values and constraints are still accounted for in the co-ordination problem.

Choice of the selection criteria:- Although, the co-ordination problem provides for treating conflicting contingency cases, the method is primarily intended for use with large systems (large number of controls compared with the number of contingencies) and concerted situations. The first criteria assures a even distribution of the control variables among the sub-systems. It assures that each subsystem receives an equal number of control variables as long as the number of control available is greater or equal to the number of contingencies in the contingency set. The second criteria tends to attribute a certain degree of controllability to each contingency. Thus, the controls tend to cluster around the highly controllable contingencies.

The first criteria is indicated for small systems, or, when the various contingencies to be enforced are in the same zone, or, when the interaction between controls is high (a same control is equally effective in various contingencies). The second criteria is indicated when the contingency selection is performed by zone and only one contingency of each zone is selected for preventive control enforcement. In this case the interaction between sub-systems is weak and the method tends to converge in one iteration.

Having associated the most effective control set with each

contingency k, the control vector can be written as

$$[\,u\,] = [\,[\,u^{k}\,]\;[\,u^{k+1}\,]\ldots[\,u^{nc}\,]\,]^{t} \qquad (7.12)$$

where the superscript indicates the contingency number.

Thus, the re-scheduling of the control set k, is to be primarily aimed at reducing the violations in contingency k, i.e., to make $J^{k}_{v1}=0$. The ideal situation occurs with large systems, when the contingency selection can be carried out by zone, and only one contingency of each zone (e.g., the one with worst impact, or the most likely) is selected for enforcement in preventive mode. In such cases the interaction variables are bound to be weak, with the set of control k, having no influence at all in contingency k+1, that is, $I_{ij}=0$, $i\neq j$, as shown in Fig. 7.2.

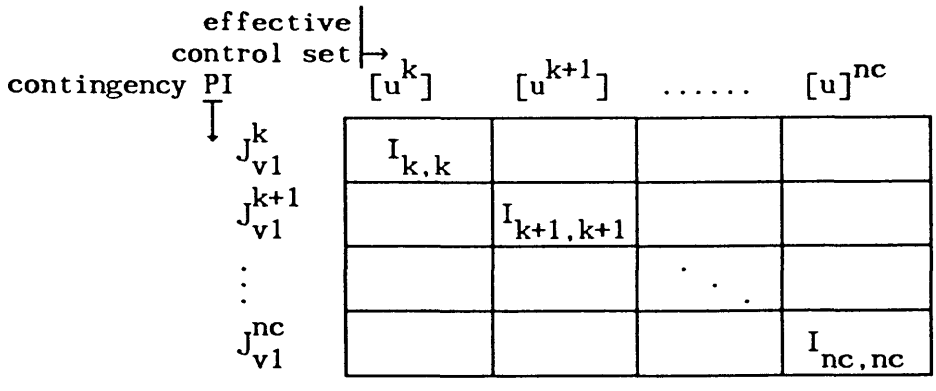


Fig. 7.2 Sub-system Interaction

Instead of being exceptions the cases above are the ones of the most practical interest, since the enforcement of preventive control is only considered for a few contingencies. Furthermore, since preventive control is expensive, power networks are never designed to be N preventive secure, in consequence, many preventive secure operating strategies do not exist at all. In addition, it should be

recognized that one can always design a set of contingencies for which a preventive solution does not exist (See, for example, [2])

Co-ordination Problem

The preventive security-constrained var dispatch problem is now stated as an nc non-linear optimisation and co-ordination problem. For a contingency k, a small optimisation problem is defined over the control vector u^k, and interaction variables from other sub-systems, u^{k+1}, are fixed during the optimisation process of sub-system k. Figure 7.3 shows diagrammatically the strategy adopted.

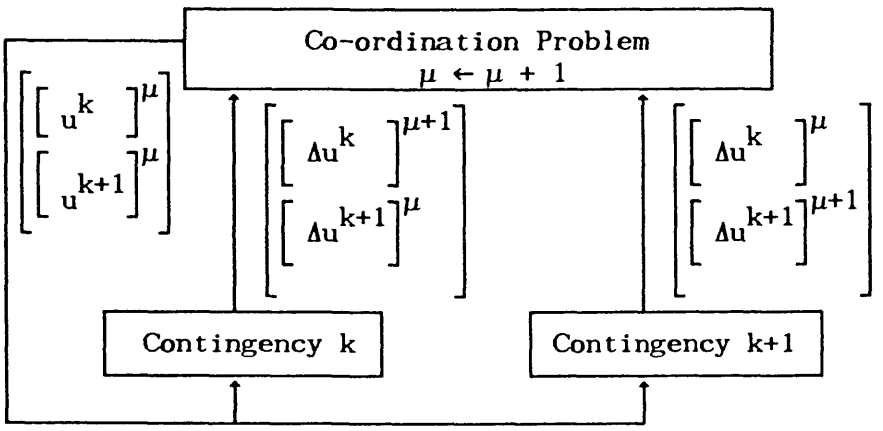


Fig. 7.3 Co-ordination-Decomposition Scheme

The results of the optimisation of each of the k contingencies are to be treated as a proposal for adjustment of the control variables of the intact system. It then becomes necessary to verify that such adjustments do not cause violations in the intact system. This is achieved by the following formulation of the co-ordination problem:-

Let the current result of the sub-system optimisation be Δu,

$$[\ \Delta u\ ] = [\ [\ \Delta u^k\ ]\ [\ \Delta u^{k+1}]\ \ldots\ [\ \Delta u^{nc}]\ ]^t \qquad (7.13)$$

Upon introducing the set of scalar multipliers α,

$$\alpha = \{ \alpha_i \mid 0 \leq \alpha_i \leq 1 \ , \ i = 1,nc \} \tag{7.14}$$

it can be written,

$$[\Delta u(\alpha)] = \begin{bmatrix} \alpha_k & [\Delta u^k] \\ \alpha_{k+1} & [\Delta u^{k+1}] \\ \vdots & \vdots \\ \alpha_{nc} & [\Delta u^{nc}] \end{bmatrix} \tag{7.15}$$

and, through the linearized sensitivity relationship,

$$[\Delta x(\alpha)] = S_u [\Delta u(\alpha)] \tag{7.16}$$

The co-ordination problem can now be stated as an upper-bound linear programming task:

Maximise
$$z = \sum_{k=1}^{nc} \alpha_k \tag{7.17}$$

Subject to
$$\Delta u^{min} \leq \Delta u (\alpha) \leq \Delta u^{max} \tag{7.18}$$

$$\Delta x^{min} \leq \Delta x (\alpha) \leq \Delta x^{max} \tag{7.19}$$

$$H(u+\Delta u(\alpha), x+\Delta x(\alpha)) \geq 0 \tag{7.20}$$

where, H are functional inequality constraints in the intact system, e.g.: bounds on var generations.

The multipliers α_k can be interpreted as the degree of acceptance of the results of the sub-system optimisation. For instance, a value for

α_k equals 1 means that the adjustments Δu^k proposed by the optimisation of contingency k do not cause any limit violations in the base case, being thus perfectly acceptable. On the other hand, a value for α_k equals zero means that no adjustments are possible. Of course any intermediate value represents the amount of adjustment which is viable. Notice also that α_k represents the length of the step in the direction of the optimum for removing violations on contingency k without creating limit violations on the intact system. Therefore, for a given result α^*, of the coordination problem, $\Delta u(\alpha^*)$ represents the optimum adjustment in the control vector so as to enforce security for all contingencies.

However, the interaction variables may cause some contingency constraint to be violated. Thus, the current value of $u(\alpha^*)^v$ is used to check the effect of the interaction variables in the constraint set corresponding to the contingency cases, and, should a violated or near violated constraint be found it is included in the set of constraints of those near-bounded base case constraints, (7.19-20), and, a reduced LP problem is solved again.

Shadow Price

The advantage of formulating, and in fact, solving two LP problems, instead of selecting the constraint set immediately after obtaining the results of the subsystem optimisation, becomes clear with the interpretation of the shadow prices (Lagrange multipliers), which are available at the solution of the LP. The shadow prices represent the amount of objective value which may be gained by a small increase in the limits of the constraints. An example is given in the next Section.

Thus, in the first LP solution it represents the increase in the voltage magnitude limits of every bus in the base case intact system

which represents an extra availability of preventive control for the outage cases. Therefore, it pinpoints those limits in the base case intact system which prevent further degree of acceptance of the proposal of adjustment made by the contingency cases, i.e., enforcement of security. This information is very important for designing a high level of system security. In the daily operation of the intact system there are several violated cases which may be tolerated. An example is an upper voltage limit at a no-loaded PQ bus at the end of a radial transmission line. In such a case a certain amount of overvoltage causes no harm at all, however, it appears very likely that this overvoltage will prevent the adjustment in the control vector, and, therefore, prevent a more secure operation. Other examples are central point of star equivalent circuit of three-winding transformers, no-loaded buses, no-loaded tertiary windings of transformers, etc. It is frequently suggested that the operators tend to know well their base case intact system. The problem is with the contingency cases. With the new methodology the operator can reflect the contingency case problems and remedies onto the base-case intact system.

The analysis of the shadow prices in the second LP solution have the same significance as for the base case intact system. The extra feature is that constraints belonging to the contingency cases which may be found to overconstrain the problem should be dropped and solved in corrective mode.

Extreme cases

It is pertinent to examine two extreme cases: (i) weak interaction between subsystems, and and (ii) strong interaction between subsystems. In case (i) the procedure is likely to be successful in only one iteration, since the control variables

selected for subproblem k do not influence at all the values of the dependant variables affected by other contingencies. This is the more important case, from the practical aspect, when the high probability contingency of each different areas in the system is chosen for the worst-case-list. Case (ii) arises when a control variable is equally effective for two contingencies in the worst-case-list. In this case iterations are needed until no more significant gain is obtained in the overall objective function (7.6), which is the summation of each individual subsystem objective.

7.5 AN EXAMPLE

The Ward-Hale 6-bus system shown in Fig.7.4 will be used to illustrate the methodology. Tables 7.1 show the pertinent data.

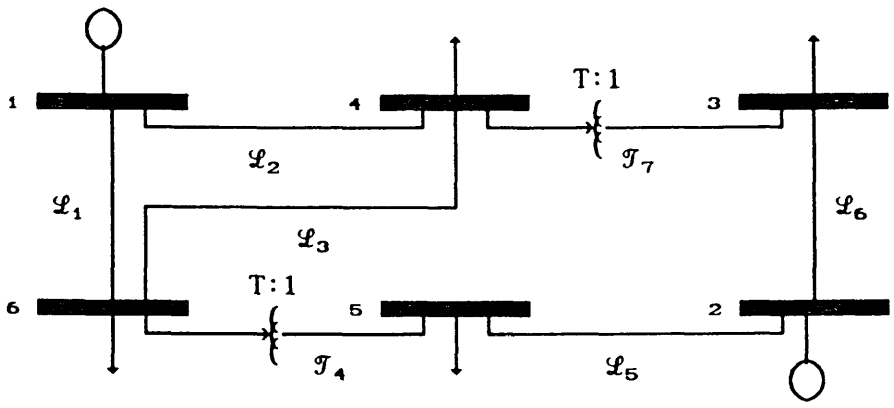


Fig. 7.4 6-Bus System

All of the single branch outages form the list of contingencies, which includes two control variable outages: tcul transformers T4 and T7.

Table 7.1 Busbar Data

Bus No/Type	Voltage (p.u) V	Vmin	Vmax	θ	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Qmin	Generation Qmax
1 SW	1.05	.950	1.10	0	3.3898	0.0	0.0	0.	-20.	100.
2 PV	1.10	.950	1.15	0	.0000	0.0	0.0	50.	-20.	100.
3 PQ	1.00	.975	1.10	0	.0000	22.5	6.5	0.	0.	0.
4 PQ	1.00	.975	1.10	0	2.9326	0.0	0.0	0.	0.	0.
5 PQ	1.00	.975	1.10	0	.0000	15.0	9.0	0.	0.	0.
6 PQ	1.00	.975	1.10	0	3.3088	25.0	2.5	0.	0.	0.

Tolerances: 1) on busbar power mismatch $< 10^{-4}$ MW/Mvar
2) on outage case limit enforcement for PQ buses < 0.05 per unit

In the following the strategy shown in Fig. 7.1 will be considered. The first step is to run a load flow in order to obtain a computed base case, shown in Table 7.2.

Table 7.2 Intact System Initial Values

Busbar Num/Type	Voltage p.u.	Angle degree	Shunt Mvar	Generation MW	Generation Mvar	Load MW	Load Mvar
1 SW	1.0500	0.00	3.74	17.65	20.31	.00	.00
2 PV	1.1000	10.30.	.00	50.00	-.34	.00	.00
3 PQ	1.0703	-1.63	.00	.00	.00	22.50	6.50
4 PQ	.9921	-1.20	2.89	.00	.00	.00	.00
5 PQ	.9937	0.62	.00	.00	.00	15.00	9.00
6 PQ	.9934	-1.80	3.27	.00	.00	25.00	2.50

These results together with the contingency list input the contingency selection program which generates the results in Fig. 7.5. These show that worst cases are contingencies 2, 5 and 7, as they present the largest PI's, as well as single voltage magnitude deviations greater than the 5% tolerance. Thus, these contingencies form the worst case list.

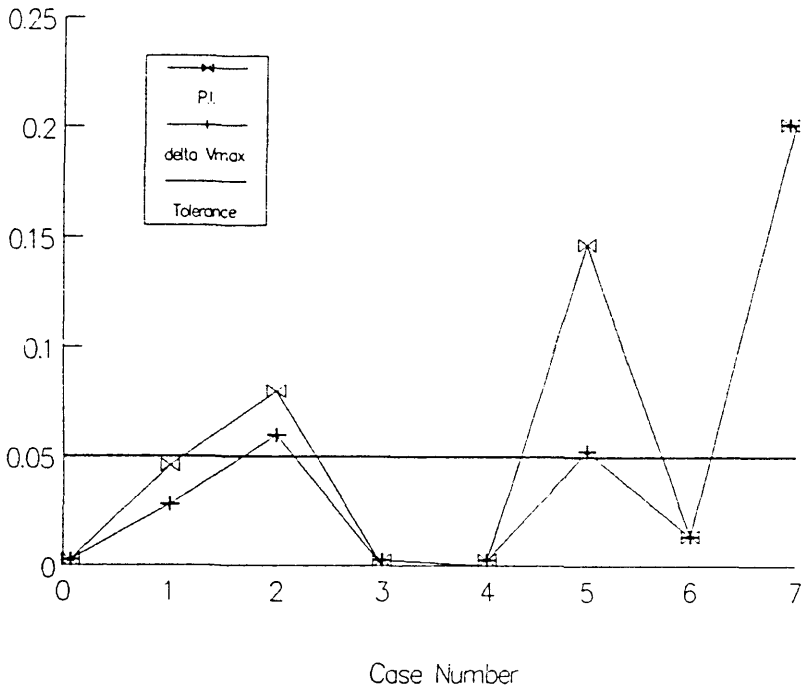


Fig. 7.5 PI - Initial Values

Execution of the exact load flow for the worst case list yields the sensitivity matrix coefficients corresponding to the PQ buses with voltage magnitudes out-of-limits.

The next step is the selection of subsystems.

The calculation of the indices I_{kj}, are illustrated below

Contingency Number 2

$$I_{2j} = \left| \sum_{i=1}^{4} S_{ij} \, \Delta u_j \right| \qquad j = 1,4$$

$$\begin{bmatrix} \Delta V_3 \\ *\Delta V_4 \\ *\Delta V_5 \\ *\Delta V_6 \end{bmatrix} = \begin{bmatrix} .42305 & .86356 & .24410 & -.50534 \\ .42247 & .74389 & .23725 & .41436 \\ .39342 & .77146 & -.48354 & .15329 \\ .56006 & .57265 & .29855 & .19541 \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta t_4 \\ \Delta t_7 \end{bmatrix}$$

$$I_{2j} \qquad 1.37595 \quad 2.08800 \quad .05226 \quad .76306$$

Contingency Number 5

$$I_{5j} = \left| \sum_{i=1}^{4} S_{ij}\, \Delta u_j \right| \qquad j = 1,4$$

$$\begin{bmatrix} \Delta V_3^* \\ \Delta V_4^* \\ \Delta V_5^* \\ \Delta V_6^* \end{bmatrix} = \begin{bmatrix} .91333 & .44918 & -.00107 & -.69924 \\ .89768 & .29667 & -.00105 & .23966 \\ 1.09503 & .19297 & -.98833 & .15589 \\ 1.03018 & .18154 & -.00252 & .14665 \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta T_4 \\ \Delta T_7 \end{bmatrix}$$

$$I_{5j} \qquad \underline{3.93622} \quad 1.12036 \quad \underline{.99297} \quad .15704$$

Contingency Number 7

$$I_{7j} = \left| \sum_{i=1}^{4} S_{ij}\, \Delta u_j \right| \qquad j = 1,4$$

$$\begin{bmatrix} *\Delta V_3 \\ \Delta V_4 \\ \Delta V_5 \\ \Delta V_6 \end{bmatrix} = \begin{bmatrix} .00000 & 1.88856 & .00000 \\ .90138 & .13007 & .13066 \\ .55452 & .50407 & -.53072 \\ .77884 & .27145 & .27448 \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta t_4 \end{bmatrix}$$

$$I_{7j} \qquad .00000 \quad \underline{1.88856} \quad .00000$$

Hence, the table of indices I_{kj} of (7.11), is

control j ⟶ / contingency k ↓		ΔV_1	ΔV_2	ΔT_4	ΔT_7	PI ↓
	7	.00000	1.88856	.00000	.00000	.201
	5	3.93622	1.12036	.99297	.15704	.147
	2	1.37595	2.08800	.05226	.76306	.080

A step-by-step application of the first criteria for the selection of the sub-systems can now be detailed

step 1 first choice max $\{I_{7j}\}$

control j ⟶ / contingency k ↓	ΔV_1	ΔV_2	ΔT_4	ΔT_7	PI ↓
7	.00000	1.88856	.00000	.00000	.201
5	3.93622	1.12036	.99297	.15704	.147
2	1.37595	2.08800	.05226	.76306	.080

$$[\ u\ ]^7 = [\ \Delta V_2\ ]$$

step 2 second choice max $\{I_{5j}\}$

control j ⟶ / contingency k ↓	ΔV_1	ΔT_4	ΔT_7	PI ↓
7	.00000	.00000	.00000	.201
5	3.93622	.99297	.15704	.147
2	1.37595	.05226	.76306	.080

$$[\ u\ ]^7 = [\ \Delta V_2\ ]$$

$$[\ u\ ]^5 = [\ \Delta V_1\ ]$$

step 3

control j ⟶ / contingency k ↓	ΔT_4	ΔT_7	PI ↓
7	.00000	.00000	.201
5	.99297	.15704	.147
2	.05226	.76306	.080

$$[\ u\ ]^7 = [\ \Delta V_2\ ]$$

$$[\ u\ ]^5 = [\ \Delta V_1\ ]$$

$$[\ u\ ]^2 = [\ \Delta T_7\ ]$$

step 4 fourth choice max $\{\ I_{7j}\ \}$

fifth choice max $\{\ I_{5j}\ \}$

control j ⟶ / contingency k ↓	ΔT_4	PI ↓
7	.00000	.201
5	.99297	.147
2	.05226	.080

$$[\ u\ ]^7 = [\ \Delta V_2\ ]$$

$$[\ u\ ]^5 = [\ \Delta V_1 \quad \Delta T_4\ ]^t$$

$$[\ u\ ]^2 = [\ \Delta T_7\ ]$$

In fact, the procedure only collects the relevant indices in a

sparse binary array

control j ⟶ / contingency k ↓	ΔV_1	ΔV_2	ΔT_4	ΔT_7	PI ↓
7	0	1	0	0	.201
5	1	0	1	0	.147
2	0	0	0	1	.080

which gives all information for the partition of the control vector

$$\begin{bmatrix} \Delta u_1 \\ \Delta u_2 \\ \Delta u_3 \\ \Delta u_4 \end{bmatrix} = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta T_4 \\ \Delta T_7 \end{bmatrix} \longrightarrow \begin{array}{l} [\ \Delta u^7\ ] = [\ \Delta V_2\ ] \\ [\ \Delta u^5\ ] = \begin{bmatrix} \Delta V_1 \\ \Delta T_4 \end{bmatrix} \\ [\ \Delta u^2\ ] = [\ \Delta T_7\ ] \end{array}$$

The optimisation of each sub-system is then performed. Table 7.3 and Fig. 7.6 summarise the results of the optimisation of each subsystem.

Table 7.3 Subsystem Optimisation Results

It	Contingency 2			Contingency 5			Contingency 7		
	O.F.	value	vf	O.F.	value	vf	O.F.	value	vf
0	.00487	1.00	.477E-2	.00849	1.00	$\begin{bmatrix} -.2470 \\ .0770 \end{bmatrix}$	.0255	1.00	-.4261
1	.00307	.63	.740E-2	.00322	.38	$\begin{bmatrix} -.1419 \\ .0440 \end{bmatrix}$	.0115	.45	-.2465
2	.00301	.62	.244E-4	.00122	.14	$\begin{bmatrix} -.0570 \\ .0000 \end{bmatrix}$	.0097	.38	-.2229
3	.00301	.62	.184E-7	.00063	.07	$\begin{bmatrix} -.0168 \\ .0000 \end{bmatrix}$			
4				.00061	.07	$\begin{bmatrix} -.0142 \\ .0000 \end{bmatrix}$			

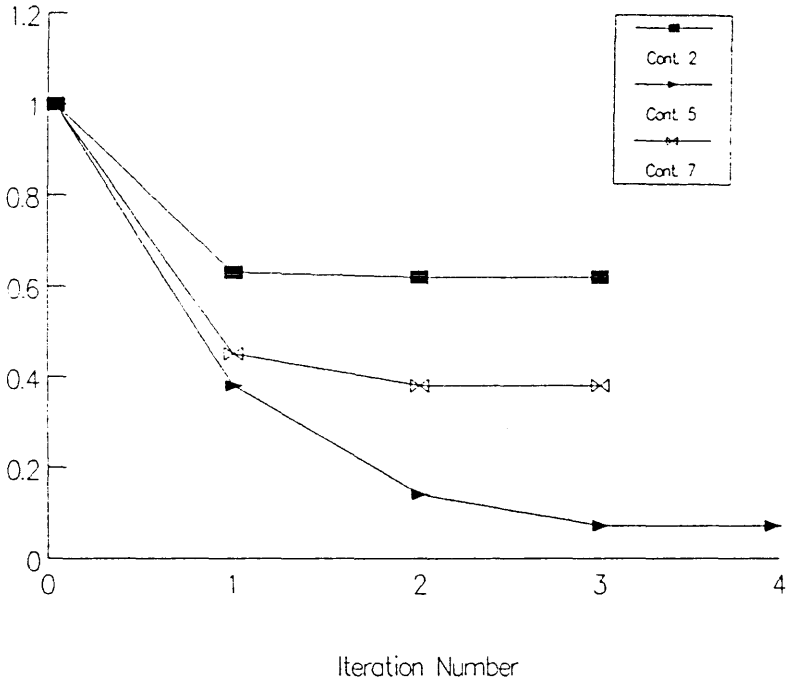


Fig. 7.6 Reduction of the Objective Function Values

Thus, the results of the optimisation of each sub-system give the proposals for increments in the base case control vector

$$[\ \Delta u\ ] = \begin{bmatrix} 0.0463 \\ 0.0500 \\ 0.0120 \\ -.0806 \end{bmatrix}$$

$$[\ \Delta u^{2}\ ] = [\ -.0806\ ]$$

$$[\ \Delta u^{7}\ ] = [\ 0.0500\ ]$$

$$[\ \Delta u^{5}\ ] = \begin{bmatrix} 0.0463 \\ 0.0120 \end{bmatrix}$$

These results are passed to the co-ordination module as a proposal for adjustments in the control vector of the base case intact system, as represented in Fig. 7.7.

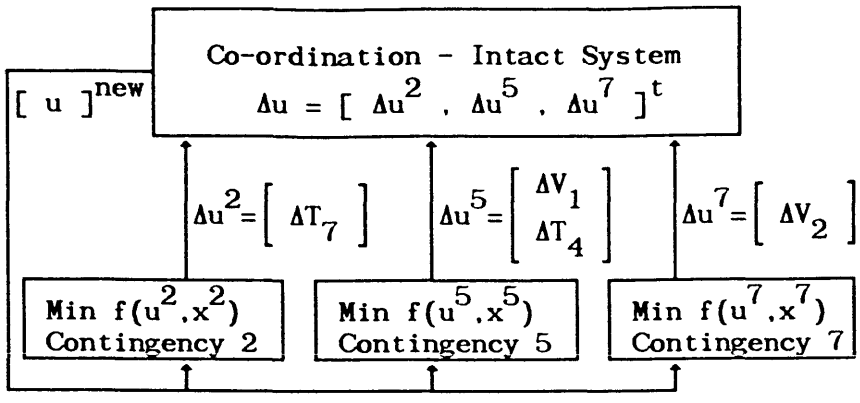


Fig. 7.7 Decomposition/Co-ordination Data Flow

Coordination problem

The base case sensitivity matrix gives the coefficients for writing the equation

$$\begin{bmatrix} \Delta V_3 \\ \Delta V_4 \\ \Delta V_5 \\ \Delta V_6 \end{bmatrix} = \begin{bmatrix} .84227 & .48380 & .11464 & -.74213 \\ .83778 & .35965 & .10629 & .19805 \\ .58495 & .69413 & -.51193 & .09489 \\ .81203 & .42494 & .23622 & .10083 \end{bmatrix} \begin{bmatrix} \alpha_1 \Delta u_1 \\ \alpha_2 \Delta u_2 \\ \alpha_1 \Delta u_3 \\ \alpha_3 \Delta u_4 \end{bmatrix}$$

The base case voltage limits are

$$\Delta V^{min} = \begin{bmatrix} .975-1.0703 \\ .975- .9921 \\ .975- .9937 \\ .975- .9934 \end{bmatrix} = \begin{bmatrix} -.0953 \\ -.0171 \\ -.0187 \\ -.0184 \end{bmatrix} \quad \Delta V^{max} = \begin{bmatrix} 1.1-1.0703 \\ 1.1- .9921 \\ 1.1- .9937 \\ 1.1- .9934 \end{bmatrix} = \begin{bmatrix} .0297 \\ .1079 \\ .1063 \\ .1066 \end{bmatrix}$$

The coordination problem is now stated as

Maximise $\quad z = \alpha_1 + \alpha_2 + \alpha_3$

Subject to

$$.04037\ \alpha_1 + .02419\ \alpha_2 + .0598\ \alpha_3 \leq .0297$$

$$.04037\ \alpha_1 + .02419\ \alpha_2 + .0598\ \alpha_3 \geq -.0953$$

$$.04006\ \alpha_1 + .01798\ \alpha_2 - .0016\ \alpha_3 \leq .10790$$

$$.04006\ \alpha_1 + .01798\ \alpha_2 - .0016\ \alpha_3 \geq -.0171$$

$$.02092\ \alpha_1 + .03471\ \alpha_2 - .0077\ \alpha_3 \leq .10630$$

$$.02092\ \alpha_1 + .03471\ \alpha_2 - .0077\ \alpha_3 \geq -.0187$$

$$.04043\ \alpha_1 + .02125\ \alpha_2 - .0081\ \alpha_3 \leq .10660$$

$$.04043\ \alpha_1 + .02125\ \alpha_2 - .0081\ \alpha_3 \geq -.0184$$

$$1.0000\ \alpha_1 \geq 0.0$$

$$1.0000\ \alpha_1 \leq 1.0$$

$$1.0000\ \alpha_2 \geq 0.0$$

$$1.0000\ \alpha_2 \leq 1.0$$

$$1.0000\ \alpha_3 \geq 0.0$$

$$1.0000\ \alpha_3 \leq 1.0$$

Results

Table 7.4a LP Results

Variable	value	slack	value	constraint	shadow price
α_1	.13648749	s_1	.12500000	c_1	.0000000
α_2	1.00000000	s_2	.00000000	c_2	24.7708695
α_3	.00000000	s_3	.04054769	c_3	.0000000
		s_4	.08445231	c_4	.0000000
		s_5	.05626532	c_5	.0000000
		s_6	.06873468	c_6	.0000000
		s_7	.04516819	c_7	.0000000
		s_8	.07983181	c_8	.0000000
		s_9	.86351251	c_9	.0000000
		s_{10}	.00000000	c_{10}	.4007927
		s_{11}	1.00000000	c_{11}	.0000000
		s_{12}	.13648749	c_{12}	.0000000
		s_{13}	1.00000000	c_{13}	.0000000
		s_{14}	.00000000	c_{14}	.0000000
Final solution reached after 2 pivots Maximum value of objective function = 1.13649					

An illustration of the shadow price interpretation is given in the following.

