UNIVERSITY OF LONDON

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

COMPUTER-AIDED DESIGN TECHNIQUES FOR POWER TRANSMISSION SYSTEMS

BY

ARTHUR OBIORA REGINALD EKWUE, B.Sc.(Eng.)

Dr. A. O. EKWUE
School of Engineering + Engineering Technology
Federal University of Technology
P.M.B. 1526, Owerri
NIGERIA

Thesis submitted for the degree of
Doctor of Philosophy in the
Faculty of Engineering.

London, April 1982

ABSTRACT

The increasing complexity of system security functions in relation to numerous national power supply failures in recent years has given rise to the need to provide the system operator with the training and capability to cope with his new role as part of the security control function. The objective of this research, therefore, is the development of fast and efficient algorithms for power system planning and operation.

An interactive computer package has been developed with colour graphics on a dedicated minicomputer for contingency analysis, fault studies and the alleviation of line overload problems.

A decoupled security enhancement algorithm has been developed for line overload alleviation as well as for abnormal system voltages on the load buses. The least-squares minimization technique is used and the various recommended strategies and execution times compared with traditional methods based on linear and non-linear programming techniques. Some advantages of this implementation include its simplicity and fast execution times.

To realise system economic benefits or postpone the need for optimal power flow calculations, static security control has been investigated making prior use of phase-shifters before generation rescheduling. Two algorithms based on linear programming and least-squares minimization methods are proposed and compared. An algorithm for the optimum location of phase-shifters for security analysis has been developed.

In an emergency situation, system security considerations override the economy of operation and the objective is to minimize the curtailment of supply. Hence the problem of load shedding to alleviate transmission line overload is investigated and an algorithm based on integer programming is proposed. This is extended to include partial loss of generation with

shedding of large units of load to maintain acceptable system frequency profile. The effect of including second order Taylor's series expansion on the solution accuracy has been studied.

A near-optimum method using phase-shifters to reinforce a loaded AC network is formulated, thus extending the possible capabilities of phase-shifters in practice. An expanded system has been investigated for security using reliability and single-line outage criteria. A comparison of both schemes is presented for a medium-sized power network.

"Courage lost all is lost
it were better not to have been born".

Von Goethe

ACKNOWLEDGEMENTS

The work presented in this thesis was carried out under the supervision of Dr. M.J. Short, Ph.D., B.Sc., D.I.C., C.Eng., M.I.E.E., M.I.E.E.E., whom I would like to thank for his constant guidance and encouragement.

The author gratefully acknowledges the interest shown by Dr. B.J. Cory, D.Sc.(Eng.), B.Sc. (Eng.), A.C.G.I., C.Eng, F.I.E.E., Sen.M.I.E.E.E., throughout the period of the research and the opportunities given to the author to disseminate some of the ideas described in this thesis to the M.Sc. (Steady-State Power System Analysis) class and a research seminar at the Technical University of Aachen, and Universität Dortmund, West Germany.

The author's gratitude is extended to Prof. E.M. Freeman for the use of his CAD equipment for the initial stages of the project and to his colleagues in the Power System Laboratory for their general assistance, particularly Dr. R.B. Prada.

The financial assistance given to the author by the Association of Commonwealth Universities, U.K. through the award of a research studentship is appreciated.

LIST OF FIGURES

1.1 Computational Aids for Power System Analysis

1.2 System Operating States

2.1 Flowchart for the Security Analysis Program

2.2 Three-phase Fault Analysis

2.3 Modification of Z-matrix

2.4 Addition of a Radial Line from a System Bus to a New Bus

2.5 Bus Tie-breakers

2.6 Simulation of a Closed Bus Tie-breaker

2.7 Short Circuit occurring on Unloaded System

2.8 Sequence Network Connection for a Single Line to Ground Fault

2.9 Fault at a Point F through an Impedance Z_f

2.10 Sequence Network Connection for a SLG Fault through Z_f

2.11 Flowchart for the Fault Analysis Program

2.12 Line-to-line Faults

2.13 Diagrammatic Representation of Line-to-line Faults

2.14 Double Line-to-ground Faults

2.15 Diagrammatic Representation of Double Line-to-ground Faults

3.1 Computer Configuration

3.2 HELP

3.3 Saskatchewan Power Corporation Network

3.4 IEEE 14-bus Network

3.5 IPSAP Heading

3.6 Base Case Results: Display of Voltage Magnitudes and Angles

3.7 Display of Bus Powers

3.8 Display of Power Flows

3.9 Correction of the Overload

3.10 Single-line Outages

3.11 Double-line Outages

3.12 Triple-line Outages

3.13 Line 1-2 Outage - Islanded Case

3.14 IEEE 14-bus Network System: Display of Bus Powers

3.15 Fault Levels (MVA) for a Three-phase Fault

3.16 Postfault Voltages for a Fault on Busbar 1

3.17 Current Flows for Line 3-6 Out

3.18 Single-phase to Ground Faults

4.1 Decoupled Security Enhancement Algorithm Flowchart

4.2 IEEE 24-bus Reliability Network

5.1 IEEE 57-bus Network

6.1 Incremental AC Model for a Phase-shifter between Buses i and j

6.2 Modified IEEE 24-bus Reliability Network

6.3 Modified IEEE 14-bus Network

6.4 Modified SPC Network

6.5 Flowchart of the Program

7.1 New Network Configuration

7.2 Flowchart for the Transmission Expansion Planning Algorithm: Single-line Outage Security Criterion

7.3 Flowchart of the Program with Reliability Concepts

8.1 Graph of log t against log (NB)

8.2 IEEE 118-bus Test System

8.3 Network Equivalents of the 118-IEEE System

A3.1 Physical Interpretation of Least-squares

A5.1 A Two-part Network

A5.2 Its Adjoint Network

LIST OF SYMBOLS

NB	number of System busbars
[J]	Jacobian matrix
S_i	complex power at bus i
P_i	real power at bus i
P_i^{sp}	specified real power at bus i
Q_i	reactive real power at bus i
Q_i^{sp}	specified reactive power at bus i
V_i	voltage at bus i
V_i^{sp}	rated voltage at bus i
δ_i	voltage angle at bus i
ψ_{ij}	phase shifting transformer angle between buses i and j
Y_{ij}	admittance between buses i and j
R_{ij}	resistance of the line between buses i and j
X_{ij}	reactance of the line between buses i and j
G_{ij}	conductance of the line between buses i and j
B_{ij}	susceptance of the line between buses i and j
θ_{ij}	impedance angle $(\tan^{-1} \frac{X_{ij}}{R_{ij}})$
Δ	incremental change
NL	number of lines in the system
$\frac{\partial I_{ij}}{\partial \delta_i}$	partial derivative of I_{ij} with respect to δ_i
V_i^{max}, V_i^{min}	maximum and minimum voltage limits at bus i
ψ_{ij}^{max}, V_{ij}^{min}	maximum and minimum phase angles of the transformer between buses i and j respectively

P_L	real load component
Q_L	reactive load component
P_g, P_g^{max}	generated real power and its maximum respectively
Q_g	generated reactive power
Q_i^m	upper limit of the reactive power generated on bus i
Q_i^m	lower limit of the reactive power generated on bus i
SPC	Saskatchewan Power Corporation
I_{ij}	current in line between buses i and j
I_{ij}^{max}	current magnitude between buses i and j
[Z]	bus impedance matrix
[Y]	bus admittance matrix
V_a	Voltage on phase a
I_a	line current on phase a
I_{ao}, I_{a1}, I_{a2}	zero, positive and negative sequence currents of I_a
Va_o, V_{a1}, V_{a2}	zero, positive and negative sequence voltages of V_a
Z_f	fault impedance
Z_o, Z_1, Z_2	zero, positive and negative sequence impedances
MVA	mega-volt-ampere
MW	mega-watt
MVAR	mega-volt-ampere-reactive
kV	Kilovolt
PQ	fixed P and Q busbar
PV	fixed P and V busbar
$\bar{\delta}$	adjoint bus angles

LIST OF TABLES

3.1A	Nodal Data for the 6-bus SPC network
3.1B	Regulated bus data
3.1C	Line data
3.1D	Voltage Correction Devices
3.2A	Nodal Data for the IEEE 14-bus Network
3.2B	Regulated bus data
3.2C	Line data
3.2D	Transformer data
3.2E	Voltage correction devices
3.3A	Bus data for the 6-bus network used for fault studies
3.3B	Line data
3.3C	Transformer data
4.1	Results of Experiment 1
4.2	Results of Experiment 2
4.3	Results of Experiment 3
4.4	Computer storage requirements
5.1	Results of the 14-bus IEEE network: Experiment 1
5.2	Results of the 24-bus IEEE network: Experiment 1
5.3	Results of Test 1
5.4	Results of Test 2
5.5	Tests with the 24-bus network: Experiment 1
5.6	Tests with the 24-bus network: Experiment 2
5.7	Tests with the 57-bus network: Experiment 1
5.8	Tests with the 57-bus network: Experiment 2
5.9	Tests with the 57-bus network: Experiment 3
6.1	Modified IEEE 24-bus: MW flows for 1 degree phase-shift
6.2	Modified IEEE 24-bus: MW flows
6.3	Modified IEEE 14-bus: MW flows for 1 degree phase-shift

6.4 Modified IEEE 14-bus: MW flows for 1 degree phase-shift

6.5 Modified SPC network: MW flows for 1 degree phase-shift

6.6 Modified SPC network: MW flows for 1 degree phase-shift

6.7 Network data for the interconnecting system for the modified 24-bus system

6.8 Network data for the interconnecting system of the modified 14-bus network

6.9 Network data for the interconnecting system of the 7-bus network

6.10 Modified IEEE 24-bus network results

6.11 Modified IEEE 14-bus network results

6.12 Modified SPC network results

6.13 Optimum phase-shifter location results

7.1 Data for the interconnecting circuits

7.2 Results of the nominal network design

7.3 Single-line outage results

7.4 Effect of phase-shifters

7.5 Variation of J with 1 degree phase-shift

7.6 Computation of estimated overload probabilities

7.7A Nodal data for IEEE 24-bus system

7.7B Regulated bus data (Real)

7.7C Regulated bus data (Reactive)

7.7D Line data

8.1 Comparison of the solution times (in seconds) for the fast decoupled loadflow

CONTENTS

			Page
ABSTRACT			2
ACKNOWLEDGEMENTS			5
LIST OF FIGURES			6
LIST OF SYMBOLS			8
LIST OF TABLES			10
CHAPTER 1:		INTRODUCTION	19
	1.1	APPLICATION OF INTERACTIVE COMPUTER GRAPHICS TO POWER SYSTEM ANALYSIS	19
	1.2	COMPUTER-AIDED-DISPATCH FOR POWER SYSTEMS	21
		1.2.1 Concepts of Security	21
		1.2.2 Economic Considerations	23
		1.2.3 Environmental Pollution	23
	1.3	TRANSMISSION SYSTEM PLANNING CONSIDERATIONS	24
	1.4	SUMMARY OF THE THESIS AND CONTRIBUTIONS	26
	1.5	CONCLUSION	29
CHAPTER 2:		DEVELOPMENT OF ALGORITHMS FOR INTERACTIVE USE	32
	2.0	INTRODUCTION	32
	2.1	SECURITY ANALYSIS	32
		2.1.1 Fast-decoupled Loadflow Method	34
		2.1.2 Multiple Line Outages	40
		2.1.3 Generator Outages	40
		2.1.4 Automatic Contingency Evaluation	41

		Page
2.2	FAULT ANALYSIS	44
	2.2.1 Three-phase Fault Analysis by Sequence Components Approach	46
	- Line changes	48
	- Transformer outages	49
	- Busbar additions	49
	- Bus tie-breakers	49
	2.2.2 Analysis of Single Phase-to-ground (SLG) Faults	50
	2.2.3 Analysis of Line-to-line Faults	53
	2.2.4 Analysis of Double-line-to-ground Faults	54
2.3	CONCLUSION	55
CHAPTER 3:	PRACTICAL IMPLEMENTATION OF IPSAP AND RESULTS	64
3.0	INTRODUCTION	64
3.1	COMPUTER CONFIGURATION	64
3.2	BENEFITS OF COLOUR GRAPHICS	65
3.3	DESCRIPTION OF NETWORK DRAWING TECHNIQUES	65
3.4	IMPLEMENTATION OF IPSAP ON A MONOCHROMATIC DISPLAY MONITOR	66
3.5	DISCUSSION OF RESULTS	66
3.6	EXAMPLE OF TERMINAL SESSION	72
3.7	CONCLUSION	72
CHAPTER 4:	SECURITY ENHANCEMENT	96
4.0	INTRODUCTION	96
4.1	MATHEMATICAL FORMULATION OF THE DECOUPLED SECURITY ENHANCEMENT ALGORITHM (DSEA)	98

		Page
	4.1.1 Line Overload Problem	98
	4.1.2 Abnormal System Voltage Problem	101
	4.1.3 Program Development	104
4.2	TESTS AND RESULTS	104
	4.2.1 6-bus Saskatchewan Power Corporation Network	105
	4.2.2 14-bus IEEE Network	105
4.3	COMPARISON OF METHODS	107
	4.3.1 Linear-programming Method	107
	4.3.2 Non-linear Programming Method	108
4.4	DISCUSSION OF RESULTS	113
4.5	CONCLUSION	114
CHAPTER 5:	INVESTIGATION OF THE LOAD SHEDDING PROBLEM	117
5.0	INTRODUCTION	117
5.1	MATHEMATICAL DEVELOPMENT	119
	5.1.1 Approximate Solution	121
5.2	TESTS AND RESULTS	121
	5.2.1 14-bus IEEE Network	121
	5.2.2 24-bus IEEE Reliability Network	122
	5.2.3 57-bus IEEE Network	123
5.3	INVESTIGATION OF THE EFFECT OF USING A SECOND ORDER TAYLOR'S SERIES EXPANSION ON THE SOLUTION ACCURACY	127
5.4	PARTIAL LOSS OF GENERATION	128
	5.4.1 Tests with IEEE 24-bus Network	129
	5.4.2 Tests with IEEE 57-bus Network	131
5.5	DISCUSSION OF RESULTS	133
5.6	PRACTICAL APPLICATIONS OF LOADSHEDDING ALGORITHMS	133
5.7	CONCLUSION	133

		Page
CHAPTER 6:	STATIC SECURITY CONTROL VIA PHASE-SHIFTERS	136
6.0	INTRODUCTION	136
6.1	INFLUENCE OF PHASE-SHIFTER SETTINGS ON MW POWER FLOWS	138
6.1.1	Modified 24-bus IEEE Reliability System	138
6.1.2	Modified 14-bus IEEE Network	138
6.1.3	6-bus Saskatchewan Power Corporation System (SPC)	139
6.2	PARTICIPATION OF PHASE-SHIFTERS IN POWER SYSTEM CONTROL	139
6.2.1	A-priori Operation of Phase-shifters	142
A.	Mathematical Development	142
B.	Methods of Solution	144
	- Linear programming	144
	- Least-squares	145
C.	Tests and Results	145
D.	Discussion of Results	145
6.3	ECONOMIC BENEFITS OF INCORPORATING PHASE-SHIFTERS IN SYSTEM INTERCONNECTIONS	150
6.4	OPTIMUM DESIGN OF PHASE-SHIFTER LOCATIONS FOR SECURITY ANALYSIS	151
6.5	CONCLUSION	154
CHAPTER 7:	TRANSMISSION SYSTEM EXPANSION PLANNING USING PHASE-SHIFTERS	166
7.0	INTRODUCTION	166
7.1	NOMINAL NETWORK DESIGN	169
7.1.1	Determination of the Interconnecting Busbars of the New Transmission Circuits	169

Page

7.1.2 Static Optimization Formulation 170

7.1.3 Case Study: IEEE 24-bus System 172

7.2 NETWORK DESIGN WITH SECURITY CONSIDERATIONS 174

7.2.1 DC Powerflow Contingency Analysis 174

7.2.2 Case Study: IEEE 24-bus System (modified) 175

7.2.3 Effect of Phase-shifters 177

7.3 NETWORK DESIGN WITH RELIABILITY CONCEPTS 178

7.3.1 Stochastic Security Analysis 181

7.3.2 Calculation of Probabilities of Failure at Consumer Load Points 185

7.3.3 Case Study: IEEE 24-bus System (modified) 187

7.4 COMPARISON OF METHODS 190

7.5 ROLE OF THE PLANNER 190

7.6 CONCLUSION 191

CHAPTER 8: CONCLUSION 200

8.1 CONCLUDING REMARKS 200

8.1.1 Computer-aided Dispatch for Security Evaluation 200

8.1.2 Transmission System Expansion Planning 202

8.1.3 Computing Systems Used 202

8.2 PRACTICAL LIMITATIONS OF IPSAP AND METHODS FOR FUTURE EXTENSION 206

8.3 SUGGESTIONS FOR FUTURE DEVELOPMENT 208

REFERENCES 210

APPENDIX 1 227

APPENDIX 2 235

APPENDIX 3 237

APPENDIX 4 239

APPENDIX 5 242

APPENDIX 6 244

APPENDIX 7 248

APPENDIX

1. IPSAP User's Manual
2. Physical Meaning of least-squares
3. Linear Relationship between line current and state variables
4. Formulation of the load shedding problem for integer programming to be used by the NAG routine
5. Development of the adjoint network of circuits
6. Problem formulation of the adjoint network equations for power system transmission planning
7. Table of Error Function

CHAPTER 1

INTRODUCTION

1.1 APPLICATIONS OF INTERACTIVE COMPUTER GRAPHICS TO POWER SYSTEM ANALYSIS

The need for enhanced security assessment, better control of power systems and optimised transmission expansion planning has resulted from the growing complexity of integrated power systems and the occurrence of several major national failures in recent years. The system operator has been recognised as an integral part of the security control function. To ensure that the reliability of the system is maintained, Dopazo et al [1] have suggested "that the operator will need to have improved security assessment and control capability together with the necessary training to carry out the enhanced functions". This requires the availability of fast computational methods to determine power system performance under normal and faulted conditions. Although digital computing methods have replaced analog computers for system analysis, batch processing requires a large paper output, has slow turnaround, and so is unsatisfactory for operational purposes where instant decisions are required. More satisfactory approaches are based on interactive computing.

Undrill et al [2] have defined an interactive computer program as "one that allows the engineer to exercise his ability to make decisions on the course of the run to optimize its future progress" and "maintain a dialogue between the computation and the engineer" who, as discussed above, becomes a major component of any real-time control system. One of the earliest applications of interactive computing to power system analysis described by Adams and Laughton [3] resulted in programs developed on time-sharing computing systems for loadflow and fault studies. Interactive programs for transient stability have also been described by Short [4].

These early interactive programs lacked direct graphical interpretation of results and, moreover, time-sharing systems have comparatively slow turnaround. Also the response times vary depending on the number of users connected to the host computer at any one moment. Engineers often prefer to communicate graphically, hence the urgent need to extend these interactive programs to include graphics so that results would be much easier to assimilate and the paper output appreciably reduced. Computational aids are outlined in Fig. 1.1.

The loadflow study, being very important to power system planning and operating engineers, has been the subject of numerous interactive programs developed and widely reported by several authors [5-9]. To serve the particular needs of a wide variety of engineers and institutions of higher learning, a user-oriented power system analysis package was developed in the University of Manchester, Institute of Science and Technology (UMIST) to be used by engineers without a computing background. Lynch and Efthymiadis [10,11] have described interactive computer graphics applied to loadflow and short-circuit problems which were later extended to include transient stability studies [12]. Khan and Bickford [13] have also described power system transient voltage and current waveform computations. The UMIST package can be utilized for the design of electrical networks: particularly interconnected low-voltage distribution systems. The programs were implemented via a Tektronic 4010/4014 storage tube VDU connected to the main PDP 10 computer. As the storage tube lacks hardware refresh facilities a component can only be deleted by redrawing the entire network on the screen.

In this thesis, an interactive minicomputer package is described having colour graphics for power system operational studies such as loadflows and contingency extension, security enhancement and fault analysis. Details of this development are given in Chapters 2, 3 and 4. A paper on the work

done in Chapters 2 and 3 has been presented by the author at a recent International Conference on Engineering Software [14].

1.2 COMPUTER-AIDED DISPATCH FOR POWER SYSTEMS

The design of a power system requires that the load forecast, generation additions and transmission and distribution additions must be planned before the operating strategies are devised. The power produced by generators is injected into the network to supply the load or neighbouring systems. The production of this power and the flows are governed by variables which can either be varied continuously or in discrete steps. Talukdar and Wu [15] have described dispatching as being "to encompass the scheduling of the essentially continuous variables". The emerging concerns in dispatching can be grouped under: security, cost and emissions. The following sections consider each in detail.

1.2.1 Concepts of Security

Dy Liacco [16] has defined security control "as a system of integrated automatic and normal controls for the maintenance of electric power service under all conditions of operation". The power system may be assumed as being operated under conditions expressible in the form of two sets of constraints as given by Dy Liacco [16] and Prada [17]:

$$\left.\begin{array}{lll} G(X,U) & = \phi & \text{load constraints} \\ H(X,U) & \geq \phi & \text{operating constraints} \end{array}\right\} \quad (1.1)$$

where G and H are function vectors and x-the vector of dependent variables while U - the vector of independent or "control" variables.

Fundamentally, the load constraints impose the physical equations which satisfy the requirements that the load demands will be met by the system, while the operating constraints impose maximum or minimum operating limits (e.g. line and voltage limits) on variables associated with the component parts of the system.

Dy Liacco [16] defined three operating states of a power system as normal, emergency and restorative. This idea has been extended by Fink and Carlsen [18] to define the system in five states : normal operating state, alert, emergency, in-extremis and restorative as shown in Fig. 1.2. In the normal operating state, all the constraints are satisfied, i.e. the generation is adequate to supply the load with no equipment overload in the system; the reserve margins are sufficient to provide an adequate level of security with respect to the stresses to which the system may be subjected.

If the security falls below an acceptable level or if the probability of disturbance increases, the system enters the alert state. All constraints are satisfied though some overloads may result as the reserve margins may not be sufficient. Preventive actions are required to restore the system to its normal state. If a sufficiently severe disturbance takes place before such preventive actions can be taken, the system enters the emergency state. The system, however, would still be intact with the emergency control actions stated by Knight [19] initiated to restore the system to at least the alert state.

If these measures are not taken in time or are ineffective, and if the initiating disturbance or a subsequent one is severe enough to stress the system, disintegration of the system results with the network in the "in-extremis" state. Both constraints in equation (1.1) are violated and the system would no longer be intact and major portions of the load would be lost. Emergency control actions should be directed towards "salvaging" as many pieces of the system as possible from total collapse which once halted, the system enters the restorative state if there were any remaining equipment operating within their rated capacity or some equipment had been restarted following the total collapse. The control actions would be taken to pick up all lost load and reconnect the system which would transit to either the alert or to the normal state depending on the circumstances.

1.2.2 Economic Considerations

There are three types of generating plant which can be considered: nuclear, hydro and fossil (coal, oil and gas). The generation costs associated with a particular type can be identified by its capital, fixed and operating costs.

The capital cost of a generating plant is the total sum of capital which must be invested in it whereas fixed costs include maintenance, management, insurance, etc. and operating costs are those incurred when the plant is operated and includes the fuel costs and the variable maintenance and labour charges.

Nuclear generating plants are usually operated at constant output levels and hydrogenerators have no variable operating costs. The costs usually required for dispatching are costs of the fuels burned in fossil plants.

1.2.3 Environmental Pollution

Where dispatching is concerned the pollutants affecting air quality are of interest; others affecting water quality are frequently neglected. Cadogan and Eisenberg [20] developed a method for the management of sulphurdioxide emissions from fossil fuel-fired generating stations which can be included in contingency evaluation, during periods of shortage of low sulphur fuel or during air pollution emergencies. The method enables sulphur pollutants to be reduced taking it into account in dispatching procedures. However, the method is rarely used except in areas of high pollution. Existing regulations in utilities place limits on the plants emissions per Btu of fuel burned which utilities meet through appropriate fuel selection and the installation of pollution control hardware.

1.3 TRANSMISSION SYSTEM PLANNING CONSIDERATIONS

The transmission lines tie the power system together and are responsible for the transfer of energy from the generating stations to load centres. The design of these systems for the required performance require that the penalties of overdesign and waste of money, or underdesign with poor reliability and high losses, should be avoided. The decision to build an EHV line will result from system studies on how best to meet the load forecast for the immediate future and in the light of long-range plans for the growth of the system.

Some of the factors usually considered are:

(i) The availability and cost of the rights-of-way: It is necessary to determine the attitudes, farming practices and religious beliefs of the local property owners. Environmental studies are required to determine any hazards to the land and to people in the immediate neighbourhood.

(ii) Insulation and conductor arrangement: The insulation of the line must be designed to withstand switching surges, impulses caused by lighting and the reduction of electrical strength caused by contamination of the insulators. Other design factors include conductor size, conductivity, and number of conductors per phase that affect tower loading as well as the I^2R loss, corona loss and radio interference effects.

(iii) Effects of weather conditions.

(iv) Type of transmission line required: The questions to be answered include: Underground or Overhead transmission? AC or DC?

Underground HV (69 to 345 KV) transmission is used in metropolitan areas where land is either too costly or is unavailable for overhead lines or where aesthetic, political or social considerations make overhead lines unacceptable.

HVDC transmission can be a viable alternative to conventional AC transmission where [21]:

(a) there are long distances between generation and load centres;

(b) asynchronous ties are required;

(c) underground or underwater cables of considerable length are necessary.

Alternatively, the advantages for ac transmission include:

(a) suitability for large-capacity generators;

(b) ease of voltage transformation.

However, Roy [22] describes developments which are underway on high-voltage overhead lines, dc breakers, improved sensors and compact substations to permit HVDC to play an ever-greater role in future power transmission. The experience of a utility (British-Columbia Hydro) has been described by Hardy et al [23].

(v) Transmission system reliability (see Endrenyi [24]):
The function of a power system is to satisfy the system load as economically as possible with an acceptable level of service quality, hence redundant elements should be present to satisfy these objectives. The security of the network should be accounted for in the design by ensuring that satisfactory performance is maintained

when subjected to credible line outages. The reliability aspect ensures that quantitative assessment of possible component outages on the system performance is carried out.

(vi) Economic Considerations (see Roy [22]):
Each transmission line option must be evaluated, taking into account the annual investments required for the project which is a function of the inflation rates and anticipated technological progress. The costs associated with losses in energy and power, operation and maintenance are added. The present worth of these costs would serve as an economic appraisal of each scheme.

1.4 SUMMARY OF THE THESIS AND CONTRIBUTIONS

This thesis is concerned with computer methods for steady-state power system security evaluation and transmission system expansion planning.

In Chapter 2, the mathematical formulations of the security analysis problem by loadflow methods and fault analysis are presented. The modifications required to achieve computational speed with reduction in computer storage requirement with acceptable solution accuracies are described. The concepts of automatic contingency evaluation are discussed and applications for line overload and voltage problems clearly shown.

Chapter 3 presents the practical implementation of the Interactive Power System Analysis Package (IPSAP) developed using the mathematical formulations of the previous chapter. The computer configuration used is described and applications of colour graphics shown. Network drawing techniques are shown and results of tests carried out on the 6-bus Saskatchewan Power Corporation network and the IEEE 14-bus are presented. Consequent implementation of IPSAP for a black and white video monitor is

described.

In Chapter 4, security enhancement procedures are reviewed and a decoupled security enhancement algorithm based on a least-squares minimization technique for the alleviation of a line overload problem and abnormal load voltages is proposed. The performance of the algorithm in terms of computer storage, execution time and various suggested control strategies is compared with those obtained using linear and non-linear programming techniques. Several tests have been carried out on the 6-bus SPC system, 14-bus and 24-bus IEEE networks with satisfactory results.

In Chapter 5, the load shedding problem is investigated and an algorithm based on integer programming proposed. Tests have been carried out on the 14-bus, 24-bus and 57-bus IEEE systems with the program extended to take into account load shedding as a result of loss of generating units in the system. Effect of incorporating second order Taylor's series expansion is investigated.

The use of phase-shifters for static security control is investigated in Chapter 6. Two algorithms based on linear programming and the least-squares minimization techniques are proposed and compared using the 6-bus SPC, 14-bus and the 24-bus networks. An optimum design of phase-shifter network structures for security analysis are proposed. The economic benefits of incorporating phase-shifters in system interconnections is presented.

A transmission system expansion planning procedure using phase-shifters is proposed in Chapter 7, using the adjoint network formulations and the steepest descent algorithm to design the nominal network. Reinforcements for security are considered using single-line outage and reliability criteria. These enable the comparison of qualitative and quantitative methods of system expansion. The role of the planner is stated.

Concluding remarks and scope for further work on the subjects presented in this thesis are presented in Chapter 8.

The contributions of this thesis are:

(1) Development of a power system package with colour graphics on a dedicated minicomputer for loadflows (extended to security studies), security enhancement and fault analysis.

(2) Development of a decoupled security enhancement program for transmission line overload alleviation and correction of abnormal system voltages on the load buses. The performance of this algorithm is compared with the control strategies obtained using linear and non-linear programming methods.

(3) The development of an integer-programming based algorithm for optimum load shedding schemes:
   - the algorithm is extended to include partial loss of generation with shedding of large blocks of load to maintain an acceptable frequency profile;
   - The investigation of the effect of including second order Taylor's series expansion in the solution accuracy.

(4) Analytical investigations into how best to represent phase-shifters in a power system centralised control environment.

(5) Proposal of two algorithms based on linear programming and least-squares minimization techniques to reduce or eliminate system overloads by a priori operation of phase-shifters. The performance of the two formulations is evaluated.

(6) Proposal of an algorithm for the optimum location of phase-shifters for security analysis.

(7) A near-optimum method for reinforcing a load AC network is proposed and the expanded system further investigated for security, using reliability and single-line outage criteria. The resulting designs are compared using a medium-sized power network.

1.5 CONCLUSION

This introductory chapter reviews the application of interactive computer graphics to power system analysis and the concept of security control. Transmission planning considerations and the contributions of this thesis have been outlined.

The work undertaken has been influenced to some extent by the characteristics and requirements of the author's own power system in Nigeria: lack of an improved modern control centre, line overloads and abnormal system voltages combine to produce frequent curtailment of supply to consumers. With a load growth of about 20% per annum, the transmission system expansion method with phase-shifters developed in Chapter 7 would determine optimum transmission requirements of that utility during the planning horizon. This method was not tested with real-data from the Nigerian utility as attempts made by the author to obtain the relevant information from his colleagues through personal contacts were unsuccessful.

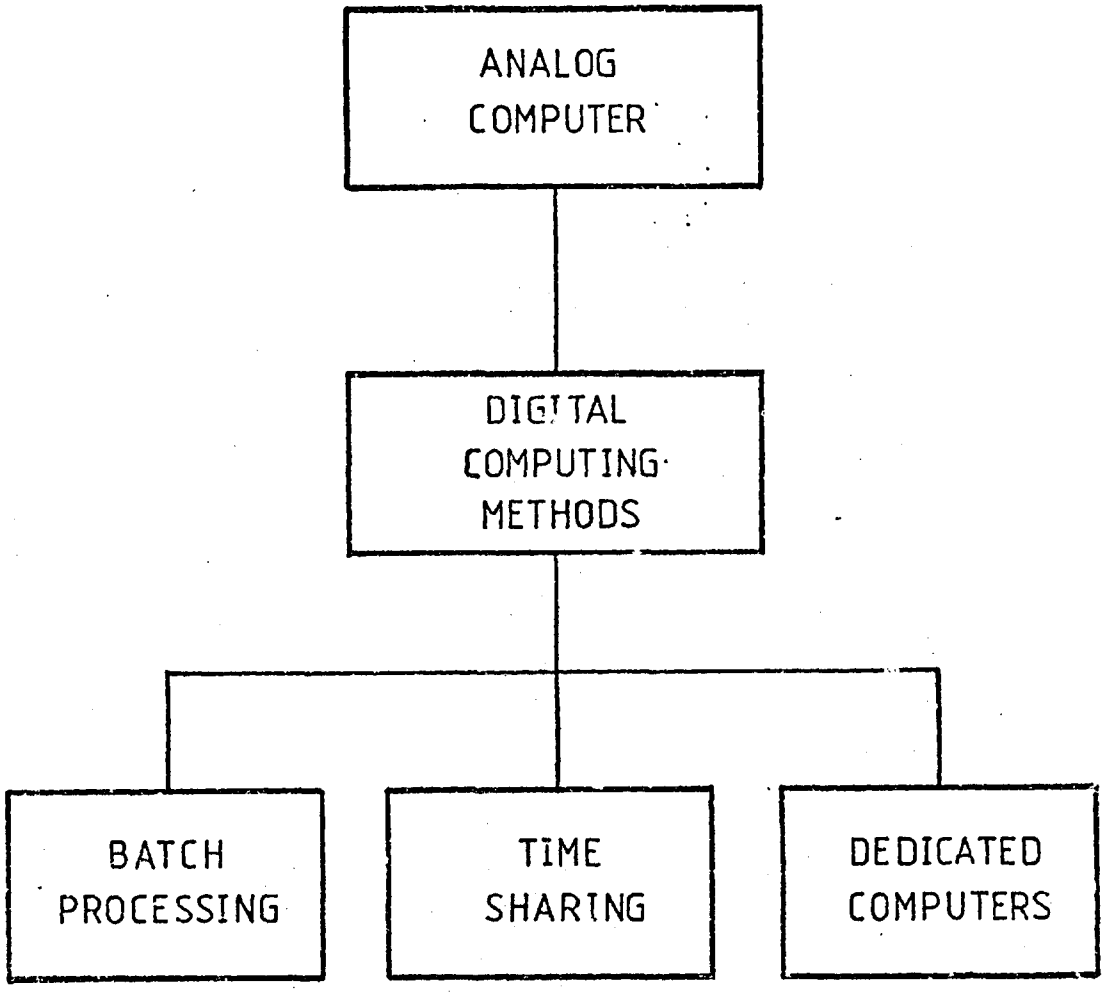


Fig. 1.1: Computational Aids for Power System Analysis.

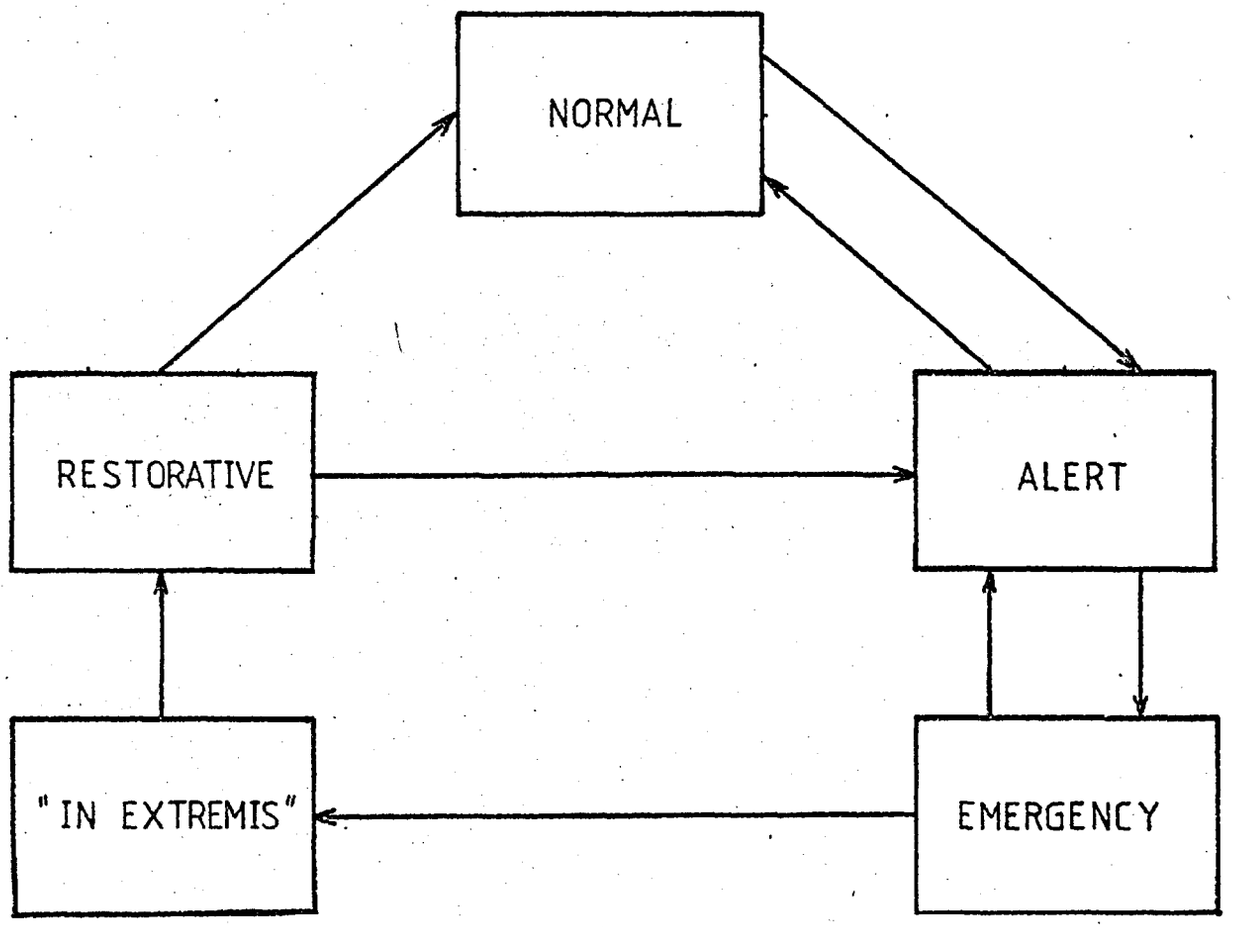


Fig. 1.2: System Operating States

CHAPTER 2

DEVELOPMENT OF ALGORITHMS FOR INTERACTIVE USE

2.0 INTRODUCTION

In the previous chapter, a review of the application of interactive computer graphics to power system analysis was presented. Two reasons for further development of an interactive package are (i) most of the available computer systems are part of power system control installations and may not serve the needs of other users and (ii) there are difficulties in providing facilities ergonomically acceptable to the majority of engineers.