The LP results in Table 7.4a shows that the largest shadow price

corresponds to constraint c_2 which is associated to the upper limit of bus 3. Consider an expansion of δV=0.0059 pu (20%) on the upper limit of this constraint, which corresponds to an increase of 0.6% on the voltage magnitude limit of busbar number 3. With this modification the new LP solution is shown in Table 7.4b. It can be seen that it represents an increase of 107.1% on the degree of acceptance for the proposal of the adjustment on the control vector submitted by the optimisation subsystem corresponding to contingency 5. Further illustration can be provided by calculating the same result applying directly the interpretation of the shadow price. Thus,

$$\Delta z = \frac{\partial z}{\partial b_2} \Delta b_2$$

$$\Delta z = 24.7708695 * 0.0059 = 0.146148$$

$$z^{new} = z^{old} + \Delta z = 1.3649 + 0.146148$$

$$z^{new} = 1.28264$$

Table 7.4b LP Results for ΔV_3^{max} = 0 0356

Variable	value	constraint	shadow price
α_1	.28263562	c_2	24.7708695
α_2	1.00000000	c_{10}	.4007927
α_3	.00000000	$c_i \ \forall \ i \neq 2,10$	.0000000
Final solution reached after 2 pivots Maximum value of objective function = 1.28264			

Adopting the results in Table 7.4a, the constraint set for the contingencies are checked and no violated or near violated further constraints are found. Then, the final adjustments in the base case control vector yield

$$\Delta u = \begin{bmatrix} 0.1365 * 0.0463 \\ 1.0000 * 0.0500 \\ 0.1365 * 0.0120 \\ 0.0000 *(-.0806) \end{bmatrix} \qquad \Delta u = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta T_4 \\ \Delta T_7 \end{bmatrix} = \begin{bmatrix} 0.0063 \\ 0.0500 \\ 0.0016 \\ 0.0000 \end{bmatrix}$$

and,

$$u^{new} = u^{old} + \Delta u \qquad u^{new} = \begin{bmatrix} V_1 \\ V_2 \\ T_4 \\ T_7 \end{bmatrix} = \begin{bmatrix} 1.056 \\ 1.150 \\ 1.027 \\ 1.100 \end{bmatrix}$$

With these values of the control variables, the PI's are recalculated, yielding the results shown in Table 7.5, which bring all contingencies to the allowed range, but contingency 7. New optimisation of contingency 7 shows that no further gain in the objective function is possible. Therefore, Table 7.5 is the final preventive results, i. e., the system is K=6 preventive secure.

Tables 7.5 and 7.6 summarise the final preventive results

Table 7.5 Performance Index (k=6 preventive secure)

Case No.	Performance Indices Initial J_{v1}	$J_{v\infty}$	No ΔV_i	Final J_{v1}	$J_{v\infty}$	No ΔV_i
0	.0000	.0000	0	.0000	.0000	0
1	.0456	.0281	3	.0000	.0000	0
2	.0800	.0597*	3	.0205	.0205	1
3	.0000	.0000	0	.0000	.0000	0
4	.0000	.0000	0	.0000	.0000	0
5	.1470	.0525*	4	.0896	.0335	3
6	.0137	.0137	1	.0080	.0080	1
7	.2010	.2010*	1	.1140	.1140*	1

* Violating quantities, No ΔV_i = number of violations

Table 7.6 Intact System Final (Preventive) Results

Busbar Num/Type		Voltage p.u.	Angle degree	Shunt Mvar	Generation MW	Generation Mvar	Load MW	Load Mvar
1	SW	1.0560	0.00	3.78	17.08	12.97	.00	.00
2	PV	1.1500	8.82	.00	50.00	4.84	.00	.00
3	PQ	1.0965	-1.64	.00	.00	.00	22.50	6.50
4	PQ	1.0126	-1.27	3.01	.00	.00	.00	.00
5	PQ	1.0299	0.35	.00	.00	.00	15.00	9.00
6	PQ	1.0165	-1.92	3.63	.00	.00	25.00	2.50

Tap settings: T4 = 102.7 % , T7 = 110.0 %

Contingency 7 is then dropped from the worst-case-list and a corrective solution is tried. As the corrective solution also fails a var expansion plan determines the alteration which should have been made in the system during some previous planning phase (potential control), and that, perhaps should be made in the future. The corrective results for contingency 7 are given in Table 7.7.

Table 7.7 Expansion plan for contingency 7.

Busbar Num/Type		Voltage p.u.	Angle degree	Shunt Mvar	Generation MW	Generation Mvar	Load MW	Load Mvar
1	SW	1.057	0.00	3.79	18.33	-2.98	.00	.00
2	PV	1.150	4.15	.00	50.00	16.31	.00	.00
3	PQ	.925	-7.84	4.38	.00	.00	22.50	6.50
4	PQ	1.054	-1.43	3.26	.00	.00	.00	.00
5	PQ	1.055	-1.81	.00	.00	.00	15.00	9.00
6	PQ	1.038	-2.87	3.57	.00	.00	25.00	2.50

Notes:
(1) Tap settings: T4 = 102.7 % , T7 = 110.0 %
(2) Switched capacitor at bus 3 = 5.12 Mvar, or, load shedding at bus 3 = 4.38 Mvar

7.6 NUMERICAL RESULTS AND COMPARISONS

In this section the methodology is applied for security enhancement of the IEEE 30-bus test system and the results are compared with those published by D.T. Sun and R.Shoults [152].

Security Enhancement - IEEE 30-bus test system

The assumptions for the security enhancement exercise were as follows:

1) System loading: It was assumed that an active power scheduling has been performed for the flat start profile. The load flow solution for the intact system is that of Table 5.5aI.

2) Operating Limits: The lower and upper voltage magnitude limits at PQ buses for the base case intact system were set as 0.975 and 1.1 p.u., respectively. For contingency cases the lower limit at PQ buses was set at 0.925 and the upper limit at 1.1, the same as in the base case. Bounds on control variables and output of var sources are as given in Appendix B. At bus 9, which is a pseudo bus (central point of a star equivalent circuit of a three winding transformer), the upper and lower limits were set as 0.9 and 1.15 pu, respectively.

Considering the above conditions the contingency screening was carried out. The results, shown in Table 4.1a., allow for the selection of the wort-case-list. Table 7.8 and Fig. 7.8 show the contingencies in the worst-case-list. Table 7.8 also shows the summary of the insecurities in each contingency case as well as the enhancement of security after the application of the method. The initial conditionsinclude 109 violating quantities for both the base case and for the contingencies in the worst-case-list, the lowest voltage magnitude being 0.7518. In the final enhanced state, only contingency 36 presents 2 buses with violating contingency limits (V_{29}=.9235 and V_{30}=.9109), and 3 others below the base case limits. The voltage magnitudes are within base case limits for all other contingencies, as also shown in Table 7.8.

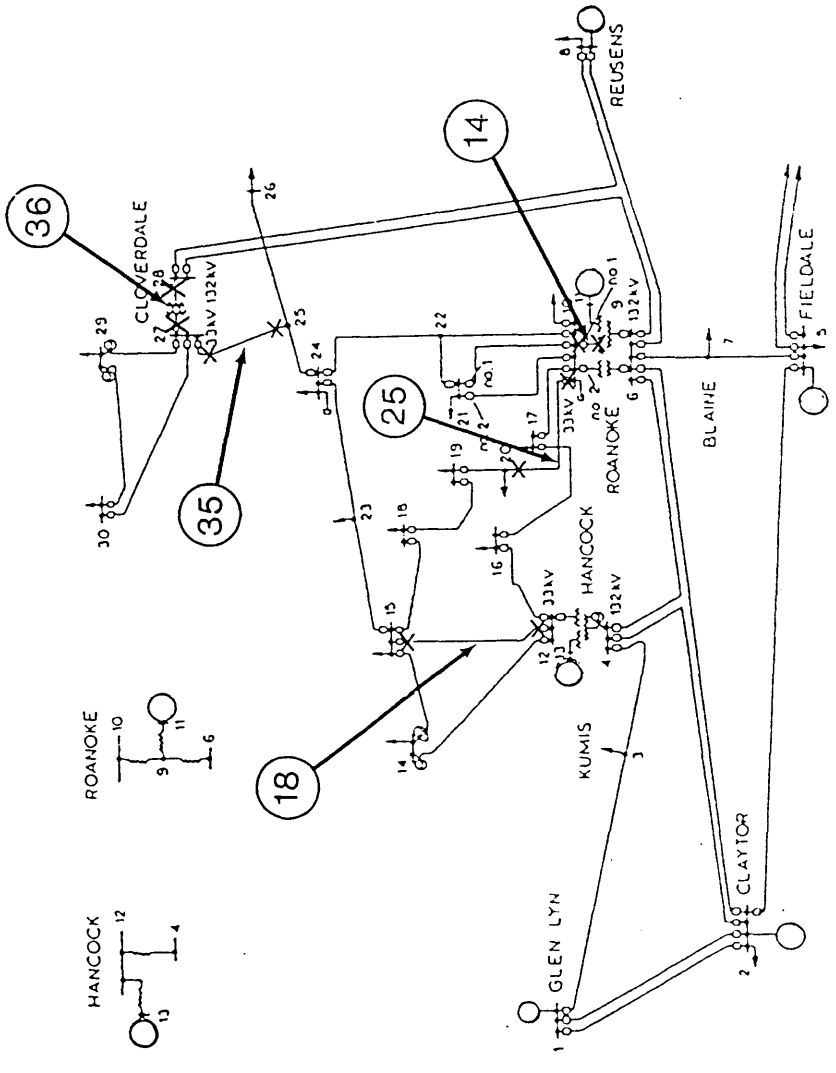


Fig. 7.8 IEEE 30 Bus Test System - The Worst-Case-List

Table 7.8 Worst-Case-List Insecurity Summary

Harmful Effects:				
Contingency/Branch: Worst-case-list				
{ 36	25	35	14	18 }
bus V	bus V	bus V	bus V	bus V
9 .9652*	10 .9655*	9 .9714*	10 .9222*<-	9 .9705*
10 .9461*	12 .9576*	10 .9578*	12 .9528*	10 .9565*
12 .9530*	14 .9415*	12 .9586*	14 .9367*	12 .9626*
14 .9353*	15 .9342*	14 .9438*	15 .9284*	14 .9412*
15 .9251*	16 .9533*	15 .9397*	16 .9304*	15 .9159*<-
16 .9420*	17 .9561*	16 .9503*	17 .9184*<-	16 .9516*
17 .9390*	18 .9113*<-	17 .9497*	18 .9125*<-	17 .9491*
18 .9191*<-	19 .9016*<-	18 .9327*	19 .9067*<-	18 .9168*<-
19 .9191*<-	20 .9024*<-	19 .9320*	20 .9096*<-	19 .9208*<-
20 .9250*	21 .9522*	20 .9376*	21 .9115*<-	20 .9289*
21 .9256*	22 .9529*	21 .9435*	22 .9130*<-	21 .9429*
22 .9240*<-	23 .9328*	22 .9439*	23 .9190*<-	22 .9435*
23 .8999*<-	24 .9400*	23 .9303*	24 .9160*<-	23 .9177*<-
24 .8771*<-	25 .9563*	24 .9271*	25 .9438*	24 .9292*
25 .8081*<-	26 .9374*	25 .9223*<-	26 .9249*<-	25 .9499*
26 .7877*<-	29 .9547*	26 .9032*<-	27 .9704*	26 .9310*
27 .7835*<-	30 .9426*	30 .9630*	29 .9495*	27 .9719*
29 .7630*<-			30 .9374*	29 .9510*
30 .7518*<-				30 .9389*
* violating quantities (base-case limits): 109 cases <- violating quantities (contingency-case limits): 29 cases				
Co-ordination Problem : base case intact system = { 1, 1, 1, 1, 1}				
29 .9259* 30 .9164*<-	10 1.1052*<-			
* violating quantities (base-case limits): 3 cases <- violating quantities (contingency-case limits): 2 cases				
Co-ordination Problem : Contingency 35 = { .749 , 1, 1, 1, 1 }				
25 .9685* 26 .9499* 27 .9452* 29 .9235*<- 27 .9109*<-				
* violating quantities (base-case limits): 5 cases <- violating quantities (contingency-case limits): 2 cases				

The intermediate results of the application of the preventive control strategy can be resumed as follows:

1st iteration:

Subsystem selection:- The second criteria for selection of the sub-system was used. The partition of the control vector, using the second criteria for selection of subsystems, yields

$$[u^{36}]=\begin{bmatrix}V_8\\T_{11}\end{bmatrix},\quad [u^{25}]=\begin{bmatrix}V_{13}\\T_{15}\end{bmatrix},\quad [u^{35}]=\begin{bmatrix}T_{12}\\T_{36}\end{bmatrix},\quad [u^{14}]=\begin{bmatrix}V_5\\V_{11}\end{bmatrix},\quad [u^{18}]=\begin{bmatrix}V_1\\V_2\end{bmatrix}$$

Subsystem Optimisation:- The results of the optimisation of each subsystem are summed up in Table 7.9 below

Table 7.9 Subsystem Optimisation
IEEE 30-bus test system

Subsystem	Cont.36	Cont.25	Cont.35	Cont.14	Cont.18
$\frac{OF\ (final)}{OF\ (initial)}$	17.9%	3.52%	1.41%	0%	0%
No. of iterations	2	3	3	3	3
Proposed Adjustment $[\Delta u^k]$	$\begin{bmatrix}.0402\\.1562\end{bmatrix}$	$\begin{bmatrix}.1000\\.0340\end{bmatrix}$	$\begin{bmatrix}.1588\\.0307\end{bmatrix}$	$\begin{bmatrix}.0162\\.0076\end{bmatrix}$	$\begin{bmatrix}.0937\\.0816\end{bmatrix}$

Coordination Problem:- The first step of the coordination problem consists of checking the viability of readjustment in the control vector in the base case intact system. The results showed no violations, that is,

$$\alpha^* = \{\ 1\ ,\ 1\ ,\ 1\ ,\ 1\ ,\ 1\ \}$$

The second step consists in verifying if the proposed adjustments of the control variables cause new violations in some of the subsystems. This step showed that the proposed adjustment would cause a constraint violation in contingency 25 (V_{10}= 1.1052; See

Table 7.8). Therefore, the linearized constraint 10 of contingency 25 had to be included in the coordination problem. With this additional constraint the solution became

$$\alpha^{*} = \{\ .749\ ,\ 1,\ 1,\ 1,\ 1\ \}$$

which, yields the update in the control variables.

$$[u^{36}]^{new}=[\ u^{36}]^{old}+\ .749[\Delta u^{36}]$$
$$[u^{25}]^{new}=[\ u^{25}]^{old}+\ 1.00[\Delta u^{25}]$$
$$[u^{35}]^{new}=[\ u^{35}]^{old}+\ 1.00[\Delta u^{35}]$$
$$[u^{14}]^{new}=[\ u^{14}]^{old}+\ 1.00[\Delta u^{14}]$$
$$[u^{18}]^{new}=[\ u^{18}]^{old}+\ 1.00[\Delta u^{18}]$$

2nd iteration:

The results of the optimisation of contingency 36 reduced the objective function to zero and gave the proposal of adjustment on the control vector below, while for the other contingencies all components of the variations on the control vector were zero.

$$[\Delta u^{36}]=\begin{bmatrix} .0314 \\ .0029 \end{bmatrix}$$

The solution of the coordination problem showed that the proposal $[\Delta u^{36}]$ was acceptable for the base case intact system, but caused new violations in contingencies 35, 25 and 18.
The control vector $[\Delta u^{36}]$ was then seen as a corrective strategy for contingency 36.

The system was thus made 4-preventive secure and 1-corrective secure. In addition, the procedure yielded the buses for the other contingencies which prevent the implementation of the preventive control for contingency 36. These buses and the corresponding non-zero Lagrange multipliers are:

Contingency 25 buses = {10,17,21,22}

λ_{10}=.1245 λ_{17}=.1120 λ_{21}= .1086 λ_{22}=.1077

Contingency 35 buses = {10,17,21,22}

λ_{10}=.1174 λ_{17}=.1069 λ_{21}= .1037 λ_{22}=.1035

Contingency 18 bus = {10}

λ_{10}=.1070

Therefore, the adjustments in the control variables to remove the violations in contingency 36 would cause overvoltage in the other contingencies. Note that the new 4-preventive state is also a more secure state for contingency 36 than the original state. With the new settings of controls, in the event of contingency 36, the voltage infeasibilities are much less than on the initial state. Furthermore, the readjustment of only 2 controls would remove these two small violations. The final scheduling is shown in Table 7.10.

Table 7.10 Security Enhancement Results

Control Variables	Control Variables Settings (pu) Initial	Final 4-Preventive	Final 1-Corrective
V_1	1.000	1.0937	
V_2	1.000	1.0816	
V_5	1.000	1.0162	
V_8	1.000	1.0301	→ 1.0615
V_{11}	1.000	1.0076	
V_{13}	1.000	1.1000	
T_{11}	.978	1.0950	→ 1.0980
T_{12}	.968	1.1268	
T_{15}	.932	.9660	
T_{36}	.968	.9987	
No.of uncovered Contingencies	38	1	0
No.of violations base case	19	0	-
No. of violations in the WCL	90	2	0
Lowest |V|	.7518	.9109	-
Losses MW	8.24	7.56	-

As can be seen in Table 7.11, a new contingency screening shows that, in fact, security was not only enhanced for the contingency list but for all the single contingencies. Table 7.12 shows the complete load flow solution for the final state.

Comparison of the results

D. S. Sun and R. Shoults [152], presented a method for calculating the preventive var dispatch, whereby using several penalty functions contingency constraints are included in a steepest descent algorithm in a two stage process. The first stage, called

Table 7.11 Performance Index (After Security Enhancement)
IEEE 30-bus test system

Cont. No.	from	to	Performance Index Voltage J_{v1}	Voltage $J_{v\infty}$	var output J_{q1}	var output $J_{q\infty}$	No.of violations V	No.of violations var
base	case		.000E+00	.000E+00	.000E+00	.000E+00	0	0
1	1	2	.000E+00	.000E+00	.000E+00	.000E+00	0	0
2	1	3	.000E+00	.000E+00	.000E+00	.000E+00	0	0
3	2	4	.000E+00	.000E+00	.000E+00	.000E+00	0	0
4	3	4	.000E+00	.000E+00	.000E+00	.000E+00	0	0
5	2	5	.000E+00	.000E+00	.000E+00	.000E+00	0	0
6	2	6	.000E+00	.000E+00	.000E+00	.000E+00	0	0
7	4	6	.000E+00	.000E+00	.000E+00	.000E+00	0	0
8	5	7	.000E+00	.000E+00	.000E+00	.000E+00	0	0
9	6	7	.000E+00	.000E+00	.105E-01	.105E-01	0	1
10	6	8	.000E+00	.000E+00	.119E-01	.119E-01	0	1
11	6	9	.000E+00	.000E+00	.000E+00	.000E+00	0	0
12	6	10	.000E+00	.000E+00	.000E+00	.000E+00	0	0
*13	9	11	-.111E+01	-.111E+01	-.111E+01	-.111E+01		
14	9	10	.000E+00	.000E+00	.382E-01	.382E-01	0	1
15	4	12	.000E+00	.000E+00	.122E-01	.122E-01	0	1
*16	12	13	-.111E+01	-.111E+01	-.111E+01	-.111E+01		
17	12	14	.000E+00	.000E+00	.000E+00	.000E+00	0	0
18	12	15	.000E+00	.000E+00	.000E+00	.000E+00	0	0
19	12	16	.000E+00	.000E+00	.178E-01	.178E-01	0	1
20	14	15	.000E+00	.000E+00	.194E-03	.194E-03	0	1
21	16	17	.000E+00	.000E+00	.154E-01	.154E-01	0	1
22	15	18	.000E+00	.000E+00	.109E-01	.109E-01	0	1
23	18	19	.000E+00	.000E+00	.692E-02	.692E-02	0	1
24	19	20	.000E+00	.000E+00	.685E-02	.685E-02	0	1
25	10	20	.000E+00	.000E+00	.150E-01	.150E-01	0	1
26	10	17	.000E+00	.000E+00	.227E-01	.227E-01	0	1
27	10	21	.000E+00	.000E+00	.492E-02	.492E-02	0	1
28	10	22	.000E+00	.000E+00	.203E-02	.203E-02	0	1
29	21	22	.000E+00	.000E+00	.998E-04	.998E-04	0	1
30	15	23	.000E+00	.000E+00	.180E-02	.180E-02	0	1
31	22	24	.000E+00	.000E+00	.172E-01	.172E-01	0	1
32	23	24	.000E+00	.000E+00	.234E-02	.234E-02	0	1
33	24	25	.000E+00	.000E+00	.805E-02	.805E-02	0	1
*34	25	26	-.111E+01	-.111E+01	-.111E+01	-.111E+01		
35	25	27	.000E+00	.000E+00	.711E-02	.711E-02	0	1
36	27	28	.163E+00	.580E-01	.000E+00	.000E+00	5	0
37	27	29	.000E+00	.000E+00	.000E+00	.000E+00	0	0
38	27	30	.106E-02	.106E-02	.121E-02	.121E-02	1	1
39	29	30	.000E+00	.000E+00	.000E+00	.000E+00	0	0
40	8	28	.000E+00	.000E+00	.268E-03	.268E-03	0	1
41	6	28	.000E+00	.000E+00	.381E-03	.381E-03	0	1

* Network splitting

Table 7.12 Final Results
(WCL 4-Preventive/1-Corrective Secure)
IEEE 30 bus test system

Bus No.	TY	Voltage Mag.	Voltage Ang.	Shunt Cap/Rea	Generation MW	Generation Mvar	Load MW	Load Mvar
1	SW	1.0937	.00	.00	139.00	2.39	.00	.00
2	PV	1.0816	-2.61	.00	57.56	69.78	21.70	12.70
3	PQ	1.0588	-4.09	.00	.00	.00	2.40	1.20
4	PQ	1.0508	-4.89	.00	.00	.00	7.60	1.60
5	PV	1.0162	-8.03	.00	24.56	3.67	94.20	19.00
6	PQ	1.0327	-5.58	.00	.00	.00	.00	.00
7	PQ	1.0179	-7.10	.00	.00	.00	22.80	10.90
8	PV	1.0301	-5.51	.00	35.00	20.66	30.00	30.00
9	PQ	1.0962	-7.29	.00	.00	.00	.00	.00
10	PQ	1.0894	-9.19	22.55	.00	.00	5.80	2.00
11	PV	1.0764	-5.48	.00	17.93	-9.96	.00	.00
12	PQ	1.0647	-8.10	.00	.00	.00	11.20	7.50
13	PV	1.1000	-6.94	.00	16.91	27.90	.00	.00
14	PQ	1.0540	-8.99	.00	.00	.00	6.20	1.60
15	PQ	1.0531	-9.17	.00	.00	.00	8.20	2.50
16	PQ	1.0680	-8.85	.00	.00	.00	3.50	1.80
17	PQ	1.0778	-9.29	.00	.00	.00	9.00	5.80
18	PQ	1.0541	-9.84	.00	.00	.00	3.20	.90
19	PQ	1.0577	-10.05	.00	.00	.00	9.50	3.40
20	PQ	1.0648	-9.89	.00	.00	.00	2.20	.70
21	PQ	1.0744	-9.61	.00	.00	.00	17.50	11.20
22	PQ	1.0740	-9.60	.00	.00	.00	.00	.00
23	PQ	1.0482	-9.63	.00	.00	.00	3.20	1.60
24	PQ	1.0498	-9.91	4.74	.00	.00	8.70	6.70
25	PQ	1.0308	-9.65	.00	.00	.00	.00	.00
26	PQ	1.0133	-10.06	.00	.00	.00	3.50	2.30
27	PQ	1.0274	-9.25	.00	.00	.00	.00	.00
28	PQ	1.0301	-5.95	.00	.00	.00	.00	.00
29	PQ	1.0077	-10.47	.00	.00	.00	2.40	.90
30	PQ	.9963	-11.35	.00	.00	.00	10.60	1.90

SYSTEM GENERATION: 290.96 MW 141.72 Mvar
SYSTEM LOAD: 283.40 MW 126.20 Mvar

FINAL TAP SETTINGS:

No.	TAP
11	109.51
12	112.68
15	96.60
36	99.87

rough action calculation, includes some of these penalty functions (global security index) in the minimisation process. The second stage, called fine tune calculations, brings more penalty functions to the objective and the optimisation process continues trying to reduce the objective function. There are neither coordination nor interaction between the two stages. Within each stage the classical steepest descent cycling is performed with increasing in the penalty coefficients after some pre-fixed number of iterations. The only difference between stages is the objective function, which, in the second stage, includes minimisation of transmission losses. It was recognized that the final results may still have violations. The reported results of a preventive var dispatch for three contingency cases on the IEEE 30-bus test system allow for some comparison with the new methodology of this thesis. The reported results are as follows:-

The pre-selected contingency set consisted of contingencies 2, 7 and 11. The transmission losses were optimised for the intact system, the optimal value reported being 9.283 MW. This optimised base case, which contains no violation, was used as starting point for the preventive dispatch. The impacts of the contingencies included 1 violation for contingency 2, 2 violations for contingency 7 and 2 violations for contingency 11. At solution there were no violations. The active transmission losses were 9.365 MW for the final preventive secure state.