The algorithms for interactive use must satisfy speed requirements so as to reduce the interaction time to make them appropriate for real-time purposes. The algorithms should also be reliable, require minimum computer storage and have wide applicability.

In this chapter, the mathematical formulations of the security analysis problem by loadflow methods and fault analysis are presented. The flowcharts of the computer programs are shown. The computer programs are written in standard FORTRAN IV to minimize the modifications necessary when implemented with a variety of graphics packages or display terminals.

2.1 Security Analysis

The security assessments of a power system are usually made off-line in system and operational planning and on-line in the operation and control of a power system as well as in interactive work to ensure that the network is maintained in a normal state of operation as long as possible. Two characteristic functions of these assessments are:

(a) Security monitoring of the system, which determines the actual state of the network on a minute-by-minute basis and shows if a system is secure or insecure. Achievement of this objective makes use of the statistical theory of state estimation to process the network data and produce the best estimates of the bus voltage values.

(b) Security analysis, which simulates the behaviour of the system for credible outages and supplies the information required for preventive actions where insecurity is detected. Each contingency in a normal condition may result in transients which are capable of leading to loss of generator synchronism, hence two modes of analysis are required: steady-state and transient security evaluations. Fast corrective actions are of immense importance when there is insecurity due to transmission line, transformer or generator outages. A cascade of outages is possible.

According to Debs and Benson in [25] transmission line outages may occur as a result of:

(i) weather conditions (lightning, storms, etc.),
(ii) operator errors,
(iii) relay malfunctioning,
(iv) maintenance operations, and
(v) accidents, such as careless drivers hitting transmission poles, etc.

Loadflow techniques have been widely used in the evaluation process to test all contingencies, thus determining the reliability and performance of the power system. These methods have been reviewed by Stott in [26].

A second approach to studying the contingency problem is through pattern recognition. Pang et al in [27], stated that a large number of off-line simulations can be performed to form a "training set". An on-line classifier when applied to the actual system compares with the training set to determine if the system is secure or not. This method is disadvantageous in that very significant engineering time is required for these off-line simulations and for networks which deviate from the training set accurate security evaluation may be impossible.

The above loadflow and pattern recognition methods when used in an off-line situation select the outages to be studied from a pre-specified set of credible contingencies. For an on-line application this is not a suitable approach. A development of "a priori" contingency selection has been suggested by Ejebe and Wollenberg in [28] and is discussed in section 2.1.4 below. The aim is to produce an algorithm which can be applied off-line or on-line to determine the credible outages to be studied. The fast-decoupled loadflow method has been used for security analysis.

2.1.1 Fast-decoupled Loadflow Method

The interactive program written for the security evaluation of power systems uses the fast-decoupled loadflow method developed by Stott and Alsac in [29] because it is simple and very reliable with a wide range of practical applications. The mathematical development of the method is as follows:

Classically, the Newton-Raphson method is an iterative process for solving a set of simultaneous non-linear equations of the form:

$$f(X) = \phi.\phi \tag{2.1}$$

which is linearized to

$$f(X^K) = - [J] [\Delta X^K] \tag{2.2}$$

where K is the iterative index. Equation (2.2) is solved for ΔX^K.

X^K is then updated to X^{K+1} as

$$X^{K+1} = X^K + \Delta X^K \tag{2.3}$$

An iterative format is thus established from equations (2.2) and (2.3) for the computer solution as

$$X^{K+1} = X^K - [J]^{-1} f(X^K) \tag{2.4}$$

In loadflow analysis, the Jacobian matrix [J] is highly sparse for large networks and this improves the speed of the solution. The loadflow equation can be stated as:

$$S_i^* = V_i^* \sum_{j=1}^{NB} Y_{ij} V_j \tag{2.5}$$

Defining

$$\left.\begin{aligned} V_i &= |V_i| \exp(j\delta_i) \\ S_i &= P_i + jQ_i \\ Y_{ij} &= G_{ij} + jB_{ij} = \frac{1}{R_{ij} + jX_{ij}} \\ &= |Y_{ij}| \exp(-j\theta_{ij}) \end{aligned}\right\} \tag{2.6}$$

equation (2.5) becomes

$$P_i - jQ_i = |V_i| \sum_{j=1}^{NB} |V_j| |Y_{ij}| \{\cos(\delta_i - \delta_j + \theta_{ij}) - j \sin(\delta_i - \delta_j + \theta_{ij})\} \tag{2.7}$$

Separating real and imaginary components of the left-hand side of equation (2.7) and expanding $(\delta_i - \delta_i + \theta_{ij})$ in terms of $(\delta_i - \delta_j)$ and θ_{ij} for each PQ or PV bus i:

$$P_i = |V_i| \sum_{j=1}^{NB} |V_j| \{ G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij} \}$$

for each PQ bus i:

$$Q_i = |V_i| \sum_{j=1}^{NB} |V_j| \{ G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij} \} \qquad (2.8)$$

where $\delta_{ij} = (\delta_i - \delta_j)$

Introducing the mismatch function:

$$\Delta P_i = P_i^{sp} - P_i$$
$$\Delta Q_i = Q_i^{sp} - Q_i \qquad (2.9)$$

Equations (2.8) and (2.9) in matrix form become:

$$\begin{bmatrix} \Delta P \\ \hline \Delta Q \end{bmatrix} = \left[\begin{array}{c|c} H & N \\ \hline J & L \end{array}\right] \begin{bmatrix} \Delta\delta \\ \hline \Delta V/V \end{bmatrix} \qquad (2.10)$$

where

$$H_{iK} = \frac{\partial \Delta P_i}{\partial \delta_K} \qquad N_{iK} = V_K \left(\frac{\partial \Delta P_i}{\partial V_K}\right)$$

$$J_{iK} = \frac{\partial \Delta Q_i}{\partial \delta_K} \qquad L_{iK} = V_K \left(\frac{\partial \Delta Q_i}{\partial V_K}\right)$$

Slack bus mismatches are not included in the above equations. Also for a PV bus i, ΔQ_i and $\Delta V_i/V_i$ are absent as the reactive power Q_i is unknown. V_i is a constant at this bus, hence ΔV_i is zero.

The decoupling principle [29] is based on the fact that numerical methods when applied to the solution of engineering problems are at their best when the system physical properties are exploited. Therefore, because of the weak relationship between the P and $|V|$ as well as between Q and δ, equation (2.10) becomes

$$\left.\begin{aligned} \Delta P &= H\Delta\delta \\ \Delta Q &= L\Delta V/V \end{aligned}\right\} \qquad (2.11)$$

Making the following assumptions, the fast decoupled loadflow algorithm is given by equation (2.12):

(i) $\cos \delta_{ij} \doteq 1$

(ii) $G_{ij} \sin \delta_{ij} \ll B_{ij}$

(iii) $Q_i \ll B_{ii}V_i^2$

$$\left.\begin{aligned} [\Delta P/V] &= [B'][\Delta\delta] \\ [\Delta Q/V] &= [B''][\Delta V] \end{aligned}\right\} \qquad (2.12)$$

B' and B" matrices are essentially the elements of [-B], the admittance matrix except that in the extraction of B', shunt reactances, series resistances and off-nominal in-phase transformer taps are neglected whereas from B" is omitted the angle-shifting effect of phase-shifters.

Naturally, the matrices B' and B" are real, constant, symmetrical and sparse. It becomes important, therefore, to evaluate and factorize them only once at the beginning of the study. The criterion used for the convergence of the power mismatches is:

$$\begin{pmatrix} |\Delta P| \\ |\Delta Q| \end{pmatrix} \leq 0.001 \ pu$$

which puts an upper bound on the errors in any calculated line flows.

In security analysis, the use of the base case solution as starting values for the calculations of the outage cases is, on average, better than using the normal flat voltage profile for each outage case. The following equations refer to the simulation of single line outage cases.

The matrix formed due to the line i-j outage:

$$[B]_{new} = [B]_{base} - b[N]\,[N]^t \tag{2.13}$$

where [N] is a column vector which has values only on the ith and jth column as:

$$N = \begin{bmatrix} \vdots \\ N_i \\ \vdots \\ N_j \\ \vdots \end{bmatrix} = \begin{bmatrix} \vdots \\ 1 \\ \vdots \\ -1 \\ \vdots \end{bmatrix} \tag{2.14}$$

and b is the series admittance of the line i-j. The general method for modifying inverted matrices can be stated as

$$[B]^{-1}_{new} = [B]^{-1}_{base} - d[M]\,[N]^t\,[B]^{-1}_{base} \tag{2.15}$$

where

$$d = (1/b + [N]^t\,[M])^{-1}$$

and

$$[M] = [B]^{-1}_{base}\,[N]$$

Therefore, similarly from equation (2.15) the new angle and voltage increments will be

$$\left.\begin{aligned} [\Delta\delta]_{new} &= [\Delta\delta]_{base} - d[M]\,[N]^t\,[\Delta\delta]_{base} \\ [\Delta V]_{new} &= [\Delta V]_{base} - d[M]\,[N]^t\,[\Delta V]_{base} \end{aligned}\right\} \qquad (2.16)$$

where $[\Delta\delta]_{base}$ and $[\Delta V]_{base}$ are obtained from equation (2.12).

Important conclusions about these equations include:

(1)(a) In equation (2.14), when the line-outage involves the slack bus, only one non-zero element exists in the [N] vector for the real power model.

(b) The outage of a line between two generator buses cannot be simulated in the reactive power model, but if only one generator is involved, only one non-zero element would be present in the [N] vector.

(2) Explicit inversion of the [B] matrices is not performed. The initial factorized elements of the [B] matrices are used for the base solution as well as for the contingency cases.

(3) Since the [B] matrices are sparse, symmetric and contant, sparsity and ordering techniques are exploited in the program development [30-32] to achieve the following advantages:

(a) computational speed,

(b) reduction in computer storage requirement, and

(c) acceptable solution accuracies.

These advantages aid the implementation of the algorithm on a minicomputer.

2.1.2 Multiple Line Outages

The above algorithm for single line outages was developed recursively for multiple simultaneous outages by Stott in [29] and used by Winokur in [33], with the vectors of equation (2.16) corrected successively as the effect of each branch outage is introduced one at a time. For a set of outaged branches 1,2, ... m, the recursion is

$$\left.\begin{aligned} [\Delta\delta_i] &= [\Delta\delta_{i-1}] - d_i\,[M_i]\,[N_i]^t\,[\Delta\delta_{i-1}] \\ [\Delta V_i] &= [\Delta V_{i-1}] - d_i\,[M_i]\,[N_i]^t\,[\Delta V_{i-1}] \end{aligned}\right\} \qquad (2.17)$$

for i = 1, 2, ...m.

The scalars d_i and the vectors $[M_i]$ are calculated at the beginning of the case from the recursive algorithm:

$$\left.\begin{aligned} [M_i] &= [B]^{-1}\,[N_i] \\ [M_i] &= [M_i] - d_j[M_j]\,[N_j]^t\,[M_i] \end{aligned}\right\} \qquad (2.18)$$

$$\text{for } j = 1,2 \ldots i-1$$

$$d_i = (1/b_i + [N_i]^t\,[M_i])^{-1}$$

for i = 1,2, ... m. If any $1/d_i = 0$, a split network results and this can be detected by the interactive program.

2.1.3 Generator Outages

A generator outage requires as input data the redistribution of scheduled MW generation to compensate for the loss of supply. It is usual to cater for the partial loss of generation at a plant, in which case it is only necessary to reflect the changes in scheduled MW in equation (2.12). The complete loss of a plant means that the net MVAR of the relevant bus must be fixed.

Different redistribution rules have been suggested by Debs and Benson in [25] such as:

(i) allowing the slack bus to absorb all lost generation,

(ii) redistribution based on economic dispatch criterion,

(iii) redistribution on the basis of spare capacity, and

(iv) redistribution of lost generation among the remaining generators in proportion to their normalized inertias.

2.1.4 Automatic Contingency Evaluation

In the planning and operation of power systems, the traditional approach for steady-state contingency analysis is to test all contingencies sequentially to evaluate system performance and reliability. This analysis consists of simulating outages of one or more generating units and transmission facilities to investigate their effects on bus voltages and line power flows. Alternatively, selection of contingency cases based on the planner's experience and intuition may be inadequate due to the possibility of omitting some critical lines.

Ejebe and Wollenberg in [28] proposed a method for ranking transmission line outages and generator outages according to the severity of their effects on bus voltage or line flows. The approach utilizes Tellegen's theorem to generate the sensitivities of a system with performance indices calculated with respect to the outages. The contingency ranking is accomplished by ordering these normalized sensitivities from the greatest to the least.

The voltage level performance index was defined by PI_V such that

$$PI_V = \sum_{i=1}^{NB} \frac{W_i}{2n} \left(\frac{|V_i| - |V_i^{sp}|}{\Delta V_i^{lim}} \right)^{2n} \qquad (2.19)$$

where ΔV_i^{lim} is the voltage deviation limit above which voltage deviations are unacceptable.

n = exponent of penality function (n = 1 preferred)

W_i = real non-negative weighting factor to emphasize the importance of the buses.

The index for quantifying the extent of line overloads may be defined in terms of a real power performance as:

$$PI_{MW} = \sum_{\ell=1}^{NL} \frac{W_L}{2n} \left(\frac{P_\ell}{P_\ell^{limit}} \right)^{2n} \qquad (2.20)$$

where P_ℓ = megawatt flow in line l, calculated from a DC loadflow model

P_ℓ^{lim} = megawatt capacity of line l

n = specified exponent

W_L = weighting factor

Equation (2.20) is computed for cases where $P_\ell > P_\ell^{lim}$

PI_{MW} has a small value when there are no overloads and a high value when there are overloads in the system. Irisarri et al in [34,35] argued that the method of Ejebe and Wollenberg was unreliable on performing tests on the AEP-EHV system. They claimed that the method had this unpredictable behaviour because the performance index defined in equation (2.20) is not always a monotonic function of the susceptance of the lines. Another reason for the unpredictable behaviour of the method was that the approximation of the change in the performance index calculated using the Taylor series expansion of equation (2.20) is valid only in the neighbourhood of the operating point and may not hold true when the susceptance change is large as in the case when simulating a line outage. Even with the inclusion of the second order sensitivities of the performance indices the method was still unreliable, hence the use of the DC loadflows was suggested.

Albuyeh in [36] presented a method based on the use of first-order sensitivities of branch power flows with respect to network changes as weighting factors in the calculation of performance indices. The relative magnitudes of the performance indices are then used to rank branches. Mikolinnas and Wollenberg [37] modified the Ejebe's algorithm by including all the terms in the infinite Taylor's series expansion for the change in the performance index instead of only the linear terms. The objective was to overcome the unpredictable behaviour of the method presented by Ejebe.

Since real power flows have been used to compute the performance index in the methods above, the contingencies which cause overloads due to predominant MVAr flow component in a line cannot be detected. The current flows or the MVA loading provide the proper information required, hence in the package developed current flows are used in the performance index:

$$PI = \sum_{j=1}^{NL} \frac{W_j}{M} \left(\frac{|I_j|}{I_j^{max}}\right)^M \qquad (2.21)$$

This has been used to rank the lines and display the severity of their loading on system performance as computed by equation (2.21) to the operator, where

M = order of the performance index = 2

$|I_j|$ = current magnitude of line j

I_j^{max} = capacity of the line j

W_j = weighting function (a value of 1 has been assumed for equal importance)

Equation (2.21) is computed for cases $|I_j| > |I_j^{max}|$.

The performance indices calculated are ordered in descending order. One of the problems of using equations (2.20) and (2.21) is the phenomenon of "masking" wherein a contingency which leaves a number of lines heavily loaded but not overloaded is ranked equally with a contingency which produces a single overloaded line. This effect can only be mitigated by increasing the order of M to,say,3. Contingencies causing system islanding or isolation of generation were removed from the ranking as in the event of generation dispatch the final value of PI is a function of how the redispatch was done. The security analysis program is shown in Fig. 2.1.

2.2 FAULT ANALYSIS

The analysis of power systems under fault conditions plays an important role in the design and operation of protection schemes. Methods using the sequence components for the three-phase and single phase-to-ground faults have been developed and used successfully for many years [38,39]. These faults are commonly considered to be the severest and the most frequent respectively. For unbalanced faults, another treatment based on phase coordinates has been proposed by Laughton in [40-43].

Generally the methods which use symmetrical components are characterized by the ability to obtain savings in computer time and storage because the sequence equations for all the balanced network elements are uncoupled.

The phase coordinate approach uses extra computer time and storage demands due to the 3 by 3 matrix representations of the network elements. Moreover, most of the fault data in many utilities are still in terms of the positive, negative and zero impedances. Reitan has in [44,45] extended the capabilities of the symmetric components approach by proposing methods for inclusion of coupled line impedances into the bus impedance matrix and the solution of simultaneous faults.

In [46], Podmore developed a technique which combines the advantages of the symmetrical components and phase coordinates techniques. The network is partitioned into a balanced subnetwork and a number of unbalanced subnetworks. The solution of the balanced subnetwork is initially obtained in terms of the sequence components and transformed to phase coordinates. The phase coordinates solution of all the subsystems are then combined to form the solution of the original unpartitioned network.

The interactive program written for the fault analysis of electrical networks has been designed to meet the following requirements because of the enormous variety of situations (network configurations, fault location and types) to be studied within a short time using limited computer facilities (according to Reichert and Hager in [47]):

(i) fast response time,

(ii) minimum storage requirements, and

(iii) adequate accuracy.

To achieve the above objectives the following assumptions have been made:

(i) network characteristics are linear,

(ii) line parameters are balanced for the three-phase short-circuits such that a short-circuit on one phase will have the same effect as that on another phase,

(iii) synchronizing machines and large induction machines are represented by a fixed voltage behind subtransient reactance,

(iv) effects of loads are neglected,

(v) shunt capacitances of lines and cables and shunt capacitors or reactors on the buses are neglected,

(vi) transformer excitation currents are considered negligible,

(vii) circuit resistances are neglected. It has been found in [47] that this leads to a (4 or 8 times) considerable speed up and the effect on the accuracy of results has been checked for various transmission networks and the deviations in short-circuit current from the results obtained by complex representation are below 0.7% for $Z = jX$, thus justifying the assumption,

(viii) one fault is considered at a time,

(ix) for single-phase-to-ground faults, the negative sequence impedance is assumed equal to the positive sequence impedance resulting in considerable savings in computer storage. However, this assumption is not true for transformers and generators, and

(x) flat voltage profile is assumed prior to fault.

2.2.1 Three-phase Fault Analysis by Sequence Components

The method employed in the interactive program was proposed by Elgerd in [39]. Essentially, the admittance matrix is formed from the line data, the matrix is inverted to obtain the impedance matrix of the system.

Using Thevenin's theorem from Fig. 2.2.

$$I_{ss} = 1.0/Z_{ss} \tag{2.22}$$

$$I_{st} = I_{ss} \frac{(Z_{ss} - Z_{st})}{Z_{st}} \tag{2.23}$$

where I_{ss} is the three-phase short circuit current at the faulted bus s.

I_{st} is the current connecting line (s-t) to the fault,

Z_{st} is the impedance of line s-t,

Z_{ss} is the driving point impedance at the faulted bus, and

Z_{st} is the transfer impedance of the faulted bus s to the bus t.

Since the admittance matrix is generally sparse for practical systems and the impedance matrix is full, a method has been developed by Takahashi et al [48] known as the sparse impedance matrix method. This generates only those node and branch elements of the Z-matrix without calculating the complete Z-matrix.

Consider as an example a 5-bus system whose Y-bus matrix is shown as:

$$[Y] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \begin{bmatrix} * & . & * & . & * \\ . & * & . & * & . \\ * & . & * & . & * \\ . & * & . & * & * \\ * & . & * & * & * \end{bmatrix} \end{array}$$

where * represents a non-zero element

and . represents a zero element.

The sparse bus impedance matrix can be generated using [48] as:

$$[Z] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \begin{bmatrix} * & . & * & . & * \\ . & * & . & * & . \\ * & . & * & . & * \\ . & * & . & * & * \\ * & . & * & * & * \end{bmatrix} \end{array}$$

This approach favours a development where short-circuit current at a faulted node and the currents of the connecting branches are required. In the required circumstances of the interactive package, this development is not useful as the fault analysis program would be used for research and teaching as well as by planning, design and operational engineers. So the Z-matrix must be generated completely. Moreover, from the example above the post-fault voltages of buses 2 and 4 may be required for a fault on bus 1. With Takahashi's modification, these post-fault values cannot be obtained. It has been argued by Gross and Hong in [49] that this method has limited facilities when large systems with more complex fault types and mutuals are included.

Line changes:

A branch is generally assumed to have been added between buses p and q of impedance r by modifying the impedance matrix as (Fig. 2.3):

$$Z_{ij}' = Z_{ij} - \frac{(Z_{ip} - Z_{iq})(Z_{jp} - Z_{jq})}{Z_{pp} + Z_{qq} - 2Z_{pq} + r} \qquad (2.24)$$

where Z_{ij}' is the modified bus impedance matrix Z_{ij}.

The sign of r is negative for a line outage and positive for a line addition.

For an impedance change of line p-q of impedance γ_0 to γ an impedance γ' is required to be computed in parallel with γ_0 so that the effective impedance is γ, i.e.

$$\gamma = \frac{\gamma'\gamma_0}{\gamma_0+\gamma'}$$

hence

$$\gamma' = \frac{\gamma_0\gamma}{\gamma_0-\gamma} \qquad (2.25)$$

The magnitude of the fault current that would flow for the fault at a point t on the line side of the open beaker at bus q is given by equation (2.26).

$$Z_{tt} = Z_{pp} + \not{Z}_{\text{line } p\text{-}q} \tag{2.26}$$

hence total fault current at point t is $-1.0/Z_{tt}$

Transformer outages:

Since the transformer excitation currents are considered negligible, transformer outage is considered as a line outage, hence equation (2.24) is similarly applied with the impedance of the transformer as negative γ.

Busbar additions:

Consider the addition of a qth bus to a p-bus system as shown in Fig. 2.4. Addition of a line p-q of impedance $\not{Z}_{pq}$ is regarded as a radial line to bus q, hence the Z-matrix of order q becomes:

$$\left.\begin{aligned} Z_{qk} &= Z_{pk} \\ Z_{kq} &= Z_{kp} \end{aligned}\right\} \quad \text{for } K \neq q$$

$$Z_{qq} = Z_{pp} + \not{Z}_{pq} \tag{2.27}$$

However, the addition of more lines to the system requires the use of the Z-matrix modification formula in equation (2.24).

Bus tie-breakers (see Brown [50]):

Certain power systems have bus tie-breakers that may be closed or opened for operating reasons. For example, a generating station may have two generators connected tc a bus system as shown in Fig. 2.5.

If either generator is out of service for overhaul or for some operating reason, it may be necessary to close the bus tie-breaker.

To tie two buses with a bus tie impedance of zero, that can be opened, a fictitious bus is introduced between the buses to be tied and a line added from P to T with an impedance $\not{z}_1$ and another from T to Q with impedance $-\not{z}_1$ as illustrated in Fig. 2.6. The impedance from bus P to bus Q is zero but now the breaker may be opened by adding a line from bus T to bus Q with impedance $+\not{z}_1$. This removes one side of the bus tie-breaker.

2.2.2 Analysis of Single phase-to-ground (SLG) Faults (see Anderson [51])

Let I_a, I_b, I_c be line currents and I_{ao}, I_{a1}, I_{a2} be the zero, positive and negative sequence currents of I_a respectively.

Let V_a, V_b, V_c be phase-to-neutral voltages and V_{ao}, V_{a1}, V_{a2} be the zero, positive and negative sequence voltages of V_a respectively.

At the fault point on phase a, from Fig. 2.7

$$\left.\begin{aligned} I_b &= I_c = 0.0 \\ V_a &= 0.0 \end{aligned}\right\} \qquad (2.28)$$

The sequence components of currents can be represented in matrix form as:

$$\begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (2.29)$$

$$\left.\begin{aligned} &\text{Also } \alpha = 1.0\angle 120^\circ \quad , \quad \alpha^2 = 1.0\angle -120^\circ \\ &\text{then} \quad \alpha^2 + \alpha + 1 = 0.0 \end{aligned}\right\} \qquad (2.30)$$

Applying equation (2.28) to (2.29)

$$\left.\begin{aligned} I_{ao} &= 1/3(I_a + I_b + I_c) = 1/3\ I_a \\ I_{a1} &= 1/3(I_a + I_b + \alpha^2 I_c = 1/3\ I_a \qquad (2.31) \\ I_{a2} &= 1/3(I_a + \alpha^2 I_b + I_c) = 1/3\ I_a \qquad (2.31) \\ \therefore\ I_{a2} &= I_{a1} = I_{a2} = 1/3\ I_a \end{aligned}\right\}$$

Similarly the sequence components of the voltages can be represented in matrix form as:

$$\begin{bmatrix} V_{ao} \\ V_{a1} \\ V_{a2} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (2.32)$$

Since $V_a = 0.0$ from equation (2.28)

then $V_{a1} = -(V_{ao} + V_{a2})$ (2.33)

Equations (2.31) and (2.33) are satisited if the three sequence networks are connected in series as shown in Fig. 2.8.

With the connection in Fig. 2.8, the sequence currents are computed as:

$$I_{ao} = I_{a1} = I_{a2} = \frac{V_f}{Z_1 + Z_2 + Z_o} \qquad (2.34)$$

where Z_1, Z_2 and Z_o are the positive, negative and zero sequence impedances respectively. Having assumed in the program a flat pre-fault voltage profile, $V_f = 1.0$. Also $Z_1 = Z_2$ was assumed, hence equation (2.34) simplifies to

to

$$I_{ao} = I_{a1} = I_{a2} \quad \frac{1.0}{2Z_1 + Z_o} \tag{2.35}$$

The sequence voltages are then computed from Fig. 2.8 as:

$$\left.\begin{aligned} V_{a1} &\doteq V_f - I_{a1}Z_1 = 1.0 - Ia_1Z_1 \\ V_{a2} &= -I_{a2}Z_2 = -I_{a1}Z_1 \\ V_{ao} &\doteq -I_{a1}Z_o \end{aligned}\right\} \tag{2.36}$$

The condition for a fault through an impedance is modelled as in Fig. 2.9.

The boundary conditions at the fault point F will be

$$\left.\begin{aligned} I_b &= 0.0 = I_c \\ V_a &= Z_f I_a \end{aligned}\right\} \tag{2.37}$$

From equation (2.31)

$$\left.\begin{aligned} I_{ao} &= I_{a1} = I_{a2} = I_{a/3} \\ \therefore \quad V_a &= Z_f I_a = 3I_a Z_f \end{aligned}\right\} \tag{2.38}$$

Since $Va=Va_1+Va_2+Va_o= 3Ia_1Z_f$ the connection of the sequence networks is as shown in Fig. 2.10.

From Fig. 2.10, the sequence currents are given by:

$$I_{ao} = I_{a1} = I_{a2} = \frac{1.0}{2Z_1 + Z_2 + 3Z_f} \tag{2.39}$$

The Fault Analysis program is shown in Fig. 2.11.

The following sections describe the mathematical formulations of the line-to-line and double line-to-ground faults, though these have not been included in the fault analysis program because such faults occur infrequently. Nevertheless, these faults are of interest to power engineers.

2.2.3 Analysis of Line-to-Line Faults

From Fig. 2.12, the fault occurs on phases b and c. The conditions at fault are:

$$\left.\begin{aligned} V_b &= V_c \\ I_a &= 0.0 \\ I_b &= -I_c \end{aligned}\right\} \qquad (2.40)$$

From the symmetric component theory

$$\begin{bmatrix} V_{ao} \\ V_{a1} \\ V_{ao} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Substituting equation (2.40) into (2.32) gives

$$V_{a1} = V_{a2}$$

also using equation (2.32) in terms of currents

$$\left.\begin{aligned} I_{a1} &= -I_{a2} \\ I_{ao} &= 0.0 \Rightarrow V_{ao} = 0.0 \end{aligned}\right\} \qquad (2.41)$$

Fig. 2.13 represents these equations derived above in a diagrammatic form. The current I_{a1} can be derived as:

$$I_{a1} = \frac{E_a}{Z_1 + Z_2} \tag{2.42}$$

From Fig. 2.13, the presence or absence of a grounded neutral at the generator does not affect the fault current.

2.2.4 Double Line-to-Ground Faults

From Fig. 2.14, at the faulted location:

$$\left.\begin{aligned} V_b &= V_c = 0.0 \\ I_a &= 0.0 \end{aligned}\right) \tag{2.43}$$

as before

$$\begin{bmatrix} V_{ao} \\ V_{a1} \\ V_{a2} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ 0 \\ 0 \end{bmatrix} \tag{2.44}$$

hence

$$\left.\begin{aligned} \text{hence } V_{ao} = V_{a1} = V_{a2} &= V_a/3 \\ &= E_a - I_{a1} Z_1 \end{aligned}\right) \tag{2.45}$$

Making use of Fig. 2.15, the current I_{a1} becomes

$$I_{a1} = \frac{E_a}{Z_1 + Z_2 Z_o/(Z_2 + Z_o)} \tag{2.46}$$

Equation (2.46) would approach the fault current for a line-to-line fault if the connection to the ground is absent, i.e. when Z_o is infinite and $I_{ao} = 0$.

2.3 CONCLUSION

This chapter has introduced the mathematical formulations used in the security analysis and fault studies in the next chapter. The concept of automatic contingency selection has been explained and a review of the subject matter presented. Automatic contingency summary is used to identify line outages for further study.

The next chapter describes the practical implementation of IPSAP (Interactive power system analysis programs) which has been developed for system operational studies and for real-time digital control. Other potential applications of IPSAP are in consulting and teaching.