Although, in the test of the methodology of this thesis a flat start point was adopted, contingencies 2,7 and 11 were found to be of low risk (See Table 4.1) if compared with the harmful set enforced in the previous section. Furthermore, for the optimised base case of Table 5.1aII, contingencies 2, 7 and 11 presented no violations at

all. However, in considering the flat start, it can be seen from Table 7.11, that the new method had enforced contingencies 2, 7 and 11 as well. Finally, it is interesting to notice that although transmission losses was not an explicit objective in the new method, both the results for the optimal base case and for the 4-preventive cases are, respectively, 23.4% and 19.3% lower than those reported in reference [152].

7.7 CONCLUSIONS

A new methodology for solving the preventive security-constrained var dispatch problem has been presented.

Despite being a new way of approaching the problem, the resulting methodology, rather than revolutionary is integrally evolutionary, consequently it can be implemented as an extension of the existing software in control centers. The procedure at each step for on-line implementation has been explained. The new methodology is also appropriated to study var/voltage requirements in a second step, after traditional linear active power studies, for which usually DC load flow approximations with 1.0 p.u. for all voltage magnitudes are employed.

CHAPTER 8

CONCLUSIONS

A global methodology for steady-state reactive power management and voltage control has been presented. The analysis of commonalities of current planning and operational techniques enable critical subject areas to be identified and a new framework to be designed. The analysis reveals that many electric utilities do not currently have advanced tools for efficient and effective var management and voltage control and there is interest in acquiring such competence. Steady-state security is the primary aim to be achieved. The innovative formulations for the var/voltage problems and the improved solution methods derived effectively meet these needs of the electric utility industry.

Despite being a new way of approaching the problem, the resulting methodology, rather than being revolutionary, is integrally evolutionary. Consequently it can easily be implemented in existing control centres. The formal procedure for integrating the methodology within modern control centres has been explained, including development of detailed flow charts and solution methods.

The original contributions of this thesis include:

1. The identification of the needs for research and development in the subject area;
2. The development of a formal automatic procedure for analysing the present system data from a var/voltage viewpoint, providing corrective and preventive strategy whilst optimising the system. A decomposition-coordination scheme has been conceived in order

to take advantage of the special structure of the problem, well established concepts have been examined and new ones derived, such as the var/voltage security framework, the concept of potential control, the concept of (N-K)preventive/(K)corrective, the multiplier α in the decomposition-coordination problem, the need for coordinated solutions, etc.

3. Improvements have been achieved in the area of decoupled load flows for ill-conditioned systems, such as networks with high r/x ratios and stringent loadings. The original achievements include monitoring of the var reserve and of the static stability limits, consideration of parallel lines, better modelling of the slack busbar, efficient enforcement of limits, uniform data structure resulting in compact program code and fast execution times.

4. Physical interpretation of the CRIC transformation, and derivation of techniques to recover sparsity when obtaining solutions that use the CRIC transformed Jacobian matrix.

5. In-depth examination of existing new hypotheses and methods for the var contingency selection problem and eventual development of an original compensation method for the reactive power. The new method is fast and accurate. A better model of the Q-V network is achieved by the implicit representation of the voltage angles into the model. The monitoring of voltage limits and var source output allows for the detection of both local and system-wide effects of the contingencies.

6. Original developments in the conjugate-gradient technique for optimal power flows include:

   i) New formulation of the problem involving fewer variables than the existing formulations

ii) Better network modelling which allows for the consideration of the slack busbar, for the implicit representation of the voltage angles, and for keeping the active power balance throughout the solution process.

iii) An original hierarchical adaptive technique for the implementation of the inequality functions (quite possibly a breakthrough).

iv) Analytic determination of the optimum step length, (eliminating the need for search and evaluations of the objective function).

v) Formulation of the objective function as a pure quadratic form, and therefore guaranteeing theoretically that the method converges in one iteration (in practice a few iterations suffice).

7. Innovative methodology for the formulation and solution of the reactive power constrained dispatch problem: the formulation of the decomposition-coordination approach, and the development of a technique for determination of the weak points in the base case system which would prevent the enforcement of the preventive solution.

8. Theoretical and practical developments in the methodology of solution of the var dispatch and expansion problems, with the extension of the economic dispatching method of the Lagrange multipliers' interpretation to the specific var/voltage problems of concern.

9. Development of procedures for sensitivity analysis, including techniques for determination of the effectiveness of the control variables in contingency situations.

10. Development of means for efficient computational implementation

of all the above mentioned techniques. The application of the above methodology is demonstrated by numerical testing with power systems of different sizes and characteristics.

11. Development of a prototype software package for microcomputers.

The microcomputer implementation of the prototype software package has proved to be a fundamental tool for achieving improvements in computer program performance. These improvements have permitted the implementation of sophisticated optimal power flow techniques in personal computers, making it possible to use them for the planning of realistic systems. The package is now being used for teaching, training and research. Apart from the programs, the package has already been used for teaching, training and research as well as a shell for further developments. So far, three undergraduate projects have used the package and several researchers have used the programs, including use for the development of expert systems. It has attracted the interest of various researchers who have visited the Group, including a visitor from the PIE project-Spain, who was impressed by the performance of the optimal load flow.

One of the goals of the E&PSG package is to provide an efficient way of reproducing realistic operational problems in the classroom environment. The optimisation of the critical steps in the classical procedure for solving an engineering problem has enabled this goal to be achieved. The result is that a better understanding and training can be realised in a shorter interval of time and the student can deal with realistic problems and explore further the concepts involved.

<u>The potential for further work includes the following items</u>:

1) The incorporation of a load-forecast program into the

security-constrained var dispatch program, so that operating conditions in the system can be investigated ahead of time. For instance, allowing for the system operator to simulate operational conditions in a time range of a few minutes to 24 hours ahead.

2) It is possible to expand the decomposition-coordination scheme in such a way that each subsystem optimisation becomes a coordination problem for lower level problems. So the approach can be extended to deal with second and higher order contingencies.

3) The problem of reactive power expansion planning on a multi-year basis can be incorporated in the var expansion planning problem.

4) As mentioned before, there is room for expert system applications. For example, it is conceivable that an expert system can analyse the Lagrange multipliers and formulate the second level problems on the var expansion problem. It can also be envisaged that an expert system can select the worst-case-list of contingencies.

5) The problems of network islanding and incorporation of a dynamic stability performance index are always worth having in perspective for incorporation in the methodology, but these are very different subjects.

6) Finally, there is room for improvement in the area of selection of effective control, although it seems that this area will always be an open area, since it is dependent on operational procedures and policies adopted, as well as being dependent on the particular network being studied.

Regarding the computational implementations of the various routines, it is believed that all individual programs are already at a competent level of performance and there is little room for improvement resulting in better programming implementation. There is, however, room for improvement in the man-machine-interface (graphics displays and ergonomics), and for the incorporation of an efficient data base system. The development of a customised LP program is also highly recommended.

REFERENCES

1. T.E. DyLiacco "System security: the computer's role," IEEE Spectrum, vol. 15, June 1978, pp. 43-50.

2. S.N. Talukdar, and F.F. Wu, "Computer-Aided Dispatch for Electric Power Systems," Proc. of the IEEE, vol. 69, 1981, pp. 1212-1231.

3. N.S. Van Nielen, "New Energy Management System for the Dutch Power Pool," IEEE PES Winter Meeting, paper 86 WM 101-0, NY, February 2-7,1986.

4. F. Mcdyer and K.Herger,"The New National Control Centre, Ireland," IEEE PES Winter Meeting, paper 86 WM 083-0, NY, 2-7 February 2-7, 1986.

5. J. Bistrom and K. Lindstrom, "The Finnish Power System Control Centre," IEEE PES Winter Meeting, paper 86 WM 047-5, NY, February 2-7, 1986.

6. C. W. Griffith, C.W. Heubach and R.E. Smith,"Gulf States Utilities' Energy System Using Software Management Support Tools, Advanced Applications, and Modern Hardware Architecture. IEEE PICA Conf. Proc., Montreal, Quebec, May 18-22, 1987.

7. F. J. Trefny, D.P. Gross and B.F. Wollenberg, "Integration of an Operations Information System into an Energy and Control System," IEEE PICA Conf. Proc., Montreal, Quebec, Canada, May 18-22, 1987.

8. H. Beltran et al.,"Highlights of the Guri Hydroelectric Plant Computer Control System," IEEE PICA Conf. Proc., Montreal, Quebec, Canada, May 18-22, 1987.

9. J. Wrubel and R. Hoffman, "The New Energy Management System at PSE&G, "IEEE PICA Conf. Proc., Montreal, Quebec, Canada, May 18-22, 1987.

10. N.K. Tripathi, C.A. Martinez and S.A. Nirenberg, "Reactive Switching Simulation at Florida Power and Light System Control Center, IEEE Trans. on Power App. and Systems, vol. PAS-104, Sept 1985, pp. 3482-3485.

11. J. Feinstein, J. Tscherne and M. Koenig, "Reactive Load and Reserve Calculation in Real Time Computer Control System," IEEE PICA Conf. Proc., Montreal, Quebec, Canada, May 18-22, 1987.

12. J.L. Carpentier, "Towards a Secure and Optimal Automatic Operation of Power Systems," IEEE PICA Conf. Proc., Montreal, Quebec, Canada, May 18-22, 1987.

13. W.L. Snyder et al. (Var Management Task Force Report) "Var Management - Problem Recognition and Control," IEEE Trans. on Power App. and Systems, vol. PAS-103, Aug 1984, pp. 2108-2116.

14. T.H. Fox et al.,"An Approach to Real-Time Reactive Monitoring for System Security," IEEE Trans. on Power App. and Systems, vol. PAS-102, Nov 1983, pp. 3687-3692.

15. L. Franchi et al.,"Optimal Short-Term Reactive Scheduling for a Large Power System," PSCC Conf. Proc., Lausanne, July 1981, pp. 319-326.

16. R.P. Schulte et al. (Systems Operations Subcommittee, Current Operational Problems Working Group Report) "Survey Report on Current Operational Problems," IEEE Trans. Power App. and Systems, vol.PAS-104, Sept 1985, pp. 1315-1320.

17. W.A. Johnson et al. (Systems Operations Subcommittee, Current Operational Problems Working Group Report) "EHV Operating Problems Associated with Reactive Control," IEEE Trans. Power App. and Systems, vol.PAS-100, 1981, pp. 1376-1381.

18. J. Svoen et al. (Power System Operation and Control Committee, Working Group Report), "Short-term scheduling - Present practices and trends," CIGRE, Electra, No. 106, 1986, pp. 64-100.

19. J. F. Christensen et al. (Power System Analysis and Techniques Committee, Working Group 38.01 Task Force 03), "Planning against voltage collapse," CIGRE, Electra, No. 111, 1986, pp. 55-75.

20. W.R. Lachs, "Insecure System Reactive Power Balance Analysis and Counter Measures," IEEE Trans. on Power App. and Systems, vol. PAS-104, Sept 1985, pp. 2413-2419.

21. M. R. Allison, "Future Voltage Control Requirements in the CEGB," IEE 2nd PSMC Conf., Durham, U.K.

22. J. S.Thorp et al.,"An Optimal Secondary Voltage-VAR Control Technique," Automatica, vol. 22, 1986, pp. 217-221.

23. J.A. Jardini and I.A. Erinmez, (Power System Analysis and Techniques Committee, Working Group 38.01 Task Force 01), "Reactive compensation for a long distance transmission system - Methodology and practice adopted by different countries in a practical case," CIGRE, Electra, No. 105, 1986, pp. 37-52.

24. N. FlatabO,(Power System Analysis and Techniques, Working Group 38.01 Task Force No. 1), "Results of an international reactive compensation exercise on a meshed network example," CIGRE, Electra, No. 105, 1986, pp. 12-18.

25. B. E. Murray and W.S. Farrant, "The Role of On-line Security Assessment in Operation," CIGRE-IFAC Symp. on Control Applications for Power System Security, paper 103-04, Florence, Italy, 1983.

26. W. F. Tinney, "Mathematical Challenges in Power System Planning," Proc. of EPRI/SIAM Conf. on Electrical Power Problems: the Mathematical Challenge, Seattle, 1980, pp. 3-20.

27. J.W. Lamont, "An Introduction and Overview of Future Power System Computing Requirements: A Panel Discussion," Proc. of EPRI/SIAM Conf. on Electrical Power Problems: the Mathematical Challenge, Seattle, 1980, pp. 515-531.

28. J. Carpentier, "CRIC, a New Active Reactive Decoupling Process in Load Flows, Optimal Power Flows and System Control," Proc. of IFAC Conf. on Power Systems and Power Plan Control, Beijing, 1986, pp. 65-70.

29. V. Arcidiacono, "Automatic Voltage and Reactive Power Control in Transmission Systems," CIGRE-IFAC Symp. on Control Applications for Power System Security, Survey Paper, Florence, Italy, 1983.

30. A. Garzillo et al., "Some Reactive Power Control Procedure in the ENEL Production and Transmission System," CIGRE-IFAC Symp. on Control Applications for Power System Security, paper 208-05, Florence, Italy, 1983.

31. A. Canepa et al., "Voltage Regulation via Automatic Load Tap Changing Transformers: Evaluation of Voltage Stability Conditions," Electric Power System Research, 1987, pp.99-107.

32. M. Ernoult et al., "Reactive Power Compensation and Voltage Control on the French EHV System: Present Situation and Prospects, "CIGRE-IFAC Symp. on Control Applications for Power System Security, paper Pref. Subj. 1, Florence, Italy, 1983.

33. O.I. Elgerd, Electric Energy System Theory: An Introduction, McGraw-Hill International Book Co., Japan, 2nd ed., 1983.

34. F.F. Wu and T.E. DyLiacco, Modern Power System Control Centers: Pre-symposium Short Course, IEEE International Symp. on Circuits and Systems- ISCA's 88, Helsinki, Finland, 1988.

35. B. Stott, O. Alsac and A.J. Monticelli, "Security Analysis and Optimisation," Proc. of the IEEE, vol. 75, No. 12, Dec. 1987.

36. J.L. Carpentier, "Differential Injections Method A General Method for Secure and Optimal Load Flows," IEEE PICA Conf. Proc., 1973, pp. 255-262.

37. L.D.B. Terra and M.J. Short, "Contingency-Constrained Reactive Power and Scheduling," Proc. of IEEE ISCA's 88, vol. 1, Helsinki, Finland, June 7-9, pp.659-663.

38. K. Behnam-Guilani, "Fast Decoupled Load Flow: The Hybrid Model," IEEE PICA Conf. Proc., Montreal, Quebec, Canada, May 18-22, 1987, pp 354-359.

39. Y. Tamura, H. Mori and S. Iwamoto, "Fast Computation Algorithm for 2nd-Order AC Load Flow with Application to Ill-Conditioned System," International Journal of Electrical Power & Energy Systems, vol. 3, Oct 1981, pp.179-186.

40. S. Iwamoto and Y. Tamura, "A Load Flow Calculation Method for Ill-Conditioned Power Systems," IEEE Trans. on Power App. and Systems, vol. PAS-100, April 1981, pp. 1737-1743.

41. F.F. Wu, "Theoretical Study of the Convergence of the Fast Decoupled Load Flow," IEEE Trans. on Power App. and Systems, vol. PAS-96, Jan/Feb 1977.

42. T.E. DyLiacco, discussion of reference 41.

43. B. Stott, discussion of reference 41.

44. S. Deckman, A. Pizzolante, A.Monticelli, B. Stott and O. Alsac, "Numerical Testing of Power System Load Flow Equivalents," IEEE Trans. on Power App. and Systems, vol. PAS-99, Nov/Dec 1980.

45. P.H. Haley and M. Ayres, "Super Decoupled Load Flow with Distributed Slack Bus," IEEE Trans. on Power App. and Systems, vol. PAS-104, No. 1, Jan 1985, pp.104-113.

46. D. Rajicic and A. Bose, "A Modification to the Fast Decoupled Power Flow for Networks with High R/X Ratios," IEEE Trans. on Power Systems, vol. 3, No. 2, May 1988, pp. 743-746.

47. W.F. Tinney and C.E. Hart, "Power Flow Solution by Newton's Method," IEEE Trans. on Power App. and Systems, vol. PAS-86, Nov 1967, pp. 1449-1446.

48. B. Stott, "Decoupled Newton Load Flow," IEEE Trans. on Power App. and Systems, vol. PAS-91, Sept/Oct 1972, pp. 1955-1959.

49. B. Stott and O. Alsac, "Fast Decoupled Load Flow," IEEE Trans. on Power App. and Systems, vol. PAS-93, 1974, pp. 859-869.

50. J.L. Carpentier, "Optimal Power Flows: Uses, Methods and Developments," IFAC Symp. on Pla. and Op., Rio de Janeiro, Invited Paper, 1985, pp. 11-21.

51. J. B. Ward and H.W. Hale, "Digital Computer Solution of Power Flow Problems," IEEE Trans. on Power App. and Systems, vol. PAS-75, June 1956, pp. 398-404.

52. D.E. Knuth, Fundamental Algorithms, vol. 1 of The Art of Computer Programming, Addison-Wesley, Reading, Massachusetts, 2nd ed., 1973.

53. M. Morozowiski Fo., Sparse Matrix in Power System Networks, LTC ed., Rio de Janeiro, Brasil, 1973. (In Portuguese)

54. H.E. Brown, "Solution of Large Networks by Matrix Methods, John Wiley & Sons Inc., NY, 1975.

55. NAG Handbook for the NAG Workstation Library, Release 1, 1986 (NAG Central Office, 256 Banbury Road, Oxford OX2 7DE, UK)

56. IMSL Library Reference Manual, 1980 (IMSL Inc, 7500 Bellaire Boulevard, Houston TX 77036)

57. W.H. Press, B.P. Flannery, S.A. Teukolsky and W.T. Vetterling, Numerical Recipes The Art of Scientific Computing, Cambridge University Press, London, 1986.

58. W. F. Tinney, "Direct Solutions of Sparse Network Equations by Optimally Ordered Triangular Factorization," Proc. of the IEEE, vol. 55, Nov 1967, pp.1801-1809.

59. W. F. Tinney, W.L. Powell and J.W.Walker, "Programming of Sparsity-Directed Ordering Schemes," Proc. of the 5th PSCC, vol. 1, paper 3.1/2, 1975.

60. R. Betancourt, "An Efficient Heuristic Ordering for Partial Refactorization," IEEE Trans. on Power Systems, vol. 3, No. 3, Aug 1988, pp.1181-1187.

61. S. Chan and V. Brandwajn, "Adjusted Solutions in Fast Decoupled Power Flow," IEEE PICA Conf. Proc.,Montreal, Quebec, Canada, May 18-22, 1987, pp. 18-22.

62. S. Chan and V. Brandwajn, "Partial Matrix Refactorization," IEEE Trans. on Power Systems, vol. PWRS-1, No.1, Feb 1986.

63. E.C. Housos, G.D. Irisarri, L. Radu and A.M. Sasson, discussion of reference 79.

64. A. Monticelli, Load Flow in Power System Networks, Ed. Edgard Blucher, Sao Paulo, Brasil, 1983. (In Portuguese)

65. A. Brameller, R.N. Allan and Y.M.Haman, Sparsity, Its Practical Application to System Analysis, Pitman, London, 1976.

66. F. Albuyeh, A. Bose and B. Heath, "Reactive Power Considerations in Automatic Contingency Selection," IEEE Trans. on Power App. and Systems, vol. PAS-101, Jan 1982, pp. 107-112.

67. J. Zaborszki, K.W. Whang, K. Prasad, "Fast Contingency Evaluation Using Concentric Relaxation," IEEE Trans. on Power App. and Systems, vol. PAS-99, Jan/Feb 1980, pp.28-36.

68. M.G. Lauby, T.A. Mikolinnas and N.D. Reppen, "Contingency Selection of Branch Outages Causing Voltage Problems," IEEE Trans. on Power App. and Systems, vol. PAS-102, Dec 1983, pp.3899-3904.

69. K. Nara, K. Tanaka, H. Kodama, R.R. Shoults M.S. Chen, P. Van Olinda and D. Bertagnolli, "On-Line Contingency Selection for Voltage Security Analysis," IEEE Trans. on Power App. and Systems, vol. PAS-104, April 1985, pp.847-856.

70. G.C. Ejebe, H.P. Van Meeteren, B.F.Wollenberg, "Fast Contingency Screening and Evaluation for Voltage Security Analysis," IEEE Trans. on Power Systems, vol. 3, Nov 1988, pp. 1582-1590.

71. S.N. Talukdar, R.D. Christie, "Assessing Security Assessment," Proc. of the IEEE ISCA's 88, vol. 2, Helsinki, June 7-9, 1988, pp.1879-1882.

72. R.D. Christie and S.N. Talukdar, "Expert Systems for On Line Security Assessment A Preliminary Design," IEEE PICA Conf. Proc., Montreal, Quebec, Canada, May 18-22, 1987, pp. 114-119.

73. D.J. Sobajic, "An Artificial Intelligence System for Power System Contingency Screening," IEEE PICA Conf. Proc., Montreal Quebec, Canada, May 18-22, 1987, pp. 107-113.

74. N. FlatabO et al. "Evaluation of Reactive Power Reserves in Transmission Systems, IFAC Conf. Proc., Rio de Janeiro, Brazil, pp. 475-482.

75. I. Dabbaghchi and G. Irisarri, "AEP Automatic Contingency Selector: Branch Outage Impacts on Load Bus Voltage Profile," IEEE Trans. on Power Systems, vol. PWRS-1, May 1986, pp. 37-45.

76. T.F. Halpin, R. Fischl, R. Fink, "Analysis of Automatic Contingency Selection ALgorithms," IEEE Trans. on Power App. and Systems, vol. PAS-103, May 1984, pp.938-945.

77. G.C. Ejebe and B.F. Wollenberg, "Automatic Contingency Selection," IEEE Trans. on Power App. and Systems, vol. PAS-98, Jan/Feb 1979, pp. 97-109.

78. T.A. Mikolinnas and B.F. Wollenberg, "An Advanced Contingency Selection Algorithm," IEEE Trans. on Power App. and Systems, vol. PAS-100, Feb 1981, pp.608-617.

79. O. Alsac, B. Stott and W.F. Tinney, "Sparsity-Oriented Compensation Methods for Modified Network Solutions," IEEE Trans. on Power App. and Systems, vol. PAS-102, May 1983.

80. P.W. Aitchison, J.L. Pereira and A. Brameller, "Extensions and Singularities in Compensated Network Solution Applicable to Security Monitoring," IEE Proceedings, vol. 134, Pt.C, No. 2, March 1987.

81. V. Brandwajn, "Exact Bounding Method for Linear Contingency Analysis," paper 86 SM 338-8, IEEE PES Summer Meeting, Mexico, 1986.

82. F.D. Galiana, "Bound Estimates of the Severity of Line Outages in Power System Contingency Analysis and Ranking," IEEE Trans. on Power App. and Systems, vol PAS-103, Sept 1984, pp. 2612-2624.

83. A. Bose and Y. Chen, discussion of reference 70.

84. G.D. Irisarri, D. Levner and A.M. Sasson, "Automatic Contingency Selection for On-Line Contingency Analysis - Real Time Tests," IEEE Trans. on Power App. and Systems, vol. PAS-98, Sept/Oct 1979, pp. 1552-1559.

85. R.G. Wasley and M. Daneshdoost, "Identification and Ranking of Critical Contingencies in Dependent Variable Space," IEEE Trans. on Power App. and Systems, vol. PAS-102, April 1983, pp.881-892.

86. T. Medicherla and S. Rostogi, "A Voltage Criterion Based Contingency Selection Technique," IEEE Trans. on Power App. and Systems, vol PAS-101, Sept 1982, pp.3523-3531.

87. M. Ilic-Spong and A. Phadke, "Redistribution of Reactive Power Flow in Contingency Studies," IEEE PICA Conf. Proc., 1985, pp. 336-344.

88. K. Behnam-Guilani, "Fast Decoupled Load Flow: The Hybrid Model," IEEE Trans. on Power Systems, vol. 3, No. 2, May 1988.

89. Brian Stott, discussion of reference 88.

90. S.K. Chang and V. Brandwajn, discussion of reference 88.

91. W.F. Tinney and V. Brandwajn, "Sparse Vector Methods," IEEE Trans. on Power App. and Systems, vol. PAS-104, No. 2, Feb 1985, pp. 295-301.

92. M.J. Short, Lecture: Voltage and VAR Control, Intercollegiate MSc Course in Electrical Engineering, Course 202, Power System Operation, Computer Monitoring and Control, Imperial College, London, Feb 11, 1986.

93. S.J. Cheng, O.P. Malik and G.S. Hope, "An Expert System for Voltage and Reactive Power Control of a Power System," IEEE Trans. on Power Systems, vol. 3, Nov 1988, pp. 1449-1455.

94. J. Zaborszky, G. Huang and K.W. Lin, "Control of Reactive Power and Voltages in Emergencies," CIGRE Conf., paper 208-01, Florence, 1983.

95. J. Zaborszky, G. Huang and K.W. Lin, "A Textured Model for Computationally Efficient Reactive Power Management, " IEEE Trans. on Power App. and Systems, vol. PAS-104, No. 7, July 1985, pp. 1718-1727.

96. M.O. Mansour and T.M. Abdel-Rahman, "Non-Linear VAR Optimization Using Decomposition and Coordination," IEEE Trans. on Power App. and Systems, vol PAS-103, Feb 1984, pp. 246-255.

97. L. Makela, "Optimal Voltage Level and Reactive Power Control Using an Approximated Sensitivity Matrix," 6th PSCC Conf. Proc., 1978.

98. W.F. Tinney and H.W. Dommel, "Steady-State Sensitivity Analysis," 4th PSCC Conf. Proc., 1972.

99. J. Peschon, D.S. Piercy, W.F. Tinney, O.J. Tveit, "Sensitivity in Power Systems," IEEE Trans. on Power App. and Systems, vol. PAS-88, Aug 1968, pp. 1687-1696.

100. F.C. Aschmoneit, K.H. Ruhose and G.G. Wagner, "Steady- State Sensitivity Analysis for Security Enhancement," 6th PSCC Conf. Proc., 1978.

101. A.M. Pretelt, "Automatic Allocation of Network Capacitors," IEEE Trans. on Power App. and Systems, vol. PAS-90, No. 1, 1971, pp.55-61.

102. H.H. Happ, "Optimal Power Dispatch - A Comprehensive Survey," IEEE Trans. on Power App. and Systems, vol. PAS-93, No. 3, May/June 1977, pp. 841-854.

103. A.M. Sasson and H.M. Merril, "Some Applications of Optimization Techniques to Power Systems Problems," Proc. of the IEEE, vol. 62, No. 7, July 1974, pp. 959- 972.

104. J.M. Layton, "Multivariable Control Theory," Peter Peregrims Ltd (Institution of Electrical Engineers) Southgate House, Stevenage, Herts, SG1 1HQ, England.