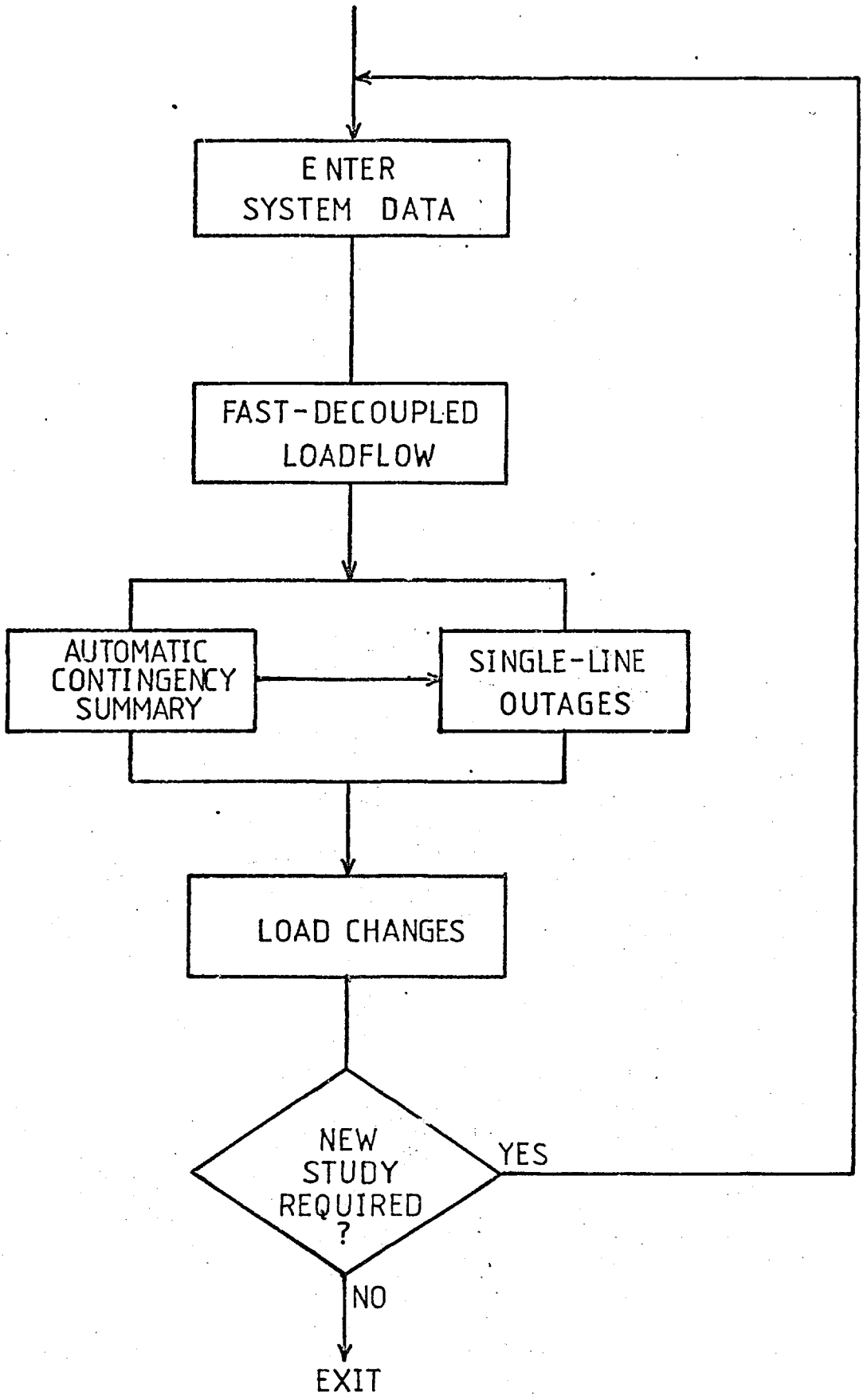


Fig. 2.1: Flowchart for the Security Analysis Program

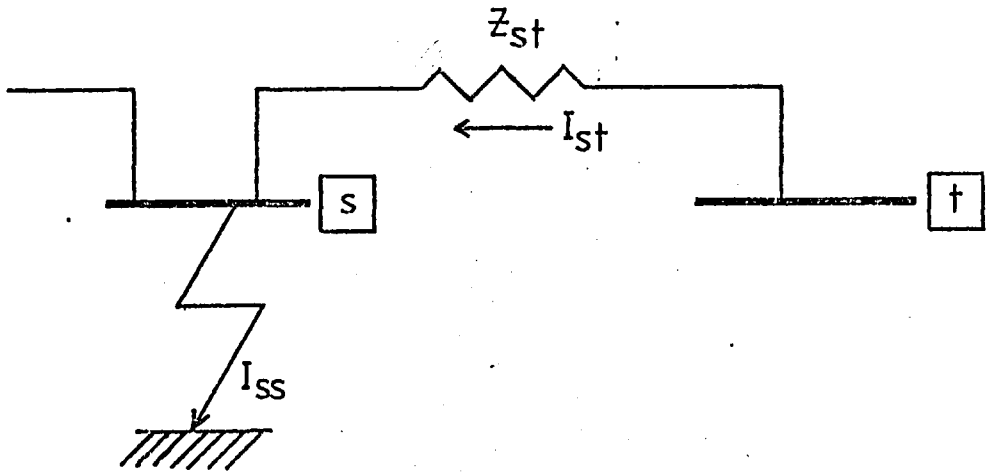


Fig. 2.2: Three-phase fault analysis

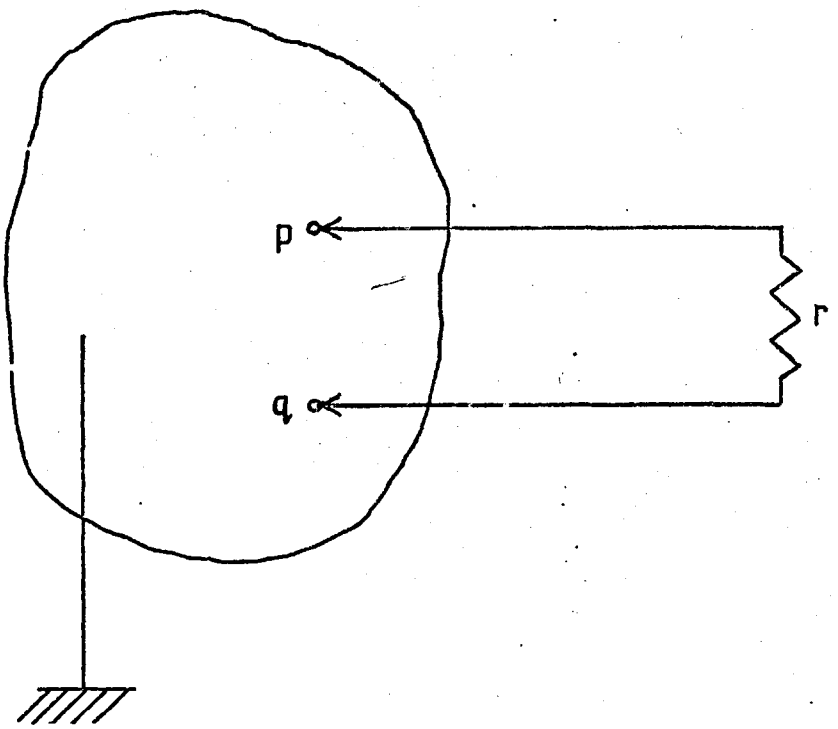


Fig. 2.3: Modification of z-matrix

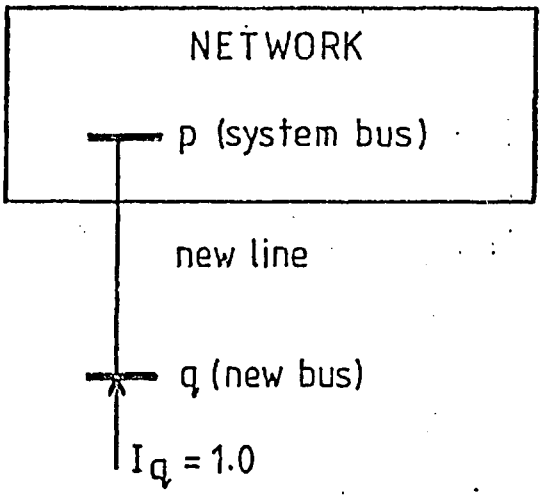


Fig. 2.4: Addition of a radial line from system bus to a new bus

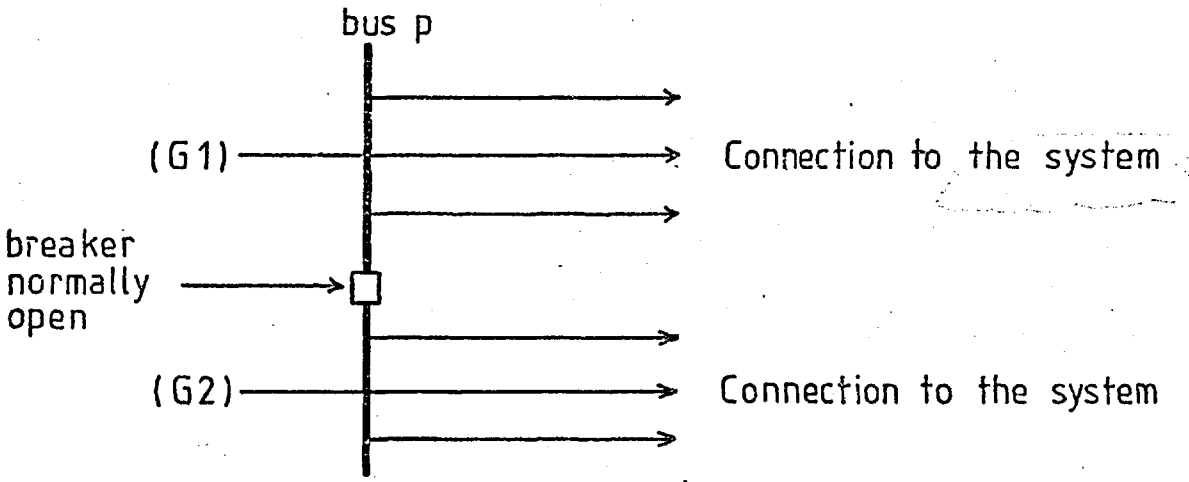


Fig. 2.5: Bus tie-breakers

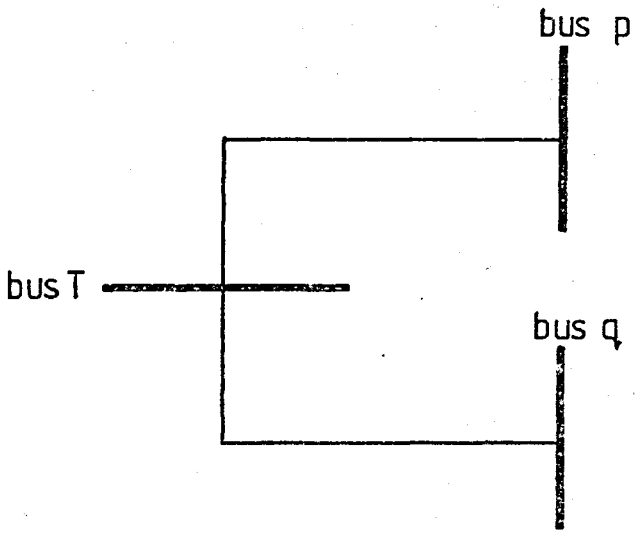


Fig. 2.6: Simulation of a closed tie breaker

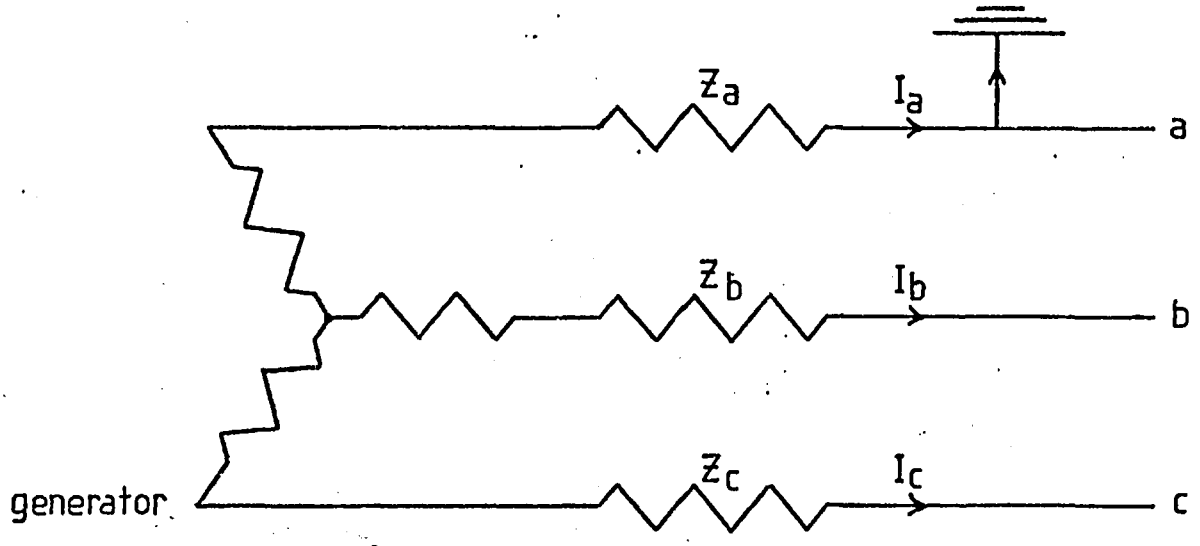


Fig. 2.7 : Short circuit occurring on unloaded system

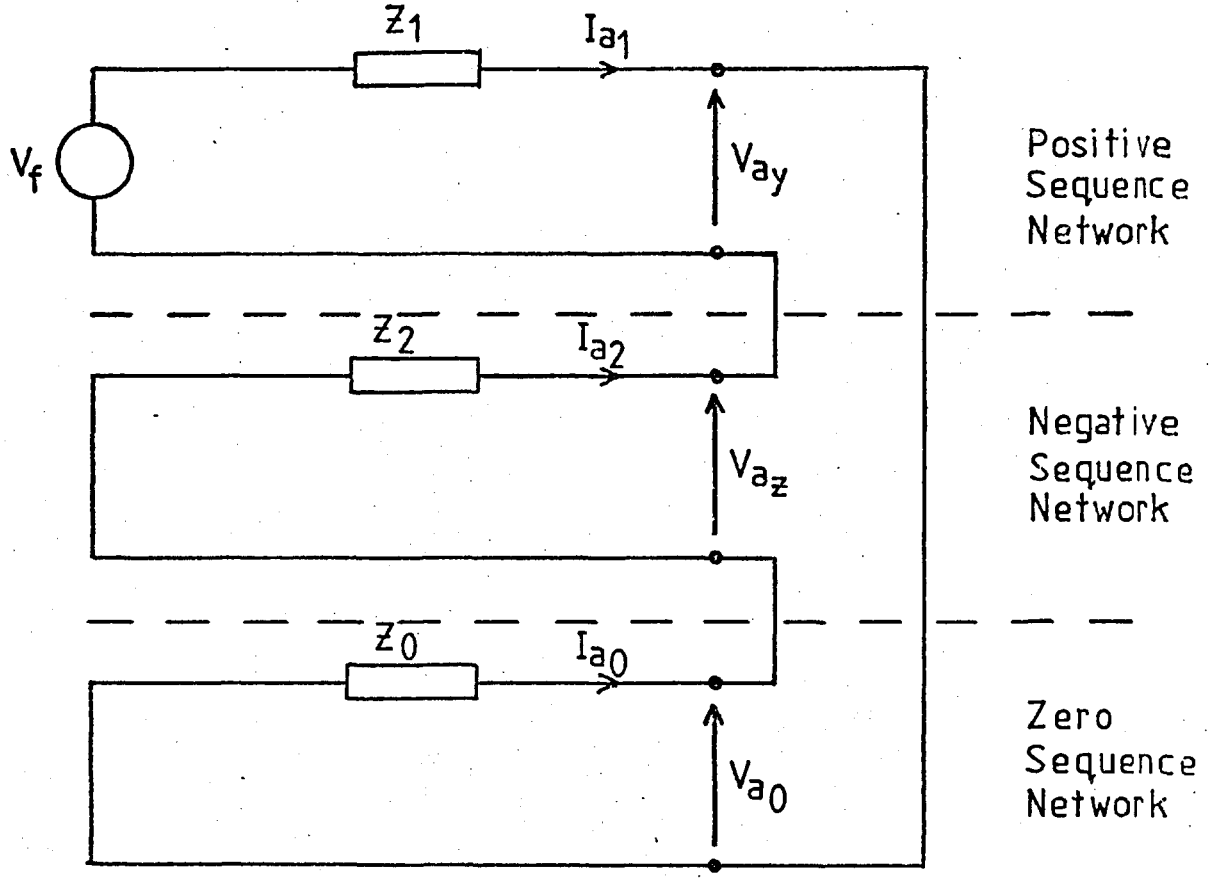


Fig. 2.8 : Sequence network connection for a single line-to-ground fault

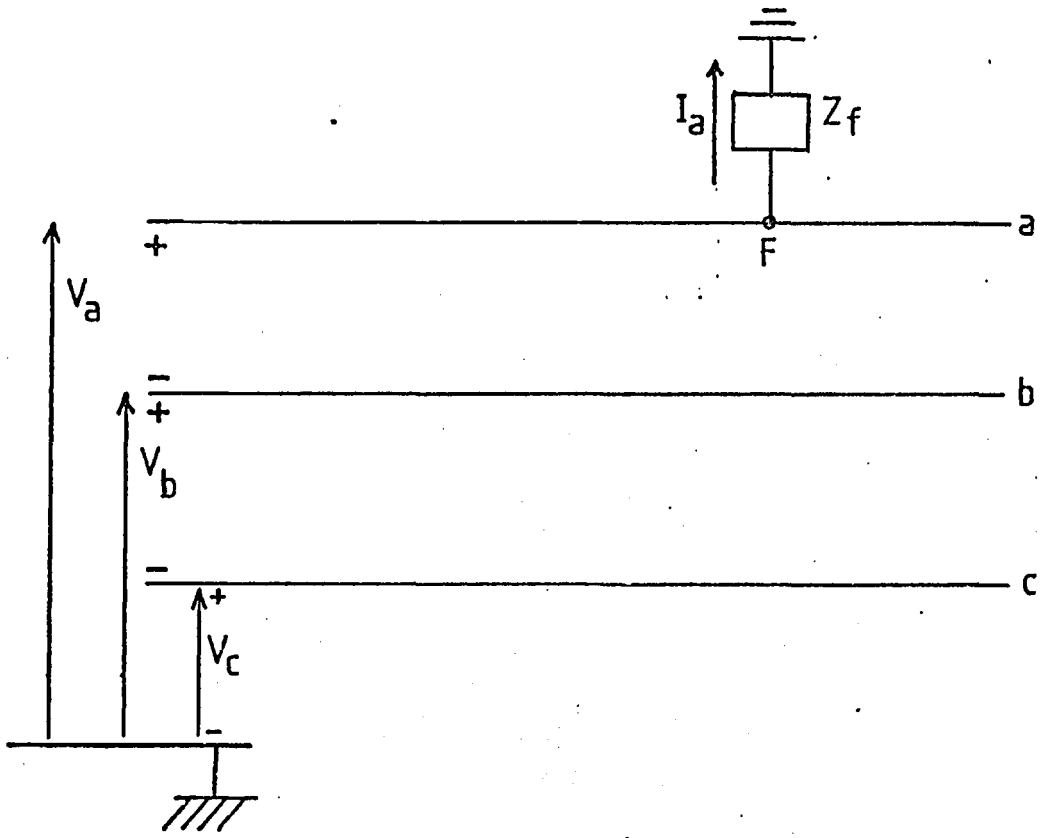


Fig. 2.9 : Fault at a point F through an impedance Z_f

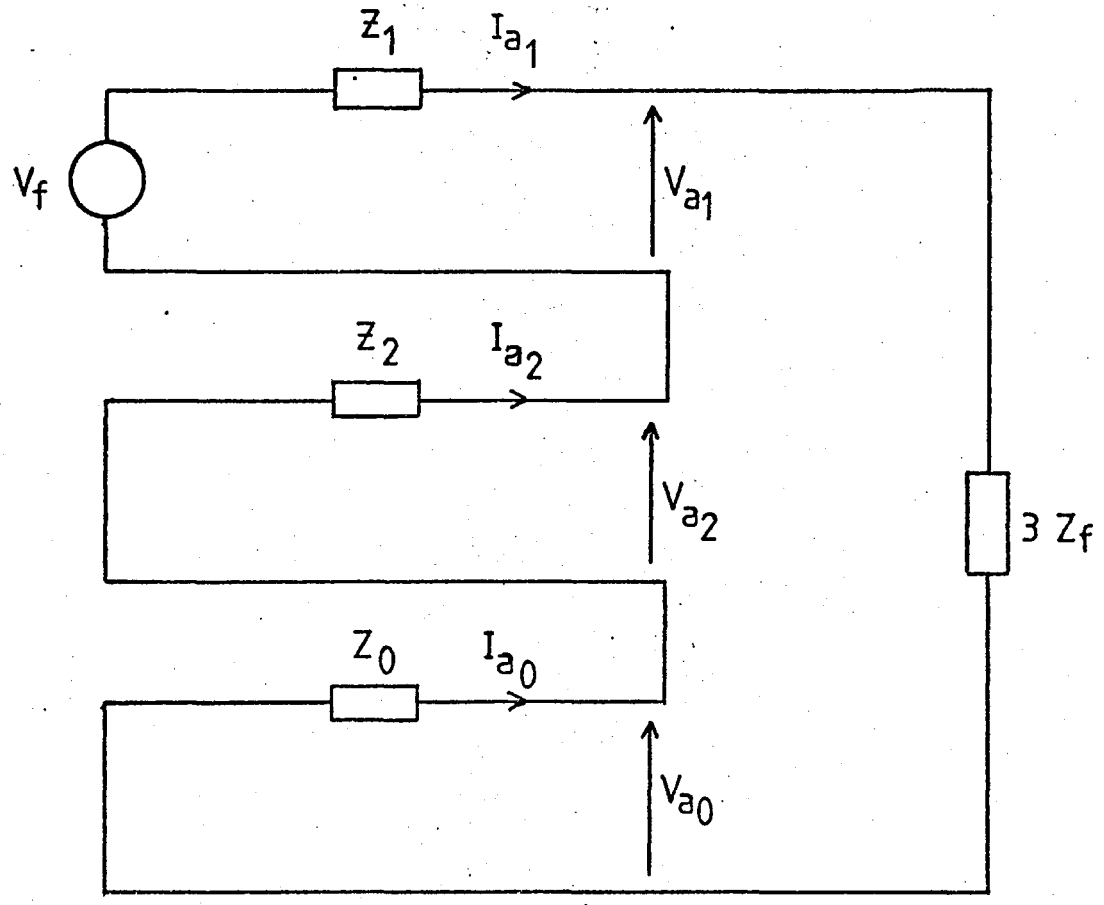


Fig. 2.10 : Sequence network connection for a SLG fault through an impedance Z_f

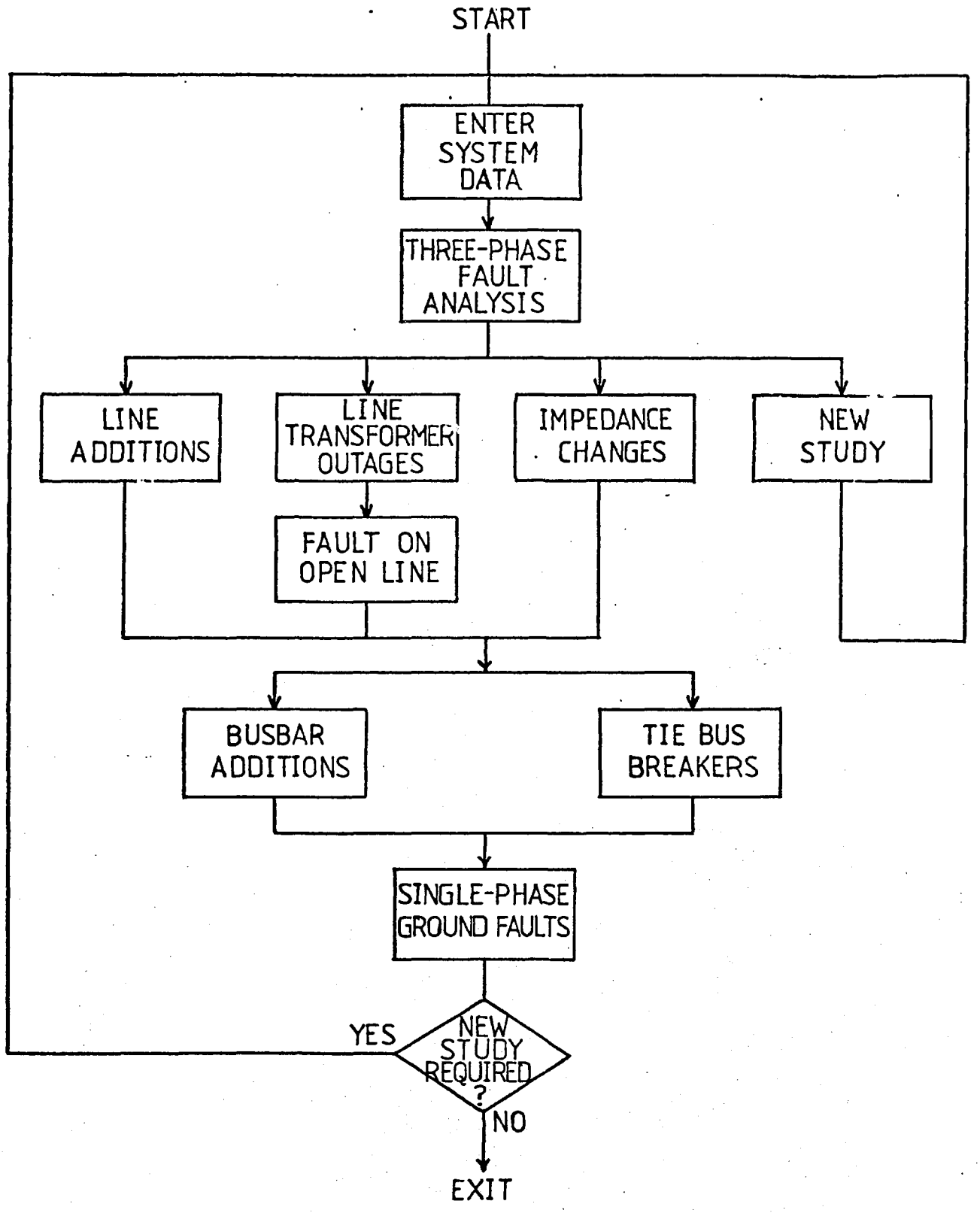


Fig. 2.11 : Flowchart for the Fault Analysis Program

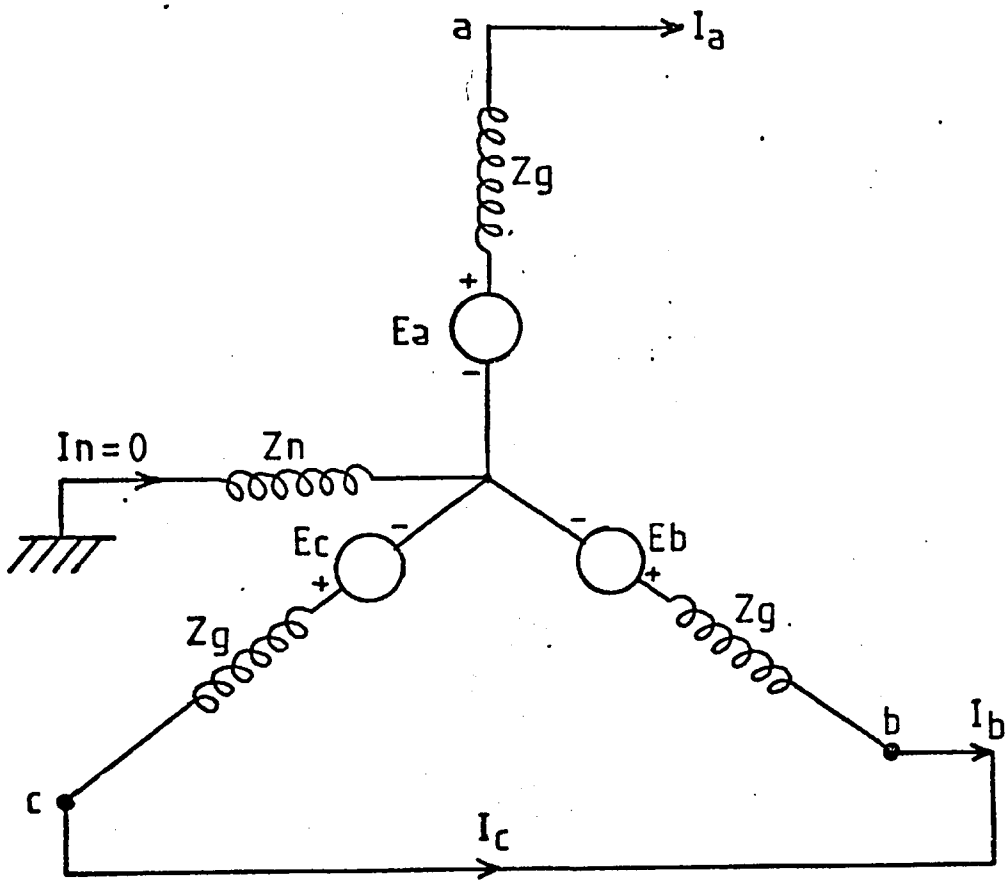


Fig. 2.12 : Line-to-Line Faults

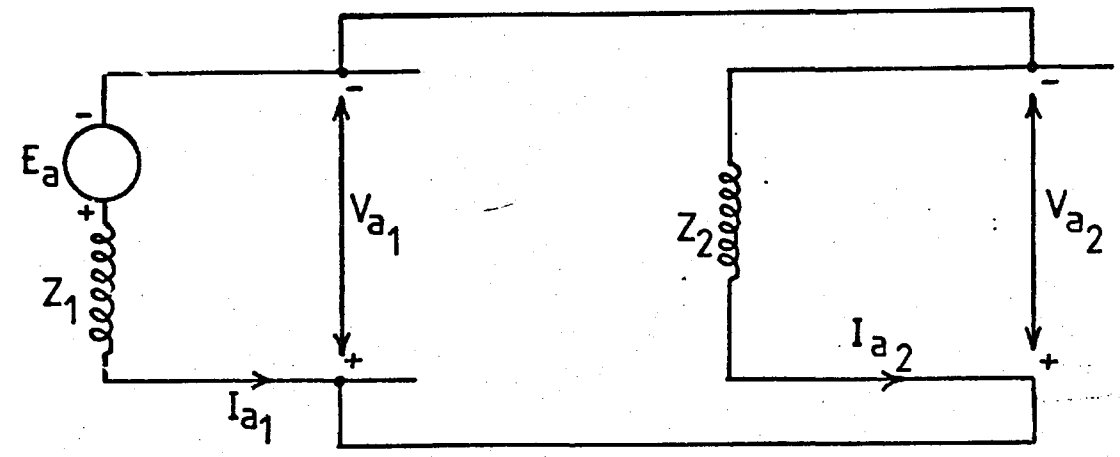


Fig. 2.13 : Diagrammatic representation of line to line faults

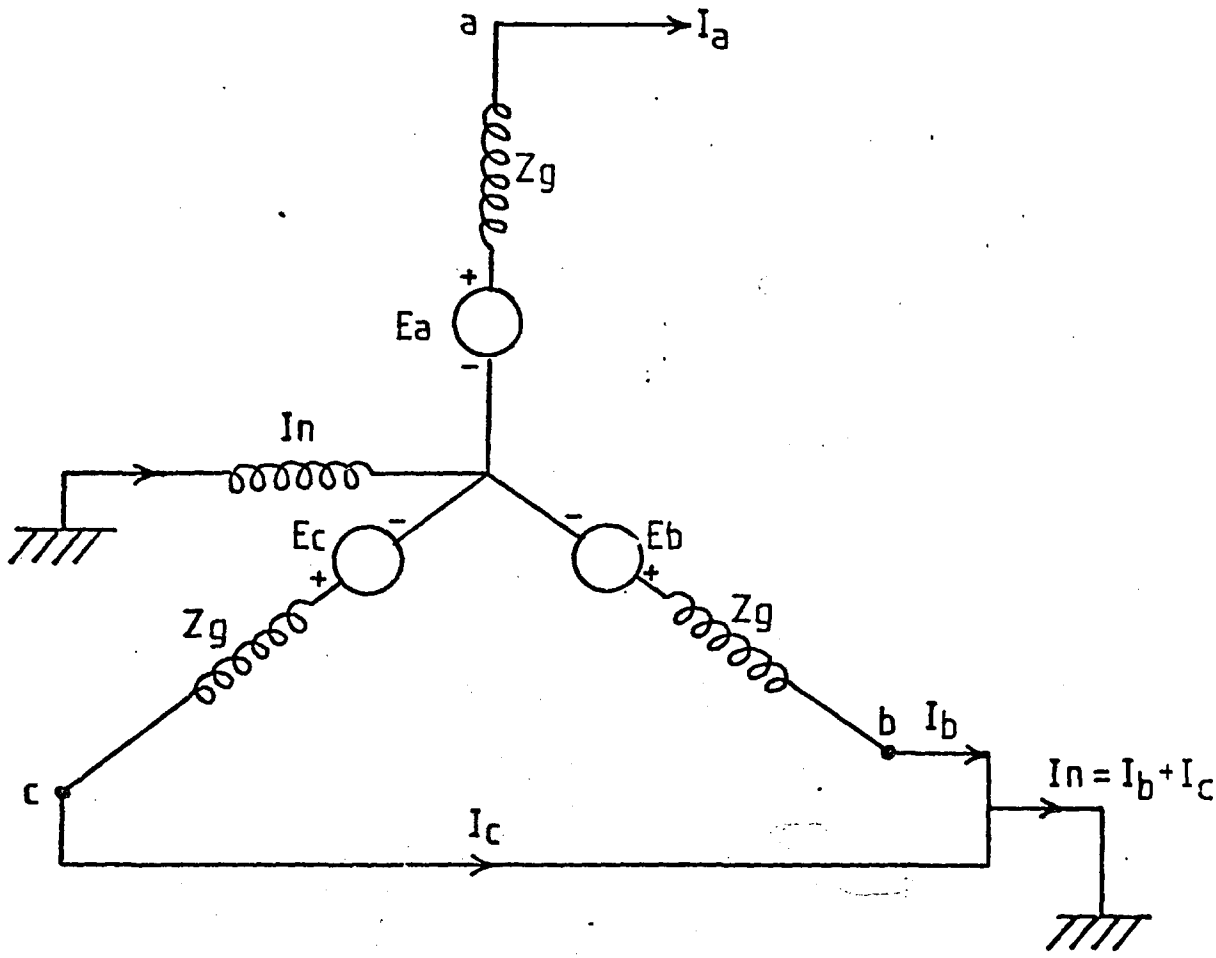


Fig. 2.14 : Double Line-to-ground faults

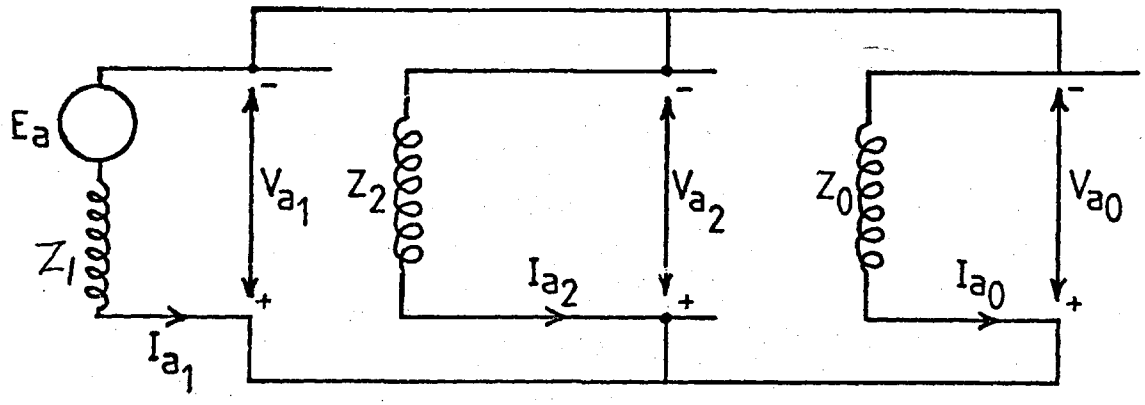


Fig. 2.15 : Diagrammatic representation of Double Line-to-ground faults

CHAPTER 3

PRACTICAL IMPLEMENTATION OF IPSAP AND RESULTS

3.0 INTRODUCTION

The mathematical developments of the Security and Fault Analyses have been described in the previous chapter with the flowcharts of the programs written included. In this chapter practical features of the implementation of the Interactive Power System Analysis Programs (IPSAP) is described. The discussion of the results of tests carried out on the 6-bus Saskachewan Power Corporation network and the IEEE 14-bus systems follows. The fault analysis of the 6-bus system presented by Anderson in [51] is discussed.

3.1 COMPUTER CONFIGURATION

Fig. 3.1 represents the system structure of the computing network which has been used to implement the interactive power system analysis programs (IPSAP). The DEC PDP11 minicomputer uses the RT-11 operating system, has a 16-bit word length, and has 32K words of central memory capacity. Mass storage is provided by a dual-disk drive unit using floppy disks each 1M words capacity and holds the system and user's software. The VDU and the line printer allow communications between the user and the system.

The graphical input devices comprise a joystick or a bit-pad and pen. These devices position the crosshair cursor on the screen for the input of the graphical information. The TV colour monitor produces pictures made up of a 512 by 512 matrix of "picture elements" or pixels with the colour information for each pixel stored on "matrox" boards. In the colour system, there are 3 bits/pixel giving a range of 8 colours.

Being dedicated to the task the minicomputer has a very fast, user acceptable interactive response.

3.2 BENEFITS OF COLOUR GRAPHICS

An important contribution of this work is the extensive use of colour graphics in the post-processing of the results obtained. This extends the available coding system of a display and alarm awareness in a real-control room environment with faster interpretation of results. Also, the operators' motivation is enhanced by the use of a good colour display system [52].

The circuits overloads are displayed in red and the outages in yellow. Cyan has been used when adding an auxiliary network to the original system under consideration for fault studies. Faulted buses and buses exceeding their short-circuit levels are shown in green whereas for power flow studies those buses exceeding their voltage limits are displayed in red but those below the limits in blue.

The decreasing cost of both software and hardware can be expected to lead to the use of colour graphics in future.

3.3 DESCRIPTION OF NETWORK DRAWING TECHNIQUES

Prior to the commencement of the computations the power system network must be drawn and the data supplied.

The network diagrams are drawn by entering the appropriate mnemonic code via the keyboard. For example, a busbar can be defined at a given cursor position on the screen by typing 'B'. Then a generator can be attached to that busbar by typing 'G'. Generally by controlling the cursor, all the circuit elements can be drawn. A subroutine 'HELP' shown in Fig. 3.2, has been created to help in drawing the symbols.

Power system data can either be created through the terminal during program execution or through a file previously created for the

purpose. For both cases, 'free format' has been used for ease of data entry.

3.4 IMPLEMENTATION OF IPSAP ON A MONOCHROMATIC DISPLAY MONITOR

IPSAP was also implemented on a similar configuration as shown in Fig. 3.1 except that a monochromatic display monitor was used; one matrix board was used instead of three. Power System Reports [53,54] have been written to describe the program usage and documentation. It is hoped that the package in its present status would be used for undergraduate experiments in steady-state power system analysis.

3.5 DISCUSSION OF RESULTS

The results of the security analysis of both the 6-bus SPC network (Fig. 3.3) and the IEEE 14-bus system (Fig. 3.4) are shown graphically in Figs. 3.6-3.14. The network data are shown in Tables 3.1 and 3.2 respectively. The IPSAP header is shown in Fig. 3.5.

The results of the base case are shown in Figs. 3.6 to 3.8. The line overload in line 3-4 (with capacity 0.45) is corrected by generation rescheduling on buses 4, 5 and 6 with load shedding of real powers of 0.094 pu and 0.22 pu on buses 2 and 3 respectively. The enhanced system is shown in Fig. 3.9. Results for single, double and triple line outages are shown in Figs. 3.10, 3.11 and 3.12 respectively. The loss of 3 lines in the system (2-3, 5-6 and 3-6) resulted in an islanded case. The first island consists of buses 3, 4 and 5, whereas the second island consists of buses 1, 2 and 6. If line 1-2 is lost, generator bus 1 (see Fig. 3.13) is isolated. This is another islanded example. The base results of the IEEE 14-bus is shown in Fig. 3.14.

TABLE 3.1A: Nodal Data

Bus No.	Generated Power	Real Power Demand	Reactive Power Demand	Voltage Magnitude (initial values)
1	1.5	0.0	0.0	1.05
2	0.0	0.5634	0.0390	1.00
3	0.0	0.9845	0.1025	1.00
4	3.8	2.4713	0.5249	1.05
5	0.5	0.9167	0.1500	1.05
6	0.0	.6998	0.0904	1.05

TABLE 3.1B: Regulated Bus Data

Bus No.	Minimum MW Capability	Maximum MW Capability	Minimum MVAR Capability	Maximum MVAR Capability
1	0.17	1.70	-0.34	0.34
4	0.4	4.0	-0.80	0.80
5	0.07	0.7	-0.14	0.14
6	0.12	1.2	-0.24	0.24

TABLE 3.1C: Line Data

Line	R	X	B/2	Capacity
1-2	0.0250	0.1682	0.1297	2.00
2-3	0.1494	0.3692	0.0206	1.00
2-6	0.0238	0.2108	0.1509	1.25
3-4	0.2130	0.8957	0.1203	0.45
3-6	0.1191	0.2704	0.0164	0.60
4-5	0.1021	0.4980	0.2492	0.90
5-6	0.0328	0.1325	0.0163	1.75

TABLE 3.1D: Voltage Correction Devices

Bus No.	Shunt Susceptance	
2	0.30	Reactor
4	0.30	Reactor
6	0.95	Reactor

System Data for the 6-Bus Saskatchewan Power Corporation Network

TABLE 3.2A: Nodal Data

Bus No.	Generated Power	Real Power Demand	Reactive Power Demand	Voltage Magnitude
1	0.0	0.149	0.05	1.00
2	0.40	0.217	0.217	1.05
3	0.0	0.942	0.190	1.10
4	0.0	0.478	-0.039	1.00
5	0.0	0.076	0.016	1.00
6	0.0	0.112	0.075	1.07
7	0.0	0.0	0.0	1.00
8	0.0	0.0	0.0	1.09
9	0.0	0.295	0.166	1.00
10	0.0	0.090	0.058	1.00
11	0.0	0.035	0.018	1.00
12	0.0	0.061	0.016	1.00
13	0.0	0.135	0.058	1.00
14	0.0	0.0	0.0	1.06

TABLE 3.2B: Regulated Bus Data

Bus No.	Minimum MW Capability	Maximum MW Capability	Minimum MVAR Capability	Maximum MVAR Capability
2	0.1	0.4	-0.40	0.50
3	-	-	0.0	0.40
6	-	-	-0.60	0.24
8	-	-	-0.60	0.24
14	0.1	1.70	-0.70	0.70

TABLE 3.2C: Line Data

Line	R	X	B/2	Capacity
1-9	0.12711	0.7038	0.0	1.00
1-13	0.17093	0.34802	0.0	1.00
2-3	0.04699	0.19797	0.0219	1.65
2-4	0.05811	0.17632	0.0187	1.65
2-5	0.05695	0.17388	0.0170	1.75
2-14	0.01938	0.05917	0.0264	1.85
3-4	0.06701	0.17103	0.0173	1.00
4-5	0.01335	0.04211	0.0064	1.00
4-7	0.0	0.20912	0.0	1.00
4-9	0.0	0.55618	0.0	0.65
5-6	0.0	0.25202	0.0	0.65
5-14	0.05403	0.22304	0.0246	0.65
6-11	0.09498	0.19890	0.0	1.00
6-12	0.12291	0.25581	0.0	1.00
6-13	0.06615	0.13027	0.0	1.00
7-8	0.0	0.17615	0.0	1.00
7-9	0.0	0.11001	0.0	1.00
9-10	0.0	0.08450	0.0	1.00
10-11	0.08205	0.19207	0.0	1.00
12-13	0.22092	0.19988	0.0	1.00

Transformer Data

Line	Nominal Tap Ratio
4-7	0.978
4-9	0.969
5-6	0.932

TABLE 3.2D:

Voltage Correction Device

Bus	Shunt Susceptance	
9	0.19	Capacitive

TABLE 3.2E:

System Data for the IEEE-14 Bus System

TABLE 3.3A: Bus Data

Bus No.	Generator Impedance	Short-Circuit Capacity (MVA)	Generator Impedance
	Positive Seq.		Negative Sequence
1	-	1000	-
2	-	100	-
3	0.24	400	0.080
4	0.032	800	0.032
5	-	100	-
6	-	200	-

TABLE 3.3B: Line Data

Line	Line Impedance		Capacity
	Positive Sequence	Zero Sequence	
1-4	0.518	1.042	3.0
1-5	0.407	1.030	0.70
2-3	0.640	1.920	0.75
3-6	1.050	2.630	0.65
4-5	0.370	0.925	0.65

TABLE 3.3C: Transformer Data

Transformer	Transformer Impedance		Capacity
	Positive Sequence	Zero Sequence	
1-2	0.30	0.30	0.2
5-6	0.133	0.133	1.5

The results of the Fault Analysis program are shown in Figs. 3.15 to 3.18. The network studied was obtained from Anderson[51] as the zero sequence impedances of the previous networks are unavailable. The data is in Table 3.3.