105. J. Zaborszky and G. Huang, discussion of reference 96.

106. W.S. Ku, discussion of reference 109.

107. A. Capasso, E. Mariani, C. Sabelli, "On the Objective Functions for Reactive Power Optimisation," IEEE PES Winter Meeting, paper A80-090-1, New York, NY, Feb 3-8, 1980.

108. K.W. Edwin and S. Lemmer, "Central Level Reactive Power Voltage Control, CIGRE Conf. Proc., paper S39-93, Florence , 1983.

109. J. Peschon, D.S. Piercy, W.F. Tinney, O.J. Tveit and M. Cuenod, "Optimum Control of Reactive Power Flow," IEEE Trans. on Power App. and Systems, vol. PAS-87, Jan 1968, pp. 40-48.

110. H. P. Azal and H. Glavitsch, "Optimal Constrained Power Flow Applied to the Swiss Power System, PSCC Conf. Proc., July 1981.

111. R.E. Palmer, R.C. Burchett, H.H. Happ and D.R. Vierath, "Reactive Power Dispatching for Power Systems," IEEE Trans. on Power App. and Systems, vol. PAS-102, Dec 1983, pp. 3905-3909.

112. IEEE VAR Management Working Group Report, "Bibliography on Reactive Power and Voltage Control," IEEE PES Summer Meeting, paper 86 SM 347-9, Mexico, July 20-25, 1986.

113. R.B. Prada, "Optimal Power Flows," Advanced Power Systems: A Short Course, Imperial College, London, Nov 1988.

114. B. Stott, O. Alsac and J.L. Marinho, "The Optimal Power Flow Problem," Proc. of EPRI/SIAM Conf. on Elec. Power Problems: The Mathematical Challenge, Seattle, 1980, pp. 327-351.

115. W.F. Tinney, J.M. Bright, K.D. Demaree and B.A. Hughes, "Some Deficiencies in Optimal Power Flow," IEEE PICA Conf. Proc., Montreal, 1987, pp.164-169.

116. P.E. Gill, W. Murray, M.A. Saunders and M.H. Wright, "Methods for Large-Scale NonLinear Optimization," Proc. of EPRI/SIAM Conf. on Elec. Power Problems: The Mathematical Challenge, Seattle, 1980, pp. 352-377.

117. M. S. Bazarra and C.M. Shetty, Nonlinear Programming, John Wiley and Sons, NY, 1979.

118. P.E. Gill, W. Murray and M.H. Wright, Practical Optimization, Academic Press, NY, 1981.

119. G. Hadley, Nonlinear and Dynamic Programing, Addison Wesley, Reading, Mass., 1964.

120. L.S. Lasdom, Optimization Theory for Large System, Mcmillan, NY, 1970.

121. D.M. Himmelblau, Applied Nonlinear Programming, McGraw- Hill Book Co., NY, 1972.

122. B.A. Murtagh and M.A. Saunders, Minos 5.0 User's Guide, Technical Report Sol 83-20. Dec 1983.

123. N.J. Balu et al., Optimization of Reactive Volt-Ampere (var) Sources in System Planning, EPRI Project EL-3729, vol. 1, Final Report, Palo Alto, Ca., 1984.

124. J.L. De La Fuent and J. Lumbreras, "A New Implementation of An Optimal Power Flow System Based on a General Purpose Nonlinear Programming Program," IEEE PICA Conf. Proc., Montreal, May 18-22, 1987, pp.422- 428.

125. R.C. Burchett, H.H. Happ and K.A. Wirgau, "Large Scale Optimal Power Flow," IEEE Trans. on Power App. and Systems, vol. PAS-101, No. 10, Oct 1982, pp.3722-3730.

126. R.C. Burchett, H.H. Happ and D.R. Vierath, "Quadratically Convergent Optimal Power Flow," IEEE Trans. on Power App. and Systems, vol. PAS-103, No. 11, Nov 1984, pp. 3267-3275.

127. L. Franchi, M. Innorta, P. Marannino, C. Sabeli, "Evaluation of Economy and/or Security Oriented Objective Functions for Reactive Power Scheduling in Large Scale Systems," IEEE Trans. on Power App. and Systems, vol. PAS-102, No. 10, Oct 1983.

128. R.A. Fernandes, F. Lange, R.C. Burchett, H.H. Happ and K.A. Wirgau, "Large Scale Reactive Power Planning," IEEE Trans. on Power App. and Systems, vol PAS-102, No.5, May 1983, pp.1083-1088.

129. R.E. Palmer, R.C. Burchett, H.H. Happ and D.R. Vierath, "Reactive Power Dispatching for Power System Voltage Security," IEEE Trans. on Power App. and Systems, vol PAS-102, No. 12, Dec 1983, pp. 3905-3909.

130. W.M. Lebow et al.,"A Hierarchical Approach to Reactive Volt Ampere (VAR) Optimization in System Planning," IEEE Trans. on Power App. and Systems, vol. PAS-104, No. 8, Aug 1985, pp. 2051-2057.

131. R. Nadira, W.M. Lebow, P.B. Usoro, "A Decomposition Approach to Preventive Planning of Reactive Volt Ampere (VAR) Source Expansion," IEEE PES Winter Meeting, paper 86 WM 088-9, NY, Feb 2-7, 1986.

132. P.A. Chamorel, A.J. Germond, "Linear Programming Applied to Reactive Power Flow Optimization in High Voltage Power Systems," PSCC Conf. Proc., Lausanne, July 1981, pp. 306-310.

133. R. Rouhani, N.J. Balu, "Optimization of Reactive Volt Ampere (VAR) Sources in System Planning," PSCC Conf. Proc., Aug 1984, pp. 92-96.

134. M. Innorta, P. Marannino, G. Montanino, "Optimal VAR Planning Procedures in Large Scale Systems," PSCC Conf. Proc., Aug 1984, pp. 97-101.

135. P. Barcia, "Optimal Location of Shunt Capacitor: A MIP Approach," PSCC Conf. Proc., Aug. 1984, pp. 87-91.

136. R.C. Burchett, H.H. Happ, D.R. Vierath and R.E. Palmer, "Power Capacitor Scheduling with Security Constraints," CIGRE/IFAC Conf. Proc., paper 209-02, Florence, 1983.

137. B. Stott and O. Alsac, "Experience with Successive Linear Programming for Optimal Rescheduling of Active and Reactive Power," CIGRE/IFAC Conf. Proc., paper 104- 01, Florence, 1983.

138. G. Opoku and C.M. Ong, "Coordination of Reactive Power Sources to Correct Bus Voltage Violations in an AC-DC System," IEEE Trans. on Power App. and Systems, vol. PAS-103, No. 6, Jun 1984, pp.1128-1134.

139. G. Opoku and C.M. Ong, "Reactive Power Control to Alleviate Bus Voltage Violations in an AC-DC System," IEEE Trans. on Power App. and Systems, vol. PAS-104, No. 1, Jan 1985, pp. 75-81.

140. J.S. Horton and L.L. Grigsby, "Voltage Optimization Using Combined Linear Programming and Gradient Techniques," IEEE Trans. on Power App. and Systems, vol. PAS-103, No. 7, July 1984, pp. 1637-1643.

141. S. RamaIyer, K. Ramachandran and S. Hariharan, "Optimal Reactive Power Allocation for Improved System Performance," IEEE Trans. on Power App. and Systems, vol. PAS-103, No. 6, June 1984, pp.1509-1515.

142. K.R.C. Mamandur and R.D. Chenoweth, "Optimal Control of Reactive Power Flow for Improvements in Voltage Profiles and for Real Power Loss Minimization," IEEE Trans. on Power App. and Systems, vol. PAS-100, No.7, July 1981.

143. J. Qiu and S.M. Shahidehpour, "A New Approach for Minimizing Power Losses and Improving Voltage Profile," IEEE PES Summer Meeting, paper 86 SM 346-1, Mexico, July 20-25, 1986.

144. H.W. Dommel and W. Tinney, "Optimal Power Flow Solutions," IEEE Trans. on Power App. and Systems, vol. PAS-87, No. 10, Oct 1968, pp. 1866-1876.

145. Y. Backlund and D. Sjelvgren, "An Extended Generalized Gradient Methodology with Second Order Information for Optimal Power Flows," 2nd International Conf. on Power System Monitoring and Control (PSMC-3), Durham, UK, July 8-11, 1986.

146. R.B. Prada, "Security in the Economic Operation of Power Systems," Ph D Thesis, Imperial College, London, July 1980.

147. P.R. Gribik, G. Gross, H.M. Mukay and R. Galperini, "Treating Voltage Constraints in Large Scale Optimal Power Flow by Augmented Lagrangians," CIGRE/IFAC Conf. Proc., paper 209-04, Florence 1983.

148. D.I. Sun, B. Ashley, B. Brewer, A.Huges and W.F. Tinney, "Optimal Power Flow by Newton Approach," IEEE Trans. on Power App. and Systems, vol. PAS-103, No. 10, Oct 1984, pp. 2864-2879.

149. R.C. Burchett, H.H. Happ, D.R. Vierath and K.A. Wirgau, "Developments in Optimal Power Flows," IEEE Trans. on Power App. and Systems, vol. PAS-101, No. 2, Feb 1982, pp.406-413.

150. J.L. Carpentier, "Contribution a L'etude du Dispatching Economique," Bull. Soc. Franc. Elec., ser. 8, No. 32, Aug 1962, pp. 431-446.(In French)

151. O. Alsac and B. Stott, "Optimal Load Flow with Steady- State Security," IEEE Trans. on Power App. and Systems, vol PAS-93, May 1974, pp. 745-751.

152. D.T. Sun and R.R. Shoults, "A Preventive Strategy Method for Voltage and Reactive Power Dispatch," IEEE Trans. on Power App. and Systems, vol. PAS-104, No. 7, July 1985, pp. 1670-1676.

153. N.R. Sandell, P. Varaiya, M. Athans, M.G. Safonov, "Survey of Decentralized Control Methods for Large Scale Systems," IEEE Trans. on Automatic Control, vol. AC-23, No. 2, April 1978, pp.108-128.

154. M.D. Mesarovic, Theory of Hierarchical Multilevel Systems, Academic Press, NY, 1970.

155. L.D.B. Terra and M. J. Short, "An Operational Planning Software Package for Power Systems," 23rd UPEC Conf. Proc., Nottingham, Sept. 20-22, 1988.

156. L.L. Freris and A.M. Sasson, "Investigations of the Load Flow Problem," Proc. of the IEE, vol. 115, No. 10, Oct. 1968, pp. 1459-170.

157. IEEE Committee Report, "IEEE Reliability Test System," IEEE Trans. on Power App. and Systems, vol. PAS-98, No. 6, Nov/Dez 1979, pp. 2047-2054.

158. L.D.B. Terra, A.S. Marques and L.B. Moraes, "A New Technique for Reactive Power Planning," Proc. of the 3rd Brazilian Energy Congress, vol. 5, Rio de Janeiro, Oct 1984, pp.1804-1813. (In Portuguese)

159. N. Hawkins, Private Communication.

160. R.B.I. Johnson, Private Communication.

161. Y. Wallach, Calculations and Programs for Networks, Prentice-Hall Inc, New Jersey, 1986, Chapter 1.

162. L.D.B. Terra and M.J. Short, "A Global Approach for VAR/Voltage Management and Scheduling," IFAC Conf. Proc., Seoul, Korea, Aug 22-25, 1989.

NOTATION

Electrical Quantities:

P_i	Net active power injected at bus i
Q_i	Net reactive power injected at bus i
S_i	Net apparent power injected at bus i
P_{gi}	Active power generation at bus i
Q_{gi}	Reactive power generation at bus i
P_{di}	Active power demand at bus i
Q_{di}	Reactive power demand at bus i
V_i	Voltage magnitude at bus i
θ_i	Voltage angle at bus i
ΔV_i	Voltage magnitude correction at bus i
$\Delta\theta_i$	Voltage angle correction at bus i
I_i	Net complex current injection at bus i
b_i, B_i	Line-charging at bus i
b_{ci}, B_{ci}	Shunt element (capacitor/reactor) connected at bus i
Q_i^{sp}, P_i^{sp}	Scheduled reactive and active powers at bus i
ΔQ_i, ΔP_i	Reactive and active power mismatches at bus i, i.e., deviation from the scheduled values
$\lvert\Delta P_{max}\rvert$	maximum absolute value of the active power mismatch in the system.
$\lvert\Delta Q_{max}\rvert$	maximum absolute value of the reactive power mismatch in the system.
ΔQ^{best}	the minimum $\lvert\Delta Q_{max}\rvert$ within υ iterations
ΔQ_i^{brsf}	reactive power mismatch at bus i at the iteration υ corresponding to ΔQ^{best}.
V_i^{brsf}	Calculated voltage magnitude at bus i at the iteration υ υ corresponding to ΔQ^{best}.
ΔQ_{ci}	compensating reactive power injection at bus i.

a_i, T_i Off-nominal turns-ratios at i side of branch i,j, where j is any bus in the network.

z_{ij}, Z_{ij} branch impedance connected between buses i and j.

r_{ij}, R_{ij} branch resistance connected between buses i and j.

x_{ij}, x_{ij} branch reactance connected between buses i and j.

y_{ij}, Y_{ij} branch admittance connected between buses i and j.

g_{ij}, G_{ij} branch conductance connected between buses i and j.

b_{ij}, B_{ij} branch susceptance connected between buses i and j.

p_{ij}, P_{ij} Active power flow in branch i,j.

I_{ij} Complex current through branch i,j.

q_{ij}, Q_{ij} Reactive power flow in branch i,j.

Δp_{ij}, ΔP_{ij} Active power loss in branch i,j.

Δq_{ij}, ΔQ_{ij} Reactive power loss in branch i,j.

θ_{ij} Voltage angle across branch i,j.

SSL_{ij} Static stability limit of branch i,j.

Passive models of the network:

Y_{bus}, Z_{bus} Bus admittance and impedance matrices.

G_{bus}, B_{bus} Real and imaginary parts of Y_{bus}, respectively.

z^{eq}, Z^{eq} Thevenin impedance.

Sets and Subsets:

$\{a \mid R(a)\}$ or $\{a : R(a)\}$ set of all a for which the relation R(a) is true.

$\{a_1,\ldots,a_n\}$ the set or multiset $\{a_k \mid 1 \leq k \leq n\}$

PV Subset of buses where P and V are independent variables.

PQ Subset of buses where P and Q are independent variables.

SW Subset of buses where V and θ are independent variables.

P_{br} Set of branch active power flows.

Q_{br} Set of branch reactive power flows.

T Subset of under load tap changing (tcul) transformers.

Cardinality:

n_{bus}, N_{bus} Number of buses in the network.

n_{pv}, N_{pv} Number of PV buses in the network.

n_{pq}, N_{pq} Number of PQ buses in the network.

n_{sw}, N_{sw} Number of SW buses in the network.

n_t, N_t Number of tcul transformers in the network.

n_c, N_c Number of contingency cases.

Relations:

$j \epsilon \Omega_k$ j is element of the set Ω_k

$j \epsilon I$ j is element of I, where I is the set of buses directly connected to bus i, including bus i.

$j \epsilon I'$ j is element of I', where I' is the set of buses directly connected to bus i, excluding bus i.

Arrays:

A, [A] rectangular array A

$\underline{b}$, [b], ($\underline{b}$) linear array b, i.e., column vector.

A_{ij} the element in row i and column j of rectangular array A.

b_i the ith element of linear array b.

A^t, [A^t], [A]^t transpose of rectangular array A.

$\underline{b}^t$, [b]^t, ($\underline{b}$)^t transpose of linear array b, i.e., row vector.

A^{-1} inverse of a square non-singular matrix.

$||b||_p$ vector norm p.

[1] identity matrix

[0] zero matrix.

Functions:

f(x), F(x) real-valued scalar function

f($\underline{x}$), F($\underline{x}$) vector-valued scalar function

$\underline{f}$(x), $\underline{F}$(x) real-valued array function

$\underline{f}(\underline{x})$, $\underline{F}(\underline{x})$	vector-valued array function

Derivatives:

F_x , $\partial f/\partial x_i$	Partial derivative of F at x_i, x_i is the ith element of $\underline{x}$.
dF/dx, f'(x)	Ordinary derivative of f at x, $x \in \mathbb{R}$.
f''(x)	second derivative of f at x, $x \in \mathbb{R}$
ΔF	Total differential of F.

Limits on quantities:

X^{max}, X_{max}	upper limit on scalar or vector quantity.
X^{min}, X_{min}	lower limit on scalar or vector quantity.
X^{lim}, X_{lim}	either X^{max} or X^{min}.

Tolerances:

ϵ_q, ϵ_p, ϵ_k	Active and reactive power tolerances.

Miscellany:

p,q,pq,ν,μ,k	Iteration counters
V ← E	give variable V the value of expression E.
$\sum_{R(k)} f(k)$	sum of all f(k) such that k is an integer and relation R(k) is true.
$\min_{R(k)} f(k)$	minimum value of all f(k) such that k is an integer and relation R(k) is true.
$\max_{R(k)} f(k)$	maximum value of all f(k) such that k is an integer and relation R(k) is true.
x^y	x to the power of y
$\lvert x \rvert$	absolute value of x
sgn x	sign of x.
ΔX	variation on variable X.
δX	small variation on variable X.
∞	infinity: larger than any number.

APPENDIX A

E&PSG - A SOFTWARE ENVIRONMENT FOR POWER SYSTEMS SECURITY ANALYSIS AND OPTIMISATION

This appendix describes an integrated software environment for power system security analysis and optimisation. The E&PSG software environment is a logical extension of the stand-alone programs developed in this thesis. A special effort had to be made to enhance the consistency of the interfaces between modules. A design goal was to allow maximum flexibility to the user in input-output data set manipulation. The above goals have been reached, and the result is summarised in this appendix. The software system design is illustrated through Fig. A.1 and Exhibits A.1 through A.5. A printout of the on-line manuals provides examples of the display patterns and accessory aspects of the software package. Finally, Table A.1 highlights difficulties and gradual improvements which led to the different versions of the package. [155]

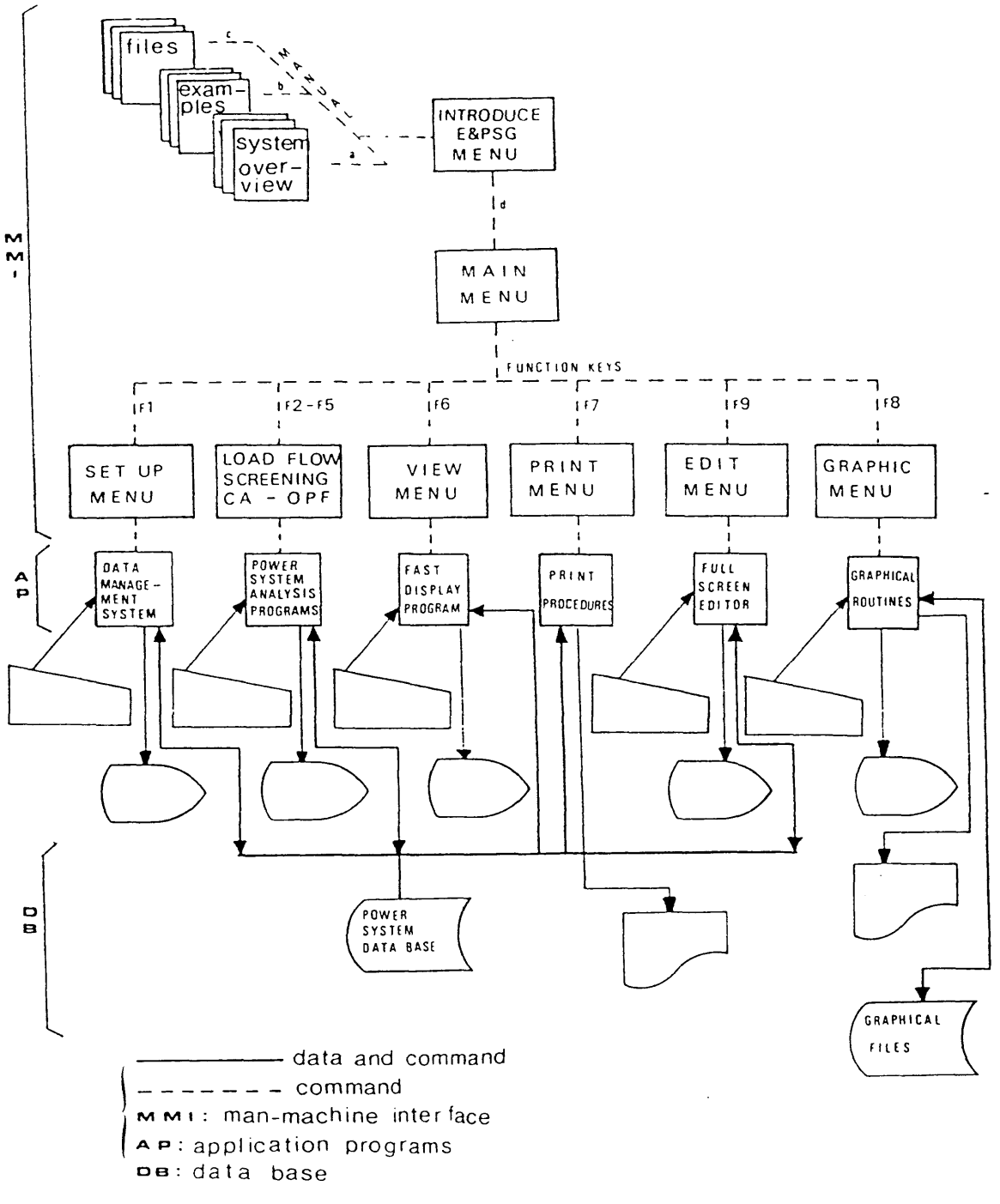


Fig. A.1 E&PSG - General Design

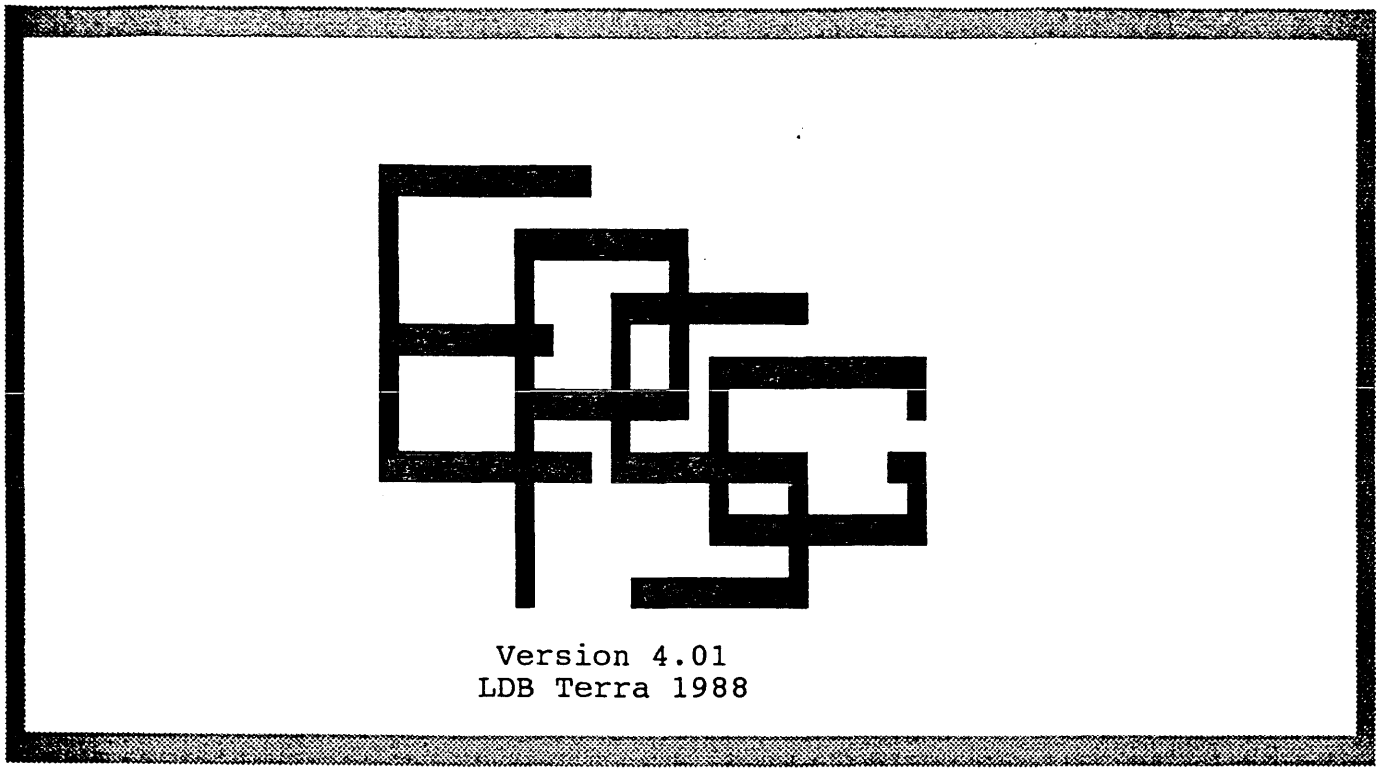


Exhibit A.1: The first display

E&PSG - Energy & Power Systems Group

Imperial College of Science, Technology and Medicine

L. D. B. Terra - University of London - U K

VERSION 4.01 December 1988

Press [a] to see system overview
Press [b] to see example - notes
Press [c] to see example - files
Press [d] to go to the main menu

Exhibit A.2: E&PSG Introductory Menu

M A I N M E N U	E&PSG - Version 4.01
KEY OPTION	KEY OPTION
F1 Set Up Input File	F6 View Files
F2 Load Flow	F7 Print Files
F3 Screening	F8 Graphical Environment
F4 Contingency Analysis	F9 Edit Files
F5 Optimal Power Flow	F10 Exit to DOS
Press the function key corresponding to the option required	

Exhibit A.3: E&PSG Main Menu

TYPE IN : NEWFILE filename1 filename2
e.g.: NEWFILE ieee14.dt$ cont.dt$
where: ieee14.dt$= new busbar/line data file cont14.dt$= new list of contingencies

Exhibit A.4: Loading data set from the Data Base
(An example of E&PSG user-friendly instruction)

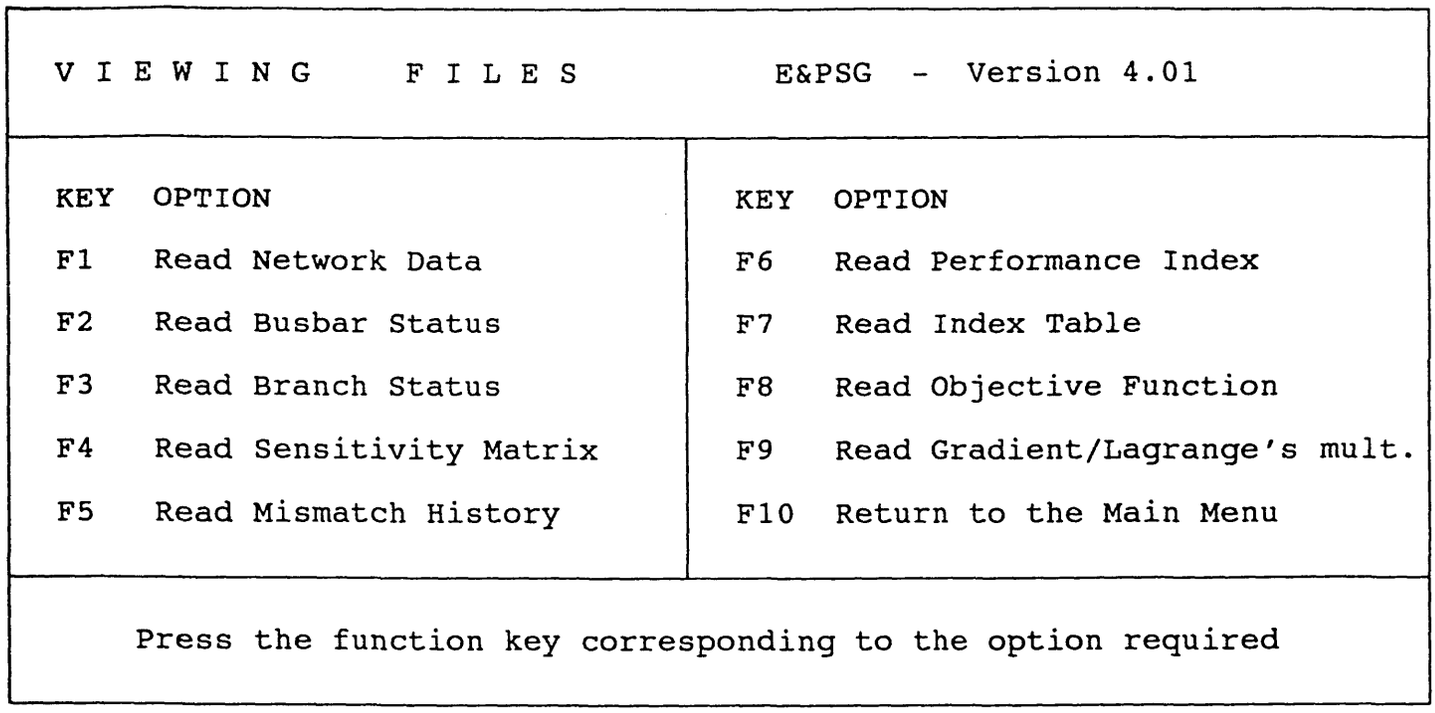


Exhibit A.5: E&PSG Viewing Files Menu

Table A.1 E&PSG Versions
Features & Improvements

Version	Bottleneck	Cause	Solution	CPU Time* 30 bus	CPU Time* 118 bus
1.0	Linear system solution	Gauss elimination		≃20 m	>24 h
			Shipley in place inverse	≃4 m	≃1 h
2.0	$L'=L-M\ H^{-1}N$	Matrix multiplication		≃3 m	≃29 m
			Direct assembling of L'.	<<s	<s
3.0	Linear system solution	Shipley in place inverse		≃4 m	≃1 h
			LDU table optimal ordering	<<s	<s
4.0	Mismatch and flows calculation. Limit checking.	Data structure		<s	≃1 m
			Two schemes of ordering	<<s	<s
4.01	var-limit enforcement	Multiple data structure		<<s	≃1 m
			Uniform data structure	<<s	<s

* Timescales with basis on IBM XT

E&PSG - A state-of-the-art software environment for power system security analysis & optimisation.