3.6 EXAMPLE OF A TERMINAL SESSION

The security enhancement program (FILE7) is run on the terminal for the 6-bus Saskatchewan Power Corporation. Appropriate assignment of logical number to the VDU and to the system disk are made (see Appendix 1), the header comes up and the first prompt requests for the file name which is given (see next page).

A loadflow is carried out based on the decoupled method with the number of iterations, bus powers and real and reactive power distribution clearly shown. Line 3-4 is overloaded with a current value of 0.513 and a capacity of 0.450. Security enhancement is first done using sensitivity analysis described in the next chapter to reschedule power flows by generation rescheduling only. The current is reduced to 0.504. If load-shedding is encouraged at the second iteration of the algorithm the overload is corrected to 0.468 using the control actions shown below. A summary of the enhancement with the overload margin obtained is equally shown.

3.7 CONCLUSION

Interactive programs have been implemented on a dedicated minicomputer enhanced with colour graphics to demonstrate analytical packages designed for security evaluation in power system operation. The FORTRAN programs have been designed to provide efficient man-computer communication. Implementation on a dedicated minicomputer is as cost effective as alternative batch or time-shared systems based on larger main frame machines. The dedicated minicomputer has the advantage that its operating system is under user's control at all times and this allows more economical and flexible

```
ASS TT 6
.ASS DY1 DK
.RUN FILE7
**********************************************************************
INTERACTIVE PROGRAM FOR DECOUPLED SECURITY ENHANCEMENT OF POWER SYSTEMS
**********************************************************************
NAME OF SYSTEM FILE ?
*LFSAN.DAT
```

BASE CASE SOLUTION

THE SOLUTION BELOW HAS OBTAINED IN 4.5 ITERATIONS

VOLTAGE MAGNITUDE	VOLTAGE ANGLE	GEN.ACTIVE POWER	REAL POWER DEMAND	GEN. REACT. POWER	REACT. POWER DEMAND	BUS NO.
1.0000	21.77	1.5000	0.0000	0.0745	0.0000	1
0.9605	6.86	0.0000	0.5634	0.0000	0.0390	2
0.9204	-1.87	0.0000	0.9845	0.0000	0.1025	3
1.0000	26.62	3.8000	2.4713	0.5526	0.5249	4
1.0000	2.66	0.5000	0.9167	0.1370	0.1500	5
1.0000	0.00	1.0614	1.6989	1.4310	0.0904	6

ACTIVE POWER GENERATION	6.8614
ACTIVE POWER DEMAND	6.6357
REACTIVE POWER GENERATION	2.1951
REACTIVE POWER DEMAND	0.9068

BRANCH I-J	CURRENT MAGNITUDE	MAXIMUM CURRENT	ACTIVE POWER FLOW I to J	ACTIVE POWER FLOW J TO I	REACTIVE POWER FLOW I TO J	REACTIVE POWER FLOW J TO I
1-2	1.503	2.000	1.500	-1.443	0.075	0.062
2-3	0.375	1.000	0.358	-0.338	-0.032	0.047
2-6	0.551	1.250	0.521	-0.513	-0.345	0.127
3-4	0.513	0.450	-0.454	0.512	0.049	-0.029
3-6	0.300	0.600	-0.193	0.203	-0.198	0.191
4-5	0.852	0.900	0.817	-0.749	-0.244	0.077
5-6	0.344	1.750	0.332	-0.328	-0.090	0.073

VALUES OF ACTIVE POWER GENERATION

BUSBAR	PRESENT	MINIMUM	MAXIMUM
1	1.500	0.700	1.700
4	3.800	0.400	4.000
5	0.500	0.070	0.700
6	1.061	0.120	1.200

VALUES OF REACTIVE POWER GENERATION

BUSBAR	PRESENT	MINIMUM	MAXIMUM
1	0.075	-0.340	0.340
4	0.553	-0.800	0.800
5	0.137	-0.140	0.140
6	1.431	-0.240	0.240

TOTAL GENERATION COSTS IS EQUAL TO 0.686138

**** LINE OVERLOADS ****

ENHANCEMENT SOLUTION
(WITH GENERATION RESCHEDULING ONLY)

THE SOLUTION BELOW WAS OBTAINED IN 4.0 ITERATIONS

VOLTAGE MAGNITUDE	VOLTAGE ANGLE	GEN. ACTIVE POWER	REAL POWER DEMAND	GEN. REACT. POWER	REACT. POWER DEMAND	BUS NO.
1.0000	21.72	1.5000	0.0000	0.0781	0.0000	1
0.9599	6.80	0.0000	0.5634	0.0000	0.0390	2
0.9169	-2.05	0.0000	0.9845	0.0000	0.1025	3
0.9800	26.23	3.7345	2.4713	0.4930	0.5249	4
1.0000	2.92	0.5739	0.9167	0.1498	0.1500	5
1.0000	0.00	1.0478	1.6998	1.4499	0.0904	6

ACTIVE POWER GENERATION	6.8564
ACTIVE POWER DEMAND	6.6357
REACTIVE POWER GENERATION	2.1708
REACTIVE POWER DEMAND	0.9068

BRANCH I-J	CURRENT MAGNITUDE	MAXIMUM CURRENT	ACTIVE POWER FLOW I TO J	ACTIVE POWER FLOW J TO I	REACTIVE POWER FLOW I TO J	REACTIVE POWER FLOW J TO I
1-2	1.503	2.000	1.500	-1.443	0.078	0.058
2-3	0.380	1.000	0.364	-0.342	-0.026	0.043
2-6	0.648	1.250	0.515	-0.507	-0.348	0.129
3-4	0.504	0.450	-0.437	0.492	0.058	-0.044
3-6	0.315	0.600	-0.205	0.216	-0.203	0.198
4-5	0.836	0.900	0.771	-0.708	-0.276	0.097
5-6	0.378	1.750	0.365	-0.360	-0.097	0.083

VALUES OF ACTIVE POWER GENERATION

BUSBAR	PRESENT	MINIMUM	MAXIMUM
1	1.500	0.170	1.700
4	3.735	0.400	4.000
5	0.574	0.070	0.700
6	1.048	0.120	1.200

VALUES OF REACTIVE POWER GENERATION

BUSBAR	PRESENT	MINIMUM	MAXIMUM
1	0.078	-0.340	0.340
4	0.493	-0.800	0.800
5	0.150	-0.140	0.140
6	1.450	-0.240	0.240

TOTAL GENERATION COSTS IS EQUAL TO 0.685635

**** LINE OVERLOADS ****

ENHANCEMENT SOLUTION

(GENERATION RESCHEDULING + LOADSHEDDING)

THE SOLUTION BELOW WAS OBTAIN IN 3.5 ITERATIONS

VOLTAGE MAGNITUDE	VOLTAGE ANGLE	GEN. ACTIVE POWER	REAL POWER DEMAND	GEN. REACT. POWER	REACT. POWER DEMAND	BUS NO.
1.0000	23.52	1.5000	0.0000	0.0508	0.0000	1
0.9645	8.63	0.0000	0.4593	0.0000	0.0318	2
0.9427	0.75	0.0000	0.7422	0.0000	0.0773	3
0.9800	26.17	3.6773	2.4713	0.4515	0.5249	4
1.0000	3.35	0.6402	0.9167	0.1305	0.1500	5
1.0000	0.00	0.6745	1.6998	1.4603	0.0904	6

ACTIVE POWER GENERATION	6.4921
ACTIVE POWER DEMAND	6.2893
REACTIVE POWER GENERATION	2.0934
REACTIVE POWER DEMAND	0.8744

BRANCH I-J	CURRENT MAGNITUDE	MAXIMUM CURRENT	ACTIVE POWER FLOW I TO J	ACTIVE POWER FLOW J TO I	REACTIVE POWER FLOW I TO J	REACTIVE POWER FLOW J TO I
1-2	1.501	2.000	1.500	-1.443	0.051	0.083
2-3	0.337	1.000	0.318	-0.301	-0.068	0.071
2-6	0.768	1.250	0.666	-0.643	-0.326	0.143
3-4	0.468	0.450	-0.405	0.451	0.050	-0.082
3-6	0.214	0.600	-0.035	0.040	-0.199	0.178
4-5	0.822	0.900	0.755	-0.694	-0.279	0.087
5-6	0.431	1.750	0.418	-0.412	-0.107	0.099

VALUES OF ACTIVE POWER GENERATION

BUSBAR	PRESENT	MINIMUM	MAXIMUM
1	1.500	0.700	1.700
4	3.677	0.400	4.000
5	0.640	0.070	0.700
6	0.674	0.120	1.200

VALUES OF REACTIVE POWER GENERATION

BUSBAR	PRESENT	MINIMUM	MAXIMUM
1	0.051	-0.340	0.340
4	0.452	-0.800	0.800
5	0.131	-0.140	0.140
6	1.460	-0.240	0.240

TOTAL GENERATION COSTS IS EQUAL TO 0.649205

CONTROL ACTIONS TAKEN

GENERATION RESCHEDULING: 0.129 AT BUS 4
GENERATION RESCHEDULING: -0.140 AT BUS 5
GENERATION RESCHEDULING: 0.387 AT BUS 6

GENERATOR TERMINAL VOLTAGE CHANGE: 0.020 AT BUS 4

LOAD SHEDDING:
REAL POWER: 0.104 REACTIVE POWER: 0.007 AT BUS 2
REAL POWER: 0.242 REACTIVE POWER: 0.025 AT BUS 3

SUMMARY

THE CURRENT FROM LINE 3 TO 4 HAS CHANGED FROM 0.513 TO 0.468
LINE CAPACITY: 0.450
OVERLOAD MARGIN ALLOWABLE 1.050
OVERLOAD MARGIN OBTAINED 1.039

programming. Interactive response is rapid and effective and the colour TV monitor provides user-acceptable graphic and mnemonic displays.

The next chapter expands on the algorithm demonstrated in section 6 and compares the control actions obtained using DSEA (Decoupled Security Enhancement Algorithm) with others based on linear and non-linear programming methods.

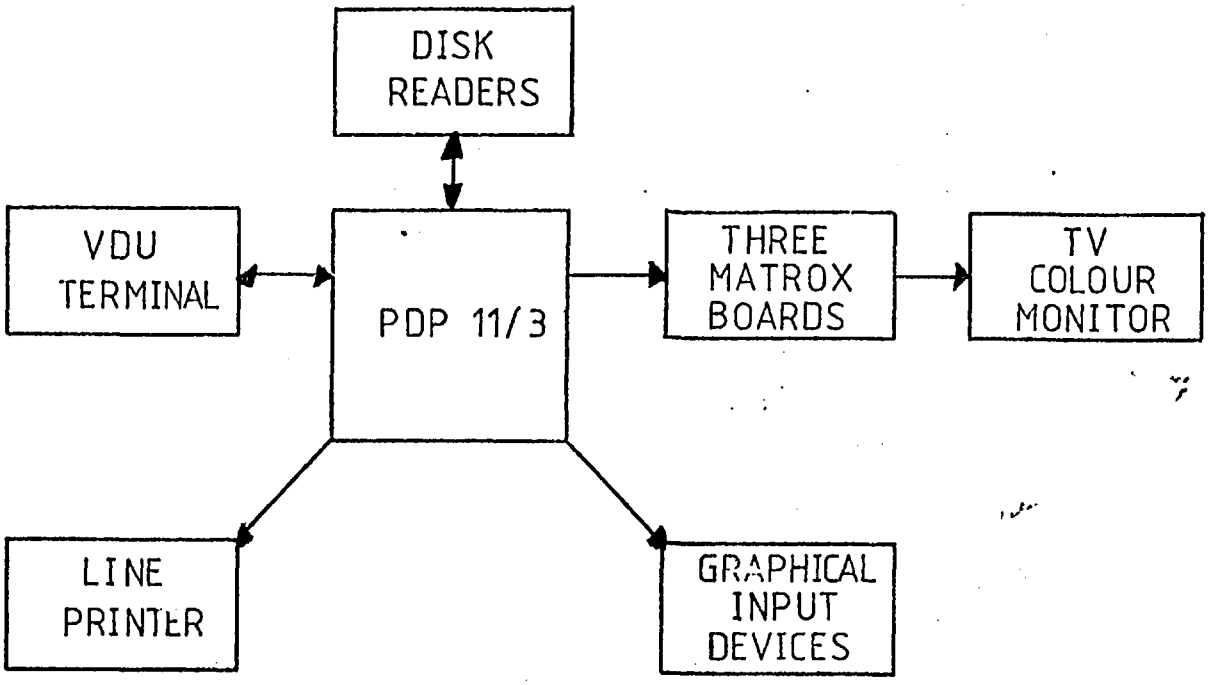


Fig. 3.1 : Computer Configuration

ROUTINE HELP AIDS NETWORK DRAWING
****

CODE	POWER SYSTEM REPRESENTATION/FUNCTION
B	BUSBAR
G	GENERATOR
L	LINE
T	TRANSFORMER
O	LOCATES THE STARTING BUS OF A LINE OR TRANSFORMER
S	LOAD
Y	SHUNT REACTOR
D	SHUNT CAPACITOR
N	REQUESTS FOR THE CIRCUIT NAME
C	SYNCHRONOUS COMPENSATOR
O,L,V,L	SETS UP A BENT LINE

Fig. 3.2: Subroutine HELP

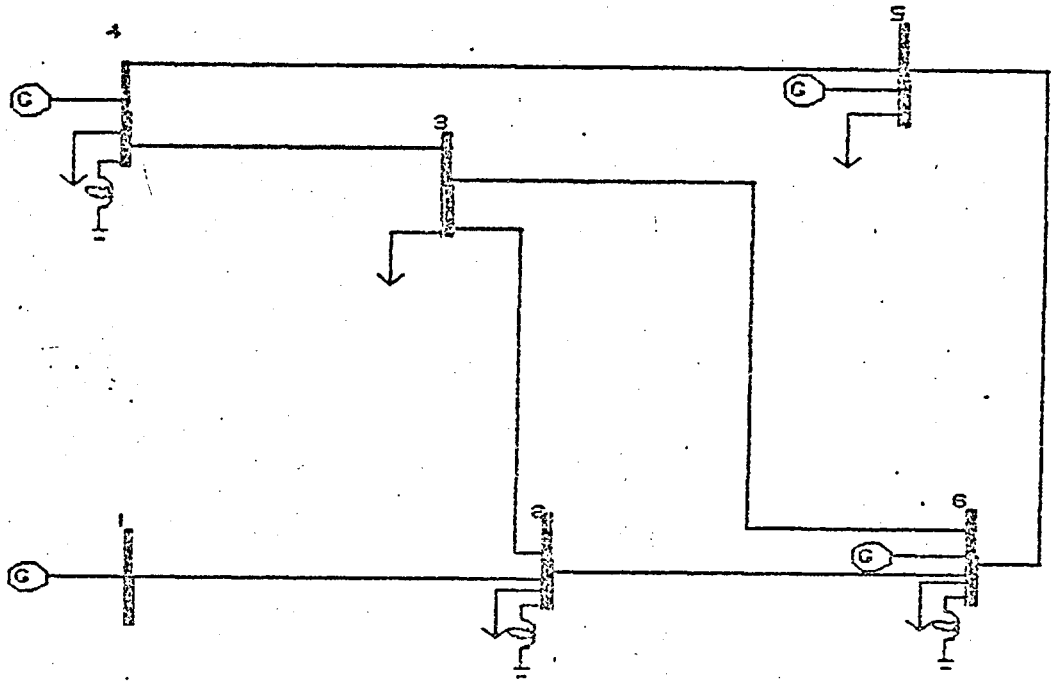


FIG. 3.3: Saskatchewan Power Corporation (SPC) 6-bus system

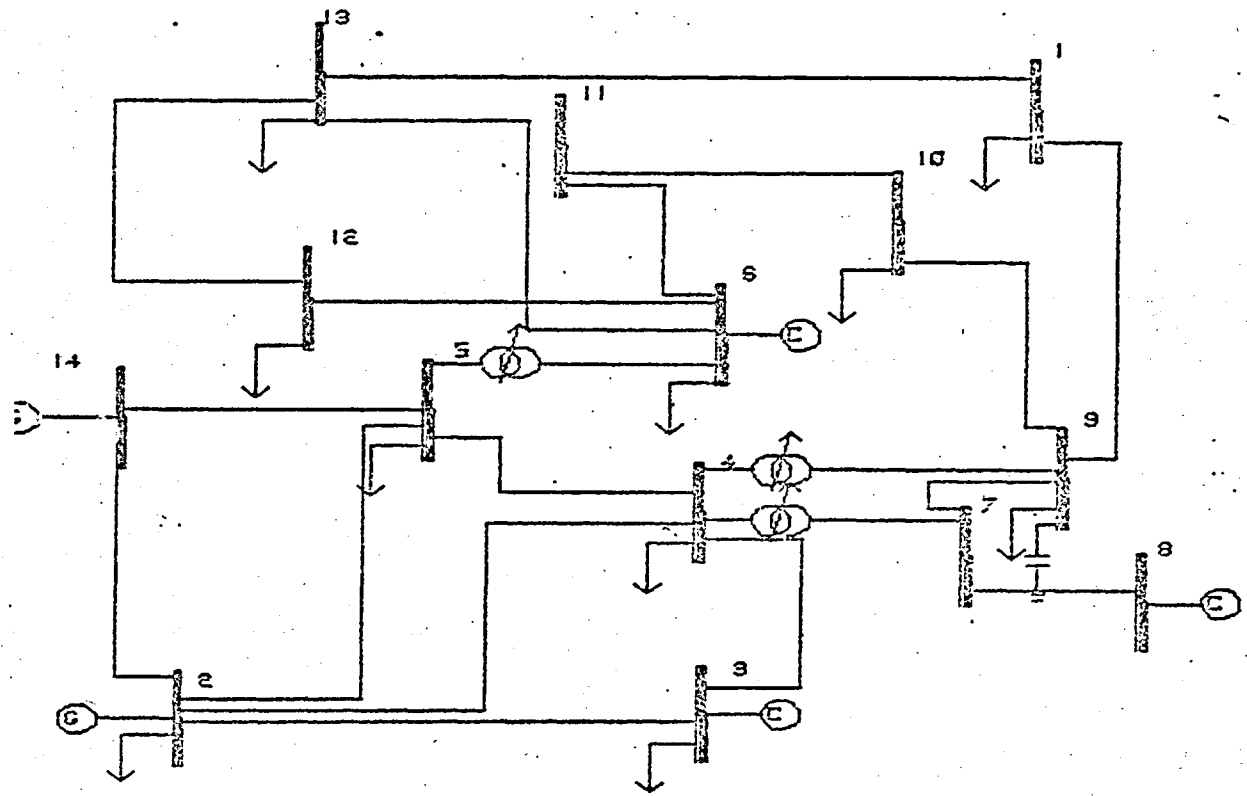


FIG. 3.4: IEEE 14-bus network diagram

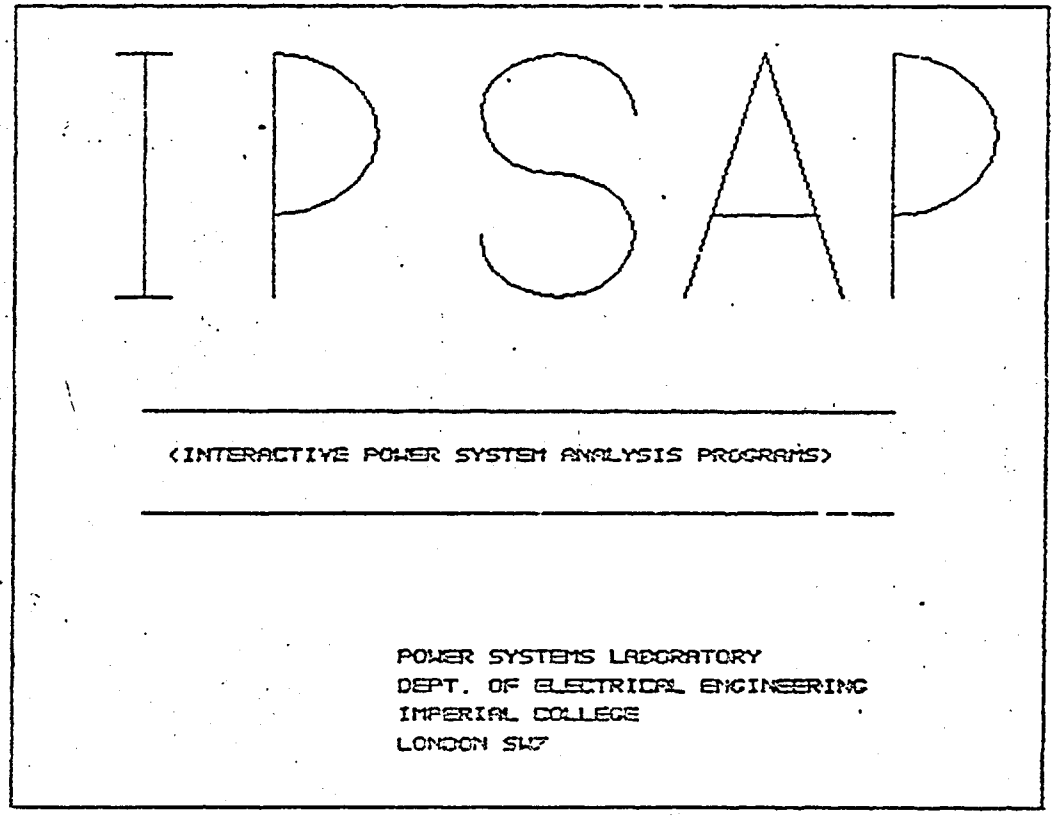


FIG. 3.5: IPSAP heading

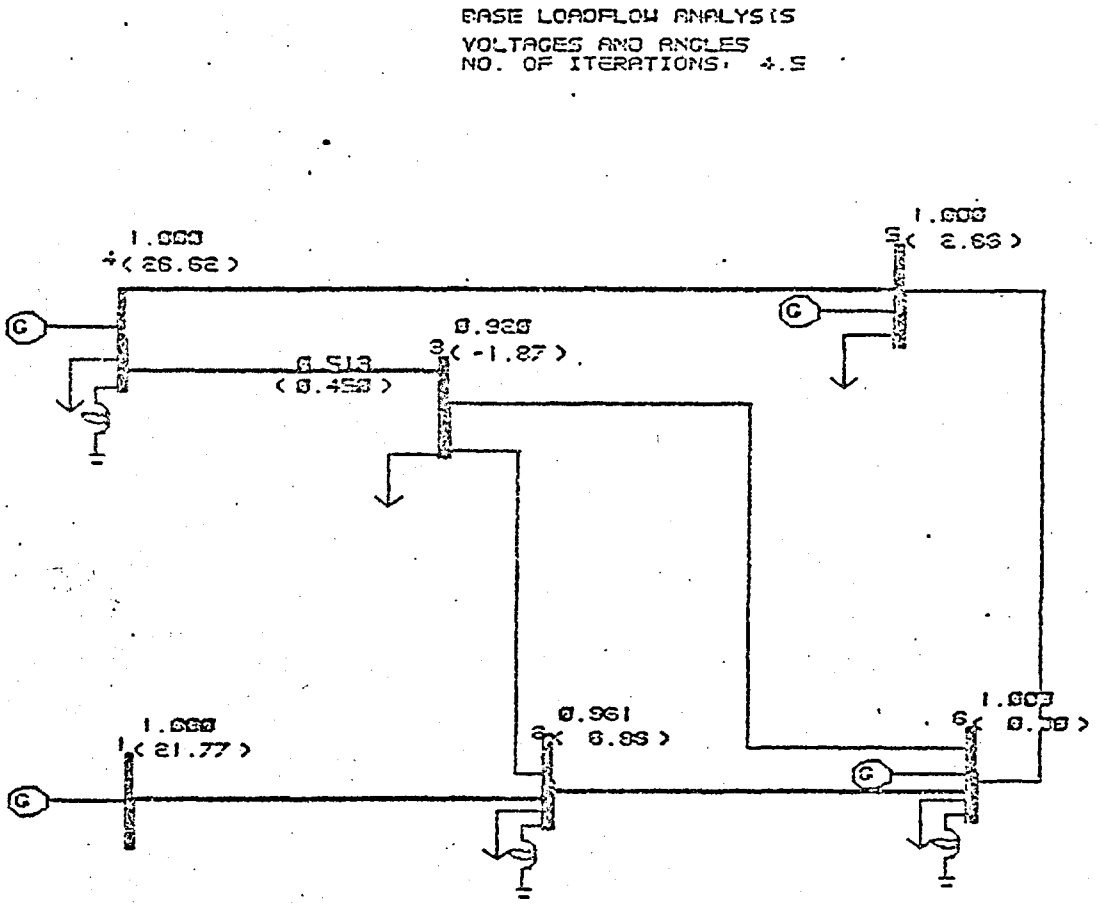


FIG. 3.6: Base case results: display of voltage magnitudes and angles line 3-4 overloaded with current value of 0.513 and capacity 0.450.

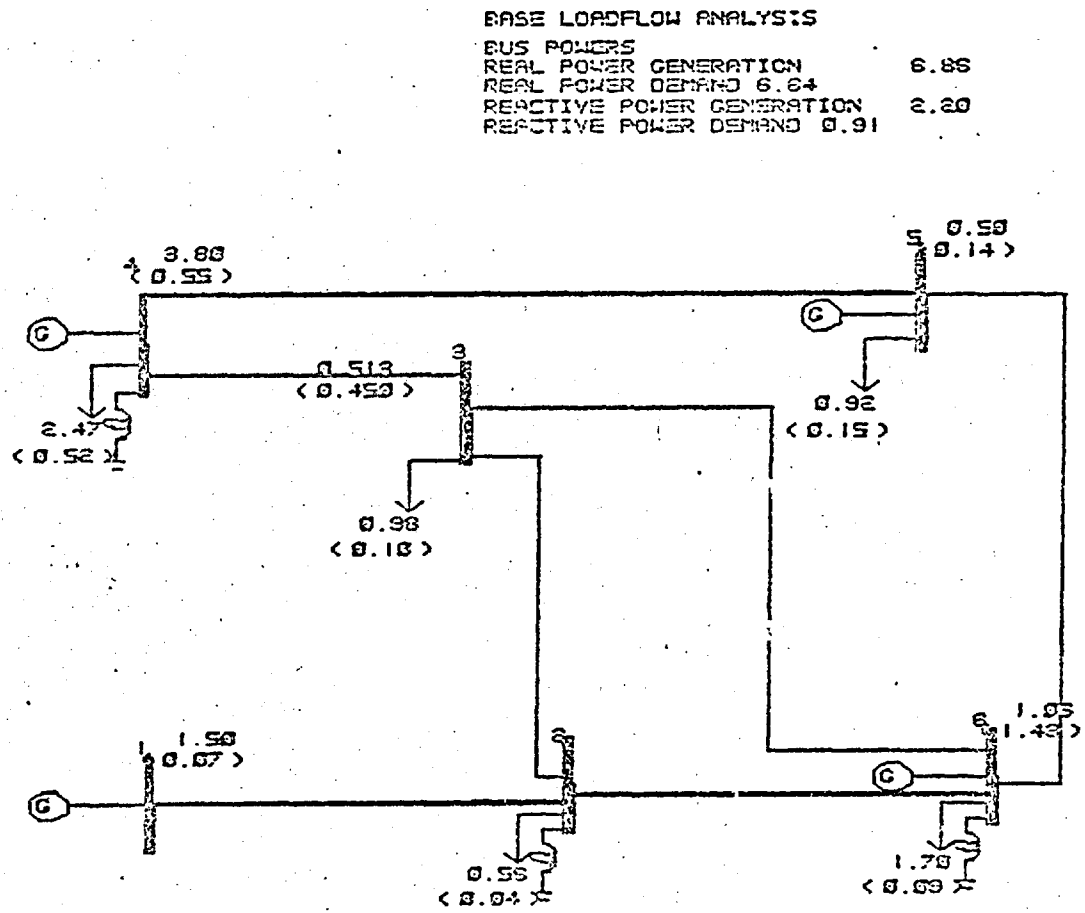


FIG. 3.7: Display of bus powers (reactive powers in brackets)

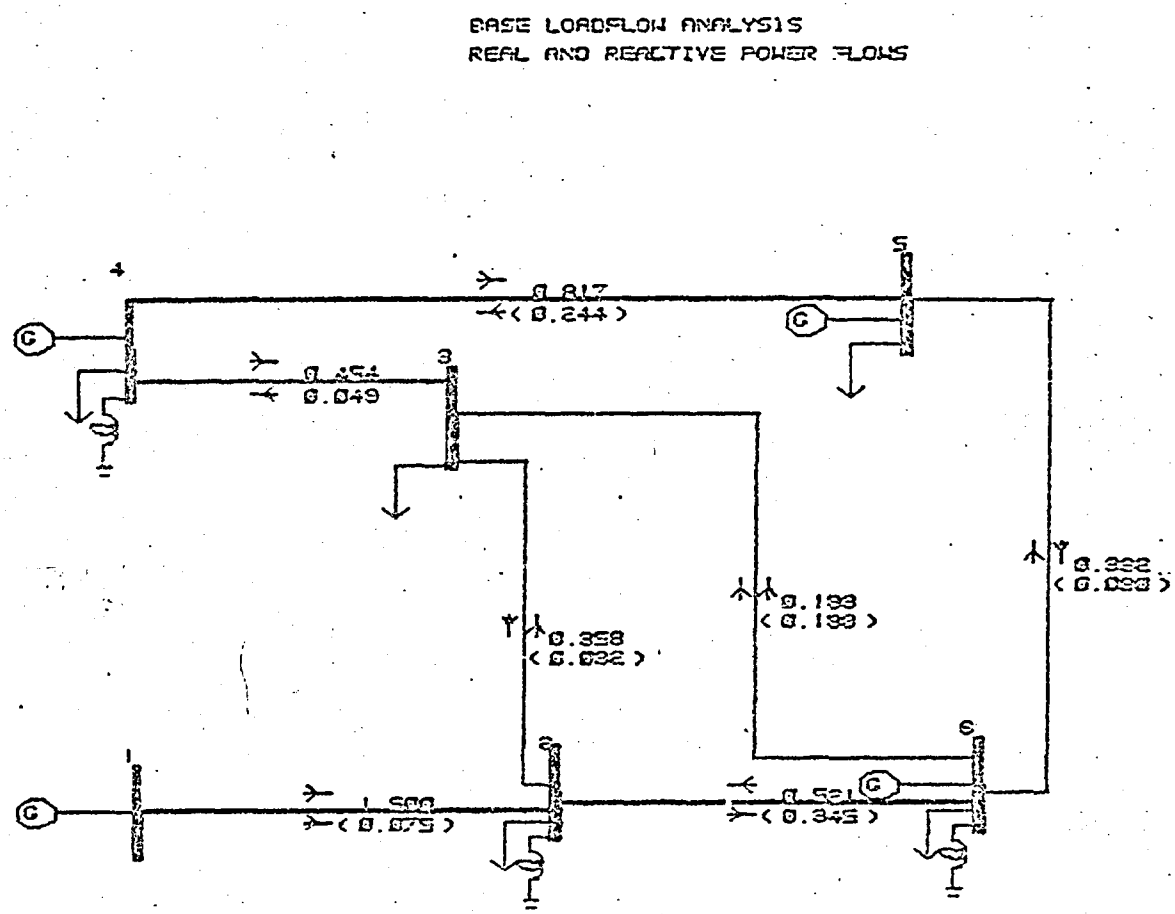


FIG. 3.8: Display of power flows (reactive power flows in brackets)