System Overview

by L D B Terra

Energy & Power Systems Group

Imperial College - London - UK

CONTENTS

1. Introduction
2. Program features
3. Building an input data set
4. Output of a data set
5. Modifying a data set
6. Utilities
7. Acknowledgments and observations
8. References

E&PSG V4.01 DEC 1988

1. Introduction

E&PSG V4.01 is a state-of-the-art software environment for steady state power system analysis and optimisation.

The main application programs are

- an AC load flow,
- a var-only optimal load flow,
- fast contingency screening,
- a contingency evaluation program, and
- procedures for selecting the most effective control variables for eliminating voltage violations for a given contingency.

Reference [3] details the mathematical models used in E&PSG V4.01

algorithms. These models encompass improvements that enable the implementation of sophisticated non-linear optimisation, var/ voltage security assessment and decoupled load flow techniques, thus making it possible to use personal computers for the planning of large scale systems. The response times are of the order of a few seconds.The ergonomic design meets the requirements of the power system industry, making the package the ideal tool for teaching, training and research.

2. Program features

To use E&PSG V4.01, you will need a 16-bit computer using MS-DOS or PC-DOS. Any 16-bit microcomputer that is fully software-compatible with the IBM PC should be able to run E&PSG V4.01. Your computer must have a minimum

of 380 Kbytes of memory, but 640 or more can provide better flexibility. Your system should have two floppy-disk drives or one floppy and one hard disk drive. Although possible, it is difficult to use E&PSG V4.01 on a system with only one disk drive. The reason for this is the size of the network data files. You will need a printer that can print at least 80 columns of text for hard copies.

E&PSG V4.01 can run systems of up to 120 buses and 180 lines or transformers. For bus and system component models see reference [2]. The programs allow for the individual representation of parallel transmission lines or off-nominal transformers. PQ and PV buses can come in any order and the swing bus can appear anywhere. For further details on component modelling please refer to [3].

The load flow method adopted is the CRIC of reference [1]. This gives the program security of convergence even for ill-conditioned systems for which other methods would fail. The program will report the best answer possible even for a physically infeasible system. This provides an efficient way of analysing various deficiencies in the system. For example, to investigate overloads and var requirements. Another useful feature provided by this scheme is the immediate identification of the worst cases in contingency analyses.

The E&PSG V4.01 provides a contingency screening routine, including bus voltage and var limits checking. There are also facilities for file manipulation. The contingency screening routine provides an easy way of performing ranking studies based on a performance index. There are six levels of output files.

For example, you can choose the output level for either all quantities or for only the violating ones, for each contingency. You can also set the maximum power mismatch and the maximum number of iterations for either all or for each contingency.

3. Building Input Data Set

There are two input files:

a) Bus, line/transformer and limits data file.
b) Contingency list

The Set Up Menu provides interactive data entry facilities for the building of input data sets. You do not need to build up a contingency list for simulating single branch outages. The screening program does this automatically. If you want to

simulate generation changes, load level variations or shunt capacitor/reactor switching you should build up a contingency list. There is a data entry program for this. So, all you have to do is to choose the corresponding option from the Set-Up Menu. The data entry program will then ask for the data. Similarly, there is a data entry program for building a new data file. The program prompts you for each record, but provides a default value for each field. You can choose the default by typing a coma instead of entering the data. For instance, you can choose setting up limits for all quantities or leaving them unlimited (default).
To run a data set, first make it active by loading it from the catalog on the program. Again, just choose the corresponding option from the Set-Up Menu. This will provide step-by-step instructions about what to do next.

4. Output Files

There are eight output files:

a) Bus Status

This file contains voltage, shunt elements, and power injections. Stars highlight variables with out-of-bound values. This file also includes maximum active and reactive power mismatches and the total active and reactive power losses.

b) Line/Transformer flows, losses and rating check

This file contains active and reactive power leaving

each bus. A minus sign shows that the power is entering the bus. Contains also active and reactive power losses in the line and the actual MVA of the line. The program checks the branch MVA against its rating and displays the percent loading of the branch.

c) Mismatch History
This file contains the history of the iterative process. This shows, at each iteration, the value of the maximum mismatch, the bus where it took place, the iteration number, and the time.

d) Performance Index
This file contains the performance indices.

e) Sensitivity Matrix*

This file contains the sensitivity coefficients of the bus voltage magnitudes with respect to the control variables (PV-bus voltage and transformer taps).

f) Gradient Vector and Lagrange Multipliers**

This file contains the components of the gradient vector and the Lagrange multipliers at the optimal point.

g) Objective Function**

This file contains the history of the optimisation

process. This includes the adaptive status of limits in the control variables (see [3] for details), optimum step length, and objective function values.

h) Index Table: Contingencies versus Most Effective Control*

This file contains a normalised index table of every contingency versus the most effective control variables for removing the voltage violations caused by each contingency.

5. Modifying Data Set

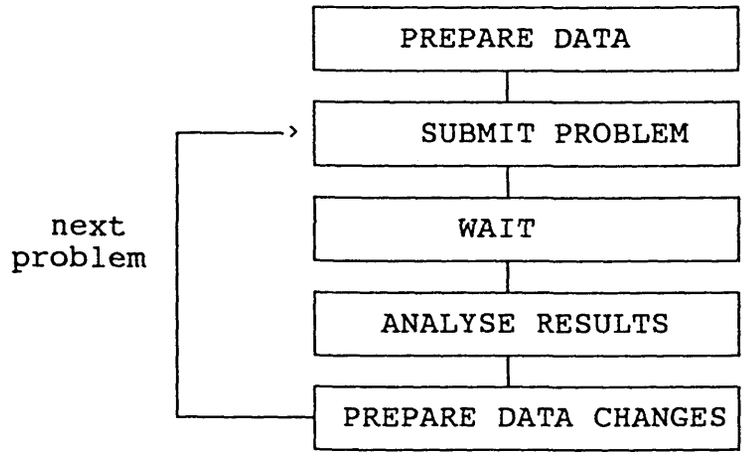
In order to ease the use and increase friendliness in file manipulation the E&PSG V4.01 incorporates two

renowned public domain utilities.
These allow for fast modification of the input data file.
One of the design goals was to minimise the time taken to perform engineering studies (see next display).

6. Utilities

a) LIST - This is a public domain utility to display the contents of an ASCII file line by line with the aid of scrolling and positioning commands. On-line help is provided.

b) PC-Write - This is a public domain word processor and text editor for the IBM Personal Computer. On-line help is provided.



7. References

[1] J. L. Carpentier (1985) Optimal Power Load Flow: Uses, Methods and Developments. Proc.IFAC Symposium on Planning and Operation of Electric Energy Systems, Rio de Janeiro, Brazil.

[2] O. I. Elgerd (1983) Electric Energy Systems Theory: An Introduction, McGraw-Hill International Book Co., 2nd ed.

[3] L. D. B. Terra (1988) A Global Methodology for Reactive Power Management and Voltage Control in Power Systems, Ph D Thesis, Imperial College, London, (in preparation)

8. Acknowledgments and observations

The E&PSG V4.01 was part of a Ph D research programme at Imperial College of Science, Technology and Medicine. Dr. M J Short was the supervisor. The financial supporters were CAPES of Brazil, UFMG and Committee of Vice-Chancellor and Principals of the UK.

An exhaustive comparative study of performance of different load flow methods showed that Carpentier's method presents the best convergence characteristics for ill-conditioned systems.

E&PSG V4.01 DEC 1988

A Graphical Environment System is under development. The phase of functional requirements and design specifications has been completed. A prototype was implemented and tested for a five bus network. These graphical capabilities will be available on E&PSG V5.0.

* Output file generated by the Contingency Analysis and the Optimal Load Flow Programs.

** Output file generated by the Optimal Power Flow Program.

L D B Terra, London, June 1989.

E&PSG - A state-of-the-art software environment for power system security analysis & optimisation

Examples - notes

by L D B Terra
Energy & Power Systems Group
Imperial College - London - UK

CONTENTS

1. Existing Input Files

2. Building a new data set

1. Existing Input Files

The following classical data files have already been built:

```
IWH6.V1$    =  WARD-HALE 6 bus test system
IEEE14.V1$ =  IEEE 14 bus test system
IEEE24.V1$ =  IEEE 24 bus test system
IEEE30.V1$ =  IEEE 30 bus test system
IEEE39.V1$ =  IEEE 39 bus test system
IEEE57.V1$ =  IEEE 57 bus test system
IEEE118.v1$=  IEEE 118 bus test system
ICEGB34.V1$=  CEGB SW 34 bus test system (UK)
ICEMIG32.V1$= CEMIG NS 32 bus test system (MG-Brazil)
```


To run an example using one of these files just go to the Set Up Menu (by pressing [F1] on the Main Menu) and press [c] (see directory and load input data set). A catalog showing the input files available will be displayed. Select the file you want to load and follow the instructions that will then be given.

The file catalog also contains the list of contingencies associated with the above data files.

For instance:

FCS14.V1$	-	Contingency list for IEEE14.V1$
FCS30.V1$	-	Contingency list for IEEE30.V1$
FCSWD.V1$	-	Contingency list for IWH6.V1$
FCSWD.V2$	-	Contingency list for IWH6.V1$

Once you have loaded the input data set the main menu is automatically shown. Then choose the option you want. Having run the case you can either modify the input files by using the appropriate option on the main menu and entering PC-Write or rerun the same input files with, say, a new set of maximum mismatches or a new limit to the number of iterations.

From within PC-Write you can perform a series of actions, such as:

CREATE NEW FILES

CREATE BACKUP FILES

RENAME FILES

ETC...

There are no rules for naming files, however

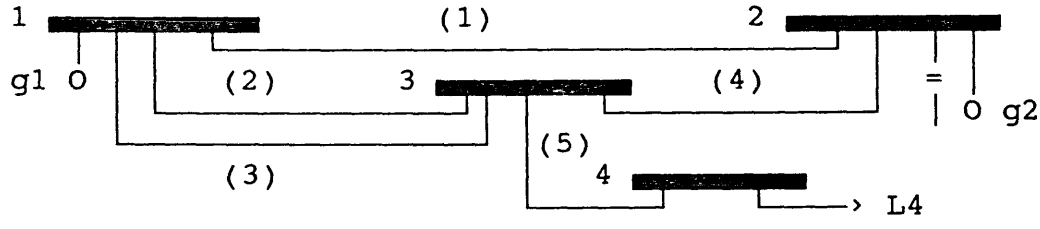
the extension name of an input data file must end with the dollar sign [$] if this file is to appear on the input file catalog. The adoption of mnemonics is recommended in order to get an organized catalog. The following pattern for naming files is suggested:

System data set : Ixxxxx.xx$

Contingency list: Fxxxxx.xx$

2. Building a new data set

Consider the system below



The generator, load, and shunt capacitor data are given in Table 1, while Table 2 shows line/transformer parameters.

Table 1. Busbar Data

no.	type	MW Gen	Mvar Gen	MW Load	Mvar Load	Mvar c/r
1	PV	30.0	-	0.0	0.0	0.0
2	SW	-	-	-	-	0.6
3	PQ	0.0	0.0	0.0	0.0	0.0
4	PQ	0.0	0.0	40.0	10.0	0.0

Table 2. Line/Transformer data (PI-equivalent circuit)

no.	L/T	resistance[%]	reactance[%]	charging[%]	tap[%]
L1	L	16.2	17.5	6.4	-
L2	L	5.1	20.0	10.0	-
L3	L	2.6	10.0	20.0	-
L4	L	3.0	32.0	0.0	
T5	T	0.0	25.0	-	95.0

Table 3 shows limits on certain variables:

Table 3. Limits

Component	limits	
Generator G1	Qmin=-15.0 Mvar	Qmax=15.0 Mvar
Bus 1	Vmin=0.900 p.u.	Vmax=1.10 p.u.
Bus 4	Vmin=0.975 p.u.	Vmax=1.05 p.u.
Transmission Line 4	Thermal limit=100.0 MVA	
Transformer 5	Nominal Power=50.0 MVA	
	Min.Tap=90% Max.Tap=110% Step=2.5%	

Finally, assume you want to study the contingencies of

Table 4 (including load level and generation changes)

Table 4. Contingencies

type	Data
Outage of Line 1	-
Switch off Capacitor bus 2	-0.300 Mvar
Switch on Capacitor bus 2	+0.600 Mvar
Load level change at bus 4	P=60. MW, Q=30. Mvar
Generator outage at bus 1	P=0.0 MW, Qmin=0.,Qmax=0.
Generator outage at bus 1	P=50. MW, Qmin=-15.,Qmax=20.

To run the case above go to the Main Menu. A series of options then guide you keystroke-by-keystroke through several E&PSG V4.01 tasks.

Several commands appear with particular keys. They provide a quick way of telling you exactly what needs to be done.

In the following the sequence of keystrokes to run this example will be summarised:

E&PSG V4.01 DEC 1988

Keystroke	Action
[F1] (Main Menu)	go to the Set Up Menu
[a] (Set Up)	build bus/branch file
[b] (Set Up)	build contingency list
[c] (Set Up)	load the above files into E&PSG input and return to the Main Menu.
etc...	

E&PSG - A state-of-the-art software environment for power system security analysis & optimisation

Example - Files

L D B Terra
Energy & Power Systems Group
Imperial College - London - UK

CONTENTS

A. INPUT FILES

1. Network data set - raw data
2. Contingency list - raw data

B. RECORD DATA FORMAT

1. Network data record
2. Contingency list record

C. GETTING STARTED

A. INPUT FILES

1. Network Data Set - raw data

```
4  5  1      .0001      .0001  4
1PV     1.0000      .0000      .0000      .0000      .0000    30.0000      .0000
2SW     1.0000      .0000      .6000      .0000      .0000      .0000      .0000
3PQ     1.0000      .0000      .0000      .0000      .0000      .0000      .0000
4PQ     1.0000      .0000      .0000    40.0000    10.0000      .0000      .0000
1  1  2      16.2000    17.5000     6.4000      .00000
2  1  3       5.1000    20.0000    10.0000      .00000
3  1  3       2.6000    10.0000    20.0000      .00001
4  2  3       3.0000    32.0000      .0000      .00000
5  3  4        .0000    25.0000      .0000    95.00000
2
1  -15.0000    15.0000      .9000     1.1000
4     .0000      .0000      .9750     1.0500
1
5  3  4    95.0000    90.0000   110.0000     2.5000    25.0000
2
2  100.0000
5   50.0000
```

END OF FILE

2. Contingency List - raw data

```
1  0  1  1  2      .0000      .0000      .0000
2  3  2  0  0      .0000     -.3000      .0000
3  3  2  0  0      .0000      .6000      .0000
4  2  4  0  0    60.0000    30.0000      .0000
5  1  1  0  0      .0000      .0000      .0000
6  1  1  0  0    50.0000   -15.0000    20.0000
```

END OF FILE

B. RECORD DATA FORMAT

1. Network Data Record Types

E&PSG Network Data - Record Type 1					
Number of Buses	Lines	PV-buses	Tolerances(MW/Mvar) P	Q	Output level
1-3	4-6	7-9	10-19	20-29	30-32
I3	I3	I3	F10.4	F10.4	I3

E&PSG Busbar Data - Record Type 2								
Busbar		Voltage		Shunt	Load		Generation	
No.	Type	Magnitude	Angle	Mvar	MW	Mvar	MW	Mvar
1-3	4-5	6-15	16-25	26-35	36-45	46-55	56-65	66-75
I3	A2	F10.4	F10.4	F10.4	F10.4	F10.4	F10.4	F10.4

E&PSG Branch Data - Record Type 3							
branch			p a r a m e t e r s				parallel
no.	from	to	r (%)	x (%)	b (%)	tap (%)	circuit
1-3	4-6	7-9	12-21	22-31	32-41	42-51	52
I3	I3	I3	F10.4	F10.4	F10.4	F10.4	I1

E&PSG Flag - Record Type 7	
This field indicates the number of following records of type 4.	
1-3	
I3	

E&PSG Operating Limits on Bus Quantities - Record Type 4					
bus no.	Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax	
1-3	4-13	14-23	24-33	34-43	
I3	F10.4	F10.4	F10.4	F10.4	

E&PSG Flag - Record Type 7	
This field indicates the number of following records of type 5.	
1-3	
I3	

E&PSG Tcul Parameters - Record Type 5							
branch no.	from	to	tap details (%) initial	minimum	maximum	step	series reactance(%)
1-3	4-6	7-9	10-19	20-29	30-39	40-49	50-59
I3	I3	I3	F10.4	F10.4	F10.4	F10.4	F10.4

E&PSG Flag - Record Type 7	
This field indicates the number of following records of type 6.	
1-3	
I3	

E&PSG Branch Details - Record Type 6		
branch number	rating (MVA)	
1-3	4-13	
I3	F10.4	

2. Contingency List Record

E&PSG Contingency List Record							
	Contingency Details				Generation/Load/Shunt Data		
No.	Code	bus	from	to	MW	Mvar1	Mvar2
1-3	4-6	7-9	10-12	13-15	16-25	26-35	36-45
I3	I3	I3	I3	I3	F10.4	F10.4	I3

Codes: 0 - branch contingency
1 - New generation schedule then MW=Pg, Mvar1=Qmin, Mvar2=Qmax
2 - Load level modification then MW=Pl, Mvar1=Ql
3 - Switching capacitor or reactor then Mvar1=Qshunt

0) First of all, go to the DOS and make a print-out of this manual. For example: Answer the DOS prompt (EPSG›) with the command

```
EPSG› copy *.doc prn:
```

1) Set up the input file for the network example of this manual.
2) Check the file built with the input file of item A.1 above.
3) Run the Load Flow Program.
4) Go to the Viewing Menu and try the several options.
5) Run the Screening Program.
6) Repeat step 4.
7) Run the Optimal Power Flow Program.
8) Repeat step 4.
9) Set up the contingency list for the example.
10) Repeat example 4.
11) Check the contingency list file with the contingency list of item A.2 above.
12) Run the Contingency Analysis Program.

APPENDIX B

NETWORK TEST SYSTEMS

This appendix provides the data for the test systems used in this thesis. The data for each of these systems includes: a descriptive title, single-phase network diagram, bus data, transmission network data and operating limits. The transmission network data are given in per cent on a 100 MVA basis.

B.1 THE WARD-HALE 6-BUS TEST SYSTEM

The Ward-Hale 6-bus 7-branch (WDHL6) test system data was taken from reference [51].

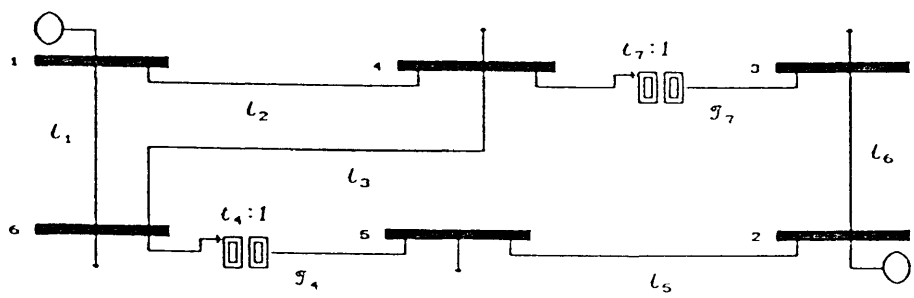


Fig. B.1 Ward-Hale 6-bus test system

Table B.1a WDHL6 Bus Data

B U S B A R D A T A

Busbar No.	Type	Voltage Mag.	Ang.	Shunt Mvar	Load MW	Mvar	Generation MW	Mvar
1	SW	1.05	.00	3.3898	.00	.00	.00	.00
2	PV	1.10	.00	.00	.00	.00	50.00	.00
3	PQ	1.00	.00	.00	55.00	13.00	.00	.00
4	PQ	1.00	.00	2.9326	.00	.00	.00	.00
5	PQ	1.00	.00	.00	30.00	18.00	.00	.00
6	PQ	1.00	.00	3.5088	50.00	5.00	.00	.00

e&psg

Table B.1b WDHL6 Branch Data

LINE/TRANSFORMER DATA

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap	rating (MVA)%
1	1	6	12.30	51.80	.00	.00	80.00
2	1	4	8.00	37.00	.00	.00	80.00
3	4	6	9.70	40.70	.00	.00	30.00
4	6	5	.00	30.00	.00	102.50	18.00
5	5	2	28.20	64.00	.00	.00	80.00
6	3	2	72.30	105.00	.00	.00	90.00
7	4	3	.00	13.30	.00	110.00	80.00

e&psg

Table B.1c WDHL6 Operating Limits

OPERATING LIMITS

bus no.	Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax
1	-10.00	100.00	.9000	1.1000
2	-20.00	20.00	.9000	1.1500
{PQ}	.00	.00	.9600	1.1000

Limits on tcul tap settings: (90%,110%)

e&psg

B.2 THE IEEE 14-BUS TEST SYSTEM

The IEEE 14-bus 20-branch (IEEE14) test system data was taken from reference [156].