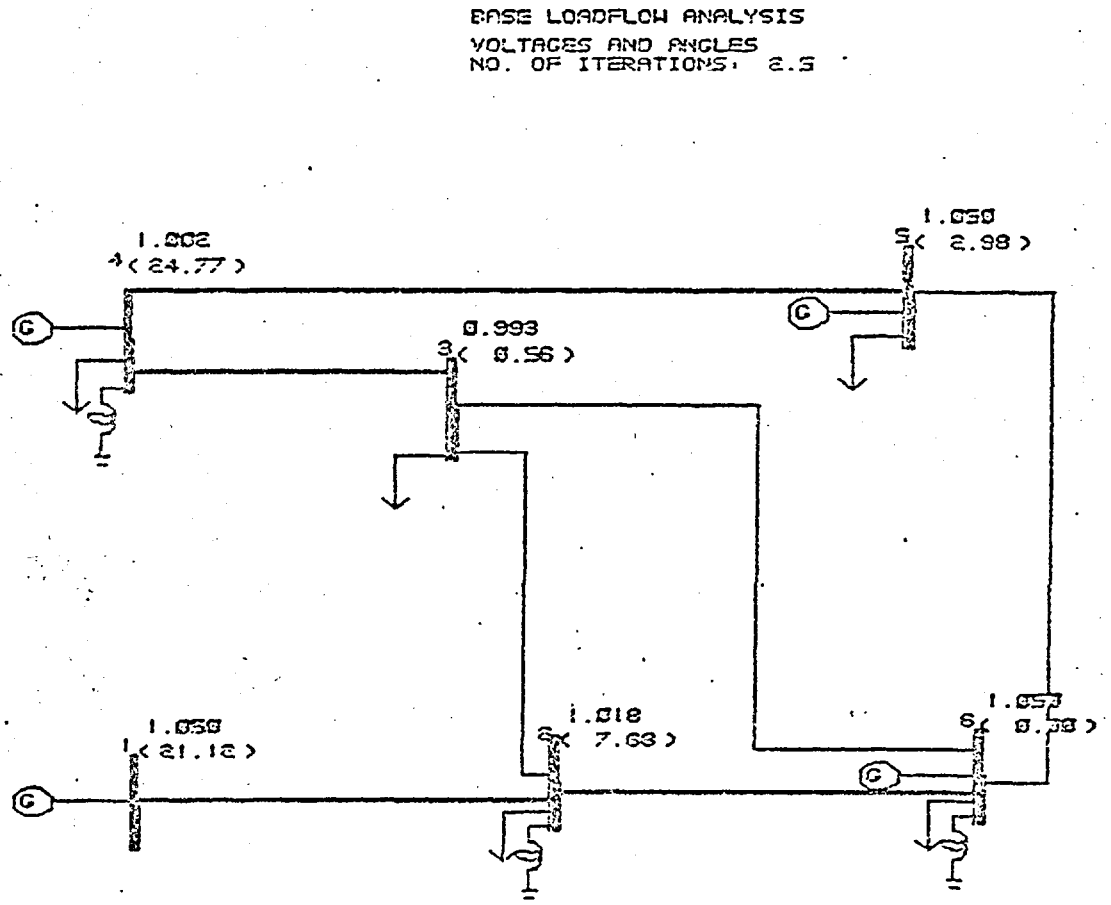


FIG. 3.9: Correction of the overload in line 3-4

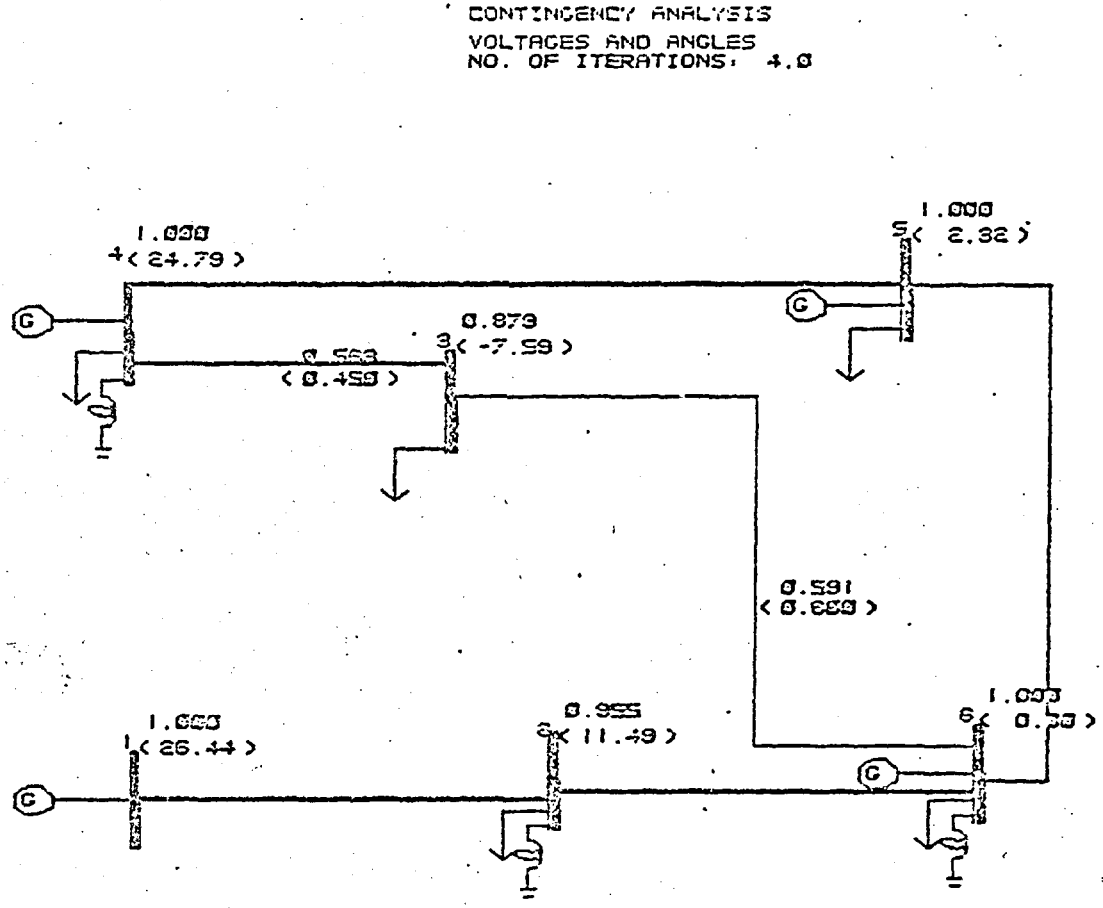


FIG. 3.10: Single line outage (2-3): display of voltages and angles

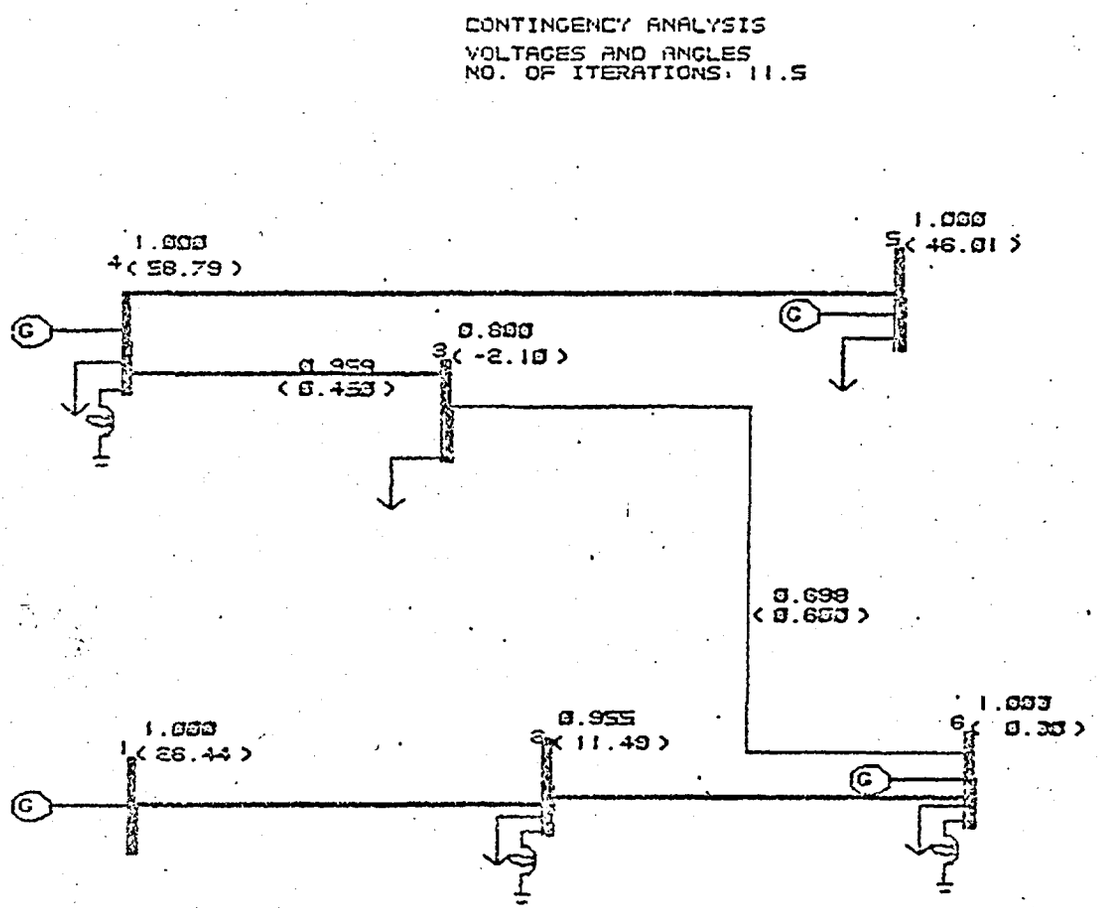


FIG. 3.11: Double line outages (2-3 and 5-6): display of voltages and angles

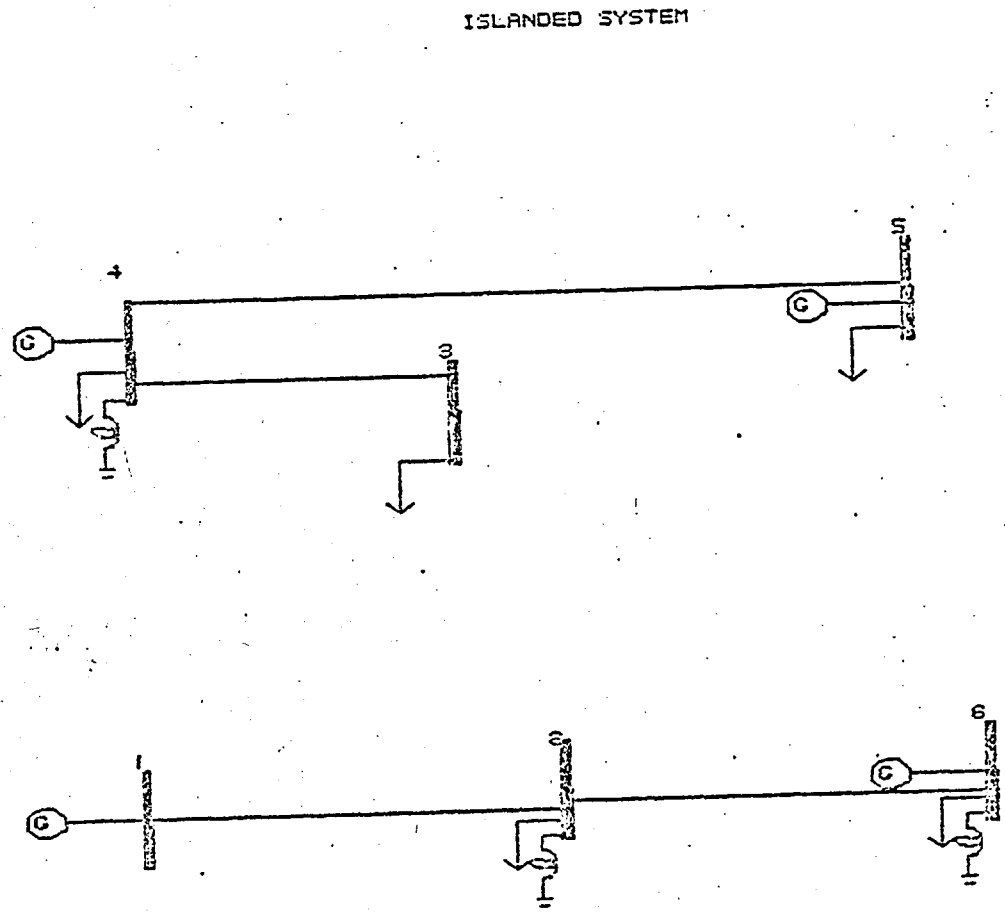


FIG. 3.12: Triple line outages (2-3, 5-6 and 3-6): islanded case

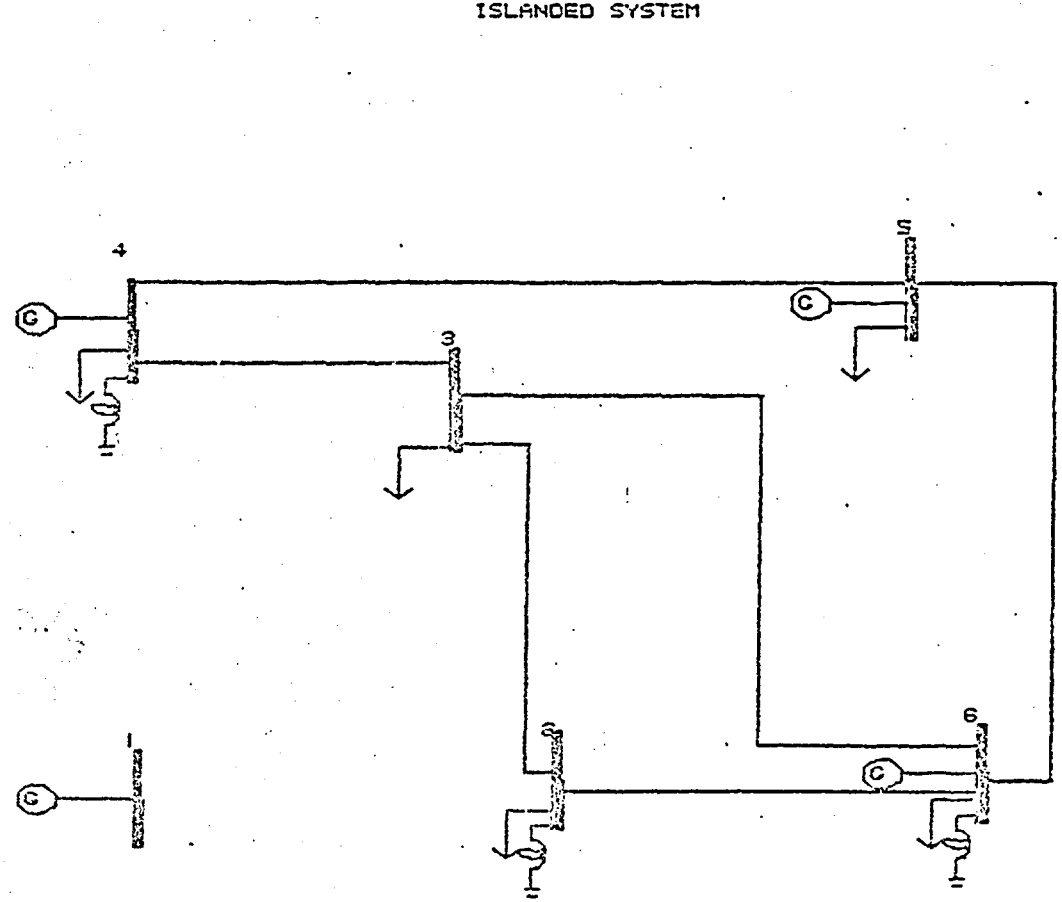


FIG. 3.13: Line 1-2 out of circuit: generator bus 1 is isolated - islanded case

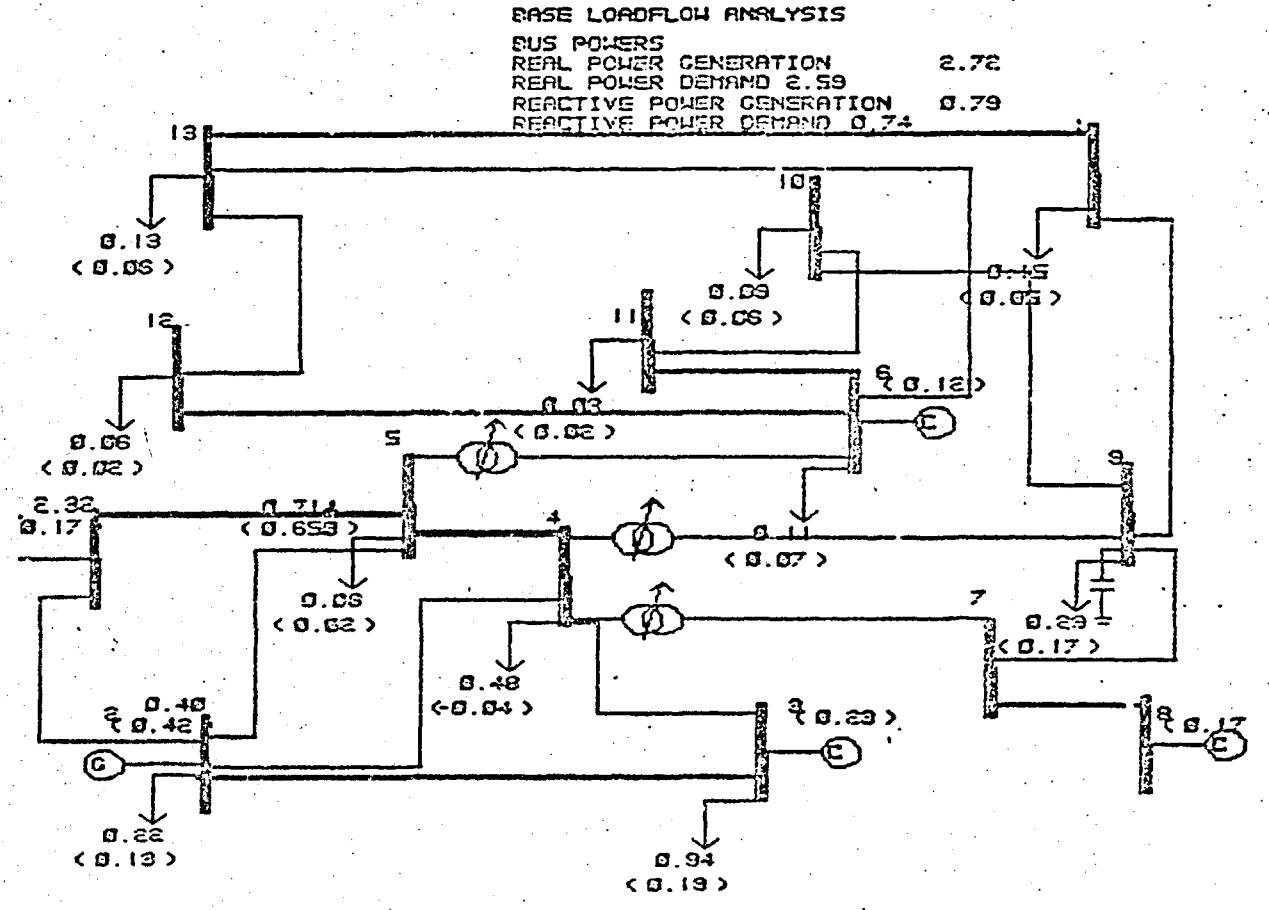


FIG. 3.14: IEEE 14-bus system, display of bus powers

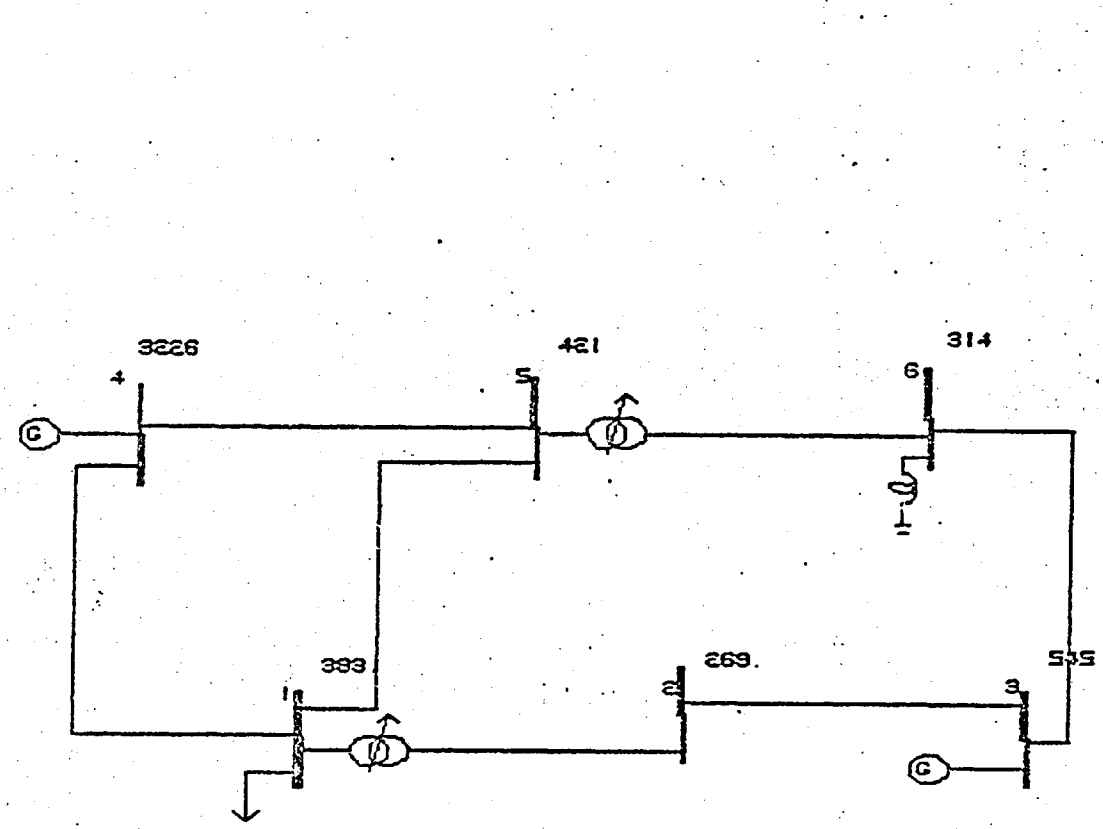


Fig. 3.15: Fault levels (MVA) for a three-phase fault analysis

POSTFAULT VOLTAGES
FAULTED BUS: 1
FAULT CURRENT: 3.830

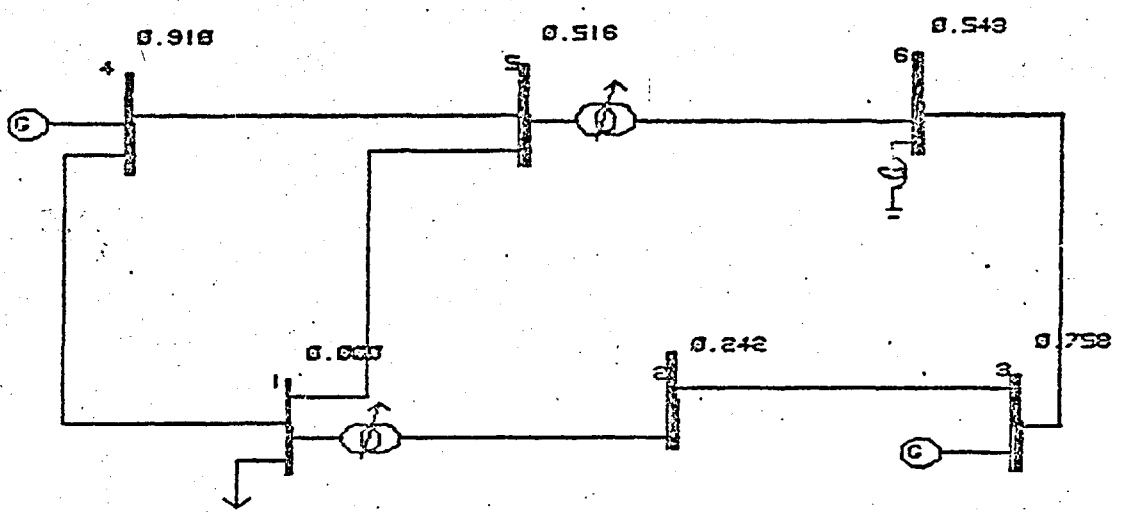


Fig. 3.16: Postfault voltages for a fault on busbar 1 (zero fault impedance is assumed)

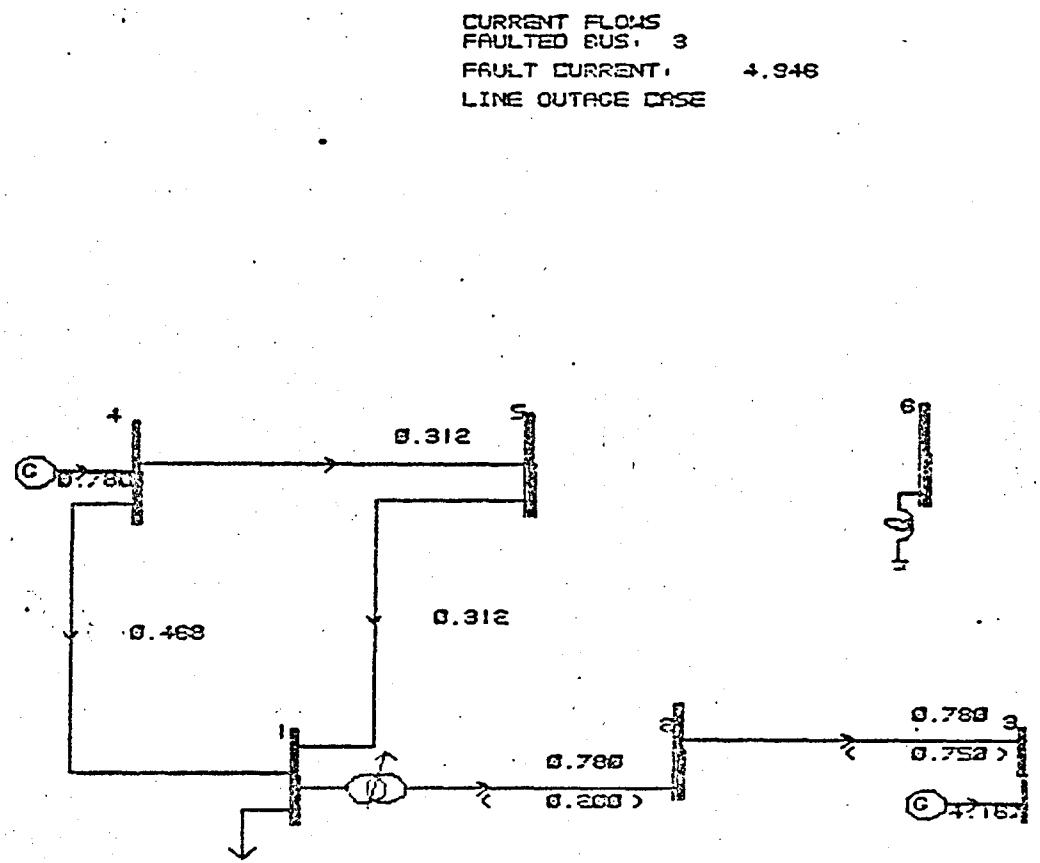


Fig. 3.17: Current flows for line 3-6 out. This resulted in transformer 5-6 being out also; the fault is on bus 3

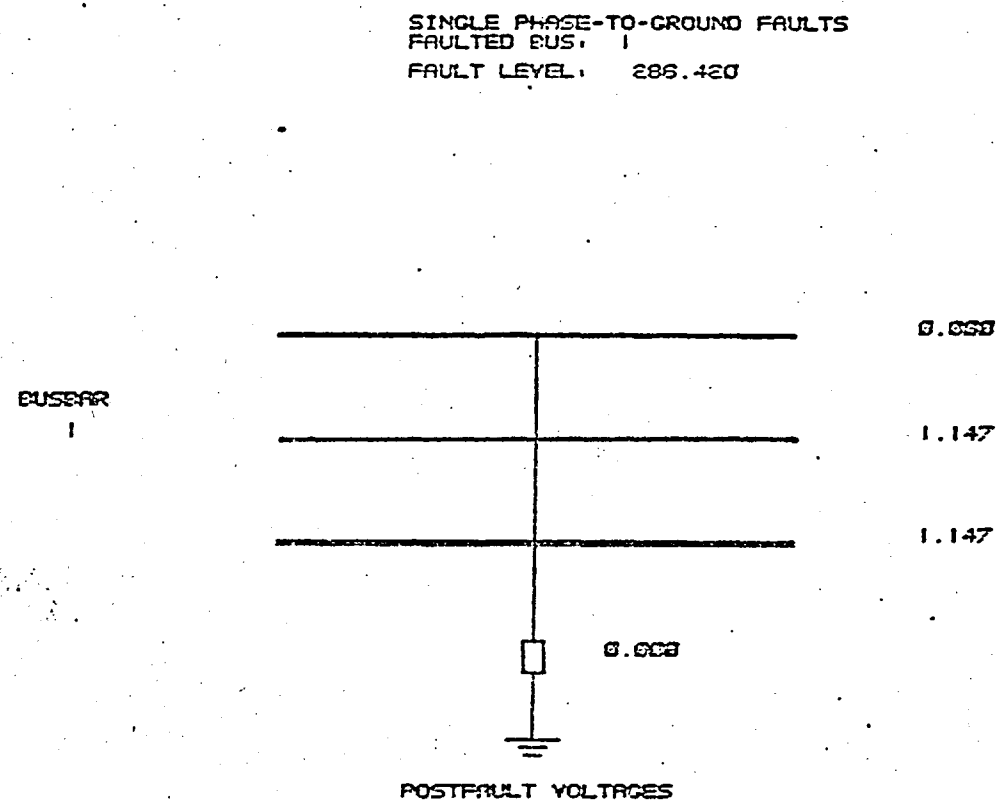


Fig. 3.18 : Single phase-to-ground faults faulted bus 1: Condition at bus 1

CHAPTER 4

SECURITY ENHANCEMENT

4.0 INTRODUCTION

The objective of the alleviation of the line overload problem and the voltage excursions on the load buses is to ensure that the constancy of supply of electricity is maintained at all times. The demand is expected to be met subject to the operational limits of system parameters within some degree of security at minimum cost.

Non-linear programming methods have been used to solve the optimal real and reactive power flows [58-64]. Computationally, these methods are very demanding due to the large number of variables and, in particular, the much larger number and types of limit constraints which define the boundaries. Currently, these non-linear relations can be approximated to linear equations and linear methods can then be applied [65-69]. The main attractions, in contrast with non-linear alternatives, include reliability and simplicity of implementation together with the fact that the accuracy and scope of the linearized model is adequate for security analysis, because the cost function of a generating plant is a non-linear function, the optimization of real power output was approximated by Nabona and Freris in [70] using quadratic programming methods. This method does not suffer the convergence problems of non-linear functions though may not be applied for real-time cases, as the run time may be up to 20 seconds for large schemes.

As suggested by Medicherla et al in [55,56], mathematical optimization techniques are computationally expensive, hence a linear method based on sensitivity analysis has been developed to solve the security enhancement problem, with load shedding applied only when generation rescheduling alone cannot alleviate line overloads. The intention is to

find a more feasible and more satisfactory operating condition to alleviate the violated constraints. This is expected to be appropriate for real-time systems where urgent decisions are required to be made available to the system operator for implementation. Successive relinearizations have often been used to improve the modelling accuracy. For short-term operation of power systems, this scheme would be attractive before proceeding to the implementation of more sophisticated optimization algorithms.

In the following sections, a logical extension of the formulations in [55,56] is presented where sensitivity relations have been employed to provide a near-term solution. The inexpensive method of least-squares minimization has been used as presented by Strang in [71] to minimize the deviations of the control variables from their nominal values (and possibly from the most economic point). Phase-shifting transformers have been modelled accurately and the voltage subproblem coupled to the development of line overload alleviation in [72] thus defining two problems which are solved successively until convergence for both solutions is reached. The incorporation of phase shifting transformers maximizes the effectiveness of distribution lines thus ensuring adequate redistribution of power flows by adjustment of phase angle settings. The transmission reliability is thus enhanced [73]. Potential advantages envisaged by the use of this program include:

(i) ease of implementation in control centres,

(ii) fast response enhanced by the use of sensitivity analysis,

(iii) savings in computer storage, and

(iv) separate solutions of either the line overload or the abnormal voltage problem.

4.1 MATHEMATICAL FORMULATION

4.1.1 Line Overload Problem

The current flowing in a transmission line can be expressed as a function of voltage magnitudes and angles as well as the phase shifting transformer angular displacements at the connecting buses as

$$I_{ij} = I_{ij}(\delta_i, \delta_j, V_i, V_j, \psi_{ij}) \tag{4.1}$$

where the variables have previously been described. Assuming an overloaded situation, equation (4.1) becomes

$$I_{ij}^{o} = I_{ij}^{o}(\delta_i^{o}, \delta_j^{o}, V_i^{o}, V_j^{o}, \psi_{ij}^{o}) \tag{4.2}$$

The problem is to determine a new set of $(\delta, V, \psi)^T$ such that I_{ij}^{o} is reduced (as low as possible) to I_{ij}^{max}. Define the overloaded vector as:

$$\Delta I_{ij} = I_{ij}^{max} - I_{ij}^{o} \tag{4.3}$$

Taking the Taylor's series expansion of (4.2) in terms of $(\delta, V, \psi)^T$ with second and higher order terms neglected.

$$\Delta I_{ij} = \frac{\partial I_{ij}}{\partial \delta_i}\Delta\delta_i + \frac{\partial I_{ij}}{\partial \delta_j}\Delta\delta_j + \frac{\partial I_{ij}}{\partial V_i}\Delta V_i + \frac{\partial I_{ij}}{\partial V_j}\Delta V_j + \frac{\partial I_{ij}}{\partial \Psi_{ij}}\Delta\Psi_{ij} \tag{4.4}$$

Equating (4.3) and (4.4) in matrix form:

$$\begin{bmatrix} \Delta I_1 \\ \Delta I_2 \\ \vdots \\ I_m \end{bmatrix} = [C] \begin{bmatrix} \Delta\delta \\ \vdots \\ \Delta\delta_{NB-1} \\ \Delta V_1 \\ \vdots \\ \Delta V_{NB} \\ \Delta\psi_1 \\ \vdots \\ \Delta\psi K \end{bmatrix} \qquad (4.5)$$

where m is the number of overloaded lines and K the number of shifters.

An Iterative-Constraint-Search (ICS) technique is utilized to select the relevant line flow constraints needed. This would result in reduction in solution time and computer storage requirements. The matrix contains a maximum of five non-zero elements on each row and is rectangular, hence its inverse does not exist though the solution of equation (4.5) exists but it is not unique.

According to Strang in [71], pseudo-inverse methods:

$$C^{+} = C^{T} (CC^{T})^{-1} \qquad (4.6)$$

are applied to obtain $(\Delta\delta, \Delta V, \Delta\psi)^{T}$. These parameters are then updated as:

$$\left.\begin{aligned} \psi_{ij}' &= \psi_{ij} + \Delta\psi_{ij} \\ V_i' &= V_i + \Delta V_i \end{aligned}\right\} \qquad (4.7)$$

$$\left.\begin{aligned} \text{provided } \psi_{ij}^{min} &\leq \psi_{ij}' \leq \psi_{ij}^{max} \\ V_i^{min} &\leq V_i' \leq V_i^{max} \end{aligned}\right\} \qquad (4.8)$$

The generator voltages as well as the slack are included in the modification as the line overload problem may be due principally to the reactive power flow on the line.

The bus powers are adjusted as in eqn. (2.12):

$$\begin{bmatrix} \frac{\Delta P}{V} \end{bmatrix} = \begin{bmatrix} B' \end{bmatrix} \begin{bmatrix} \Delta\delta \end{bmatrix} \tag{4.9}$$

to determine the change in injected powers to effect generation rescheduling and load shedding. Making use of the common engineering assumption of constant power factor, particularly where the load composition on a bus is not known, the reactive power component of the load to be shed is

$$\Delta Q_L = K\Delta P_L \tag{4.10}$$

hence the following constraints must be satisfied before another loadflow is run:

$$\left.\begin{aligned} P'_L &= P_L - \Delta P_L \\ Q'_L &= Q_L - \Delta Q_L \\ P'_g &= P_g + \Delta P \end{aligned}\right\} \tag{4.11}$$

subject to

$$\left.\begin{aligned} 0 \leq P'_g &\leq P_g^{max} \\ 0 \leq P'_L &\leq P_L \\ 0 \leq Q'_L &\leq Q_L^{max} \quad \text{(If the initially specified load is inductive)} \\ Q_L^{min} \leq Q'_L &\leq \phi \quad \text{(If the initially specified load is capacitive)} \end{aligned}\right\} \tag{4.12}$$

The dependence of load on voltage and frequency is neglected.

An interactive program making use of the line alleviation sub-problem was developed using colour graphics. Some of the results were presented by the author in [72]. Appendix 2 shows some of the equations employed in the formulation.

4.1.2 Abnormal System Voltage Problem

The reactive power flow of a general NB-node system is described in the steady-state by a set of NB simulataneous equations as

$$g = Q_g + Q_L - \Sigma V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \delta_{ij})$$

$$+ \Sigma V_i^2 Y_{ij} \cos \delta_{ij} - Y_{ii} V_i^2 = 0 \qquad (4.13)$$

The variables and parameters in equation (4.13) can be classified into:

1. independent or operating variables $\underset{\sim}{u}$
2. controlled or dependent variables $\underset{\sim}{X}$
3. uncontrolled variables denoted by p

according to Hano et al in [74] and Kishore and Hill in [75]. These are the specified variables in the load flow equations excluding the operating variables. For the satisfaction of the loadflow problem, equation (4.13) can be stated as

$$g(\underset{\sim}{X}, \underset{\sim}{u}, p) = 0 \qquad (4.14)$$

For a condition with abnormal system voltage an operating point is defined as

$$g(\underset{\sim}{X}^{\circ}, \underset{\sim}{u}^{\circ}, p) = 0 \qquad (4.15)$$

If a small change Δu from u° in $\underset{\sim}{u}$ causes a change ΔX from X° in $\underset{\sim}{X}$ then the Taylor series expansion of equation (4.15) neglecting high order terms is used:

$$g(X^\circ + \Delta X,\ u^\circ + \Delta u,\ p) = g(X^\circ,\ u^\circ,\ p) + g_x \Delta X$$

$$g_u \Delta u = 0 \qquad (4.16)$$

where g_x is the Jacobian matrix of g with respect to X given by

$$g_x = \frac{\partial(g_1, g_2, \ldots\ldots g_{NB})}{\partial(X_1, X_2, \ldots\ldots X_{NB})} \qquad (4.17)$$

and

$$g_u = \frac{\partial(g_1, g_2, \ldots\ldots\ldots g_{NB})}{\partial(u_1, u_2, \ldots\ldots\ldots u_M)} \qquad (4.18)$$

g_x is usually a square matrix whereas g_u is not but of the order NB by M where M is the number of operating variables. Combining equations (4.17) and (4.18)

$$\Delta X = -g_x^{-1} g_u \Delta u = S\Delta u \qquad (4.19)$$

where $S = -g_x^{-1} g_u$ is the sensitivity matrix of order NB by M.

The above derived sensitivity relation has been used by Thanikachalam and Tudor in [76] to bring a potentially dangerous condition into a secure operating state using linear programming to adjust the power productions of some generators such that the increase in hourly cost is a minimum.

In matrix form equation (4.19) becomes

$$\begin{bmatrix} \Delta X_1 \\ \Delta X_2 \\ \vdots \\ \Delta X_K \end{bmatrix} = \begin{bmatrix} \quad S \quad \end{bmatrix} \begin{bmatrix} \Delta u_1 \\ \Delta u_2 \\ \vdots \\ \Delta u_M \end{bmatrix} \qquad (4.20)$$

where K is the number of buses with abnormal system voltages. Usually M > K hence the right pseudo-inverse methods can be used as

$$\Delta u = S^T(S.S^T)^{-1} \Delta X \tag{4.21}$$

Alternative solutions may be as follows according to Shoults and Chen in [77]:

1. If K = M

$$\Delta u = S^{-1} \Delta X \tag{4.22}$$

2. If K > M

$$\Delta u = (S^T.S)^{-1} S^T \Delta X \tag{4.23}$$

This is the minimum left pseudo-inverse equation. These equations are subject to

(i) $V_i^{min} \leq V_i \leq V_i^{max}$
at the load buses i

(ii) $Q_i^{min} \leq Q_i \leq Q_i^{max}$
where Q_i^{min} may be the present reactive power generation at bus i.

(iii) $n_h^{min} \leq n_h \leq n_h^{max}$
where n_h^{max} and n_h^{min} represent the transformer maximum and minimum tap ratios

For effective utilization of this algorithm it is assumed that the transmission system has the ability to support voltage levels within desirable limits at load buses, i.e. maximum, and appropriately distributed reactive power must be available at every moment. Also the real power flow is assumed to be unaffected by the reactive power injections.

The physical significance of the least-squares minimization technique is shown in Appendix 3.

4.1.3 Program Development

The flowchart for the implementation of the program is shown in Fig. 4.1. KP and KQ are used to specify whether separate solutions of the problem are required, i.e. KP = 0 implies that only the voltage/reactive power problem is required, hence computations are carried out only in the second loop of the program.

KPMAX is the number of passes of the generation rescheduling which would be looped before load shedding is employed. At convergence, both KP and KQ take values of zero and the various control strategies are made available to the operator.

4.2 TESTS AND RESULTS

According to Chan and Schweppe in [67] there are basically two approaches to testing load shedding and generation rescheduling algorithms:

1. Induce overloads by removing heavily loaded lines from the network.
2. Turn the base case into an overloaded system by setting current limits on certain lines below their base case values.

The second approach is used in this chapter. The voltages are assumed to lie between 0.95 and 1.05 on the load buses though a voltage deviation of ± 0.002 is allowable. Only line overloads of more than 5% are considered in the problem constraints.

4.2.1 6-bus SPC Network (see Fig. 3.3)

(a) Experiment 1

Overload in lines 3-4 with no abnormal system voltages. The current changed from 0.49 with a capacity of 0.45 to 0.47 by:

(1) increase in real generation in bus 5,

(2) decrease in real generation in buses 4 and 5,

(3) change in generator terminal voltage of bus 4, and

(4) loadshedding in buses 3 and 4.

Only one pass of the algorithm was required.

(b) Experiment 2

Reducing the generator terminal voltages to 1 pu and considering only the voltage/reactive power problem, abnormal system voltage was detected in bus 3.

A total (capacitive) generation to raise the voltage on bus 3 from 0.9204 to 0.95 is 0.179 pu (VARS) with 3 passes of the algorithm.

4.2.2 14-bus IEEE Network (see Fig. 3.4)

(a) Experiment 1

System abnormalities:

(1) line overload in lines 5-14 of percentage 9.85,

(2) unacceptable voltages on the load buses 9,10,11,12 and 13.