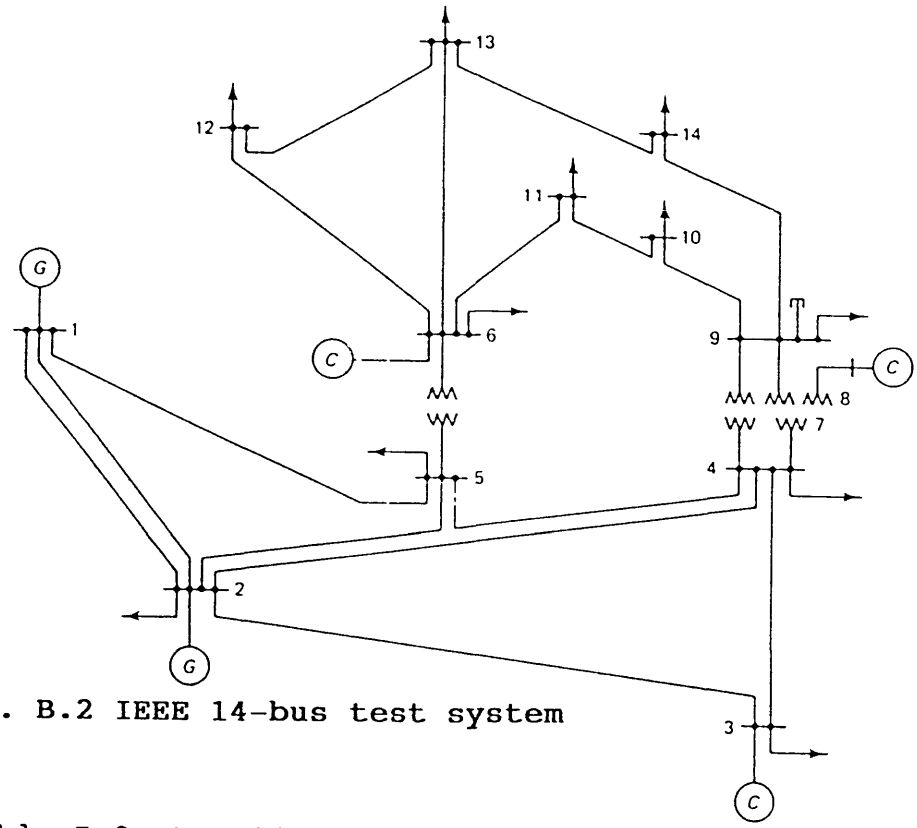


Fig. B.2 IEEE 14-bus test system

Table B.2a IEEE14 Bus Data

B U S B A R D A T A								
Busbar		Voltage		Shunt	Load		Generation	
No.	Type	Mag.	Ang.	Mvar	MW	Mvar	MW	Mvar
1	SW	1.060	.00	.00	.00	.00	.00	.00
2	PV	1.045	.00	.00	21.70	12.70	40.00	.00
3	PV	1.010	.00	.00	94.20	19.00	.00	.00
4	PQ	1.000	.00	.00	47.80	-3.90	.00	.00
5	PQ	1.000	.00	.00	7.60	1.60	.00	.00
6	PV	1.070	.00	.00	11.20	7.50	.00	.00
7	PQ	1.000	.00	.00	.00	.00	.00	.00
8	PV	1.090	.00	.00	.00	.00	.00	.00
9	PQ	1.000	.00	19.00	29.50	16.60	.00	.00
10	PQ	1.000	.00	.00	9.00	5.80	.00	.00
11	PQ	1.000	.00	.00	3.50	1.80	.00	.00
12	PQ	1.000	.00	.00	6.10	1.60	.00	.00
13	PQ	1.000	.00	.00	13.50	5.80	.00	.00
14	PQ	1.000	.00	.00	14.90	5.00	.00	.00

e&psg

Table B.2b IEEE14 Branch Data

LINE/TRANSFORMER DATA

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)	rating (MVA)
1	1	2	1.94	5.92	2.64	.00	1689.0
2	1	5	5.40	22.30	2.46	.00	450.0
3	2	3	4.70	19.80	2.19	.00	505.0
4	2	4	5.81	17.63	1.87	.00	
5	2	5	5.69	17.39	1.70	.00	
6	3	4	6.70	17.10	1.73	.00	584.0
7	4	5	1.33	4.21	.64	.00	
8	4	7	.00	20.91	.00	97.80	450.0
9	4	9	.00	55.62	.00	96.90	450.0
10	5	6	.00	25.20	.00	93.20	400.0
11	6	11	9.50	19.89	.00	.00	
12	6	12	12.29	25.58	.00	.00	
13	6	13	6.61	13.03	.00	.00	
14	7	8	.00	17.61	.00	.00	150.0
15	7	9	.00	11.00	.00	.00	
16	9	10	3.18	8.45	.00	.00	
17	9	14	12.71	27.04	.00	.00	
18	10	11	8.20	19.21	.00	.00	
19	12	13	22.09	19.99	.00	.00	
20	13	14	17.09	34.80	.00	.00	

e&psg

Table B.2c IEEE14 Operating Limits

OPERATING LIMITS

bus no.	Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax
1	-100.00	100.00	.9000	1.1000
2	-40.00	50.00	.9000	1.1000
3	.00	40.00	.9000	1.1000
6	-6.00	24.00	.9000	1.1000
7	.00	.00	.8000	1.2000
8	-6.00	24.00	.9000	1.1000
{PQ}	.00	.00	.9750	1.1000

Limits on tcul tap settings: (90%,110%)

e&psg

B.3 THE IEEE 24-BUS TEST SYSTEM

The IEEE 24-bus 34-branch (IEEE24) test system data was taken from reference [157].

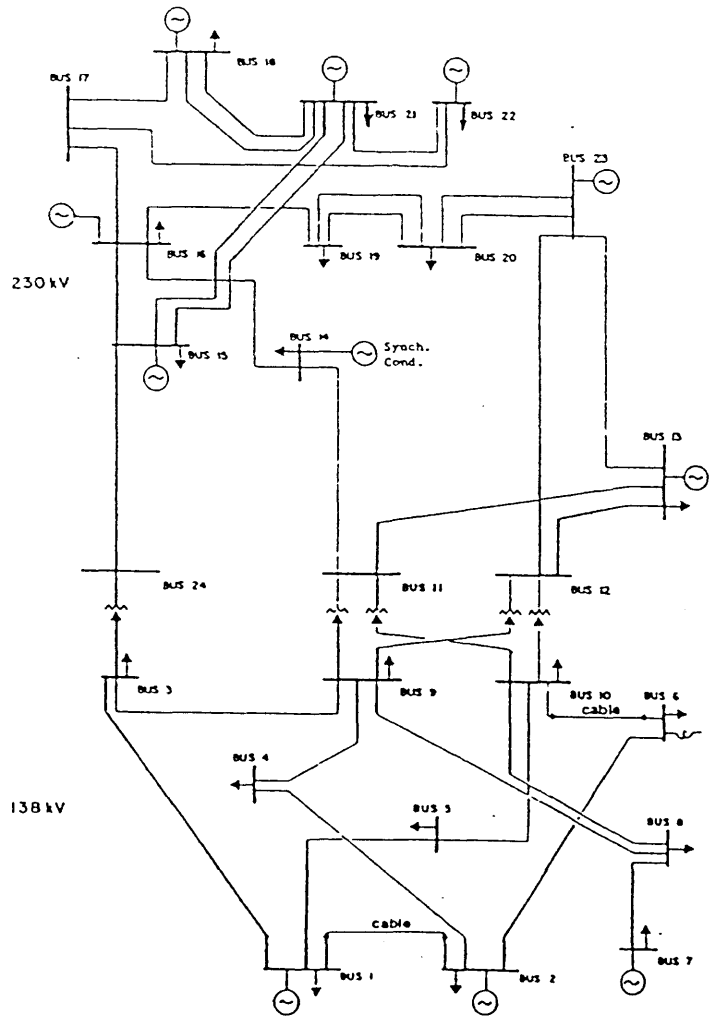


Fig. B.3 IEEE 24-bus test system

Table B.3a IEEE24 Bus Data

B U S B A R D A T A

No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
a	PQ	1.00	.00	.00	.00	.00	.00	.00
1	PV	1.00	.00	.00	125.00	25.00	270.00	.00
2	PV	1.00	.00	.00	333.00	68.00	350.00	.00
3	PV	1.00	.00	.00	.00	.00	135.00	.00
4	PV	1.00	.00	.00	.00	.00	295.00	.00
5	PV	1.00	.00	.00	194.00	39.00	.00	.00
6	PQ	1.00	.00	.00	128.00	26.00	.00	.00
7	PQ	1.00	.00	.00	181.00	37.00	.00	.00
8	PQ	1.00	.00	.00	74.00	15.00	.00	.00
9	PQ	1.00	.00	.00	71.00	14.00	.00	.00
10	PQ	1.00	.00	.00	171.00	35.00	.00	.00
13	PV	1.00	.00	.00	317.00	64.00	185.00	.00
14	PQ	1.00	.00	-100.00	136.00	28.00	.00	.00
15	PV	1.00	.00	.00	108.00	22.00	170.00	.00
16	PV	1.00	.00	.00	.00	.00	655.00	.00
17	SW	1.00	.00	.00	265.00	54.00	.00	.00
18	PV	1.00	.00	.00	97.00	20.00	170.00	.00
19	PV	1.00	.00	.00	100.00	20.00	130.00	.00
21	PQ	1.00	.00	.00	175.00	36.00	.00	.00
22	PQ	1.00	.00	-100.00	195.00	40.00	.00	.00
24	PQ	1.00	.00	.00	180.00	37.00	.00	.00

a={11,12,20,23}

e&psg

Table B.3c IEEE24 Operating Limits

OPERATING LIMITS

bus no.	Mvar generation Qmin	Mvar generation Qmax	voltage magnitude Vmin	voltage magnitude Vmax
1	-90.00	180.00	.9000	1.1000
a	-50.00	200.00	.9000	1.1000
3	-60.00	96.00	.9000	1.1000
13	-50.00	110.00	.9000	1.1000
15	-50.00	120.00	.9000	1.1000
16	-125.00	310.00	.9000	1.1000
17	-24.00	100.00	.9000	1.1000
18	-50.00	172.00	.9000	1.1000
19	-50.00	99.00	.9000	1.1000
{PQ}	.00	.00	.9500	1.1000

Limits on tcul tap settings: (90%,120)

a={2,4,5}

e&psg

Table B.3b IEEE24 Branch Data

LINE/TRANSFORMER DATA

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)
1	1	10	1.59	6.14	3.32	.00
2	6	7	.25	1.98	33.32	.00
3	6	16	.14	1.08	18.20	.00
4	7	19	.30	2.31	9.70	.00
5	8	21	2.68	10.37	5.62	.00
6	8	18	3.28	12.67	6.86	.00
7	9	15	2.18	8.45	5.82	.00
8	9	22	2.28	8.83	4.78	.00
9	10	21	4.27	16.51	8.94	.00
10	10	22	4.27	16.51	8.94	.00
11	17	23	.61	4.76	19.98	.00
12	17	20	.61	4.76	19.98	.00
13	17	16	1.11	8.65	36.36	.00
14	5	20	.54	4.18	17.58	.00
15	5	19	.50	3.89	16.36	.00
16	2	4	.16	1.29	21.80	.00
17	2	12	.18	1.44	6.06	.00
18	3	4	.87	6.78	28.48	.00
19	3	12	1.35	10.53	44.24	.00
20	4	13	.31	2.45	41.20	.00
21	11	13	.67	5.19	21.82	.00
22	11	24	.23	8.39	.00	100.00
23	23	21	.23	8.39	.00	100.00
24	23	22	.23	8.39	.00	100.00
25	23	16	1.24	9.66	40.60	.00
26	13	19	.22	1.73	7.28	.00
27	12	19	.33	2.59	10.90	.00
28	20	21	.23	8.39	.00	100.00
29	20	22	.23	8.39	.00	100.00
30	15	18	.26	1.39	92.22	.00
31	15	24	5.46	21.12	11.44	.00
32	21	24	3.08	11.90	6.44	.00
33	18	14	4.97	19.20	10.40	.00
34	22	14	1.39	6.05	491.80	.00

e&psg

B.4 THE IEEE 30-BUS TEST SYSTEM

The IEEE 30-bus 41-branch (IEEE30) test system data was taken from reference [151].

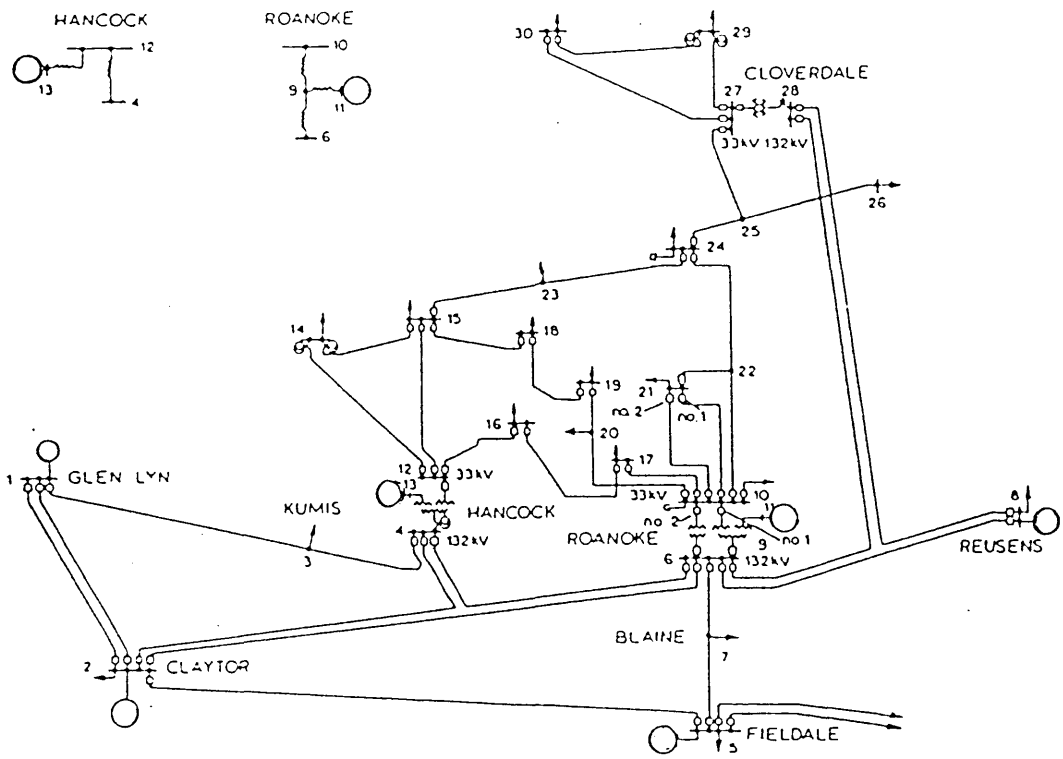


Fig. B.4 IEEE 30-bus test system

Table B.4a IEEE30 Bus Data

B U S B A R D A T A

Busbar No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
a	PQ	1.00	.00	.00	.00	.00	.00	.00
1	SW	1.00	.00	.00	.00	.00	.00	.00
2	PV	1.00	.00	.00	21.70	12.70	57.56	.00
3	PQ	1.00	.00	.00	2.40	1.20	.00	.00
4	PQ	1.00	.00	.00	7.60	1.60	.00	.00
5	PV	1.00	.00	.00	94.20	19.00	24.56	.00
7	PQ	1.00	.00	.00	22.80	10.90	.00	.00
8	PV	1.00	.00	.00	30.00	30.00	35.00	.00
10	PQ	1.00	.00	19.00	5.80	2.00	.00	.00
11	PV	1.00	.00	.00	.00	.00	17.93	.00
12	PQ	1.00	.00	.00	11.20	7.50	.00	.00
13	PV	1.00	.00	.00	.00	.00	16.91	.00
14	PQ	1.00	.00	.00	6.20	1.60	.00	.00
15	PQ	1.00	.00	.00	8.20	2.50	.00	.00
16	PQ	1.00	.00	.00	3.50	1.80	.00	.00
17	PQ	1.00	.00	.00	9.00	5.80	.00	.00
18	PQ	1.00	.00	.00	3.20	.90	.00	.00
19	PQ	1.00	.00	.00	9.50	3.40	.00	.00
20	PQ	1.00	.00	.00	2.20	.70	.00	.00
21	PQ	1.00	.00	.00	17.50	11.20	.00	.00
23	PQ	1.00	.00	.00	3.20	1.60	.00	.00
24	PQ	1.00	.00	4.30	8.70	6.70	.00	.00
26	PQ	1.00	.00	.00	3.50	2.30	.00	.00
29	PQ	1.00	.00	.00	2.40	.90	.00	.00
30	PQ	1.00	.00	.00	10.60	1.90	.00	.00

a={6,9,22,25,27,28}

e&psg

Table B.4b IEEE30 Branch Data

LINE/TRANSFORMER DATA

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)	rating (MVA)
1	1	2	1.92	5.75	2.64	.00	130.00
2	1	3	4.52	18.52	2.04	.00	130.00
3	2	4	5.70	17.37	1.84	.00	65.00
4	3	4	1.32	3.79	.42	.00	130.00
5	2	5	4.72	19.83	2.09	.00	130.00
6	2	6	5.81	17.63	1.87	.00	65.00
7	4	6	1.19	4.14	.45	.00	90.00
8	5	7	4.60	11.60	1.02	.00	70.00
9	6	7	2.67	8.20	.85	.00	130.00
10	6	8	1.20	4.20	.45	.00	32.00
11	6	9	.00	20.80	.00	97.80	65.00
12	6	10	.00	55.60	.00	96.90	32.00
13	9	11	.00	20.80	.00	.00	65.00
14	9	10	.00	11.00	.00	.00	65.00
15	4	12	.00	25.60	.00	93.20	65.00
16	12	13	.00	14.00	.00	.00	65.00
17	12	14	12.31	25.59	.00	.00	32.00
18	12	15	6.62	13.04	.00	.00	32.00
19	12	16	9.45	19.87	.00	.00	32.00
20	14	15	22.10	19.97	.00	.00	16.00
21	16	17	8.24	19.23	.00	.00	16.00
22	15	18	10.70	21.85	.00	.00	16.00
23	18	19	6.39	12.92	.00	.00	16.00
24	19	20	3.40	6.80	.00	.00	32.00
25	10	20	9.36	20.90	.00	.00	32.00
26	10	17	3.24	8.45	.00	.00	32.00
27	10	21	3.48	7.49	.00	.00	32.00
28	10	22	7.27	14.99	.00	.00	32.00
29	21	22	1.16	2.36	.00	.00	32.00
30	15	23	10.00	20.20	.00	.00	16.00
31	22	24	11.50	17.90	.00	.00	16.00
32	23	24	13.20	27.00	.00	.00	16.00
33	24	25	18.85	32.92	.00	.00	16.00
34	25	26	25.44	38.00	.00	.00	16.00
35	25	27	10.93	20.87	.00	.00	16.00
36	27	28	.00	39.60	.00	96.80	65.00
37	27	29	21.98	41.53	.00	.00	16.00
38	27	30	32.02	60.27	.00	.00	16.00
39	29	30	23.99	45.33	.00	.00	16.00
40	8	28	6.36	20.00	2.14	.00	32.00
41	6	28	1.69	5.99	.65	.00	32.00

e&psg

Table B.4c IEEE30 Operating Limits

OPERATING LIMITS				
bus no.	Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax
1	-20.00	250.00	.9500	1.0500
2	-20.00	100.00	.9500	1.0500
5	-15.00	80.00	.9500	1.1000
8	-15.00	60.00	.9000	1.1000
11	-10.00	50.00	.9500	1.1000
13	-15.00	60.00	.9500	1.1000
{PQ}	.00	.00	.9500	1.1000
Limits on tcul tap settings: (90%,120%)				
e&psg				

B.5 THE CEMIG 32-BUS TEST SYSTEM

The Cemig 32-bus 32-branch (CEMIG32) test system data was taken from reference [158].

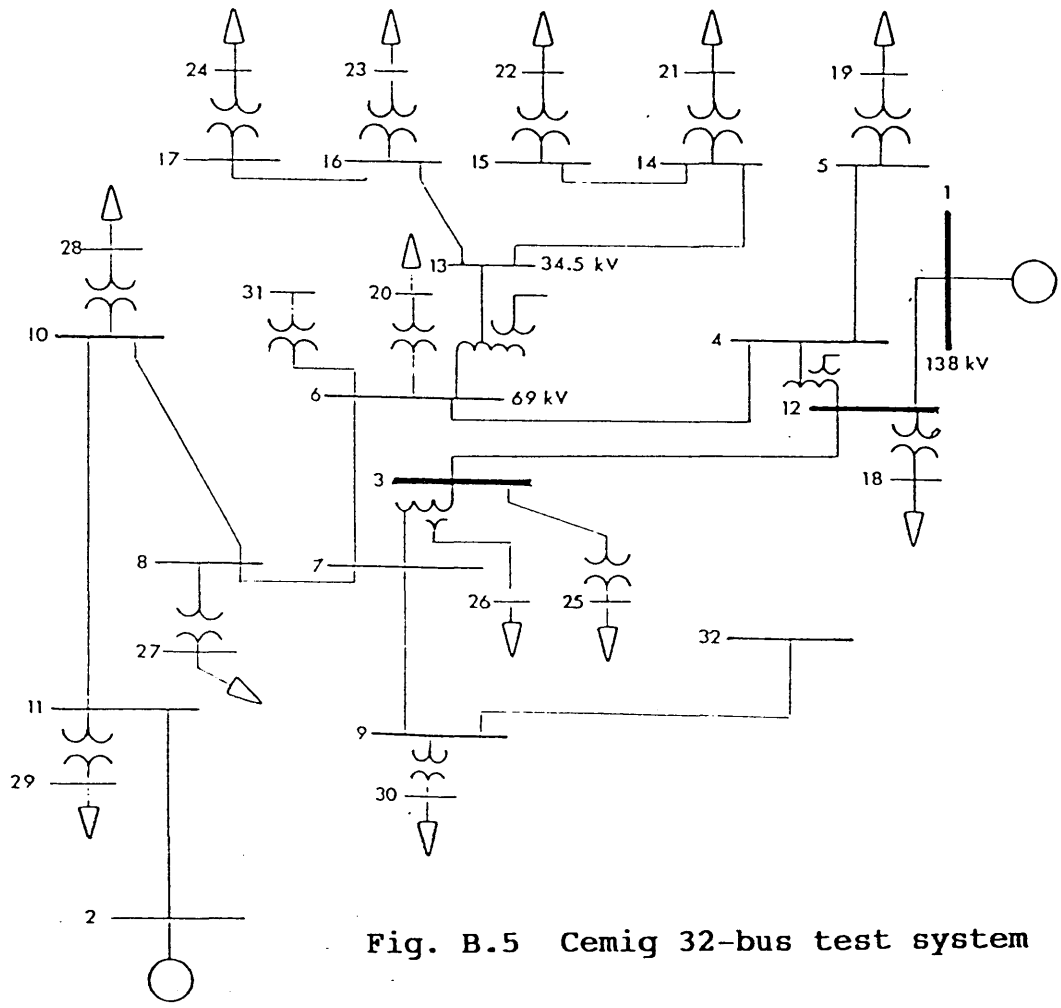


Fig. B.5 Cemig 32-bus test system

Table B.5a CEMIG32 Bus Data

B U S B A R D A T A

Busbar No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
1	SW	1.00	.00	.00	.00	.00	.00	.00
2	PV	1.00	.00	.00	.00	.00	3.50	.00
a	PQ	1.00	.00	.00	.00	.00	.00	.00
18	PQ	1.00	.00	.00	10.50	5.10	.00	.00
19	PQ	1.00	.00	.40	5.10	2.50	.00	.00
20	PQ	1.00	.00	.40	4.00	1.60	.00	.00
21	PQ	1.00	.00	.00	1.60	.50	.00	.00
22	PQ	1.00	.00	.20	3.10	1.00	.00	.00
23	PQ	1.00	.00	.00	.90	.30	.00	.00
24	PQ	1.00	.00	.20	2.40	.80	.00	.00
25	PQ	1.00	.00	.60	13.80	5.40	.00	.00
26	PQ	1.00	.00	.00	6.10	3.00	.00	.00
27	PQ	1.00	.00	.20	1.90	.80	.00	.00
28	PQ	1.00	.00	.20	8.60	3.40	.00	.00
29	PQ	1.00	.00	.00	3.60	1.20	.00	.00
30	PQ	1.00	.00	.40	9.20	3.90	.00	.00

a={3-17,31,32}

e&psg

Table B.5b CEMIG32 Branch Data

LINE/TRANSFORMER DATA

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)
1	1	12	3.57	7.51	3.20	.000
2	12	3	5.71	15.71	3.68	.000
3	12	4	.00	27.40	.00	102.564
4	4	5	245.70	73.14	.48	.000
5	4	6	46.36	70.51	.94	.000
6	6	7	18.52	28.16	.37	.000
7	7	8	26.04	39.02	.54	.000
8	8	10	20.79	31.14	.43	.000
9	10	11	22.80	34.66	.46	.000
10	11	2	20.17	30.67	.41	.000
11	3	7	.00	19.89	.00	105.263
12	7	9	25.35	37.98	.52	.000
13	6	13	.00	22.82	.00	102.564
14	13	14	136.78	69.62	.07	.000
15	14	15	167.67	85.34	.08	.000
16	13	16	280.62	145.23	.13	.000
17	16	17	136.78	71.76	.07	.000
18	12	18	.00	54.80	.00	100.000
19	5	19	.00	64.50	.00	105.263
20	14	21	.00	194.40	.00	102.564
21	15	22	.00	138.40	.00	105.263
22	16	23	.00	500.00	.00	105.263
23	17	24	.00	194.81	.00	105.263
24	6	20	.00	89.33	.00	102.041
25	7	26	.00	25.39	.00	100.000
26	9	30	.00	70.40	.00	102.564
27	8	27	.00	290.00	.00	102.564
28	10	28	.00	68.80	.00	105.263
29	11	29	.00	137.80	.00	105.263
30	25	3	.00	55.07	.00	95.238
31	6	31	.00	105.93	.00	102.564
32	9	32	17.10	18.41	.23	.000

e&psg

Table B.5c CEMIG32 Operating Limits

OPERATING LIMITS

bus no.	Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax
1	-999.99	9999.99	1.0000	1.0500
2	-2.00	5.00	.9000	1.0500
{4-17}	.00	.00	.9000	1.1000
{18-32}	.00	.00	.975	1.0500

Limits on tcul tap settings: (80%,120%)

e&psg

B.6 THE CEGB 34-BUS TEST SYSTEM

The CEGB 34-bus 56-branch (CEGB34) test system data was taken from reference [159].