The control actions displayed are:

(1) reduce the real generation on bus 14,

(2) change the generator terminal voltage on bus 14,

(3) shed load on buses 4, 5 and 6,

(4) switch in shunt reactors in buses 9,10,11,12 and 13, and

(5) only one pass of the decoupled security enhancement algorithm was required to reduce the current in 5-14 from 0.714 of

capacity 0.65 to 0.537 with acceptable voltages.

(b) Experiment 2

To consider the effectiveness of the algorithm to consider only the voltage/reactive power subproblem, the loads on the following busbars were changed to create abnormal system voltages in buses 11 and 12:

bus 1 from 0.149 + j0.05 to 0.298 + j0.10

bus 5 from 0.076 + j0.016 to 0.152 + j0.032

Only one pass of the subroutine was required with reactive power generation of 0.038 and 0.022 (VAR) pu on buses 11 and 12 respectively.

(c) Experiment 3

The objective of this test is to make use of the combined adjustment of reactive power generation and transformer tap changers to correct abnormal system voltage.

The load configuration as in Experiment 2 with the load on bus 4 reduced from 0.478 - j0.039 to 2.912 + j0.2561 to create abnormal voltage of 0.94969 pu on bus 4.

The corrective actions are:

(1) capacitive reactive generation of 0.0037 on bus 4,

(2) transformer tap changes in:

  (a) 4-7 by 0.0141

  (b) 4-9 by 0.0209

(3) reduce the real generation on bus 14,

(4) change the generator voltage on bus 14, and

(5) shed load on buses 4, 5 and 6.

More tests carried out will be discussed in the next section.

4.3 COMPARISON OF METHODS

The performance of the Decoupled Security Enhancement Algorithm (DSEA) has been compared with two methods based on linear and non-linear programming techniques in terms of execution times and storage requirements. In the following section, the methods are briefly stated and tests carried out on the 24-bus reliability network [78] (see Fig. 4.2). A CDC 6600 computer was used for the comparison because of the capacity limitation of the present DEC system.

4.3.1 Linear Programming Method (LP)

The method was developed by Chan and Schweppe in [67].

Neglecting the load dependence on voltage, a mathematical optimization problem is formulated which attempts to:

(i) minimize load shedding

(ii) minimize deviations from the nominal state

These objectives are translated to the mimimization of a scalar penality function, J which is the sum of two terms:

$$J = \Sigma h_i(\Delta P_L, \Delta Q_L) + \Sigma K_i(\Delta P_g, \Delta Q_g) \qquad (4.25)$$

where h_i and K_i are non-linear penalty functions which take on a unique minimum at the nominal state. The penalty of load shedding (h_i) is always made much greater than that of the generation rescheduling (K_i) so that load shedding will be used only as a last resort. Equation (4.25 is minimized subject to

$$\left.\begin{array}{lll} 0 \leq |I_{ij}|^2 & \leq & |I_{ij}^{max}|^2 \\ 0 \leq P_g & \leq & P_g^{max} \\ V^{min} \leq V & \leq & V^{max} \end{array}\right\} \qquad (4.26)$$

The transmission network is represented by an AC loadflow model expressed mathematically as:

$$\left.\begin{array}{l} P_g - P_L - g(\underline{V}, \underline{\delta}) = 0 \\ Q_g - Q_L - g(\underline{V}, \underline{\delta}) = 0 \end{array}\right\} \qquad (4.27)$$

4.3.2 Non-linear Programming Method (NLP)

The method is a two-stage optimization algorithm developed by Wu et al in [64] and used by Prada in [17]. Solution is arrived at by exploiting the structural properties of the optimal power flow problem formulation, including the physical characteristics of the variables.

First stage:

Solves the problem of minimum cost subject to

(1) power flow equations
(2) slack bus voltage constraints
(3) slack bus power constraints
(4) voltage constraints at each PV bus
(5) power constraints at each PV bus with variable generation
(6) transformer constraints

The minimum cost problem is solved with all but constraint (3) with a modified reduced gradient method and constraint (3) handled by limiting the step-size along the direction of movement. An interstage calculation is carried out to ensure that the reactive power Q at each PV bus i is maintained

within reasonable limits as well as that of the slack. The reactive power Q_i is set to Q_i^L whenever a violation occurs

where

$$Q_i^L = \begin{cases} Q_i^M & \text{if upper limit is violated} \\ Q_i^m & \text{if lower limit is violated} \end{cases}$$

and switch the bus temporarily from PV to PQ.

Second stage of optimization:

Solve the equation given by:

$$PI = \sum_i S_i(V_i - V_i^{max})^2 + \sum_j S_j(|I_j| - |I_j|^{max})^2 \quad (4.28)$$

where i contains all PQ buses with voltage magnitude limit violation and j contains all branches with current magnitude limit violation. The penalty function was introduced to force the variables back to the limits. The penality function method will, in general, exhibit slow convergence hence it has been introduced at this stage to handle the "soft limits" - voltage mangitudes in PQ busbars as well as branch current magnitudes.

For the various tests carried out, a 5% overloaded margin has been allowed. Loadshedding is encouraged only when there is no feasible solution.

Experiment 1

Overload in line 7-16 of percentage 8.5% of line capacity 2.1 with a current of 2.28.

TABLE 4.1: RESULTS OF EXPERIMENT 1

	DSEA	LP	NLP
1. Control strategies	(i) real generation rescheduling only on buses 1, 7,10 and 24 (ii) Change in generator terminal voltage in bus 7	(i) real generation rescheduling on buses 7 and 24	(i) real generation rescheduling on buses 1,7, 14 and 22. (ii)change in voltages on buses 1,7,9, 10,11,17 and 19
2. Line current on solution	2.17	2.16	2.10
3. Overload margin obtained (in percentage)	3.33	2.85	-
4. Time (seconds)	0.598	6.071	51.909

Experiment 2

Overloads in

(a) 7-16: current value of 2.28 (2.1 capacity), 8.57%

(b) 11-14: current value of 3.92 (3.5 capacity), 12%

TABLE 4.2: RESULTS OF EXPERIMENT 2

	DSEA	LP	NLP
1. Control strategies	(i) real power rescheduling on buses 1,7,9, 10 and 24 (ii) change in terminal generator voltages of buses 7,11 and 24 (iii) load shedding in bus 4	(i) change in real power rescheduling on buses 7,11 and 24	(i) changes in buses 1,7,9, 10,11,14,17, 19 and 22 (ii) changes in voltages on buses 1,7,9, 11,14,17 and 24 (iii) generated reactive power on buses 10,19 and 22
2. Line current on solution 7-16 11-14	2.16 3.67	2.17 3.62	2.18 3.49
3. Overload Margin 7-16 11-14	2.85 4.85	3.33 3.42	3.81 -
4. Time (seconds)	1.22	5.512	131.184

Experiment 3

Overloads in

(a) 7-16: overload percent 20% capacity 1.9

(b) 11-14: overload percent 12.1% capacity 3.5

TABLE 4.3: RESULTS OF EXPERIMENT 3

	DSEA	LP	NLP
1. Control strategies	(i) real power rescheduling on buses 1,7, 9,10 and 24 (ii) change in generator terminal voltages of buses 7,11 and 14 (iii) load shedding in buses 3,4, 5 and 20	(i) change in real power rescheduling in buses 7,11 and 24	(i) changes in 7,9,10,11, 14,17,19 and 22 (ii) changes in voltages 1, 7,9,11,14, 17, 19 and 24 (iii) generated reactive power on buses 10 and 22
2. Line current 7-16 on solution 11-14	1.98 3.41	1.96 3.64	1.97 3.50
3. Overload 7-16 Margin 11-14	4.21 -	3.16 4.0	3.68 -
4. Time (in seconds)	4.035	6.874	195.48

TABLE 4.4:. COMPUTER STORAGE REQUIREMENTS

DSEA	LP	NLP
61.4 KB	66 KB	110.6 KB

4.4 DISCUSSION OF RESULTS

From the experiments discussed in the previous section, the following deductions can be made:

(1) The DSEA is fast and thus seems attractive for real-time control calculations. Feasible and satisfactory operating conditions can be obtained without considering the economics of operation.

(2) The DSEA has good convergence properties. The IEEE 24-bus network was tested for three line overloads. The linear and non-linear programming methods produced diverged solutions whereas the solution with DSEA converged, though with considerable loadshedding.

(3) The optimization techniques are computationally expensive, though for long-term planning schemes their use is to be encouraged, whereas for short-term operational purposes the use of the Decoupled Security Enhancement Algorithm is adequate.

(4) The DSEA has lower computer storage requirements than either the LP or NLP methods. With the DSEA, a reduction in paper output results, hence its interactive implementation has advantages.

4.5 CONCLUSION

This chapter has described three methods for the determination of control actions for the relief of network overloads and abnormal system voltages. Non-linear programming methods permit flexibility and accuracy of modelling though convergence is not assured at all times and there are long execution times.

The linear programming approach has a more favourable convergence behaviour and can guarantee solutions to feasible problems in return for modelling limitations.

For corrective control purposes where the solution speed is an important factor in the performance comparisons of the three methods, the proposed DSEA is to be preferred. Whether automatically initiated by the computer system or requested interactively by the operator, the solution of realistically sized systems would be made available for display in a matter of seconds using the DSEA. The size of the problem to be solved is reduced by considering only the most critical constraints and ignoring the rest.

The DSEA would be attractive for use in hydro-system security scheduling as no direct costs are involved, since deviation from the initial schedule is expected to be achieved. The incorporation of 'inexpensive' controllable variables,such as reactive injections, generator terminal voltage magnitudes and transformer tap setting is important - especially in preventive control calculations as well as where abnormal system voltages may be of interest.

The work done by the author in this chapter would in future be compared with the work of Vervloet and Bramellar in [79]. Adequate review of the subject of optimal power flows cannot be claimed. However, a recent paper by Carpentier [80] has treated the subject in some detail. Methods for investigating the load shedding problem will be reviewed in the next chapter whereas chapter 6 will extend the security enhancement procedures through the a-priori operation of phase-shifters.

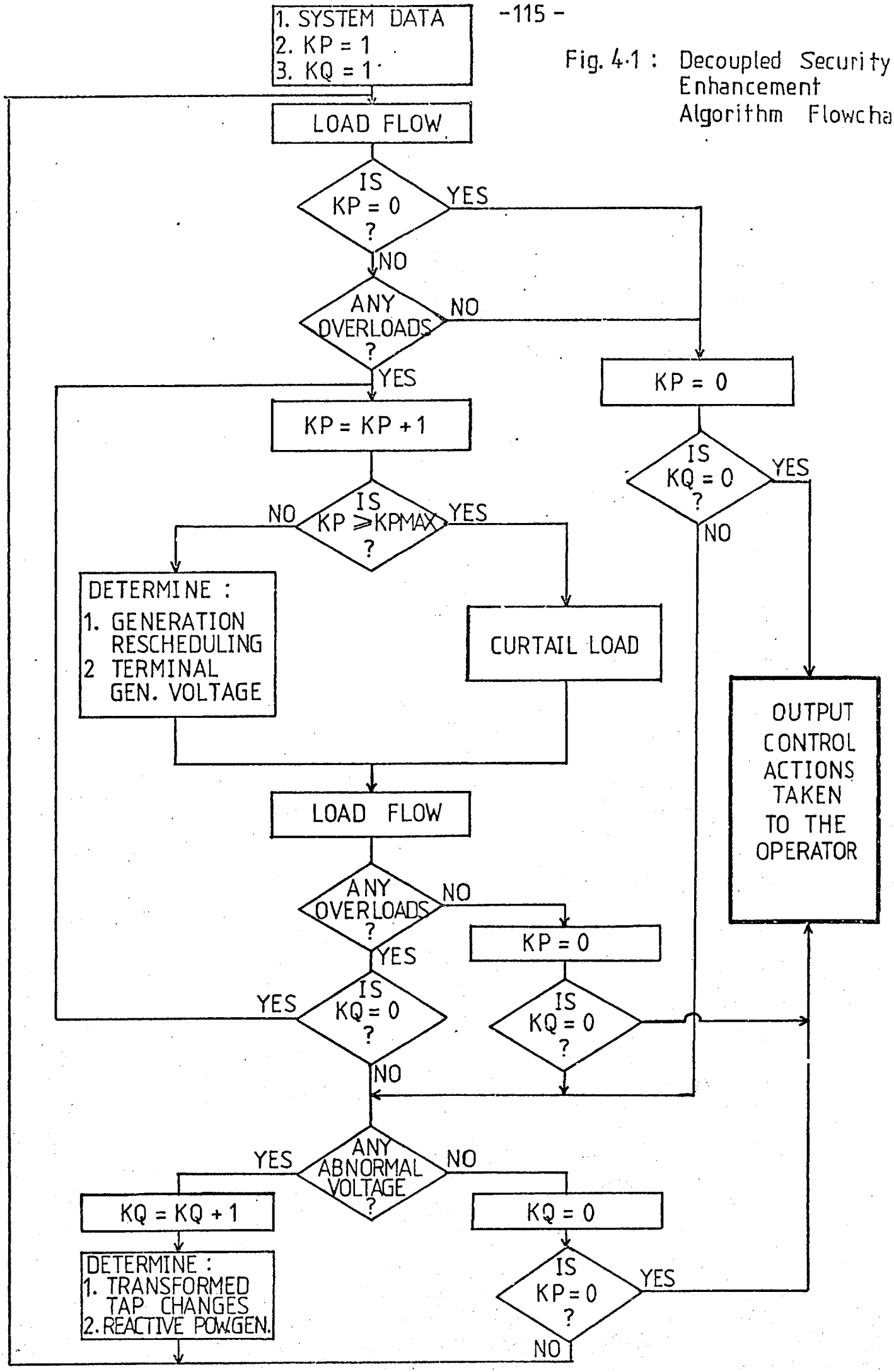


Fig. 4-1 : Decoupled Security Enhancement Algorithm Flowchart

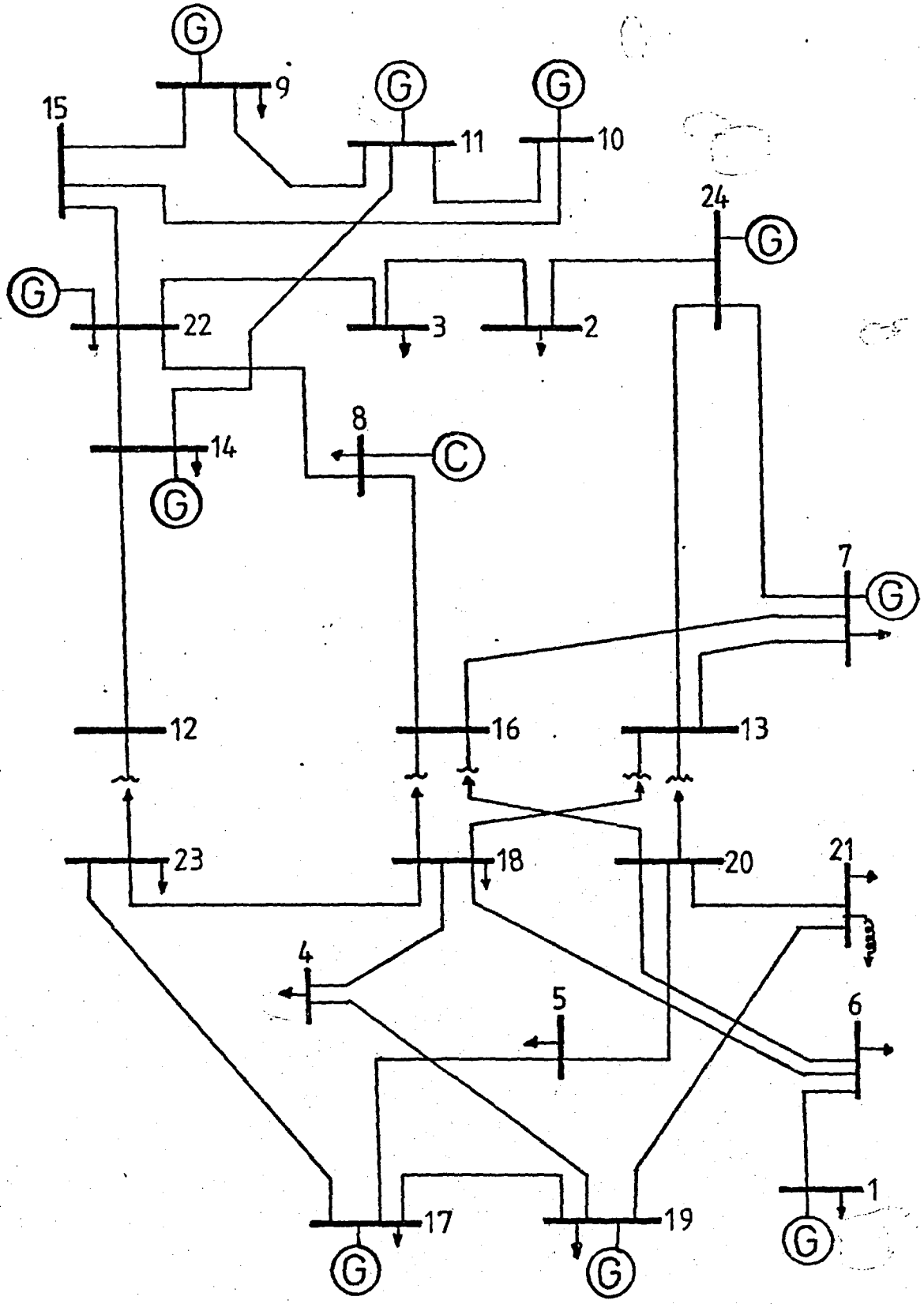


Fig. 4.2 : IEEE 24-Bus Reliability Network

CHAPTER 5

INVESTIGATION OF THE LOAD SHEDDING PROBLEM

5.0 INTRODUCTION

The previous chapter has reviewed various mathematical methods for security enhancement of power networks but the load shedding problem has not been fairly attended to, hence the purpose of this chapter.

In an emergency situation, system security considerations override the economy of operation and the objective is generally to minimize service curtailment (or inconvenience) instead of minimizing the hourly cost of operation. In an optimal loadflow analysis, "overconstrained" cases are of interest and they usually occur when the feasible region is empty and no solution exists. The solution to such a problem can be achieved by load shedding with the aid of fast and secure computation programs.

Early developments were based on non-linear and linear programming methods [81-83]. In [81], Hadju et al discussed a systematic approach towards minimizing the curtailment of service in a power system after a severe fault. The problem of minimizing the curtailment under a given set of emergency conditions is formulated as a problem of static optimization subject to operational and equipment constraints. The Newton-Raphson method and the Kuhn-Tucker theorem for optimization were employed to obtain a solution. This was extended by Subramanian [82] using linear programming and sensitivity analysis. Ghoneim et al in [83] developed linearized models of the load shedding problem based on the approximate linear relationship between active loads at the different nodes and the active loadings of the different branches. These models were solved using linear and dynamic programming techniques.

Some disadvantages of these early developments are:

(i) These methods deal with continuous optimization variables, whereas in reality the loads are dropped in discrete increments, hence increased accuracy of solution should not be a primary consideration [81-83].

(ii) Reactive parts of the loads have been included as independent variables [82]. This doubles the number of constraints and consequently increases computation time.

(iii) Some of the constraints in [82] do not ensure that the solution represents a normal operating state (in the sense that no line loading or bus voltage limits are exceeded).

(iv) DC loadflow analysis has been used in [83] based on linear and dynamic programming techniques. The dynamic programming approach suffers from:

(a) being appropriate for small systems only, and

(b) the accuracy of the method decreases as the value of the incremental load to be shed increases and depends entirely on the DC model used.

In view of the above disadvantages, a search for an appropriate algorithm to solve the load shedding problem was initiated having the following objectives:

(i) The algorithm is based on integer programming methods to reflect the discrete nature of load shedding in practice.

(ii) It is assumed that the power factors of the loads stay approximately constant during load shedding. This reduces the computation time.

(iii) The constraints include line loading and bus voltage limits. It is possible to switch shunt capacitors/ reactors to maintain an acceptable voltage profile.

(iv) A full AC formulation is adopted.

(v) The algorithm is able to solve a line overload problem as well as partial loss in generation. In the latter case, much larger blocks of load are expected to be shed to prevent a drop in frequency.

Satisfactory results are obtained using the IEEE test systems: 14-bus, 24-bus and 57-bus networks.

5.1 MATHEMATICAL DEVELOPMENT

(i) Determine the sensitive bus(es) for load curtailment. From equation (4.9)

$$[\frac{\Delta P}{V}] = [B'] [\Delta\delta]$$

The vector $[\Delta P]$ is very sparse hence the sensitive buses are those elements of $[\Delta P]$ that are positive.

(ii) Assuming the value of each block of load to be shed is 0.02 pu (chosen arbitrarily) then the maximum number of blocks of load on the buses is defined by [IB] with

$$[IB]_K = \text{Integer } [\frac{\Delta P}{0.02}] \qquad (5.1)$$

where K is the number of positive elements of $[\Delta P]$.

(iii) Form the constraint matrix defined by [IA] of order K by K determined as follows:

(a) Each diagonal element of [IA] is given a value of 1.

(b) If the number of buses connected to bus i and contained in the vector [IB] is ℓ, the off-diagonal elements of the row corresponding to bus i is $1/\ell$.

(c) If none is so connected and contained in [IB], the elements are zero.

(iv) The problem to be solved can then be formulated as:

$$\text{maximize} \quad \sum_{i=1}^{K} C_i X_i \tag{5.2}$$

where C_i is the weighting function to reflect the importance of the loads (so far equal importance ie $C_i = 1$ is assumed) and X_i is the number of blocks of load to be shed subject to

$$\left.\begin{array}{l} [IA]\,[X] \leq [IB] \\ \\ \text{and} \\ \\ X_i \geq 0 \end{array}\right\} \tag{5.3}$$

Solve for X_i for i = 1 to K.

The solution of the problem is obtained by making the modifications shown in Appendix 4 so that a conventional Numerical Algorithms Group (NAG) can be employed.

(v) The new load powers are calculated as:

$$\left.\begin{aligned} P_i^{new} &= P_i^{old} - X_i\,(0.02) \\ \text{and} \\ Q_i^{new} &= K_{pi} * P_i^{new} \\ \text{where} \quad K_{pi} &= \frac{Q_i^{old}}{P_i^{old}} \end{aligned}\right\} \qquad (5.4)$$

(vi) Solve another loadflow

5.1.1 Approximate Solution

Where the integer programming based algorithm developed above cannot solve the line overload problem (or reduce the current overload), an approximate solution can be achieved by shedding a unit block of load each time on the sensitive buses defined by equation (5.1). The new bus powers become

$$\left.\begin{aligned} P_i^{new} &= P_i^{old} - 0.02 \\ \text{and} \\ Q_i^{new} &= P_i^{new} * K_{pi} \end{aligned}\right\} \qquad (5.5)$$

where K_{pi} has previously been defined in equation (6.11).

5.2 TESTS AND RESULTS

5.2.1 14-bus IEEE Network (see Fig. 3.4)

Experiment 1:

Overload in line 2-4 (capacity 0.4): current changed from 0.54 (34% overload) to 0.42 (4.25% overload acceptable) by shedding loads as shown in Table. 5.1.

TABLE 5.1:

Buses	Blocks	Total load shed (real powers only)
3	7	0.14
4	14	0.28
6	1	0.02

Time of Solution: 3.5 seconds.

Experiment 2:

Overload in line 10-11 (capacity 0.1): Current changed from 0.11 (11% overload) to 0.1 by using the approximate solution technique and shedding 5 blocks of load in bus 1 of value 0.1 pu after 2.97 seconds.

5.2.2 24-bus IEEE Reliability Network (see Fig. 4.2)

Experiment 1:

Overload in line 7-16 (capacity 1.9): Current changed from 2.28 (20% overload) to 1.99 (4.7% overload acceptable) by shedding loads as shown in Table 5.2.

TABLE 5.2:

Buses	Blocks	Total load shed
3	9	0.18
5	9	0.18
20	9	0.18

Solution time is 5.57 seconds.

Experiment 2:

Overload in line 11-14 (capacity 3.5): Current changed from 3.92 (12% overload) to 3.63 (3.7% overload acceptable) by shedding load on bus 4 (10 blocks) with solution time as 2.34 seconds.

Experiment 3:

Overload in line 19-21 (capacity 0.2): Current changed from 0.24 (20% overload) to 0.21 by shedding 7 blocks of load on bus 18 totalling 0.14 pu after 3.87 seconds.

5.2.3 57-bus IEEE Network (Fig. 5.1)

Experiment 1:

Overload in line 2-3 (capacity 0.90): Current changed from 0.98 (8.88% overload) to 0.93 (3.33% overload acceptable) with no load shedding. Solution time obtained was 4.83 seconds.

Experiment 2:

Overload in line 12-17 (capacity 0.4): Current changed from 0.48 (20% overload) to 0.40 with no load shedding in 4.82 seconds.

The above overloads are cleared by generation rescheduling alone as busbars 3 and 12 are generator buses hence only shifts in generation have taken place.

Experiment 3:

Overload in line 46-47 (capacity 0.45): Current changed from 0.53 (17.77% overload) to 0.49 (8.8% overload) by relaxing the overload constraint to 10%. 6 and 5 blocks of load are shed in buses 14 and 47 of value 0.12 pu and 0.1 pu respectively.

The above solution is obtained in 45.1 seconds.

Experiment 4:

Overload in line 7-29 (capacity 0.5): Current changed from 0.64 (28% overload) to 0.54 (8% overload) by relaxing the overload constraints to 10%. 30, 9 and 3 blocks of load are shed in busbars 6, 28 and 52 respectively. Each unit of load is 0.02 pu.

The above result is obtained in 30.3 seconds.

Experiment 5:

Overload in line 9-55 (capacity 0.15): Current changed from 0.27 (80% overload) to 0.163 (8.6% overload) by relaxing the constraints to 10%. 5, 9 and 4 blocks of load are shed in busbars 10, 13 and 54 respectively. The solution is obtained in 17.46 seconds.

5.3 INVESTIGATION OF THE EFFECT OF USING A SECOND ORDER TAYLOR'S SERIES EXPANSION ON THE SOLUTION ACCURACY

Based on the fact that equation (4.1) is a multivariable function, an investigation was carried out to determine to what extent the accuracy of the solution is affected by including second order Taylor's series factors in the modelling to obtain an improved $(\Delta\delta, \Delta V)^T$.

The second order terms which are significant can be included in the algorithm without actually storing these elements separately.

Taking Taylor's series expansion of equation (4.1), including second order terms but neglecting high order terms and phase-shifting angles:

$$I_{ij} = \frac{\partial I_{ij}}{\partial \delta_i} \Delta\delta_i + \frac{\partial I_{ij}}{\partial \delta_j} \Delta\delta_j + \frac{\partial^2 I_{ij}}{\partial \delta_i \partial \delta_j} \Delta\delta_i \Delta\delta_j + 1/2 \frac{\partial^2 I_{ij}}{\partial^2 \delta_i} (\Delta\delta_i)^2 + 1/2 \frac{\partial^2 I_{ij}}{\partial^2 \delta_j} (\Delta\delta_j)^2$$

$$+ \frac{\partial I_{ij}}{\partial V_i} \Delta V_i + \frac{\partial I_{ij}}{\partial V_j} \Delta V_j + \frac{\partial^2 I_{ij}}{\partial V_i V_j} \Delta V_i \Delta V_j$$

$$+ 1/2 \frac{\partial^2 I_{ij}}{\partial^2 V_i} (\Delta V_i)^2 + 1/2 \frac{\partial^2 I_{ij}}{\partial^2 V_j} (\Delta V_j)^2 + \frac{\partial^2 I_{ij}}{\partial \delta_i \partial V_j} \Delta \delta_i \Delta V_j \qquad (5.6)$$

But from the loadflow equations:

$$\frac{\partial^2 I_{ij}}{\partial V_i^2} = \frac{\partial^2 I_{ij}}{\partial V_j^2} = \frac{\partial^2 I_{ij}}{\partial \delta_i \partial \delta_j} = \frac{\partial^2 I_{ij}}{\partial \delta_i \partial V_j} = \frac{\partial^2 I_{ij}}{\partial \delta_j \partial V_i} = 0$$

Equation (5.6) becomes in matrix form:

$$[\Delta I_{ij}] = [C_1] \begin{bmatrix} \Delta\delta_i \\ \Delta\delta_j \\ \vdots \\ \Delta V_j \\ \vdots \\ \Delta V_j \end{bmatrix} + [C_2] \begin{bmatrix} (\Delta\delta_i)^2 \\ (\Delta\delta_j)^2 \\ \\ \Delta\delta_i \Delta V_i \\ \\ \Delta\delta_j \Delta V_j \end{bmatrix} \qquad (5.7)$$

The proposed model in equation (5.7) is non-linear because of the presence of the products of the unknowns ($\Delta\delta_i \Delta V_i$ and $\Delta\delta_j \Delta V_j$). For obtaining a solution of this set of non-linear equations without excessive computing effort, these are converted to a set of linear equations and solved using the following steps:

(i) Transform equation (5.7) into

$$[\Delta I_{ij}] - [C_2] \begin{bmatrix} (\Delta\delta_i)^2 \\ (\Delta\delta_j)^2 \\ (\Delta\delta_i\ \Delta V_i) \\ (\Delta\delta_j\ \Delta V_j) \end{bmatrix} = [C_1] \begin{bmatrix} (\Delta\delta_i) \\ (\Delta\delta_j) \\ (\Delta V_i) \\ (\Delta V_j) \end{bmatrix} \qquad (5.8)$$

(ii) Neglect the second-order terms in equation (5.8) and solve

$$[\Delta I_{ij}] = [C_1] \begin{bmatrix} \Delta\delta_i \\ \Delta\delta_j \\ \Delta V_i \\ \Delta V_j \end{bmatrix} \qquad (5.9)$$

for $(\Delta\delta, \Delta V)^T$ as previously stated in equations (4.6)

(iii) Determine the matrix $[C_2]$ and using the $(\Delta\delta, \Delta V)^T$ computed in step (ii) above, determine the vector $((\Delta\delta)^2, (\Delta\delta, \Delta V))^T$ and then subtract the product from $[\Delta I_{ij}]$ in equation (5.8) and solve for improved values of $(\Delta\delta, \Delta V)^T$.

(iv) This new value of the state vector $(\Delta\delta, \Delta V)^T$ is used to complete the solution.

Two tests are carried out on the 24-bus IEEE reliability system to determine the respective values of $(\Delta\delta, \Delta V)^T$ obtained in steps (ii) and (iii) above.

TABLE 5.3: Test 1: Overload in 7-16

	$*10^{-3}$ step (ii)	$*10^{-3}$ step (iii)	$*10^{-6}$ (step (iii)-step (ii))
$\Delta\delta_7$	-8.80405	-8.80773	-3.68
$\Delta\delta_{16}$	-8.65487	-8.65849	-3.62
ΔV_7	-1.36575	-1.36632	-0.57
ΔV_{16}	-1.41303	-1.41362	-0.59

TABLE 5.4: Test 2: Overload in 11-14

	$*10^{-3}$ step (ii)	$*10^{-3}$ step (iii)	$*10^{-6}$ (step (iii)-step (ii))
$\Delta\delta_{11}$	-4.9465	-4.95000	-3.50
$\Delta\delta_{14}$	-4.95623	-4.95979	-3.51
ΔV_{11}	-0.77125	-0.77180	-0.55
ΔV_{14}	-0.36441	-0.36467	-0.26

5.4 PARTIAL LOSS OF GENERATION

Following the loss of a generator during system operation, the deficiency in generation is shared by the remaining generators immediately in proportion to their inertias and later by supplementary governor control.

In [81], the events following this failure are divided into four phases:

Phase 1:

The equipment fails. The high-speed protections isolate the fault, thus dropping the load previously supplied by this particular equipment.

Phase 2:

Further deterioration of service may be caused by the cutting out of additional equipment, due to slow acting overload (backup) protections or loss of synchronism between various groups of generators. The duration may be from several seconds to many minutes.

Phase 3:

No further load is dropped but the restitution of the system commences.

Phase 4:

The equipment that failed is repaired and reconnected.

To prevent a drop in system frequency, larger blocks of load, 0.05 should be shed and the algorithm is modified to take care of partial loss of generation. Two assumptions are made:

(i) the system frequency is constant,

(ii) there are no overloads in the system.

The problem, therefore, is that the demand is not satisfied hence a new operating condition would be sought using load shedding to force the perturbed system to a new stable equilibrium state.

The mathematical treatment of the partial loss in generation is presented below; for a partial loss of generation in bus i

$$\frac{\Delta P_i}{V_i} = [B'_i] \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \vdots \\ \Delta\delta_{NB-1} \end{bmatrix} \qquad (5.10)$$

where $[B'_i]$ is the ith row of the $[B']$ matrix for NB system buses. The least-squares technique is used on equation (5.10) to produce the incremental voltage angles ($\Delta\delta$). The incremental powers (representing the maximum to be shed) can be computed from equation (5.10).

Therefore the rest of the developments can be similarly obtained and the problem formulated and solved by integer programming. Tests are carried out using the IEEE 24-bus and 57-bus systems using blocks of load of 0.02 and 0.05 respectively with results compared.

5.4.1 Tests with the IEEE 24-bus Network

The 24-bus network has 10 generators.

TABLE 5.5: Test 1: Partial loss of generation in generator 1 with initially generated active power of 2.128 pu

Fraction of generation	Value of each block of load			
	0.05 pu		0.02 pu	
	Bus	Blocks	Bus	Blocks
0.5	2	35	2	35
			3	1
0.25	3	1		
			3	4
			4	1
			8	1
0.125	3	2	3	5
			4	1
			8	1
			20	1

TABLE 5.6: Test 2: Partial loss of generation in generator 7 with initial generated active power : 2.97 pu

Fraction of generation	Value of each block of load			
	0.05 pu		0.02 pu	
	Bus	Blocks	Bus	Blocks
0.5	3	6	3	17
	3	1	3	1
*0.25	18	1	18	1
	20	1	20	1
	3	1	3	1
*0.125	18	1	18	1
	20	1	20	1

* + proximate method

5.4.2 Tests with the IEEE 57-bus Network (see Fig. 6.1)

The network has 4 generators.

TABLE 5.7: Test 1: Partial loss of generation 8 with active power: 4.5 pu

Fraction of generation	Value of each block of load			
	0.05 pu		0.02 pu	
	Bus	Blocks	Bus	Blocks
0.05	29	1	10	2
	55	1	13	2
			29	3
			55	2
0.25	9	6	6	1
			9	16
0.125	6	1	6	4
	9	16	9	35

TABLE 5.8: Test 2: Partial loss of generation bus 3 with active power: 0.4 pu

Fraction of generation	Value of each block of load			
	0.05 pu		0.02 pu	
	Bus	Blocks	Bus	Blocks
0.05	2 15	1 2	2 15	2 5
0.25	15	3	15	8
*0.125	5 6 13 14 18	1 1 1 1 1	5 6 13 14 18	1 1 1 1 1

*Solution obtained by the approximate method

TABLE 5.9: Test 3: Partial loss of generation bus 12 with active power; 3.10 pu

Fraction of generation	Value of each block of load			
	0.05 pu		0.02 pu	
	Bus	Blocks	Bus	Blocks
0.05	10 13 16 17	35 35 15 5	10 13 16 17	35 35 35 14
0.25	9 17	4 7	9 9	10 18
0.125	9	4	9	11

5.5 DISCUSSION OF RESULTS

(1) Satisfactory results are obtained for all systems considered with the proposed integer programming based algorithm. For large systems it might be appropriate to relax the line overload constraint to, say, 10% to reduce the solution time (under practical conditions).

(2) From the results obtained in section 5.3, including second order Taylor's series expansion does not provide any significant improvement on the solution accuracy. However, for emergency situations the deviations from the nominal state are large, hence they should be included.

(3) The execution times generally depend on:

(a) the overload percent and the constraint allowable,

(b) the number of overloads in the system, and

(c) the number of "sensitive" buses where load shedding may take place.

(4) Larger blocks of load should be shed for partial loss in generation to maintain better frequency control. The results obtained by comparing the number of blocks shed when 0.05 or 0.02 pu load justify this conclusion.

(5) In general, the demands are corrected as well as the generated powers to maintain system frequency.

5.6 PRACTICAL APPLICATIONS OF LOAD-SHEDDING ALGORITHMS

The method for load-shedding developed in this thesis assumes that the frequency is within acceptable range, hence it has not been taken into consideration. However during emergency situations, loads would exceed the generation, hence frequency variation becomes important and should be

considered in the analysis. Underfrequency relays can be used to disconnect automatically definite blocks of load or sectionalize the transmission system as soon as the frequency drops to a pre-determined value.

The problem, therefore, is what setting should be made on frequency relays to trip off the load. First, the amount of load to be dropped must be determined and at what frequency should this take place. This depends on the rate of decay of frequency in the overloaded system and requires that the characteristics of load should be known as well as the amount of spinning reserve capacity.

Relays need to be calibrated to determine the rate of frequency decay. Lockay and Burtnyk in [88] have defined the required expression for a 60 hertz frequency as:

$$f = 60 \left[\frac{1 + \left(\frac{d-1}{1}\right) OL}{1 + OL} \right] \qquad (5.11)$$

where

OL = overload percent

d = load reduction rate (percent load reduction per 1% drop in frequency)

5.7 CONCLUSION

This chapter has presented a proposal for optimal load-shedding schemes to alleviate line overloads using integer programming methods. This was extended to cover incidents of partial generator loss to ensure that the system frequency is maintained constant. To the best of the author's knowledge no previous algorithm has been described taking into account the essentially discrete natureof load-shedding in practice. An investigation was carried out on the effect of including significant second order Taylor's series terms in the algorithm. It was found that these terms had little effect on the results except in emergency situations when large deviations from the normal state would be included.

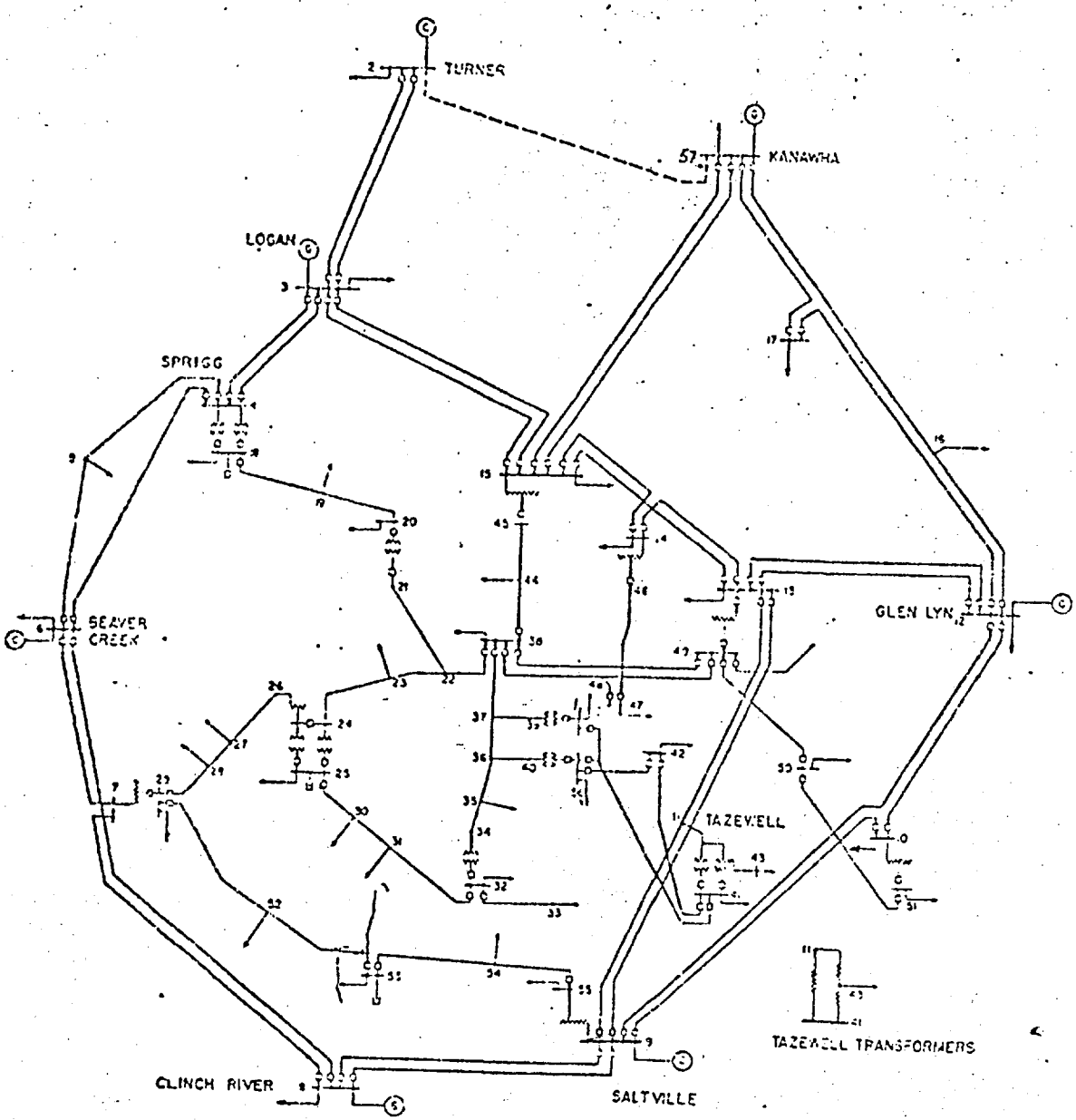


Fig. 5.1: IEEE 57-bus system.

CHAPTER 6

STATIC SECURITY CONTROL VIA PHASE-SHIFTERS

6.0 INTRODUCTION

In Chapter 4 was presented an algorithm for line overload alleviation and for the correction of abnormal system voltages. This was extended in the previous chapter using an integer-based load shedding procedure. Since generation changes are made, economic considerations are eventually involved. This chapter investigates the influence of phase-shifters in an AC system and assesses the extent to which phase-shifters can assist in power system centralized control, thus adding an extra dimension to the field of interactive security evaluation introduced in the previous chapters.

Phase-shifters, through their angular control of phase angles, can

(i) bring about increased power transfer between areas of a system and neighbouring systems,

(ii) postpone the need for future transmission reinforcements, and

(iii) provide for possible relief of overloaded transmission circuits in both the preventive and the corrective modes of power system operation.

In order to utilize effectively this phase-shifter capability, system operators must be provided with some means of determining optimum phase-shifter settings and this is the objective of the work described in this chapter.

The incremental AC model of phase-shifters derived by Stott and Hobson in [66] and Thanikachalam et al in [89] is used (since control over active power is to be exercised) and shown in Fig. 6.1.

$$\left.\begin{aligned} \Delta P_i &= V_i V_j b_{ij} \Delta\psi_{ij} \\ \Delta P_j &= -\Delta P_i \end{aligned}\right\} \qquad (6.1)$$

Constant phase-shifter impedances are assumed. This assumption holds depending on the degree of accuracy required, the time available for the calculations in power system control centres and the magnitude of impedance change with angle for particular phase-shifters. The variations of impedance change with angular settings must be taken into account for emergency conditions because of the wide range of angles that may be involved. Another assumption is that the variations in the tap settings are made over a small range, hence the voltage magnitudes remain unchanged.

This chapter, therefore, has the following aims:

(i) investigation of the influence of phase-shifters on power flows in an AC system,

(ii) assessment of the extent to which phase-shifters can assist in power system centralized control,

(iii) development of a linear programming algorithm in an AC network. An alternate algorithm based on a least-squares minimization technique is also developed and the performance of both algorithms compared in terms of computer time and control strategies,

(iv) exploration of the potential advantages of including phase-shifters in an optimal power flow program,

(v) optimum design of phase-shifter network locations for security analysis.

The results obtained using three modified test systems: IEEE 14-bus and 24-bus reliability systems and the 6-bus SPC network are presented.

6.1 INFLUENCE OF PHASE-SHIFTER SETTINGS ON MW POWER FLOWS

Two experiments are performed:

Experiment 1:

Assuming initial phase-settings to be zero, a loadflow is run to obtain the MW flows.

Experiment 2:

For each phase-shifter, the phase angle is increased by 1 degree (with the other phase-shifter settings remaining at zero) and the new power flows are determined for each case.

Comparisons are made of incremental power flows in all lines in the system. The results are presented in Tables 6.1. - 6.5.

6.1.1 Modified IEEE 24-bus Reliability System

Phase-shifters are placed in lines

15-24
15-25
25-26
24-26

with interconnection points at busbars 15,24 and 26 with a generator on bus 25 as shown in Fig. 6.2. The 24-bus network was used by Prada in [17] with DC converters inserted in the lines replaced here by phase-shifters. Comparisons can be made on the two modes of AC transmission, i.e. modes including either DC links or phase-shifters.

6.1.2 Modified IEEE 14-bus Network [Fig. 6.3]

Three phase-shifters are placed on lines 7-14, 5-14 and 4-14 with interconnection points at busbars 4, 5 and 7 with a new generator on bus 14 and bus 15 as the slack.

6.1.3 Modified Saskatchewan Power Corporation 6-bus System [Fig. 6.4]

Two phase-shifters are placed on lines 2-6 and 3-6 with a new generator bus on bus 6 and the interconnection points at busbar 2 and 3. Bus 7 is the slack.

From the experiments carried out on the systems above, increased MW flows were obtained for lines very close to the phase-shifters, the lines containing the phase-shifters having the largest power changes. The data of the new circuits are shown in Tables 6.7-6.9.

6.2 PARTICIPATION OF PHASE-SHIFTERS IN POWER SYSTEM CONTROL

Two possible representations are considered:

(1) Including phase-shifters in the decoupled security enhancement algorithm (DSEA) as described in chapter 4.

(2) A-priori operation of phase-shifters before generation rescheduling procedures. Two algorithms based on linear programming and least-squares minimization techniques are developed and tested to minimize or eliminate overloads in AC systems.

6.2.1 Including Phase-shifters in the DSEA

A number of tests are carried out on the system shown in Fig. 4.2. 5% overload is assumed acceptable. Control strategies are compared for the cases where phase-shifters are included.

Experiment 1A (without phase-shifters):

Overload in line 16-18 (capacity 1.1). Current changed from 1.35 to 1.15 in 6.81 seconds.

10 iterations of generation rescheduling and loadshedding and 3 iterations of the voltage/reactive power control gave the following control strategies:

TABLE 6.7: NETWORK DATA FOR THE INTERCONNECTING SYSTEM FOR THE MODIFIED 24-BUS IEEE SYSTEM

Phase-shifting transformer	X	Capacity
15-24	0.0966	5.0
15-25	0.0678	10.0
26-25	0.0865	10.0
24-26	0.0678	5.0

TABLE 6.8: NETWORK DATA FOR THE INTERCONNECTING SYSTEM FOR THE MODIFIED 14-BUS IEEE SYSTEM

Phase-shifting transformer	X	Capacity
7-14	0.1	1.0
5-14	0.1	1.0
4-14	0.1	1.0

TABLE 6.9: NETWORK DATA FOR THE INTERCONNECTING SYSTEM FOR THE MODIFIED 6-BUS IEEE SYSTEM

Phase-shifting transformer	X	Capacity
2-6	0.1	1.0
3-6	0.1	2.0

(1) Generation rescheduling on buses 1, 17 and 24.

(2) Loadshedding on buses 3,5,6 and 20.

(3) Reactor switching on bus 20.

Experiment 1B (with phase-shifter on line 16-18):

The current was reduced to 1.14 in 5.11 seconds. 5 iterations of generation rescheduling and loadshedding and 2 iterations of the voltage/reactive power are required to obtain:

(1) Generation rescheduling on buses 1,17 and 24.

(2) Loadshedding on buses 3,5,6 and 20.

(3) Reactor switching on bus 20.

(4) Phase-shifting angle of -1 degrees.

Experiment 2A (without phase-shifter):

Overloads in (a) 16-18 (capacity 1.1)

(b) 7-16 (capacity 2.1)

Currents in (a) 16-18 changed from 1.35 to 1.15

(b) 7-16 changed from 2.28 to 1.98 in 7.06 seconds

10 iterations of generation rescheduling and loadshedding with 3 iterations of the voltage/reactive power control algorithm resulted in:

(1) Generation rescheduling on buses 1,7,10,17 and 24.

(2) Loadshedding on buses 3,5,6 and 20.

(3) Reactor switching on bus 20.

Experiment 2B (with phase-shifter on line 16-18):

Currents in (a) 16-18 reduced to 1.14

(b) 7-16 reduced to 1.98 in 6.57 seconds

6 iterations of generation rescheduling and loadshedding with 3 iterations of the voltage/reactive power control algorithm resulted in:

(1) Generation rescheduling on buses 1,7,10,17 and 24.

(2) Loadshedding on buses 3,5,6 and 20.

(3) Reactor switching on bus 20.

(4) Phase-shifting angle of -1 degrees.

The tests above indicate that, with phase-shifters, the solution time is reduced. More generation rescheduling and load-shedding are required to restore system security when phase-shifters are not included.

6.2.2 A priori Operation of Phase-shifters

(A) Mathematical Development

(1) Determination of the Sensitivity Matrix [S]:

The matrix consists of phase-shifter distribution factors where the order of S is NL by ph, where NL is the number of lines in the system and ph is the number of phase-shifters.

The matrix S can be derived as:

for each phase-shifter pq determine:

(i) S_{pq},pq: the change in current flow in the phase-shifter for a change in the phase angle [89]:

$$S_{pq},pq = \frac{1}{Z_{pp} + Z_{qq} - 2Z_{pq} + \not{Z}_{pq}} \qquad (6.2)$$

where $\not{Z}_{pq}$ is the impedance of the shifter and Z_{pp}, Z_{qq}, Z_{pq} are the elements of the impedance matrix with line pq removed. The original network matrix is modified by Kron's reduction technique as formulated by Brown in [50] to reflect this change in the computer program.

(ii) S_{ij},pq: the change in current flow in the line i-j for a unit change of angle in the phase-shifter pq. This is given by Thanikachalam et al in [89] and Ku and Olinda in [90] as:

$$S_{ij},pq = L_{ij},pq * S_{pq}, pq \tag{6.3}$$

where L_{ij},pq is the line outage distribution factor given by:

$$-\left(\frac{\not{Z}_{pq}}{\not{Z}_{ij}}\right)\left(\frac{Z_{ip} - Z_{iq} - Z_{jp} + Z_{jq}}{Z_{pp} + Z_{qq} - 2Z_{pq} - \not{Z}_{pq}}\right) \tag{6.4}$$

(2) Step (ii) above is repeated for each line in the system

(3)(a) From (1) and (2), a column matrix is formed for each phase-shifter.

(b) From the superposition principle, the matrix S is formed as:

$$S_{NL,ph} = \begin{bmatrix} S_{1,1} & S_{1,2} & \cdots\cdots\cdots\cdots & S_{1,ph} \\ S_{2,1} & S_{2,2} & \cdots\cdots\cdots\cdots & S_{2,ph} \\ S_{NL,1} & S_{NL,2} & & S_{NL,ph} \end{bmatrix}^{1} \tag{6.5}$$

The matrix, once derived, is stored and is unique for each system.

(4) For any system condition (with all the phase-shifters in operation):

$$\begin{bmatrix} \Delta I_1 \\ \Delta I_2 \\ \vdots \\ \Delta I_{NL} \end{bmatrix} = [S_{NL,ph}] \begin{bmatrix} \Delta\psi_1 \\ \Delta\psi_2 \\ \vdots \\ \Delta\psi_{ph} \end{bmatrix} \qquad (6.6)$$

For an overloaded condition (say K overloaded lines) an iterative constraint search is made to obtain:

$$\begin{bmatrix} \Delta I_1 \\ \Delta I_2 \\ \vdots \\ \Delta I_K \end{bmatrix} = [S_{K,ph}] \begin{bmatrix} \Delta\psi_1 \\ \Delta\psi_2 \\ \vdots \\ \Delta\psi_{ph} \end{bmatrix} \qquad (6.7)$$

This constraint search reduces the problem constraints to only the critical lines in the system with savings in execution times.

(B) Methods of Solution

Linear Programming method:

Minimize $\Sigma W_i . \Delta\psi_i$ for i = 1,2, ... ph, (6.8)

subject to

(i) $-180 \leq \Delta\psi_i \leq 180$)
(ii) equation (6.7)) (6.9)

W_i is the weighting function to emphasize the importance of each phase-shifter, a value of unity has been assumed for equal importance.

Least-squares minimization technique:

assuming ph > K

$$[\Delta\psi] = [S]^{+} [\Delta I] \qquad (6.10)$$

where S^T is the right pseudo-inverse of S defined as:

$$S^{+} = S^{T} (SS^{T})^{-1} \qquad (6.11)$$

with S^T as the transpose of S.

With both methods of solution, the phase-shifter settings are obtained and the incremental power computed using equation (6.1).

The flowchart of the program is shown in Fig. 6.5. KPMAX is the number of times (maximum) the logic would be operated upon before entry to the optimal power flow algorithm. An arbitrary value of 7 has been chosen for these studies.

(C) Tests and Results

The two algorithms developed in the last section were used on the three test systems shown in Figs. 6.2-6.4 with satisfactory results. Initial phase-angles of zero are assumed and a maximum of ±180° allowed with the minimum shift of ±1°. These figures were chosen arbitrarily and for all cases considered a 5% overloaded margin is assumed to be acceptable. Only single line outages were considered.

The times of solution are also shown in Tables 6.10-6.12.

TABLE 6.10: 27-BUS SYSTEM RESULTS

Line Outage	Overloaded Lines	Overload Percent	Corrective Actions			Remarks		Time (Seconds)	
			Shifter (degrees)	LP	LS	LP	LS	LP	LS
10-15	9-15	23.5	1 2 3 4	- 19 - -	39 60 -65 - 3	reduced to 7.9% overload	overload eliminated	0.012	0.012
15-25	9-15 21-26	6.9 16.0	1 2 3 4	28 - 12 -	-70 - 96 49	eliminated overloads	eliminated overloads	0.010	0.016
21-26	15-22	10-66	1 2 3 4	- - 12 -	- 5 - 8 9 - 2	reduced to 8.3% overload	reduced to 10.26% overland	0.013	0.024
6-18	6-20	62.5	no feasible solution			-		-	
11-14	15-22 9-15 10-15	70.5 220.5 13.4	no feasible solution			-		-	

TABLE 6.11: 15-BUS SYSTEM RESULTS

Line Outage	Overloaded Lines	Overload Percent	Corrective Actions					Time (Seconds)	
			Shifter (degrees)	LP	LS	LP	LS	LP	LS
1-13	4-7	13.0	1 2 3	- - 5	-1 -1 4	Overload eliminated	Overload eliminated	0.007	0.011
4-9	4-7	18.0	1 2 3	- - 6	-2 -2 5	overload eliminated	overload eliminated	0.006	0.012
5-15	2-15	12.8	1 2 3	- 63 -	-27 19 9	overload reduced to 11.9%	overload reduced to 12%	0.006	0.012
6-11	4-7	27.0	1 2 3	- - 10	-3 -3 8	overload eliminated	reduced to 7.5% overload	0.006	0.012
6-13	4-7	6.5	1 2 3	- - 2	-1 -1 2	overload eliminated	overload eliminated	0.006	0.013
7-8	4-7	15.5	1 2 3	- - 6	-2 -2 5	overload eliminated	reduced to 5.5%	0.007	0.012
10-11	4-7	19.0	1 2 3	- - 7	-2 -2 6	overload eliminated	reduced to 6% overload	0.006	0.012
2-15	4-5 5-15	29.5 106.5	no feasible solution			-		-	

TABLE 6.12: 7-BUS SYSTEM RESULTS

Line Outage	Overloaded Lines	Overload Percent	Corrective Actions			Remarks		Time (Seconds)	
			Shifter (degrees)	LP	LS	LP	LS	LP	LS
2-7	5-7	27.71	no feasible solution			-		-	
3-4	5-7	75.66	no feasible solution			-		-	
3-7	5-7	13.49	1 2	23 -	18 -18	reduced the overload to 4.57%	reduced the overload to 5.78%	0.006	0.012
4-5	3-4	23.0	no feasible solution						

(D) Discussion of Results

(1) For each case considered, the least-squares approach (LS) required all the phase-shifters in the system to operate so as to reduce or eliminate the overloads. The alternative linear programming (LP) method did not require this. The LP technique searches for an optimum value whereas the LS determines the minimum deviation from a nominal state (which in this case is a zero setting for each phase-shifter).

(2) From Tables 6.10 - 6.12, the LS solution times are greater than those of the LP method because a matrix inversion is used to compute the pseudo-inverse. The solution time is dependent on the order of the sensitivity matrix (number of overloaded lines by the number of phase-shifters).

(3) In terms of computer storage, the LS algorithm required 104.4 KB of core memory whereas the LP required 103.5 KB.

(4) Satisfactory results are obtained when only up to 2 overloaded lines are considered. However for multiple overloaded lines, the performance of the algorithms may not be adequate. A heuristic approach would be to consider the multiple overloaded cases as single overloaded lines in turn.

(5) The LP algorithm, generally, gave more acceptable results than the LS method. Hence it can be recommended for implementation in control centres where standard LP routines are available. The advantages include (as deduced above): fewer phase-shifters operated upon at any one moment, low computer storage and faster execution times. By contrast, The LS technique requires the operation of all the phase-shifters at any one moment.

(6) The LP approach proposed has considerable advantages in terms of speed and versatility over the method described by Thanikachalam et al [89] which is characterised by a slow small-step search process.

(7) Unfeasible solutions may be as a result of:

(a) phase-shifter locations are not the optimum for security analysis,

(b) line overloads may be due to predominant MVAR flows in the systems; phase-shifters are for real power rescheduling only,

(c) the overload percent may be too large, i.e. large disturbance occurrence, which is not applicable to the method developed here, as sensitivity analysis assumes small changes.

6.3 ECONOMIC BENEFITS OF INCORPORATING PHASE-SHIFTERS IN SYSTEM INTERCONNECTIONS

The benefits to be derived would be economical since the overloads in a system can often be reduced without the need for generation rescheduling.

Considering the equipment costs, Rubino and Tishniski in [92] carried out economic studies of the installation of special phase-shifting transformers in system interconnections. In that study, it was stated, based on 1973 prices, that phase-shifting transformers cost about $8/KW and rotary transformers were estimated in the $30-40/KW range, whereas for a HVDC scheme with an asynchronous tie and only scheduled power transmitted, the conversion equipment was in the range of $75 to $100/KW. Based on the above cost comparisons, phase-shifters in the range of ±180 degrees were purchased. It was realized in [92] that if a major

disturbance occurs, such as loss of a large unit or loss of a transmission line, phase-shifters cannot respond quickly enough to compensate, hence a DC link is superior for this purpose.

6.4 OPTIMUM DESIGN OF PHASE-SHIFTER LOCATIONS FOR SECURITY ANALYSIS

In the previous sections, the influence of phase-shifters on power flows was determined. The study was extended by the development of two algorithms based on linear programming and least-squares minimization technique for the a priori operation of phase-shifters to reduce or eliminate system overloads. Fixed phase-shifter locations were assumed. The major effect of having these phase-shifters was in those lines connected closely to the phase-shift transformers.

The present study aims at developing a simple mathematical technique to determine the best location of a phase-shifter, to achieve a reduction/elimination of the line overload problem. This investigation which would be appropriate for operational planning assumes that the locations so determined are included in the transmission corridor made available to the system planner.

(1) It was determined in equation (4.9) that the maximum incremental real powers to be rescheduled are:

$$\left[\frac{\Delta P}{V}\right] = [B'] [\Delta\delta]$$

The vector $[\Delta P]$ is very sparse hence the sensitive buses are those elements of $[\Delta P]$ that are non-zero. Let this number be K.

(2) The possible combinations of phase-shifters required can be obtained by

$$M = \frac{K!}{2!(K-2)!} \qquad (6.12)$$

(3) For each possible combination determine:

(a)

$$S_{pq,pq} = \frac{1}{Z_{pp} + Z_{qq} - 2Z_{pq} - \not{Z}_{pq}} \tag{6.13}$$

where Z, the impedance matrix of the system with the shifter p-q included and $\not{Z}_{pq}$, the impedance of the shifter. An arbitrary value of $j0.1$ has been assumed.

(b) $$S_{ij,pq} = L_{ij,pq} * S_{pq,pq} \tag{6.14}$$

where

$$L_{ij,pq} = -\left(\frac{\not{Z}_{pq}}{\not{Z}_{ij}}\right)\left(\frac{Z_{ip} - Z_{iq} - Z_{jp} + Z_{jq}}{Z_{pp} + Z_{qq} - 2Z_{pq} + \not{Z}_{pq}}\right) \tag{6.15}$$

$S_{pq,pq}$ and $S_{ij,pq}$ have previously been defined.

(4) Rank the possible phase-shifters according to equation (6.15) in descending order. This represents the degree of the influence of each phase-shifter on the line overload.

The number of phase-shifters required can then be chosen from this table. For this initial investigation only one phase-shifter is required.

(5) According to equation (6.1):

$$\Delta P_i = V_i V_j b_{ij} \Delta\psi_{ij}$$

$$\Delta P_j = -\Delta P_i$$

for a phase-shifter i-j with series admittance b_{ij}. It should be ensured, however, that the P_i or P_j be obtained from the vector in equation (4.9). Therefore from equation (6.1) the shift in phase angle from an initial value of zero, is determined.

(6) An approximate check is made using a DC loadflow analysis on the flows.

Tests and Results:

The tests were carried out on the IEEE 24-bus reliability network.

TABLE 6.13: OPTIMUM PHASE-SHIFTER LOCATION RESULTS

	Experiment 1	Experiment 2	Experiment 3
Overloaded line	19-21	7-16	11-14
Current	0.24	2.28	3.92
Capacity	0.2	1.9	3.5
Percentage overload	20	20	12
Phase-shifter location	3-17	1-7	4-9
Shift in phase angle (degrees)	1.0	1.0	2.0
Current in the overloaded line (from a DC analysis)	0.19	2.18	3.77
Current in the phase-shifter (from a DC loadflow analysis)	2.98	2.42	3.92
Remarks	Overload cleared	Overload reduced to 14%	Overload reduced to 7%

The following deductions can be made:

(i) The installation of a phase-shifter reduced or eliminated the line overloads.

(ii) Appropriate impedance values of the shifters can be chosen.

(iii) The capacity of the shifter should be greater than the flow through it to prevent further overloads.

(iv) Since the location of the phase-shifter is the optimum, small shifting in angles would be expected, as was found to be the case in this study.

(v) The advantages of this development include the economic benefits achieved by avoiding generation rescheduling as far as possible.

(vi) The problem of obtaining unfeasible solutions with the previously proposed algorithms based on linear programming and least-squares will be avoided.

6.5 CONCLUSION

This chapter has discussed investigations into how best to manipulate phase-shifters for static security control of power systems. A priori operation is recommended since it is more economical if generation rescheduling can be avoided. The development of two algorithms (and the comparison of their performance) to reduce or eliminate system overloads has been presented. The LP approach, solved using the Revised Simplex technique, is found to perform satisfactorily for all the cases considered. Complex distribution factors have been defined - previously published linearizations involved only reactive portions of the system impedance matrix (see Ku and Olinda in [90] and El-Abiad and Stagg in [91])

Preliminary results were presented in a paper by Cory et al in [93] where phase-shifting transformers were used to give some operational flexibility in AC systems comparable to the use of embedded multi-terminal DC systems. Though a DC link is the most versatile device to cater for the various requirements for interconnections, each case must be examined on its own merits to see whether a technical-economic compromise can be achieved by using other devices.

The chapter concluded with an operational planning method for the optimum location of phase-shifters for security analysis. Some of the results of the work have been submitted by the author in a paper in [94].

From practical considerations, phase angle control can be implemented by using transformers to generate phase-quadrature voltage components to be injected into lines via series connected boosting transformers. An on-load tap changer is usually employed for controlled phase shift with the exciting transformer. However, on-load tap changers require regular maintenance and are frequently the problem component. Hence the design described by Mathur and Sharaf in a recent paper [95] using thyristors would result in a very fast and maintenance free phase-shifting device for power transmission lines.

The work done in this chapter using phase-shifters has resulted in a further interest in developing a method using this device to reduce the risk levels of buses in system planning, as described in the next chapter. This results in the ability of phase-shifters to reschedule power flows to eliminate system overloads.

C. 27-BUS SYSTEM (modified IEEE 24-bus system)

TABLE 6.1: ΔMW FLOWS FOR 1 DEGREE PHASE-SHIFT

		15-24	15-25	26-25	24-26
17-19	0.055	0.054	0.058	0.052	0.064
17-23	-0.726	-0.721	-0.728	-0.724	-0.738
5-17	0.011	0.015	0.011	0.010	0.007
4-19	-0.068	-0.065	-0.066	-0.072	-0.065
19-21	-0.587	-0.585	-0.582	-0.594	-0.575
18-23	-0.749	-0.735	-0.749	-0.752	-0.764
12-23	1.495	1.522	1.506	1.481	1.484
4-18	-0.672	-0.675	-0.674	-0.668	-0.675
5-20	-0.721	-0.725	-0.721	-0.720	-0.717
20-21	-0.817	-0.803	-0.801	-0.844	-0.788
12-14	-1.495	-1.522	-1.506	-1.481	-1.484
1-6	-0.650	-0.650	-0.650	-0.650	-0.650
6-18	-1.173	-1.173	-1.174	-1.171	-1.176
6-20	-1.211	-1.211	-1.210	-1.213	-1.208
16-18	1.469	1.478	1.471	1.463	1.465
13-18	1.474	1.482	1.474	1.470	1.469
16-20	1.578	1.588	1.587	1.564	1.590
13-20	1.583	1.591	1.589	1.570	1.594
7-16	1.859	1.861	1.857	1.855	1.859
8-16	1.217	1.235	1.230	1.201	1.225
7-13	1.836	1.842	1.839	1.830	1.838
13-17	-1.242	-1.252	-1.245	-1.231	-1.246
7-27	-0.404	-0.413	-0.406	-0.395	-0.407
8-22	-3.157	-3.175	-3.170	-3.141	-3.165
14-22	0.731	0.725	0.734	0.732	0.741
11-14	5.060	5.082	5.074	5.047	5.059
15-22	4.228	4.266	4.260	4.206	4.234
3-22	-2.226	-2.237	-2.245	-2.222	-2.233
9-15	1.265	1.246	1.253	1.277	1.266
10-15	1.320	1.317	1.318	1.322	1.320
9-11	-0.595	-0.576	-0.583	-0.607	-0.596
2-3	-0.415	-0.426	-0.434	-0.411	-0.422
2-27	-0.865	-0.854	-0.846	-0.869	-0.858
10-11	1.680	1.683	1.682	1.678	1.680
15-24	1.392	1.481	1.424	1.356	1.342
23-24	-1.848	-1.800	-1.839	-1.862	-1.888
15-25	-3.061	-3.029	-2.879	-2.990	-3.016
26-25	-3.317	-3.347	-3.255	-3.198	-3.361
24-26	-0.491	-0.538	-0.450	-0.540	-0.322
21-26	-2.803	-2.786	-2.782	-2.838	-2.760

TABLE 6.2: ΔMW FLOWS FOR 1 DEGREE PHASE-SHIFT

	15-24	15-25	26-25	24-26
17-19	0.001	0.003	0.003	0.009
17-23	0.005	0.002	0.002	0.012
5-17	0.004	-	0.001	0.004
4-19	0.003	0.002	0.004	0.003
19-21	0.002	0.005	0.007	0.012
18-23	0.014	-	0.003	0.015
12-23	0.027	0.011	0.014	0.011
4-18	0.003	0.002	0.004	0.003
5-20	0.004	-	0.001	0.004
20-21	0.014	0.004	0.027	0.029
12-14	0.027	0.011	0.014	0.011
1-6	-	-	-	-
6-18	-	0.001	0.002	0.003
6-20	-	0.001	0.002	0.003
16-18	0.009	0.002	0.006	0.004
13-18	0.004	-	0.004	0.005
16-20	0.010	0.009	0.014	0.012
13-20	0.008	0.006	0.013	0.011
7-16	0.002	0.002	0.004	-
8-16	0.018	0.013	0.016	0.008
7-13	0.006	0.003	0.006	0.002
13-17	0.010	0.003	0.011	0.004
7-27	0.009	0.002	0.009	0.003
8-22	0.018	0.013	0.016	0.008
14-22	0.006	0.003	0.001	0.010
11-14	0.022	0.014	0.013	0.001
15-22	0.038	0.032	0.022	0.006
3-22	0.009	0.019	0.004	0.007
9-15	0.019	0.012	0.012	0.001
10-15	0.003	0.002	0.022	-
9-11	0.019	0.012	0.012	0.001
2-3	0.011	0.019	0.004	0.007
2-27	0.011	0.019	0.004	0.007
10-11	0.003	0.002	0.002	-
15-24	0.089	0.032	0.036	0.050
23-24	0.048	0.009	0.014	0.004
15-25	0.032	0.182	0.071	0.045
26-25	0.030	0.062	0.109	0.044
24-26	0.047	0.041	0.049	0.169
21-26	0.017	0.021	0.035	0.043

B. 15-BUS SYSTEM (modified IEEE 14-Bus System)

TABLE 6.3: MW FLOWS FOR 1 DEGREE PHASE-SHIFTER

		2-14	5-14	6-14
1-9	-0.031	-0.034	-0.034	-0.024
1-13	-0.118	-0.115	-0.115	-0.125
2-3	0.672	0.683	0.665	0.668
2-4	0.429	0.451	0.415	0.421
2-5	0.274	0.302	0.253	0.267
2-14	0.420	0.525	0.472	0.443
2-15	-1.612	-1.595	-1.623	-1.616
3-4	-0.290	-0.279	-0.296	-0.293
4-5	-0.640	-0.616	-0.668	-0.635
4-7	0.182	0.187	0.187	0.171
4-9	0.103	0.106	0.106	0.087
5-6	0.183	0.198	0.208	0.143
5-14	0.002	0.056	0.090	0.037
5-15	-0.637	-0.655	-0.625	-0.633
6-11	0.171	0.166	0.165	0.182
6-12	0.093	0.092	0.092	0.094
6-13	0.229	0.227	0.227	0.235
6-14	-0.422	-0.399	-0.387	0.293
7-8	0.0	0.0	0.0	0.0
7-9	0.182	0.187	0.187	0.171
9-10	-0.041	-0.036	-0.035	-0.051
10-11	-0.131	-0.126	-0.125	-0.141
12-13	0.031	0.030	0.030	0.032

TABLE 6.4: ΔMW FLOWS FOR 1 DEGREE PHASE-SHIFT

	2-14	5-14	6-14
1-9	.003	.003	0.007
1-13	.003	.003	0.007
2-3	.011	.007	0.004
2-4	.022	.014	0.008
2-5	.028	.021	0.007
2-14	.105	.052	0.023
2-15	.006	.011	0.004
3-4	.011	.006	0.003
4-5	.024	.028	0.005
4-7	.005	.005	0.009
4-9	.003	.003	0.006
5-6	.015	.025	0.040
5-14	.054	.088	0.035
5-15	.018	.012	0.004
6-11	.005	0.006	0.011
6-12	.001	0.001	0.001
6-13	.002	0.002	0.006
6-14	.023	0.035	0.129
7-8	-	-	-
7-9	0.005	0.005	0.011
9-10	0.005	0.006	0.010
10-11	0.005	0.006	0.010
12-13	0.001	0.001	0.001

A. 7-BUS SYSTEM (modified SPC 6-bus network)

TABLE 6.5: MW FLOWS FOR 1 DEGREE PHASE-SHIFT

		2-6	3-6
1-2	1.50	1.50	1.50
2-3	0.151	0.173	0.128
2-6	-0.179	-0.048	-0.136
2-7	0.914	0.934	0.893
3-4	-0.382	-0.385	-0.379
3-6	-0.821	-0.778	-0.689
3-7	0.364	0.346	0.383
4-5	0.914	0.910	0.917
5-7	0.420	0.417	0.422

TABLE 6.6: ΔMW FLOWS FOR 1 DEGREE PHASE-SHIFT

	2-6	3-6
1-2	-	-
2-3	0.022	0.023
2-6	0.131	0.043
2-7	0.020	0.021
3-4	0.003	0.003
3-6	0.043	0.132
3-7	0.018	0.019
4-5	0.004	0.003
5-7	0.003	0.002