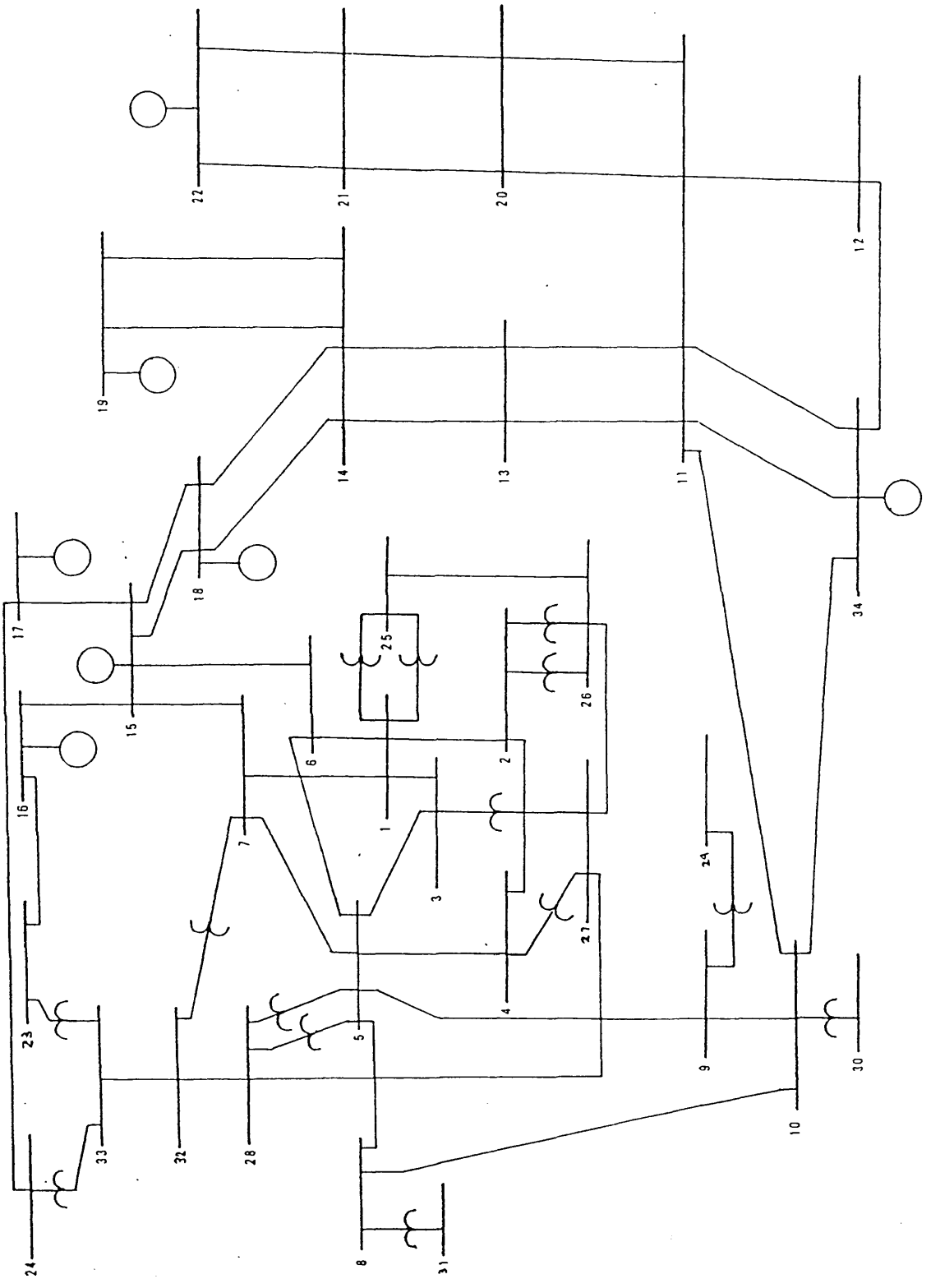


Fig. B.6 CEGB 34-bus test system

Table B.6a CEGB34 Bus Data

B U S B A R D A T A

Busbar No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
a	PQ	1.00	.00	.00	.00	.00	.00	.00
11	PQ	1.00	.00	-200.00	422.00	-63.80	.00	.00
12	PQ	1.00	.00	.00	200.40	48.40	.00	.00
13	PQ	1.00	.00	.00	469.10	96.50	.00	.00
14	PQ	1.00	.00	.00	108.80	-86.30	.00	.00
15	PV	1.00	.00	.00	.00	.00	1099.10	.00
16	PV	1.00	.00	.00	.00	.00	207.80	.00
17	PV	1.00	.00	.00	.00	.00	207.80	.00
18	PV	1.00	.00	.00	392.60	-42.50	.00	.00
19	PV	1.00	.00	.00	38.60	22.70	.00	.00
20	PQ	1.00	.00	.00	518.50	117.30	.00	.00
21	PQ	1.00	.00	.00	358.40	153.10	.00	.00
22	PV	1.00	.00	.00	-817.90	-21.00	.00	.00
25	PQ	1.00	.00	11.00	294.82	63.70	.00	.00
26	PQ	1.00	.00	26.00	131.62	39.12	.00	.00
27	PQ	1.00	.00	20.00	157.94	46.94	.00	.00
28	PQ	1.00	.00	13.00	142.15	22.35	.00	.00
29	PQ	1.00	.00	2.00	40.01	5.59	.00	.00
30	PQ	1.00	.00	37.00	368.52	91.64	.00	.00
31	PQ	1.00	.00	9.00	84.23	22.35	.00	.00
32	PQ	1.00	.00	3.00	31.59	6.71	.00	.00
33	PQ	1.00	.00	10.00	200.06	.00	.00	.00
34	SW	1.00	.00	.00	156.00	57.40	1804.50	.00

a={1-10,23,24}

e&psg

Table B.6b CEGB34 Branch Data

LINE/TRANSFORMER DATA

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap(%)	parallel circuit
1	1	25	.1418	8.3418	.0000	111.10	0
2	1	25	.1230	7.9708	.0000	111.10	1
3	2	26	.1809	8.0000	.0000	100.10	0
4	2	26	.1473	7.9666	.0000	100.10	1
5	3	27	.1628	8.4166	.0000	95.80	0
6	4	27	.1614	8.3541	.0000	95.80	0
7	5	28	.1701	8.3125	.0000	110.20	0
8	5	28	.1743	8.3041	.0000	110.20	1
9	8	31	.0750	3.8800	.0000	103.80	0
10	9	29	.0730	4.1200	.0000	105.60	0
11	10	30	.0400	2.0560	.0000	102.40	0
12	7	32	.1458	8.0458	.0000	116.90	0
13	23	33	.1859	8.0000	.0000	94.00	0
14	24	33	.1697	8.0875	.0000	94.00	0
15	25	26	.0000	11.7210	.0000	.00	0
16	27	28	.0000	3.4641	.0000	.00	0
17	27	26	.0000	7.9060	.0000	.00	0
18	28	32	.0000	10.3801	.0000	.00	0
19	33	32	.0000	2.2255	.0000	.00	0
20	23	16	.0944	.7590	12.4715	.00	0
21	24	17	.0943	.7571	11.7106	.00	0
22	1	2	.1173	.9338	28.7869	.00	0
23	1	3	.2284	1.8398	55.4600	.00	0
24	2	4	.1106	.9019	26.5625	.00	0
25	3	5	.1180	.9832	27.7200	.00	0
26	4	5	.1173	.9776	27.5683	.00	0
27	5	8	.0436	.5956	24.7304	.00	0
28	6	15	.0641	.5102	15.7178	.00	0
29	7	15	.0641	.5102	15.7178	.00	0
30	8	10	.1122	1.5332	63.6572	.00	0
31	9	10	.0645	.8821	36.6269	.00	0
32	10	11	.0963	1.3157	54.6167	.00	0
33	10	34	.0728	.9951	41.2900	.00	0
34	11	12	.0483	.6598	27.3966	.00	0
35	11	34	.0306	.3964	74.0400	.00	0
36	11	13	.0936	.7448	22.9675	.00	0
37	11	13	.0936	.7448	22.9700	.00	1
38	11	20	.0779	1.0648	44.2132	.00	0
39	11	20	.0779	1.0648	44.2100	.00	1
40	12	34	.0246	.3362	13.9605	.00	0
41	13	14	.0211	.2885	11.9788	.00	0
42	13	14	.0211	.2885	11.9788	.00	1
43	14	18	.1964	1.5628	48.1920	.00	0
44	14	18	.1964	1.5628	48.1920	.00	1
45	14	19	.0523	.7130	75.4700	.00	0
46	15	16	.0350	2.4146	5.8978	.00	0

continue

Table B.6b CEGB34 Branch Data (Continuation)

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap(%)	parallel circuit
47	15	17	.0350	2.4146	5.8978	.00	0
48	15	18	.2077	1.6536	50.9800	.00	0
49	20	21	.0617	.8432	35.0116	.00	0
50	20	21	.0617	.8432	35.0100	.00	1
51	21	22	.0523	.7150	29.6548	.00	0
52	21	22	.0520	.7110	29.5000	.00	1
53	1	6	.4090	3.4082	96.1112	.00	0
54	1	7	.4090	3.4082	96.1100	.00	0
55	5	6	.0918	.7305	22.5150	.00	0
56	5	7	.0918	.7305	22.5150	.00	0

e&psg

Table B.6c CEGB34 Operating Limits

OPERATING LIMITS

bus no.	Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax
15	-360.00	660.00	.9500	1.1000
{16-17}	-120.00	120.00	.9500	1.1000
{18-22,34}	-99999.	9999.00	.9500	1.1000
34	-330.00	470.00	.9500	1.1000
{PQ}	.00	.00	.9500	1.1000

Limits on tcul tap settings: (90%,120%)

e&psg

B.7 THE IEEE 39-BUS TEST SYSTEM

The IEEE 39-bus 46-branch (IEEE39) test system data was taken from reference [160].

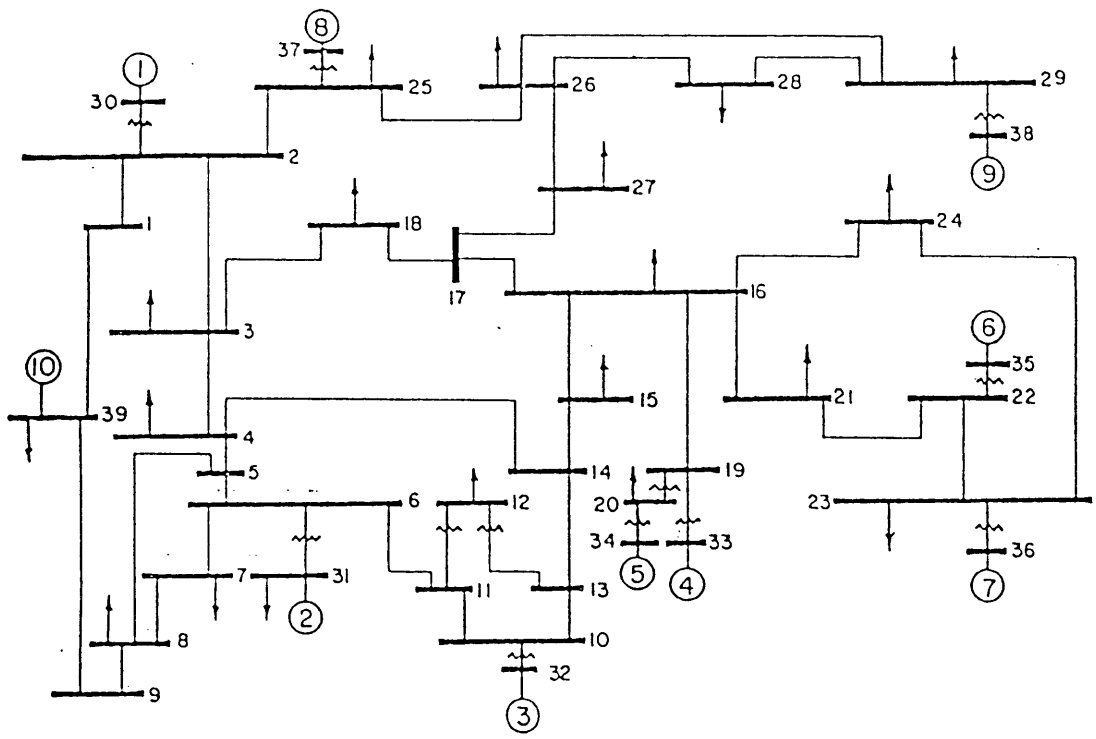


Fig. B.7 IEEE 39-bus test system

Table B.7a IEEE39 Bus Data

B U S B A R D A T A

Busbar No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
a	PQ	1.00	.00	.00	.00	.00	.00	.00
3	PQ	1.00	.00	.00	322.00	2.40	.00	.00
4	PQ	1.00	.00	.00	500.00	184.00	.00	.00
7	PQ	1.00	.00	.00	233.80	84.00	.00	.00
8	PQ	1.00	.00	.00	522.00	176.00	.00	.00
12	PQ	1.00	.00	.00	8.50	86.00	.00	.00
15	PQ	1.00	.00	.00	320.00	153.00	.00	.00
16	PQ	1.00	.00	.00	329.40	32.30	.00	.00
18	PQ	1.00	.00	.00	158.00	30.00	.00	.00
20	PQ	1.00	.00	.00	680.00	103.00	.00	.00
21	PQ	1.00	.00	.00	274.00	115.00	.00	.00
23	PQ	1.00	.00	.00	247.50	84.60	.00	.00
24	PQ	1.00	.00	.00	308.60	92.20	.00	.00
25	PQ	1.00	.00	.00	224.00	47.20	.00	.00
26	PQ	1.00	.00	.00	139.00	17.00	.00	.00
27	PQ	1.00	.00	.00	281.00	75.50	.00	.00
28	PQ	1.00	.00	.00	206.00	27.60	.00	.00
29	PQ	1.00	.00	.00	283.00	26.90	.00	.00
30	PV	1.04	.00	.00	.00	.00	250.00	.00
31	SW	.98	.00	.00	9.20	4.60	.00	.00
32	PV	.98	.00	.00	.00	.00	650.00	.00
33	PV	.99	.00	.00	.00	.00	632.00	.00
34	PV	1.01	.00	.00	.00	.00	508.00	.00
35	PV	1.04	.00	.00	.00	.00	650.00	.00
36	PV	1.06	.00	.00	.00	.00	560.00	.00
37	PV	1.02	.00	.00	.00	.00	540.00	.00
38	PV	1.02	.00	.00	.00	.00	830.00	.00
39	PV	1.03	.00	.00	1104.00	250.00	1000.00	.00

a={2,5,6,9-11,13,14,17,19,22}

e&psg

Table B.7b IEEE39 Branch Data

LINE/TRANSFORMER DATA

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)
1	1	2	.35	4.11	69.88	.00
2	1	39	.10	2.50	75.00	.00
3	2	3	.13	1.51	25.72	.00
4	2	25	.70	.86	14.60	.00
5	2	30	.00	1.81	.00	97.56
6	3	4	.13	2.13	22.14	.00
7	3	18	.11	1.33	21.30	.00
8	4	5	.08	1.28	13.42	.00
9	4	14	.08	1.29	13.82	.00
10	5	6	.02	.26	4.34	.00
11	5	8	.08	1.12	14.76	.00
12	6	7	.06	.92	11.30	.00
13	6	11	.07	.82	13.90	.00
14	6	31	.00	2.50	.00	93.46
15	7	8	.04	.46	7.80	.00
16	8	9	.23	3.63	38.04	.00
17	9	39	.10	2.50	120.00	.00
18	10	11	.04	.43	7.30	.00
19	10	13	.04	.43	7.30	.00
20	10	32	.00	2.00	.00	93.46
21	12	11	.16	4.35	.00	99.40
22	12	13	.16	4.35	.00	99.40
23	13	14	.09	1.01	17.24	.00
24	14	15	.16	2.17	36.60	.00
25	15	16	.09	.94	17.10	.00
26	16	17	.07	.89	13.42	.00
27	16	19	.16	1.95	30.40	.00
28	16	21	.08	1.35	25.48	.00
29	16	24	.03	.59	6.80	.00
30	17	18	.07	.82	13.20	.00
31	17	27	.13	1.73	32.16	.00
32	19	33	.07	1.42	.00	99.40
33	19	20	.07	1.38	.00	94.34
34	20	34	.09	1.80	.00	99.50
35	21	22	.08	1.40	25.66	.00
36	22	23	.06	.96	18.46	.00
37	22	35	.00	1.43	.00	97.56
38	23	24	.22	3.50	36.10	.00
39	23	36	.05	2.72	.00	100.00
40	25	26	.32	3.23	51.30	.00
41	25	37	.06	2.32	.00	97.56
42	26	27	.14	1.47	23.96	.00
43	26	28	.43	4.74	78.02	.00
44	26	29	.57	6.25	102.90	.00
45	28	29	.14	1.51	24.90	.00
46	29	38	.08	1.56	.00	97.56

e&psg

Table B.7c IEEE39 Operating Limits

OPERATING LIMITS				
bus no.	Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax
{30,32-39}	-400.00	500.00	.900	1.10
31	-99999.	99999.	.900	1.10
{PQ}	.00	.00	.950	1.10
Limits on tcul tap settings: (90%,120%)				
e&psg				

B.8 THE IEEE 57-BUS TEST SYSTEM

The IEEE 57-bus 80-branch (IEEE57) test system data was taken from reference [161].

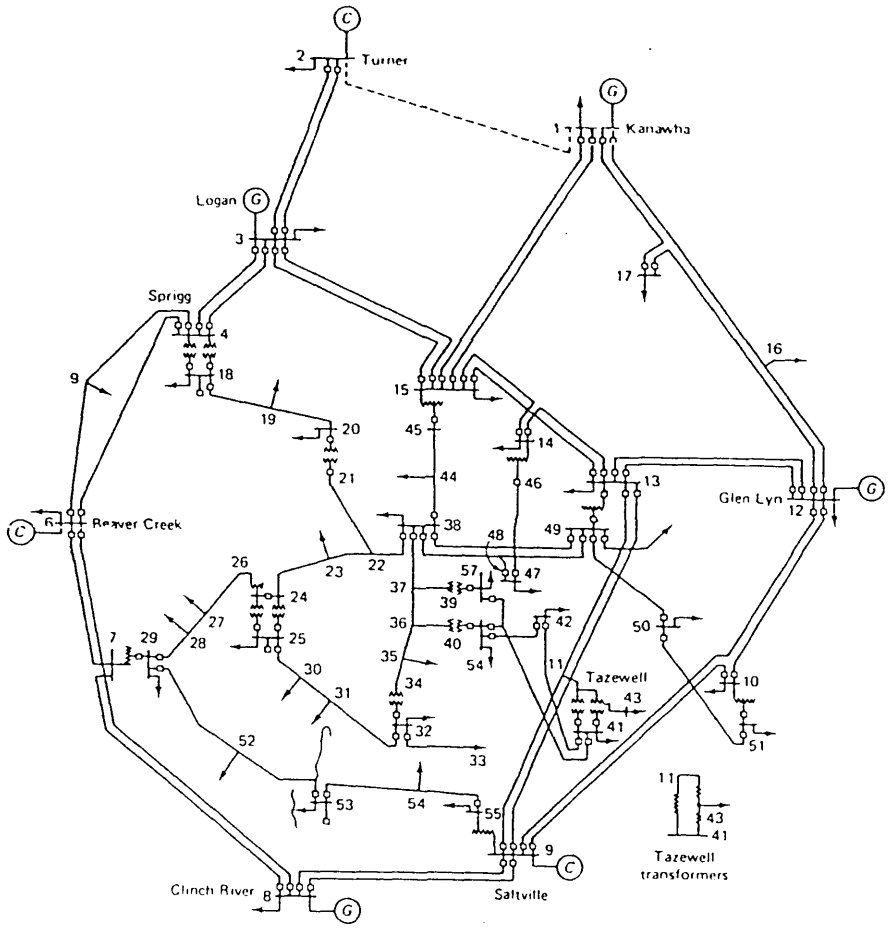


Fig. B.8 IEEE 57-bus test system

Table B.8a IEEE57 Bus Data

B U S B A R D A T A

No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
a	PQ	1.00	.00	.00	.00	.00	.00	.00
1	SW	1.04	.00	.00	55.00	17.00	.00	.00
2	PV	1.01	.00	.00	3.00	88.00	.00	.00
3	PV	.99	.00	.00	41.00	21.00	40.00	.00
5	PQ	1.00	.00	.00	13.00	4.00	.00	.00
6	PV	.98	.00	.00	75.00	2.00	.00	.00
8	PV	1.00	.00	.00	150.00	22.00	450.00	.00
9	PV	.98	.00	.00	121.00	26.00	.00	.00
10	PQ	1.00	.00	.00	5.00	2.00	.00	.00
12	PV	1.01	.00	.00	377.00	24.00	310.00	.00
13	PQ	1.00	.00	.00	18.00	2.30	.00	.00
14	PQ	1.00	.00	.00	10.50	5.30	.00	.00
15	PQ	1.00	.00	.00	22.00	5.00	.00	.00
16	PQ	1.00	.00	.00	43.00	3.00	.00	.00
17	PQ	1.00	.00	.00	42.00	8.00	.00	.00
18	PQ	1.00	.00	10.00	27.20	9.80	.00	.00
19	PQ	1.00	.00	.00	3.30	.60	.00	.00
20	PQ	1.00	.00	.00	2.30	1.00	.00	.00
23	PQ	1.00	.00	.00	6.30	2.10	.00	.00
25	PQ	1.00	.00	5.90	6.30	3.20	.00	.00
27	PQ	1.00	.00	.00	9.30	.50	.00	.00
28	PQ	1.00	.00	.00	4.60	2.30	.00	.00
29	PQ	1.00	.00	.00	17.00	2.60	.00	.00
30	PQ	1.00	.00	.00	3.60	1.80	.00	.00
31	PQ	1.00	.00	.00	5.80	2.90	.00	.00
32	PQ	1.00	.00	.00	1.60	.80	.00	.00
33	PQ	1.00	.00	.00	3.80	1.90	.00	.00
35	PQ	1.00	.00	.00	6.00	3.00	.00	.00
38	PQ	1.00	.00	.00	14.00	7.00	.00	.00
41	PQ	1.00	.00	.00	6.30	3.00	.00	.00
42	PQ	1.00	.00	.00	7.10	4.40	.00	.00
43	PQ	1.00	.00	.00	2.00	1.00	.00	.00
44	PQ	1.00	.00	.00	12.00	1.80	.00	.00
47	PQ	1.00	.00	.00	29.70	11.60	.00	.00
49	PQ	1.00	.00	.00	18.00	8.50	.00	.00
50	PQ	1.00	.00	.00	21.00	10.50	.00	.00
51	PQ	1.00	.00	.00	18.00	5.30	.00	.00
52	PQ	1.00	.00	.00	4.90	2.20	.00	.00
53	PQ	1.00	.00	6.30	20.00	10.00	.00	.00
54	PQ	1.00	.00	.00	4.10	1.40	.00	.00
55	PQ	1.00	.00	.00	6.80	3.40	.00	.00
56	PQ	1.00	.00	.00	7.60	2.20	.00	.00
57	PQ	1.00	.00	.00	6.70	2.00	.00	.00

a={4,7,11,21,22,24,26,34,36,37,39,40,45,46,48}

e&psg

Table B.8b IEEE57 Branch Data

LINE/TRANSFORMER DATA							
branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)	parallel circuit
1	1	2	.83	2.80	12.90	.00	0
2	2	3	2.98	8.50	8.18	.00	0
3	3	4	1.12	3.66	3.80	.00	0
4	4	5	6.25	13.20	2.58	.00	0
5	4	6	4.30	14.80	3.48	.00	0
6	6	7	2.00	10.20	2.76	.00	0
7	6	8	3.39	17.30	4.70	.00	0
8	8	9	.99	5.05	5.48	.00	0
9	9	10	3.69	16.79	4.40	.00	0
10	9	11	2.58	8.48	2.18	.00	0
11	9	12	6.48	29.50	7.72	.00	0
12	9	13	4.81	15.80	4.06	.00	0
13	13	14	1.32	4.34	1.10	.00	0
14	13	15	2.69	8.69	2.30	.00	0
15	1	15	1.78	9.10	9.88	.00	0
16	1	16	4.54	20.60	5.46	.00	0
17	1	17	2.38	10.80	2.86	.00	0
18	3	15	1.62	5.30	5.44	.00	0
19	4	18	.00	55.50	.00	97.00	0
20	4	18	.00	43.00	.00	97.80	1
21	5	6	3.02	6.41	1.24	.00	0
22	7	8	1.39	7.12	1.94	.00	0
23	10	12	2.77	12.62	3.28	.00	0
24	11	13	2.23	7.32	1.88	.00	0
25	12	13	1.78	5.80	6.04	.00	0
26	12	16	1.80	8.13	2.16	.00	0
27	12	17	3.97	17.90	4.76	.00	0
28	14	15	1.71	5.47	1.48	.00	0
29	18	19	46.10	68.50	.00	.00	0
30	19	20	28.30	43.40	.00	.00	0
31	20	21	.00	77.67	.00	95.88	0
32	21	22	7.36	11.70	.00	.00	0
33	22	23	.99	1.52	.00	.00	0
34	23	24	16.60	25.60	.84	.00	0
35	24	25	.00	118.20	.00	100.00	0
36	24	25	.00	123.00	.00	100.00	1
37	24	26	.00	4.73	.00	104.30	0
38	26	27	16.50	25.40	.00	.00	0
39	27	28	6.18	9.54	.00	.00	0
40	28	29	4.18	5.87	.00	.00	0
41	7	29	.00	6.48	.00	96.70	0
42	25	30	13.50	20.20	.00	.00	0
43	30	31	32.60	49.70	.00	.00	0
44	31	32	50.70	75.50	.00	.00	0
45	32	33	3.92	3.60	.00	.00	0
46	32	34	.00	95.30	.00	102.56	0

continue

Table B.8b IEEE57 Branch Data (Continuation)

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)	parallel circuit
47	34	35	5.20	7.80	.32	.00	0
48	35	36	4.30	5.37	.16	.00	0
49	36	37	2.90	3.66	.00	.00	0
50	37	38	6.51	10.09	.20	.00	0
51	37	39	2.39	3.79	.00	.00	0
52	36	40	3.00	4.66	.00	.00	0
53	22	38	1.92	2.95	.00	.00	0
54	11	41	.00	74.90	.00	95.50	0
55	41	42	20.70	35.20	.00	.00	0
56	41	43	.00	41.20	.00	.00	0
57	38	44	2.89	5.85	.20	.00	0
58	15	45	.00	10.42	.00	95.50	0
59	14	46	.00	7.35	.00	90.00	0
60	46	47	2.30	6.80	.32	.00	0
61	47	48	1.82	2.33	.00	.00	0
62	48	49	8.34	12.90	.48	.00	0
63	49	50	8.01	12.80	.00	.00	0
64	50	51	13.86	22.00	.00	.00	0
65	10	51	.00	7.12	.00	93.00	0
66	13	49	.00	19.10	.00	89.50	0
67	29	52	14.42	18.70	.00	.00	0
68	52	53	7.62	9.84	.00	.00	0
69	53	54	18.78	23.20	.00	.00	0
70	54	55	17.32	22.65	.00	.00	0
71	11	43	.00	15.30	.00	95.80	0
72	44	45	6.24	12.42	.40	.00	0
73	40	56	.00	119.50	.00	95.80	0
74	41	56	55.30	54.90	.00	.00	0
75	42	56	21.25	35.40	.00	.00	0
76	39	57	.00	135.50	.00	98.00	0
77	56	57	17.40	26.00	.00	.00	0
78	38	49	11.50	17.70	.60	.00	0
79	38	48	1.32	4.82	.00	.00	0
80	9	55	.00	12.05	.00	94.00	0

e&psg

Table B.8c IEEE57 Operating Limits

OPERATING LIMITS

bus no.	Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax
1	-9999.	99999.	.9000	1.1000
2	-17.00	50.00	.9000	1.1000
3	-10.00	60.00	.9000	1.1000
6	-8.00	25.00	.9000	1.1000
8	-140.00	200.00	.9000	1.1000
9	-3.00	9.00	.9000	1.1000
12	-50.00	155.00	.9000	1.1000
{PQ}	.00	.00	.9500	1.1000

Limits on tcul tap settings: (90%,110%)

e&psg

B.9 THE IEEE 118-BUS TEST SYSTEM

The IEEE 118-bus (IEEE118) test system data was taken from reference [123].

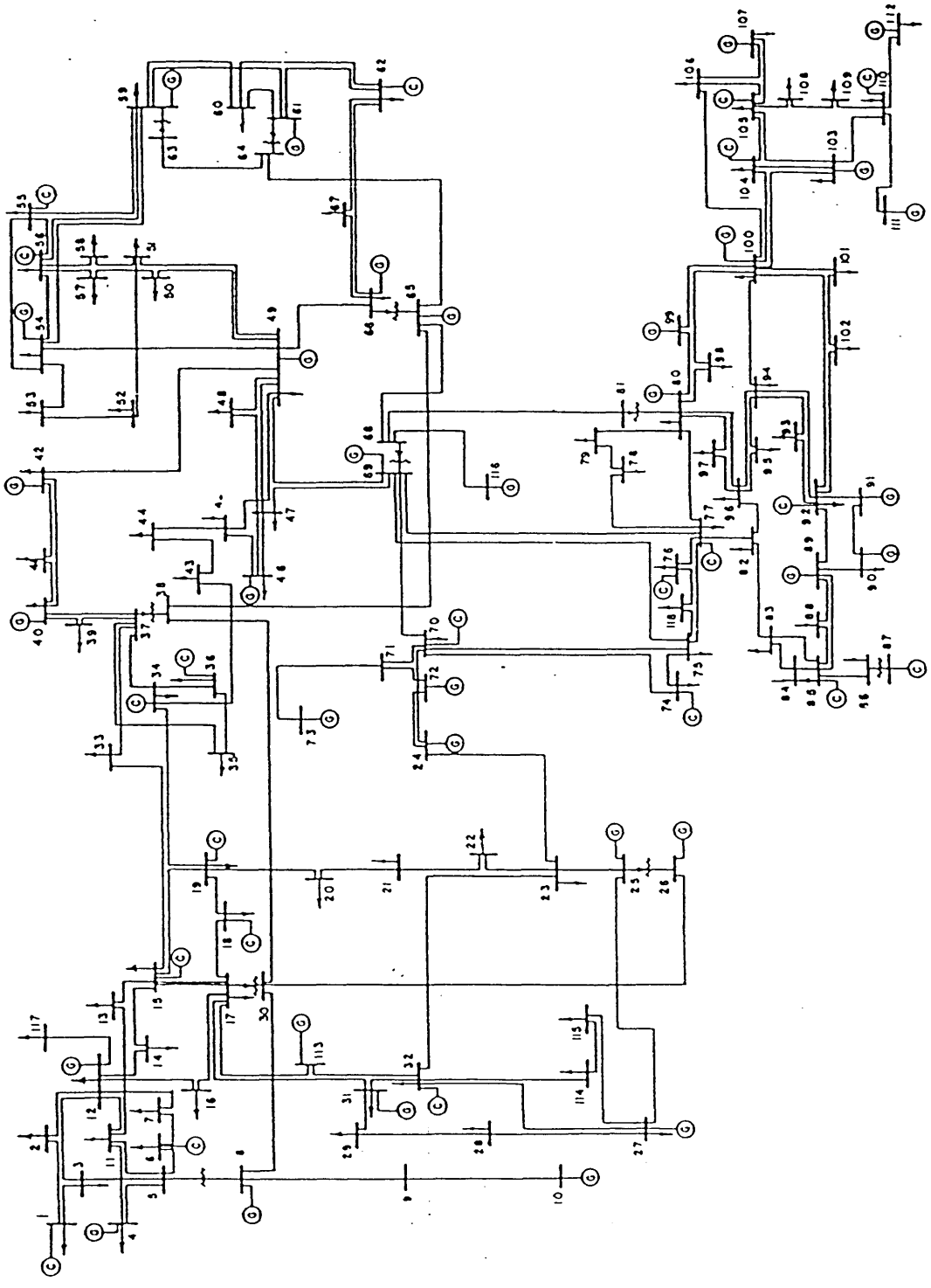


Fig. B.9 IEEE 118-bus test system

Table B.9a IEEE118 Bus Data

B U S B A R D A T A

Busbar No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
1	PV	1.00	.00	.00	51.00	27.00	.00	.00
2	PQ	1.00	.00	.00	20.00	9.00	.00	.00
3	PQ	1.00	.00	.00	39.00	10.00	.00	.00
4	PV	1.00	.00	.00	39.00	12.00	100.00	14.00
5	PQ	1.00	.00	-40.00	.00	.00	.00	.00
6	PV	1.00	.00	.00	52.00	22.00	5.00	18.00
7	PQ	1.00	.00	.00	19.00	2.00	.00	.00
8	PV	1.00	.00	.00	28.00	.00	100.00	-8.00
9	PQ	1.00	.00	.00	.00	.00	.00	.00
10	PV	1.00	.00	.00	.00	.00	100.00	-71.00
11	PQ	1.00	.00	.00	70.00	23.00	.00	.00
12	PV	1.08	.00	.00	47.00	10.00	30.00	75.00
13	PQ	1.00	.00	.00	34.00	16.00	.00	.00
14	PQ	1.00	.00	.00	14.00	1.00	.00	.00
15	PV	1.00	.00	.00	90.00	30.00	5.00	5.00
16	PQ	1.00	.00	.00	25.00	10.00	.00	.00
17	PQ	1.00	.00	.00	11.00	3.00	.00	.00
18	PV	1.00	.00	.00	60.00	34.00	5.00	23.00
19	PV	1.00	.00	.00	45.00	25.00	5.00	14.00
20	PQ	1.00	.00	.00	18.00	3.00	.00	.00
21	PQ	1.00	.00	.00	14.00	8.00	.00	.00
22	PQ	1.00	.00	.00	10.00	5.00	.00	.00
23	PQ	1.00	.00	.00	7.00	3.00	.00	.00
24	PV	1.00	.00	.00	13.00	.00	100.00	91.00
25	PV	1.00	.00	.00	.00	.00	100.00	33.00
26	PV	1.00	.00	.00	.00	.00	300.00	-118.00
27	PV	1.00	.00	.00	71.00	13.00	100.00	9.00
28	PQ	1.00	.00	.00	17.00	7.00	.00	.00
29	PQ	1.00	.00	.00	24.00	4.00	.00	.00
30	PQ	1.00	.00	.00	.00	.00	.00	.00
31	PV	1.00	.00	.00	43.00	27.00	100.00	37.00
32	PV	1.00	.00	.00	59.00	23.00	5.00	12.00
33	PQ	1.00	.00	.00	23.00	9.00	.00	.00
34	PV	1.00	.00	14.00	59.00	26.00	5.00	15.00
35	PQ	1.00	.00	.00	33.00	9.00	.00	.00
36	PV	1.00	.00	.00	31.00	17.00	5.00	-5.00
37	PQ	1.00	.00	-25.00	.00	.00	.00	.00
38	PQ	1.00	.00	.00	.00	.00	.00	.00
39	PQ	1.00	.00	.00	27.00	11.00	.00	.00
40	PV	1.00	.00	.00	66.00	23.00	101.70	-100.00
41	PQ	1.00	.00	.00	37.00	10.00	.00	.00
42	PV	1.00	.00	.00	96.00	23.00	106.60	9.00
43	PQ	1.00	.00	.00	18.00	7.00	.00	.00
44	PQ	1.00	.00	10.00	16.00	8.00	.00	.00
45	PQ	1.00	.00	10.00	53.00	22.00	.00	.00
46	PV	1.00	.00	10.00	28.00	10.00	111.10	-6.00

continue

Table B.9a IEEE118 Bus Data (Continuation)

Busbar No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
47	PQ	1.00	.00	.00	34.00	.00	.00	.00
48	PQ	1.00	.00	15.00	20.00	11.00	.00	.00
49	PV	1.00	.00	.00	87.00	30.00	100.00	139.00
50	PQ	1.00	.00	.00	17.00	4.00	.00	.00
51	PQ	1.00	.00	.00	17.00	8.00	.00	.00
52	PQ	1.00	.00	.00	18.00	5.00	.00	.00
53	PQ	1.00	.00	.00	23.00	11.00	.00	.00
54	PV	1.00	.00	.00	113.00	32.00	109.40	148.00
55	PV	1.00	.00	.00	63.00	22.00	15.00	5.00
56	PV	1.00	.00	.00	84.00	18.00	7.20	-5.00
57	PQ	1.00	.00	.00	12.00	3.00	.00	.00
58	PQ	1.00	.00	.00	12.00	3.00	.00	.00
59	PV	1.00	.00	.00	277.00	113.00	120.10	74.00
60	PQ	1.00	.00	.00	78.00	3.00	.00	.00
61	PV	1.00	.00	.00	.00	.00	205.00	-46.00
62	PV	1.00	.00	.00	77.00	14.00	10.00	2.00
63	PQ	1.00	.00	.00	.00	.00	.00	.00
64	PQ	1.00	.00	.00	.00	.00	.00	.00
65	PV	1.00	.00	.00	.00	.00	100.00	114.00
66	PV	1.00	.00	.00	39.00	18.00	100.00	-28.00
67	PQ	1.00	.00	.00	28.00	7.00	.00	.00
68	PQ	1.00	.00	.00	.00	.00	.00	.00
69	SW	1.00	.00	.00	.00	.00	200.00	.00
70	PV	1.00	.00	.00	66.00	20.00	10.00	.00
71	PQ	1.00	.00	.00	.00	.00	.00	.00
72	PV	1.00	.00	.00	12.00	.00	100.00	-100.00
73	PV	1.00	.00	.00	6.00	.00	100.00	-27.00
74	PV	1.00	.00	12.00	68.00	27.00	5.00	.00
75	PQ	1.00	.00	.00	47.00	11.00	.00	.00
76	PV	1.00	.00	.00	68.00	36.00	.00	8.00
77	PV	1.00	.00	.00	61.00	28.00	30.70	38.00
78	PQ	1.00	.00	.00	71.00	26.00	.00	.00
79	PQ	1.00	.00	20.00	39.00	32.00	.00	.00
80	PV	1.00	.00	.00	130.00	26.00	100.00	-31.00
81	PQ	1.00	.00	.00	.00	.00	.00	.00
82	PQ	1.00	.00	20.00	54.00	27.00	.00	.00
83	PQ	1.00	.00	10.00	20.00	10.00	.00	.00
84	PQ	1.00	.00	.00	11.00	7.00	.00	.00
85	PV	1.00	.00	.00	24.00	15.00	10.00	3.00
86	PQ	1.00	.00	.00	21.00	10.00	.00	.00
87	PV	1.00	.00	.00	.00	.00	124.20	32.00
88	PQ	1.00	.00	.00	48.00	10.00	.00	.00
89	PV	1.00	.00	.00	.00	.00	400.00	-5.00
90	PV	1.00	.00	.00	163.00	42.00	150.70	60.00
91	PV	1.00	.00	.00	10.00	.00	125.60	-19.00
92	PV	1.00	.00	.00	65.00	10.00	10.00	.00
93	PQ	1.00	.00	.00	12.00	7.00	.00	.00
94	PQ	1.00	.00	.00	30.00	16.00	.00	.00

continue

Table B.9a IEEE118 Bus Data (Continuation)

Busbar No.	Busbar Type	Voltage Mag.	Voltage Ang.	Shunt Mvar	Load MW	Load Mvar	Generation MW	Generation Mvar
95	PQ	1.00	.00	.00	42.00	31.00	.00	.00
96	PQ	1.00	.00	.00	38.00	15.00	.00	.00
97	PQ	1.00	.00	.00	15.00	9.00	.00	.00
98	PQ	1.00	.00	.00	34.00	8.00	.00	.00
99	PV	1.00	.00	.00	42.00	.00	124.90	-23.00
100	PV	1.00	.00	.00	37.00	18.00	100.00	300.00
101	PQ	1.00	.00	.00	22.00	15.00	.00	.00
102	PQ	1.00	.00	.00	5.00	3.00	.00	.00
103	PV	1.00	.00	.00	23.00	16.00	18.70	11.00
104	PV	1.00	.00	.00	38.00	25.00	20.00	5.00
105	PV	1.00	.00	20.00	31.00	26.00	20.00	5.00
106	PQ	1.00	.00	.00	43.00	16.00	.00	.00
107	PV	1.00	.00	6.00	50.00	12.00	120.10	.00
108	PQ	1.00	.00	.00	2.00	1.00	.00	.00
109	PQ	1.00	.00	.00	8.00	3.00	.00	.00
110	PV	1.00	.00	6.00	39.00	30.00	.00	1.00
111	PV	1.00	.00	.00	.00	.00	100.00	-8.00
112	PV	1.00	.00	.00	68.00	13.00	118.10	13.00
113	PV	1.00	.00	.00	6.00	.00	100.00	6.00
114	PQ	1.00	.00	.00	8.00	3.00	.00	.00
115	PQ	1.00	.00	.00	22.00	7.00	.00	.00
116	PV	1.00	.00	.00	184.00	.00	250.00	115.00
117	PQ	1.00	.00	.00	20.00	8.00	.00	.00
118	PQ	1.00	.00	.00	33.00	15.00	.00	.00

e&psg

Table B.9b IEEE118 Branch Data

LINE/TRANSFORMER DATA						
branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)
1	1	2	3.03	9.99	2.54	.00
2	1	3	1.29	4.24	1.08	.00
3	2	12	1.87	6.16	1.56	.00
4	3	5	2.41	10.80	2.84	.00
5	3	12	4.84	16.00	4.06	.00
6	4	11	2.09	6.88	1.74	.00
7	4	5	.18	.80	.20	.00
8	5	11	2.03	6.82	1.74	.00
9	5	6	1.19	5.40	1.42	.00
10	6	7	.45	2.08	.54	.00
11	7	12	.86	3.40	.86	.00

continue

Table B.9b IEEE118 Branch Data (Continuation)

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)
12	8	30	.43	5.04	51.40	.00
13	5	8	.00	2.67	.00	95.50
14	8	9	.24	3.05	116.20	.00
15	9	10	.26	3.22	123.50	.00
16	11	12	.59	1.96	.50	.00
17	11	13	2.22	7.31	1.88	.00
18	12	16	2.12	8.34	2.14	.00
19	12	117	3.29	14.00	3.58	.00
20	12	14	2.15	7.07	1.82	.00
21	13	15	7.44	24.44	6.26	.00
22	14	15	5.95	19.50	5.02	.00
23	15	17	1.32	4.37	4.44	.00
24	15	19	1.20	3.94	1.00	.00
25	15	33	3.80	12.44	3.20	.00
26	16	17	4.54	18.01	4.66	.00
27	17	113	.91	3.01	.76	.00
28	17	18	1.23	5.05	1.28	.00
29	17	31	4.74	15.63	4.00	.00
30	18	19	1.11	4.93	1.14	.00
31	19	20	2.52	11.70	2.98	.00
32	19	34	7.52	24.70	6.32	.00
33	20	21	1.83	8.49	2.16	.00
34	21	22	2.09	9.70	2.46	.00
35	22	23	3.42	15.90	4.04	.00
36	23	32	3.17	11.53	11.72	.00
37	23	24	1.35	4.92	4.92	.00
38	23	25	1.56	8.00	8.64	.00
39	24	70	10.22	41.15	10.20	.00
40	24	72	4.88	19.60	4.88	.00
41	25	27	3.18	16.30	17.64	.00
42	26	25	.00	3.82	.00	111.11
43	26	30	.79	8.60	90.80	.00
44	27	32	2.29	7.55	1.92	.00
45	27	115	1.64	7.41	1.98	.00
46	27	28	1.91	8.55	2.16	.00
47	28	29	2.37	9.43	2.38	.00
48	29	31	1.08	3.31	.82	.00
49	30	38	.46	5.40	42.20	.00
50	30	17	.00	3.88	.00	111.11
51	31	32	2.98	9.85	2.50	.00
52	32	113	6.15	20.30	5.18	.00
53	32	114	1.35	6.12	1.62	.00
54	33	37	4.15	14.20	3.66	.00
55	34	36	.87	2.68	.56	.00
56	34	37	.26	.94	.98	.00
57	34	43	4.13	16.81	4.22	.00
58	35	36	.22	1.02	.26	.00
59	35	37	1.10	4.97	1.32	.00

continue

Table B.9b IEEE118 Branch Data (Continuation)

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)
60	37	39	3.21	10.60	2.70	.00
61	37	40	5.93	16.80	4.20	.00
62	38	37	.00	3.75	.00	111.11
63	38	65	.90	9.86	104.60	.00
64	39	40	1.84	6.05	1.54	.00
65	40	41	1.45	4.87	1.22	.00
66	40	42	5.55	18.30	4.66	.00
67	41	42	4.10	13.50	3.44	.00
68	42	49	3.58	16.10	17.20	.00
69	43	44	6.08	24.54	6.06	.00
70	44	45	2.24	9.01	2.42	.00
71	45	46	4.00	13.56	3.33	.00
72	45	49	6.84	18.60	4.44	.00
73	46	47	3.80	12.70	3.16	.00
74	46	48	6.01	18.90	4.72	.00
75	47	49	1.91	6.25	1.60	.00
76	47	69	8.44	27.78	7.10	.00
77	48	49	1.79	5.05	1.26	.00
78	49	50	2.67	7.52	1.86	.00
79	49	51	4.86	13.70	3.42	.00
80	49	66	.90	4.59	4.96	.00
81	49	69	9.85	32.40	8.28	.00
82	49	54	3.98	14.50	14.68	.00
83	50	57	4.74	13.40	3.32	.00
84	51	52	2.03	5.88	1.40	.00
85	51	58	2.55	7.19	1.78	.00
86	52	53	4.05	16.35	4.04	.00
87	53	54	2.63	12.20	3.10	.00
88	54	55	1.69	7.07	2.02	.00
89	54	56	.27	.95	.72	.00
90	54	59	5.03	22.93	5.98	.00
91	55	56	.48	1.51	.38	.00
92	55	59	4.73	21.58	5.64	.00
93	56	57	3.43	9.66	2.42	.00
94	56	58	3.43	9.66	2.42	.00
95	56	59	4.07	12.00	11.14	.00
96	59	60	3.17	14.50	3.76	.00
97	59	61	3.28	15.00	3.88	.00
98	60	61	.26	1.35	1.46	.00
99	60	62	1.23	5.61	1.46	.00
100	61	62	.82	3.76	.98	.00
101	62	66	4.82	21.80	5.78	.00
102	62	67	2.58	11.70	3.10	.00
103	63	64	.17	2.00	21.60	.00
104	63	59	.00	3.86	.00	111.11
105	64	65	.27	3.02	38.00	.00
106	64	61	.00	2.68	.00	90.90
107	65	66	.00	3.70	.00	101.00

continue

Table B.9b IEEE118 Branch Data (Continuation)

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)
108	65	68	.14	1.60	63.80	.00
109	66	67	2.24	10.15	2.68	.00
110	68	116	.03	.40	16.40	.00
111	68	69	.00	3.70	.00	90.50
112	68	81	.17	2.02	80.80	.00
113	69	75	4.05	12.20	12.40	.00
114	69	77	3.09	10.10	10.38	.00
115	69	70	3.00	12.70	12.20	.00
116	70	71	.88	3.55	.86	.00
117	70	74	4.01	13.23	3.36	.00
118	70	75	4.28	14.10	3.60	.00
119	71	72	4.46	18.00	4.44	.00
120	71	73	.87	4.54	1.18	.00
121	74	75	1.23	4.06	1.02	.00
122	75	118	1.45	4.81	1.10	.00
123	75	77	6.01	19.99	4.98	.00
124	76	118	1.64	5.44	1.36	.00
125	76	77	4.44	1.48	3.68	.00
126	77	78	.37	1.24	1.26	.00
127	77	80	1.08	3.31	7.00	.00
128	77	82	2.98	8.53	8.18	.00
129	78	79	.54	2.44	.64	.00
130	79	80	1.56	7.04	1.86	.00
131	80	96	3.56	18.20	4.94	.00
132	80	97	1.83	9.34	2.54	.00
133	80	98	2.38	10.80	2.86	.00
134	80	99	4.54	20.60	5.46	.00
135	81	80	.00	3.70	.00	111.11
136	82	96	1.62	5.30	5.44	.00
137	82	83	1.12	3.66	3.80	.00
138	83	84	6.25	13.20	2.58	.00
139	83	85	4.30	14.80	3.48	.00
140	84	85	3.02	6.41	1.22	.00
141	85	86	3.50	12.30	2.76	.00
142	85	88	2.00	10.20	2.76	.00
143	85	89	2.39	17.30	4.70	.00
144	86	87	2.82	20.74	4.44	.00
145	88	89	1.39	7.12	1.92	.00
146	89	90	1.58	6.53	15.88	.00
147	89	92	.79	3.80	9.62	.00
148	90	91	2.54	8.36	2.14	.00
149	91	92	3.87	12.72	3.26	.00
150	92	93	2.58	8.48	2.18	.00
151	92	94	4.81	15.80	4.06	.00
152	92	100	6.48	29.50	7.72	.00
153	92	102	1.23	5.59	1.46	.00
154	93	94	2.23	7.32	1.88	.00
155	94	95	1.32	4.34	1.10	.00

continue

Table B.9b IEEE118 Branch Data (Continuation)

branch no.	from	to	parameters r (%)	x (%)	b (%)	tap (%)
156	94	96	2.69	8.69	2.30	.00
157	94	100	1.78	5.80	6.04	.00
158	95	96	1.71	5.47	1.48	.00
159	96	97	1.73	8.85	2.40	.00
160	98	100	3.97	17.90	4.76	.00
161	99	100	1.80	8.13	2.16	.00
162	100	101	2.77	12.62	3.28	.00
163	100	103	1.60	5.25	5.36	.00
164	100	104	4.51	20.40	5.40	.00
165	100	106	6.05	22.90	6.20	.00
166	101	102	2.46	11.20	2.94	.00
167	103	110	3.91	18.13	4.60	.00
168	103	104	4.66	15.84	4.06	.00
169	103	105	5.35	16.25	4.08	.00
170	104	105	.99	3.78	.98	.00
171	105	106	1.40	5.47	1.44	.00
172	105	107	5.30	18.30	4.72	.00
173	105	108	2.61	7.03	1.84	.00
174	106	107	5.30	18.30	4.72	.00
175	108	109	1.05	2.88	.76	.00
176	109	110	2.78	7.62	2.02	.00
177	110	111	2.20	7.55	2.00	.00
178	110	112	2.47	6.40	6.20	.00
179	114	115	.23	1.04	.28	.00

e&psg

Table B.9c IEEE118 Operating Limits

bus no.	OPERATING LIMITS Mvar generation Qmin	Qmax	voltage magnitude Vmin	Vmax
a	-100.00	300.00	.90	1.10
b	.00	8.00	.90	1.10
c	-5.00	15.00	.90	1.10
d	-5.00	23.00	.90	1.10
6	-5.00	30.00	.90	1.10
12	-30.00	75.00	.90	1.10
26	-300.00	600.00	.90	1.10
55/56	-5.00	11.00	.90	1.10
69	-9999.99	9999.99	.90	1.10
74	.00	4.00	.90	1.10
77	-10.00	38.00	.90	1.10
105	-5.00	5.00	.90	1.10
110	.00	1.00	.90	1.10
116	-250.00	525.00	.90	1.10
{PQ}	.00	.00	.95	1.10

a={4,8,10,24,25,27,31,40,42,46,49,54,59,61,
65,66,72,73,80,87,89,90,91,99,100,107,
111-113}, b={1,62,70,76,85,92},
c={19,36,103,104}, d={15,18,32,34}
Limits on tcul tap settings:(90%,115%)

e&psg

B.10 THE CEGB 729-BUS 1105-BRANCH SYSTEM

The following dimensions and data reflect the size of the largest system that was used in testing [159].

Dimensions

Number of buses = 729
Number of PV buses = 108
Number of PQ buses = 620
Number of branches = 1105
Number of shunt elements = 199
Number of zones = 13

Summary of Bus Data

Active Power:
Demand(P_L) = 53152. MW
Generation(P_g) = 53967 MW

Fixed Reactive Power:
Demand(Q_L) = 19803. Mvar
Generation(Q_g) = 2806. Mvar

Reactive Regulating Capability
Generation(Q_g^{max}) = 27103 Mvar
Absorption($-Q_g^{min}$) = 9218 Mvar

Summary of Branch Data

Total susceptance = 14882. Mvar
Total shunt gain = 6323. Mvar
Total shunt loss = 1130. Mvar
Total gain = 20075. Mvar
Limits on tcul tap settings = (80%,120%)

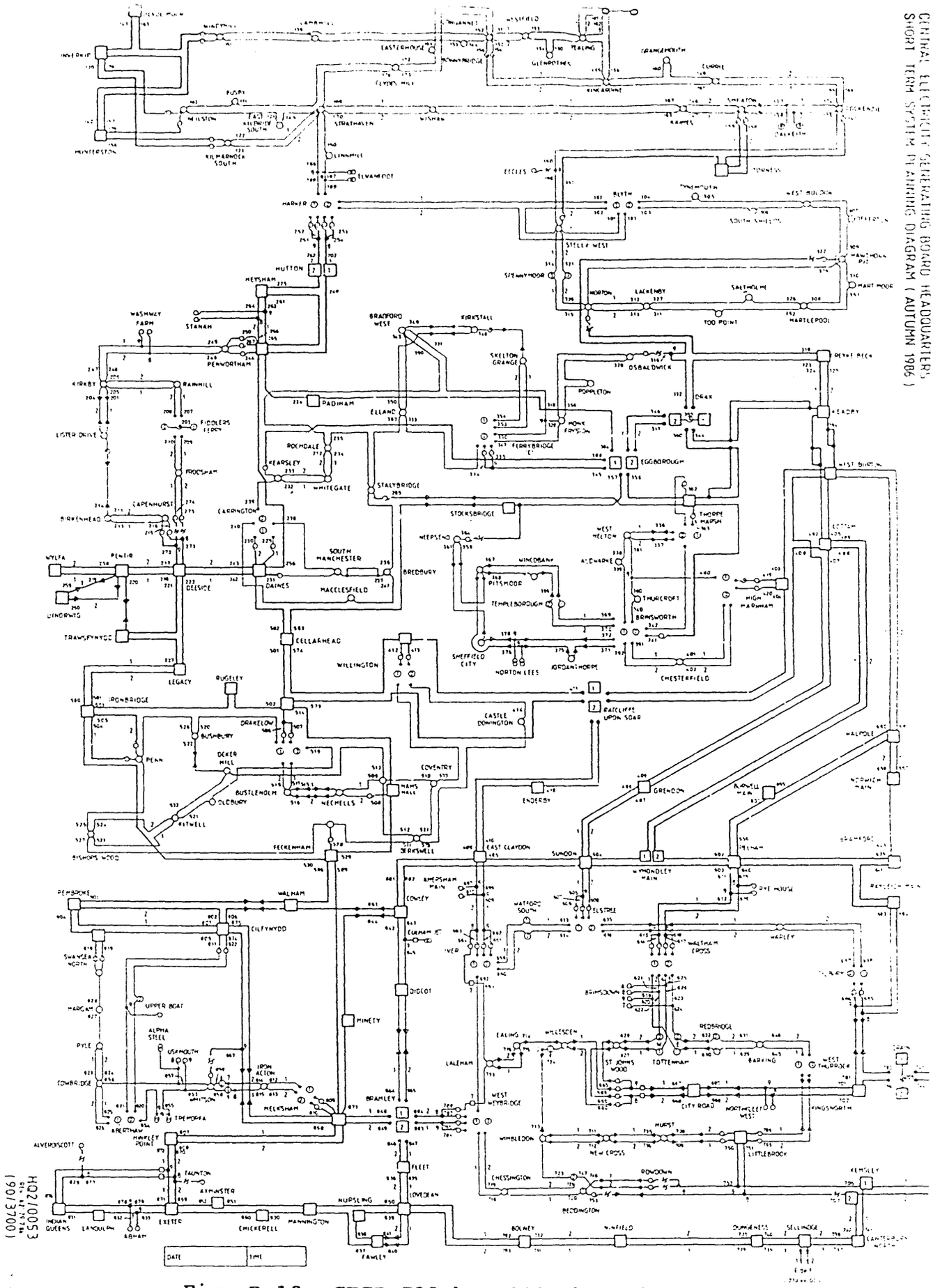


Fig. B.10 CEGB 729-bus 1105-branch system