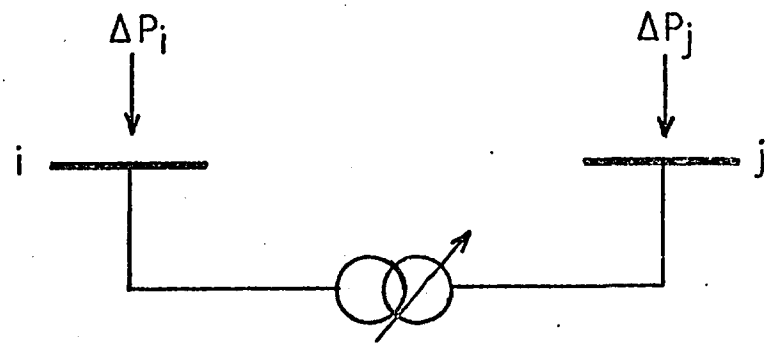


Fig. 6.1 : Incremental AC model for a phase-shifter between busses i and j

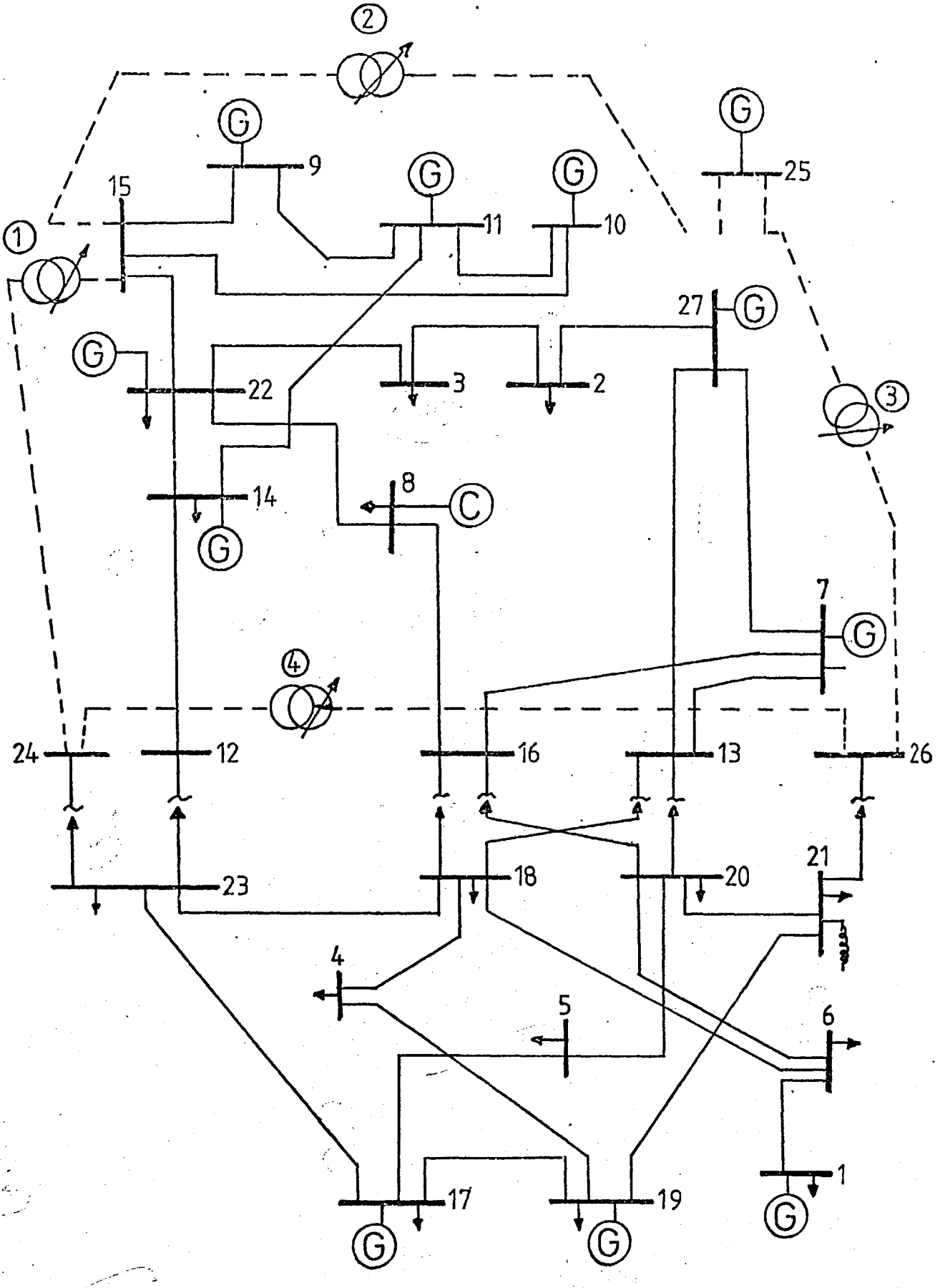


Fig. 6.2 : Modified IEEE 24-Bus reliability network

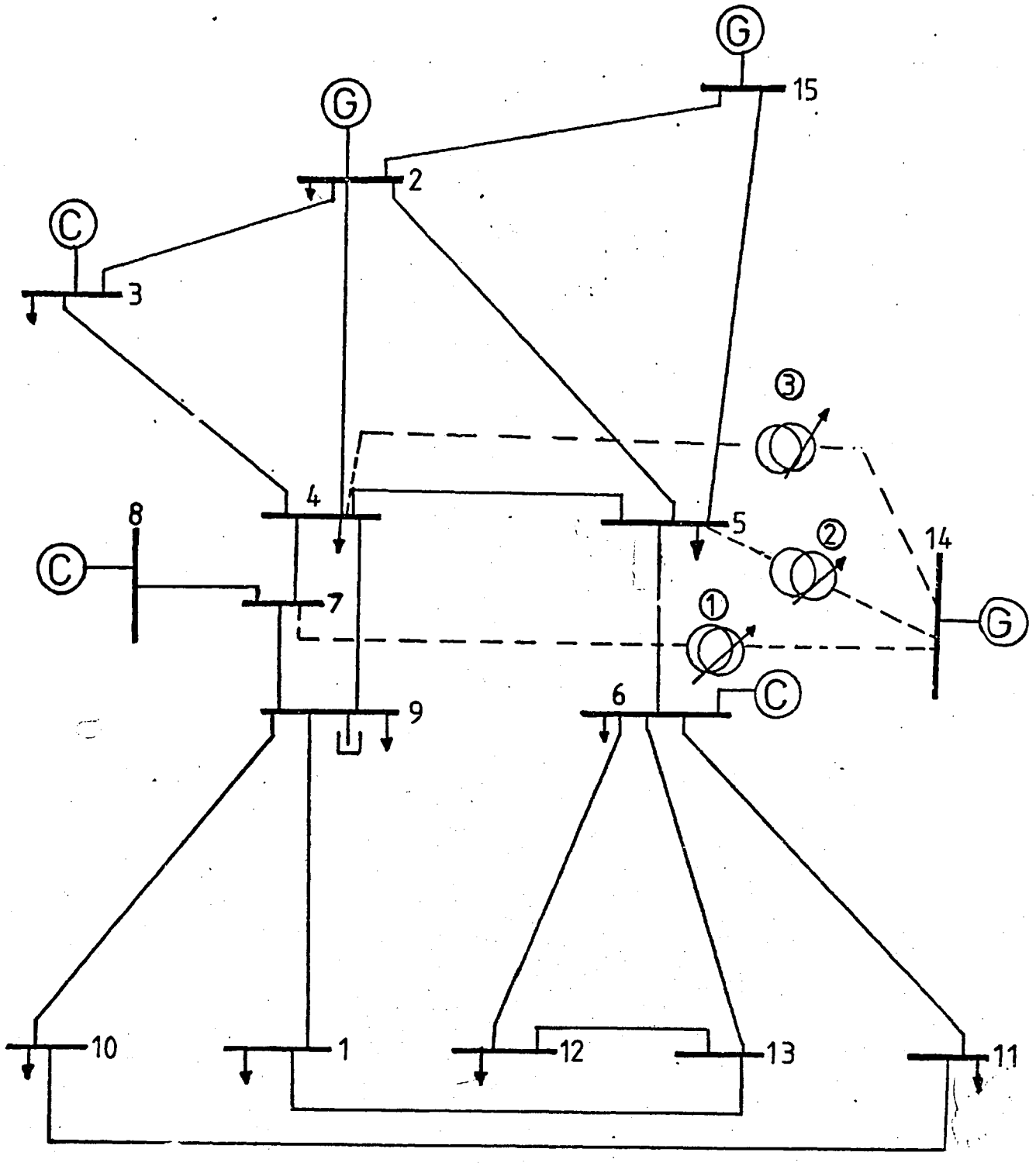


Fig. 6.3 : Modified IEEE 14-Bus Network

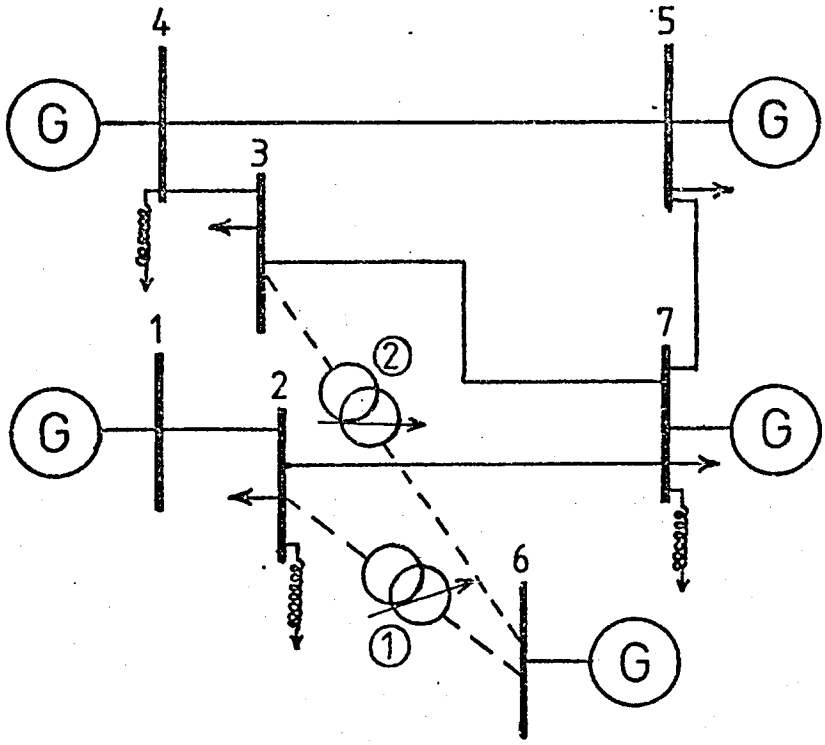


Fig. 6.4 : Modified SPC network

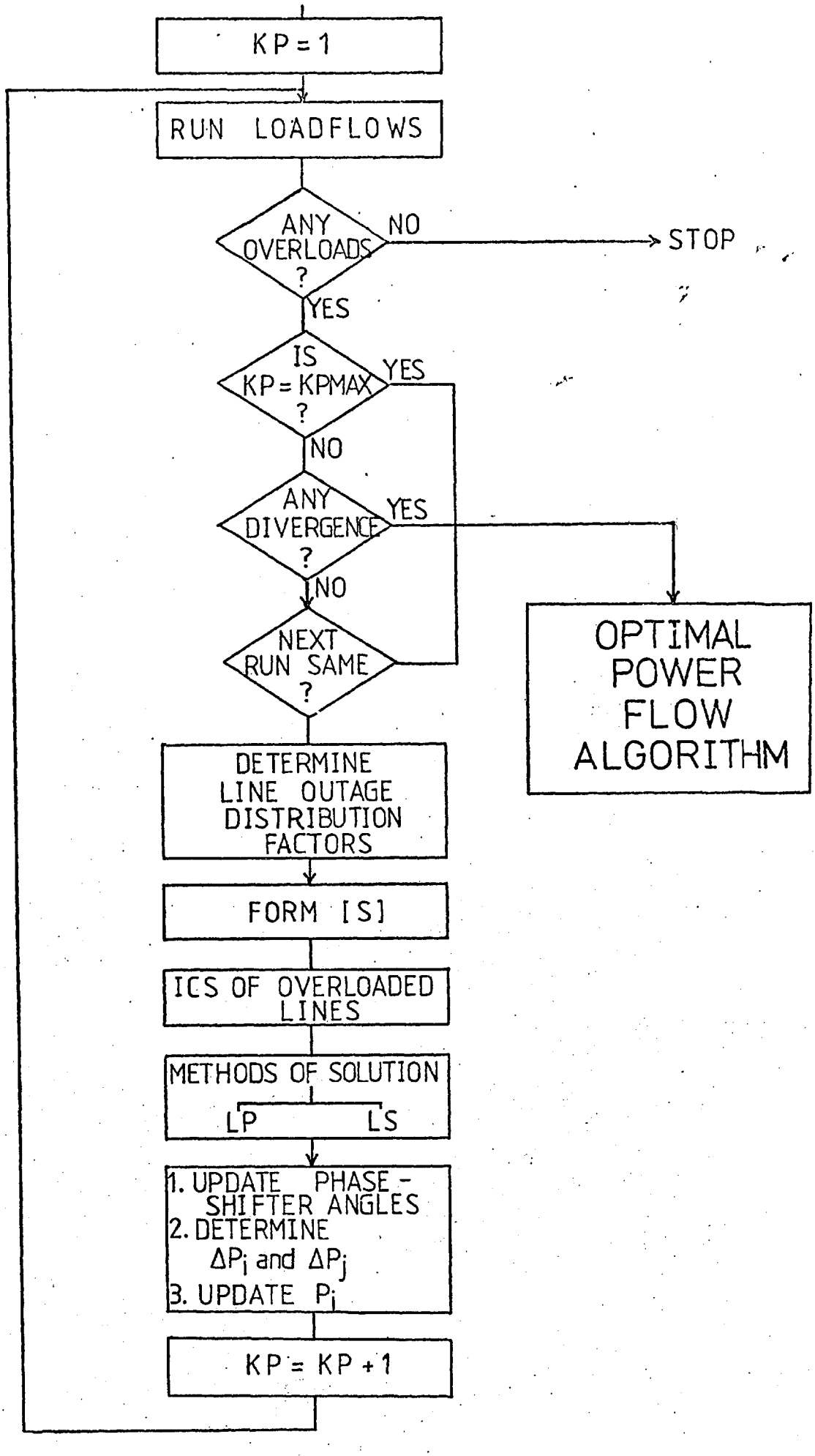


Fig. 6.5 : Flowchart of the Program

CHAPTER 7

TRANSMISSION SYSTEM EXPANSION PLANNING WITH PHASE-SHIFTERS

7.0 INTRODUCTION

The choice of an optimal transmission network expansion plan is a difficult task for which no satisfactory solution has yet been found as the following constraints identified by Sasson and Merrill in [96] are difficult to analyse mathematically.

(i) economical constraints subject to reliability criteria,

(ii) environmental constraints,

(iii) legal constraints, and

(iv) political constraints.

The size and locations of the generating units are usually known but differences in demand patterns or in generation availability from those expected can change the flows in a network. Nevertheless, the network is expected to be able to transmit power from the generating units to load centres as required. Advances in computer technology now have made it feasible to calculate the appropriate number and best locations of new equipment to be added to an existing system to maintain an acceptable reliability level. The transmission expansion problem has been solved by a static optimization formulation in [97-102] for designing the network for some future time.

In [97], Kattenbach et al developed a procedure using a DC loadflow approach, of finding minimum-cost capacity additions required to accommodate known changes in demands and generation. The expansion schedule involving linear and dynamic programming was produced. The required input data are the load and generator nodes and magnitudes by years, the initial transmission

grid, cost of losses and cost of permissible line additions per mile. Their program tests for reliability by solving the yearly loadflows for overloads for single outages. An optimum series of line additions by years is obtained which considers all possible line combinations between the given network nodes. These eliminate all overloads and minimize the sum of the operating and construction costs over the planning period.

Garver [98] formulated the same problem as a power flow problem using linear programming to find the most direct route from generation to loads assuming that all rights-of-way carry power but those without transmission lines are penalised to discourage flow through them. A line is added to the right-of-way having the largest overload and a new linear flow computed. The process was terminated when all overloads were eliminated. Similar linear programming ideas have been used by Adams and Deif in [99,100] using the generalised current injection technique.

Puntel et al in [101] and Sullivan in [102] defined the problem such that the susceptance is installed in the rights-of-way to minimize the cost of installing transmission line capacity and penalising overloads on each of the transmission line and transformers. Minimization is done by first computing a gradient vector through the use of an adjoint network based on Tellegen's theorem stated by Director and Rohrer in [104] and Calahan [105]. Round-off procedures are used to choose the line additions.

The same transmission expansion problem has been considered from a dynamic programming point of view by Dusonchet and El-Abiad in [106] where the optimal sequence of network additions through a period of years is determined. A number of possible expansion strategies was randomly selected and a neighbourhood of possible alternatives developed around each one. Dynamic programming is then used to find the best strategy in each neighbourhood with the present worth of investment minimized. Since the number of feasible network configurations for a typical power system is

very large, Lee et al [107] stated that the dynamic programming technique is quite impractical.

Koglin and Müller [108-110] working at the Technical University of Darmstadt, West Germany have developed a technique through optimal switching of lines to reduce the overloading of transmission circuits. They argued that switching is desirable when the measure of changing the load dispatch either fails or is not feasible in a short period of time or is undesirable because of higher costs.

Three switching possibilities were considered:

(a) Switching-off of branches - this weakens the network.

(b) Switching-on of stand-by branches - particularly useful in meshed networks.

(c) Changing-over in substations (the connecting or splitting of busbars, the changing-over of transformers, lines, injections and loads to other busbars).

The method of Koglin and Müller results in a large number of variants, hence the search for a more favourable configuration for individual substations as well as for several connected substations. Their algorithm can be applied along with generation rescheduling and load shedding, if necessary.

In this thesis, therefore, an approach based on a single-stage optimization method is employed to develop a network augmentation procedure based on sensitivity analysis and the adjoint network approach. The influence of a phase-shifting transformer (used to transmit power from a new generating station to a loaded AC system) is investigated. In Appendix 5, the development of the adjoint network of circuits is presented with the power system problem formulation in Appendix 6.

7.1 NOMINAL NETWORK DESIGN

7.1.1 Determination of the Optimum Interconnecing Busbars of the New Transmission Circuits (i.e. Busbars i and j of Fig. 7.1)

The number of possible combinations of new transmission circuits is equal to NB where NB is the number of busbars in the AC system. For each possible line combination p-q (q = 1,2,.... NB), the value of S_{pq} is determined as (from eqn. (6.13)):

$$S_{pq} = \frac{1}{Z_{pp} + Z_{qq} - 2Z_{pq} - \not{Z}_{pq}}$$

where S_{pq} is the change in current flow in the transmission line p-q for a change in the phase-shifter assumed on line p-q with impedance $\not{Z}_{pq}$ and the Z elements are those of the bus impedance matrix. The various values of S_{pq} are ranked and for maximum transfer of energy in the transmission circuit, the transmission line p-q with the largest S_{pq} determines busbar i in Fig. 7.1, whereas busbar j should be a line with least S_{pq} but as close as possible to busbar i. It is, however, assumed that the lines p-i and p-j are available rights-of-way in the planner's list, otherwise the next highest lines in the S_{pq} list could be chosen instead.

Alternatively, if the cost of line additions is available to the planner, an index based on the cost per unit MW flow would be used instead. This is defined by C_{pq} where

$$C_{pq} = \frac{\text{cost of line addition}}{S_{pq}} \qquad (7.1)$$

Lines to be chosen are those with least C_{pq} and are close to each other.

Since the future load demand should be satisfied reliably, a certain load growth percentage is assumed and set the new generation at bus p such that the total load plus reserve margin is exactly matched. If no overloaded

lines exist, the design of the nominal network is complete. Otherwise, the problem reduces to using the static optimization method developed in the next section to determine the new transmission circuits such that overloads in them will be avoided.

7.1.2 Static Optimization Formulation

Minimize

$$J = \sum_{n=1}^{NR} \frac{W_n}{2} [I_n - I_n^{max}]^2 + K_n B_n \qquad (7.2)$$

where K_n is the vector of unit line costs

W_n is the weighting factor to emphasise the importance of the right-of-way and B_n the susceptance of the lines in the right-of-way.

NR - the number of rights-of-way in the network.

Eqn. (7.3) is solved subject to

$$\left.\begin{array}{l} \text{(i) The satisfaction of the DC loadflow equations.} \\ \text{(ii) } B_n^{min} \leq B_n \leq B_n^{max}. \end{array}\right\} \qquad (7.3)$$

This constraint governs the number of lines required in each right-of-way.

The gradient of eqn. (7.2) with respect to B_n is given as

$$\frac{\partial J}{\partial B} = \begin{bmatrix} \partial_1\bar{\partial}_1 + \bar{\partial}_1(I_1 - I_1^{max})\, W_1 + K_1 \\ \partial_2\bar{\partial}_2 + \bar{\partial}_2(I_2 - I_2^{max})\, W_2 + K_2 \\ \vdots \\ \partial_{NR}\bar{\partial}_{NR} + \bar{\partial}_{NR}(I_{NR} - I_{NR}^{max})\, W_{NR} + K_{NR} \end{bmatrix} \qquad (7.4)$$

where $\bar{\partial}_L$ represents the difference between the adjoint bus angles of right-of-way L.

I_L and I_L^{max} represent the current flow and capacity of lines in the right-of-way L.

Since equation (7.4) is a function of right-of-way parameters only (bus angles and costs), additional right-of-ways can be created easily.

The steepest descent algorithm is used to choose successive values of B as

$$B_n' = B_n - \alpha \frac{\partial J}{\partial B} \qquad (7.5)$$

where α is some scalar parameter that controls the magnitude of the step. Though chosen arbitrarily its objective is to ensure that the minimization of J along a given direction is achieved. Too small a value causes too many iterations to be carried out to clear the overload though convergence is eventually assured, but when α is very large, oscillations around the minimum value may occur, hence an engineering judgement is required to obtain optimum α.

With improved values of B_n computed in eqn. (7.5) the DC loadflow is recalculated and overloaded lines are checked for. If none exist, the design of the nominal network is complete, otherwise the process continues. A large negative value of $\partial J/\partial B$ indicates that an increase in susceptance would produce a relatively large decrease in the performance index J, whereas a relatively large positive value of $\partial J/\partial B$ indicates a relatively large decrease in J. The flowchart is shown in Fig. 7.2.

The main reason for using a DC loadflow is that the gain in accuracy resulting from the use of an AC loadflow model would often seem unjustified in a long-term planning context although it might be justified in a short-term (1- or 2-year) context. An AC loadflow could actually be substituted for the DC model. However, it would cause a substantial increase of computation time.

The following assumptions have been made before analysing the IEEE 24-bus network:

(i) The load is increased by 5% after a future period and a new generating plant (with the availability of the required fuel assured) to be built to satisfy the load growth.

(ii) Equal importance of the rights-of-way are assumed, i.e. W = 1 from eqns. (7.3) and (7.4).

(iii) Impedance of the new transmission circuit is shown in Table 7.1.

(iv) The step parameter α = 0.01.

(v) The unit cost of 0.1 has been assumed to penalise line additions in each right-of-way.

(vi) Maximum of 6 lines in each right-of-way.

7.1.3 Case Study : IEEE 24-bus System

From the sensitivity analysis carried out in section 7.1 and reference to Fig. 7.2, the new bus p is 25, i = 1 and j = 5. The results of the nominal network design are shown in Table 7.2.

The number of lines to be added in each right-of-way is high because overloads are not planned for unlike those in [99] -where a 10% overload was acceptable when a 6-bus network was studied. Rights-of-way 13-24 and 7-24 have exceeded the limit of 6 extra lines. Other measures such as utilizing lines of higher voltage should be resorted to in order to reinforce those rights-of-way. In this study, this has been treated as a 'soft' constraint.

Some of the results have been presented at the recent UPEC, held in Manchester, by the author [111].

TABLE 7.1: Data for the Interconnecting Circuits [17]

	R	X	B/2	Capacity
1-25	0.0160	0.1805	0.006	2.2
5-25	0.0080	0.0902	0.003	2.2

TABLE 7.2: Results of the Nominal Network Design

Overloaded lines	Number of Extra lines	Remarks
12-23	3	-
12-14	2	-
13-18	3	-
13-20	1	-
7-16	3	-
13-24	8	violated constraint
7-24	8	violated constraint
8-22	5	-

7.2 NETWORK DESIGN WITH SECURITY CONSIDERATIONS

Once the nominal network has been designed the DC contingency analysis technique developed in the next section is used to determine which contingencies would be credible. A performance index defined by eqn. (2.21) is used. Each credible outage is tested individually and a composite $\partial J/\partial B$ is computed by summing the gradient for each test. This composite $\partial J/\partial B$ guides the addition of new lines. The process terminates when as many as possible of the overloads caused by the contingencies tested have been eliminated by appropriate network additions. The IEEE 24-bus reliability network is studied.

7.2.1 DC Powerflow Contingency Analysis

The basic equation is of the form:

$$P = K\delta \tag{7.6}$$

Clearly, if for a fixed set of power injections P, a line is removed, both the K matrix and the δ vector will change from their base-case values K°, and δ° by an amount ΔK and $\Delta\delta$ such that

$$P^\circ = (K^\circ + \Delta K)\ (\delta^\circ + \Delta\delta) = K^\circ\delta^\circ + K\Delta\delta^\circ + \Delta K\Delta\delta \tag{7.7}$$

Neglecting the non-linear term ($\Delta K\Delta\delta$) then

$$P_o = K^\circ\delta^\circ + \Delta K\delta^\circ + K^\circ\Delta\delta \tag{7.8}$$

but from eqn. (7.6), the initial base-case situation is

$$P_o = K^\circ\delta^\circ$$

hence

$$\Delta\delta = (K^\circ)^{-1}\ \Delta K\delta^\circ \tag{7.9}$$

Updating

$$\delta' = \delta^\circ + \Delta\delta \tag{7.10}$$

and new power flows computed as

$$P_{ij}' = - K_{ij}(\delta_i' - \delta_j') \qquad (7.11)$$

and overloads checked.

Important aspects of the derivation are:

(i) $(K^\circ)^{-1}$ is computed only once at the start of the contingency study and stored for use for all the line outages.

(ii) For the removal of a line p-q, only elements in K° that change are K_{pp}, K_{qq} and K_{pq} where

$$\left.\begin{aligned} \Delta K_{pp} &= K_{pq} \\ \Delta K_{qq} &= K_{pq} \\ \Delta K_{pq} &= \Delta K_{qp} = K_{pq} \end{aligned}\right\} \qquad (7.12)$$

7.2.2 Case Study : IEEE 24-bus System

With the completion of the nominal design in section 7.1.3 above, using the single line outage criterion resulted in the following line additions (assuming a 5% load growth):

TABLE 7.3: Single-line Outage Results

Line	Number of extra line additions	Remarks
7-23	1	
18-23	1	
5-20	1	
12-14	3	
6-20	1	
16-18	1	
7-16	4	constraint violated
7-13	1	
13-24	8	constraint violated
7-24	8	constraint violated
8-22	1	
14-22	1	
9-11	1	
2-24	1	
1-25	1	

The right-of-way having more than 6 extra lines should be upgraded. From the previous study, the right-of-way 13-24 and 7-24 have already exceeded their limits. The addition of the above lines produces a reliable network designed with economics and security except that 1.70% overload is still present in the right-of-way 12-23. This can be accepted under practical conditions as being negligible.

7.2.3 Effect of Phase-shifters

A phase-shifter is placed in lines 1-25 and 5-25 and the influence of each case on the power flows investigated for 1 degree phase-shift.

TABLE 7.4:

Right-of-way	Power Flows		
	Without phase-shifter	With phase shifter on 1-5	With phase-shifter on 5-25
17-19	-0.081	-0.072	-0.090
17-23	-0.571	-0.566	-0.575
5-17	-0.738	-0.724	-0.751
4-19	0.079	0.074	0.085
19-21	0.2	0.203	0.197
18-23	-0.173	-0.177	-0.169
12-23	2.634	2.633	2.635
4-18	-0.856	-0.851	-0.862
5-20	-1.126	-1.103	-1.149
20-21	1.228	1.225	1.231
12-14	-2.634	-2.633	-2.635
1-6	-1.744	-1.781	-1.708
6-18	-1.960	-1.977	-1.944
6-20	-1.579	-1.599	-1.559
16-18	2.011	2.014	2.007
13-18	2.47	2.474	2.467
16-20	2.761	2.757	2.764
13-20	3.220	3.217	3.223
7-16	3.183	3.183	3.183
8-16	1.588	1.588	1.587
7-13	2.373	2.373	2.373
13-24	-3.318	-3.318	-3.317
7-24	-2.399	-2.399	-2.399
8-22	-3.625	-3.625	-3.624
14-22	0.125	0.125	0.124
11-14	4.867	4.867	4.867
15-22	1.837	1.473	1.474
3-22	1.474	1.473	1.474
9-15	0.578	0.578	0.578
10-15	1.259	1.259	1.258
9-11	-0.475	-0.475	-0.474
2-3	3.374	3.374	3.375
2-24	-4.718	-4.718	-4.719
10-11	1.741	1.741	1.742
1-25	-0.928	-0.989	-0.965
5.25	1.118	1.082	0.961

TABLE 7.5: Variation of J with 1 degree Phase-shift

	J without phase-shift	with shifter on 1-5	J with shifter on 5-25
Iteration 1	21.97413	21.97622	21.97206
Iteration 2	14.89438	14.89853	14.89026

The flows in the lines very close to the phase-shifter are changed remarkably but from Table 7.5, the effect of the phase-shifter on 5-25 is more predominant. This is because the susceptance of line 5-25 is greater than that of 1-25.

7.3 NETWORK DESIGN WITH RELIABILITY CONCEPTS

With the growing concentration of power production in large stations, frequently remote from load centres, more and more consumers depend for supply on the integrity of transmission networks. These play a vital role in pooling generation capacity, at all load levels, to achieve maximum security and economy of supply [112]. A network can be designed for single contingency outages (as in the previous sections of this thesis), double contingency outages or any specified multiple outage criteria, none of these transmission adequacy criteria, however, provide a quantitative measure of the level of system reliability. This is because the number of customer interruptions and the quality of service should reside within prespecified tolerance levels. For this reason many utilities have introduced probability assessments of the combined generation and transmission system to indicate areas where reinforcement is needed; industrial consumers, for example, place reliability

of electrical supply high on their priority list for proposed factory locations. This is not supposed to replace the deterministic criteria outlined above but to complement the design obtained therefrom.

The 'reliability' of a power transmission has been defined by Fernando [113] and Induruwa [114] as "its ability to transport electrical energy of acceptable quality continuously from the generation centres to the load centres in the quantities required". The limits of acceptable quality differ from system to system and mainly dictated by the statutory regulations governing voltage and frequency limits. According to Fernando [113], two categories of studies leading to the evaluation of quantitative reliability indices at principal load points of a transmission network can be performed and are (a) loss of continuity studies and (b) composite reliability studies. Loss of continuity studies are mainly suitable in practice for the performance judgement of subtransmission and distribution networks where the high redundancy normally provided can justify the consideration of reliability as a matter of continuity only. In this thesis, the interest lies in primary transmission planning, hence a loss of continuity study is not applicable. Composite reliability studies analyse the generation facilities and the primary transmission facilities of a power system in a composite manner to provide quantitative reliability indices at the principal load points.

Pioneering work on the reliability evaluation of a composite system was conducted by Billinton [115,116]. Billinton and Bhavaraju [117] described the development of two load point reliability indices, namely probability of failure and frequency of failure at a bus. The approach is computationally expensive when applied to a large system as the Gauss-Seidel technique, which has a slow convergence and the number of iterations directly proportional to the number of system buses, was used. The use of Stott's fast-decoupled loadflow method [29] to analyse each contingency state was

presented by Billinton et al [119]. It was assumed that the risk evaluation is performed only if the base case loadflow with all the system components are performing satisfactorily. Additional busbar and overall system indices based upon the load curtailment required to alleviate line overloads were described by Billinton et al in [120] and extended in [121] to include all possible simultaneous independent outage combinations of generating units, transmission lines and transformers. Dandeno et al in [122] described another method for composite system reliability evaluation by not evaluating the reliability of individual load points in the system.

Planning of power networks is complicated by uncertainties in the network configuration and load states. These load uncertainties can be due to:

(a) Measurement error or forecast inaccuracy.

(b) Load is known or assumed within limits.

(c) Unscheduled outage.

These uncertainties have generally been accounted for by repetitive loadflow calculations, one loadflow calculation for each combination of possible load and network availability. This thesis proposes a method for systematically dealing with both uncertainties. The stochastic security analysis is used to evaluate the probabilities of line overloads occurring in the system. Using these probabilities and with the computation of the probability of network state determined, the required probability indices are calculated for each bus which relates to the event that the load will not be satisfied at that bus. It is assumed that the base case solution of the loadflow analysis, with all circuits present, performs satisfactorily. This technique is applied to the nominal network designed for the enhanced IEEE 24-bus system presented in section 7.1. Some of the unavailable network data is assumed. This enables a reinforced network design to be completed to compare

with the technique presented in section 7.2. The comparison is presented in section 7.4. It is generally assumed that the generating capacity is completely reliable.

7.3.1 Stochastic Security Analysis

The application of stochastic loadflow methods which take into account the uncertainty of the load forecast in the security analysis has the advantage of producing loadflow results over the forecast error and eliminates the requirement of repetitive loadflow calculations.

Borkowska [123] produced the first paper on probabilistic loadflows. The input data was treated as probabilistic distribution functions and a method for calculating probabilistic distribution of line flows. Though based on a DC model, Allan et al in [124] extended the model and incorporated AC as given in references [125, 126]. The method calculates the output variables as random variables and also gives their probability density functions computed using mathematical convolution techniques [127]. At the American Electric Power Corporation, New York another approach using the least-squares method was formulated by Dopazo et al [128]. Normal distribution of input data was assumed and the mean values and variances of line flows were computed. Using the central limit theorem, line flows were assumed to have the normal distributions and the confidence limits evaluated.

According to Prada [17], the choice of a suitable method depends on the kind of probability density function of the input variables. If all are normally distributed the second approach,which involves less programming complexity, storage and computing time than the first, should be employed. If the number of non-normally distributed variables is very small, the second approach may be used. However, since both methods require linearizations of the loadflow equations, these are approximations.

Although these methods assume independence of the input data, concepts taking into account correlations of the input data have been published in the literature by Allan and Al-Shakarchi in [129] and Aboytes and Cory in [130]. As for applications of stochastic loadflow, there are some for security analysis investigations by Aboytes [131], Allan et al [132] and Prada and Cory in [133]. The method used in this thesis is that proposed by Prada and Cory in [133] using the AEP approach.

The programming logic is relatively simple hence can be coupled to any transmission system planning program. The AEP approach to the stochastic loadflow can be outlined as below.

The loadflow equation, taking into account the stochastic variations, can be given by

$$y = f(X) + \varepsilon \tag{7.13}$$

$$E(\varepsilon\varepsilon^t) = V \text{ (diagonal matrix)} \tag{7.14}$$

$$E(\varepsilon) = 0 \tag{7.15}$$

where

y = bus specified value

X = variable

$f(x)$ = corresponding equation for y

ε = variation

E = expected value

Linearizing eqn. (7.13) about X_n

$$y = f(X_n) + J(X_n)\,\Delta X + \varepsilon \tag{7.16}$$

where $J(X)$ is the Jacobian matrix of $f(X)$.

Defining $\Delta y = y - f(X_n)$ then

$$\Delta y = J(X_n)\,\Delta X + \varepsilon \tag{7.17}$$

Since eqn. (7.17) is linearized the correction $\Delta\hat{X}$ can be obtained by using least-squares as

$$\Delta\hat{X} = [J^t(X_n)\, V^{-1}\, J(X_n)]^{-1}\, J^t(X_n) V^{-1}\ \Delta y \tag{7.18}$$

The estimate X and the covariance matrix C_x can be given by

$$\left.\begin{aligned} \hat{X} &= X_n + \Delta X \\ C_x &= [J^t(X_n)\, V^{-1}\, J(X_n)]^{-1} \end{aligned}\right\} \tag{7.19}$$

Since the initial loadflow solution is used to obtain the average values:

$$C_x = [J^t(\hat{X})\, V^{-1}\, J(\hat{X})]^{-1} \tag{7.20}$$

the line flow, a non-linear function with respect to X is expressed as:

$$W = g(X) \tag{7.21}$$

The mean value $\hat{W}$, the covariance matrix $C_{\hat{W}}$ and the variance σ_W^2 are given as:

$$\hat{W} = g(\hat{X}) \tag{7.22}$$

$$C_{\hat{W}} = K(\hat{X})[J^t(\hat{X})\, V^{-1}\, J(\hat{X})]^{-1}\, K^t(\hat{X}) \tag{7.23}$$

$$\sigma_W^2 = \text{diagonal}\ [C_{\hat{W}}] \tag{7.24}$$

where K(X) is the Jacobian matrix of $g(\hat{X})$. Only the non-zero elements of the matrices defined in eqns. (7.20) and (7.23) are computed.

The density function of a normal distribution is given by f(X) where

$$f(X) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(X-\hat{X})^2}{2\sigma^2}\right) \tag{7.25}$$

The distribution function is

$$F(X) = \int_{-\infty}^{X} f(\xi)d\xi \tag{7.26}$$

$$= 0.5 + \int_{0}^{X} f(\xi)d\xi \tag{7.27}$$

Defining

$$\text{erf}\left(\frac{X-\hat{X}}{\sigma}\right) \triangleq \int_{0}^{X} \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\xi-X)^2}{2\sigma^2}\right) d\xi \tag{7.28}$$

then

$$F(X) = 0.5 + \text{erf}\left(\frac{X-\hat{X}}{\sigma}\right) \tag{7.29}$$

The probability of finding X greater than its maximum limit is given by PR where

$$PR = 0.5 - \text{erf}\left(\frac{X^{max} - \hat{X}}{\sigma}\right) \tag{7.30}$$

Eqn. (7.30) is used to monitor transmission branch overloads for all line outages. Bus voltages are not considered critical as line overloads hence the voltage criterion is relaxed. Considerable savings in computing time can be effected by making use of the tabulated values of erf (X) from X = 0 to X = 3 in Papoulis [134] shown in Appendix 7.

The results of the stochastic contingency analysis obtained above should include the probabilities of occurrence of events in a single calculation. This addition would enable an accurate formulation of the stochastic contingency problem. It is assumed that every outage is statistically independent, i.e. the influence of the fluctuating environment, stormy and normal weather is not considered. Therefore the probability of the event which involves an outage can then be obtained more readily as a product of probabilities. Consider a system with 3 lines with

probabilities of line outages as p_1, p_2 and p_3 respectively. The following table shows the computation of the estimated overload probabilities OP_1^{Est}, OP_2^{Est}, OP_3^{Est} respectively.

TABLE 7.6: Computation of Estimated Overload Probabilities

Lines in Service	Lines out of Service	Event Probability	Event No.
1,2,3	-	$p_a = (1-P_1)(1-P_2)(1-P_3)$	1
1,2	3	$P_b = (1-P_1)(1-P_2)P_3$	2
1,3	2	$P_c = (1-P_1)(1-P_3)P_2$	3
2,3	1	$P_d = (1-P_2)(1-P_3)P_1$	4

The estimated overload probabilities of the system are:

$$\left.\begin{aligned} OP_1^{Est} &= P_a OP_1^1 + P_b OP_1^2 + P_c OP_1^3 \\ OP_2^{Est} &= P_a OP_2^1 + P_b OP_2^2 + P_d OP_2^4 \\ OP_3^{Est} &= P_a OP_3^1 + P_c OP_3^3 + P_d OP_3^4 \end{aligned}\right\} \qquad (7.31)$$

where OP_y^x is the overload probability of line y at the Xth event.

7.3.2 Calculation of Probabilities of Failure of Consumer Load Points

The function of a power transmission network is to carry electric power from the generators to the load. Therefore, the points of final interest are the load buses. The effect of overloaded lines on the total operation of the network can be determined by computing loadflow sensitivity factors defined by Hayes et al in [135]. The line flow sensitivity factor is defined as the incremental reactive power flow in a line due to

incremental bus reactive power. Therefore the sensitivity factor of line flow in line r to power at bus K is defined as

$$S_{rK} = \frac{\partial Q_r}{\partial Q_K} \tag{7.32}$$

where Q_r is the reactive power in line r and Q_K is the reactive power load at bus K. This value can be approximated by the elements of the $[B'']^{-1}$ matrix of the decoupled loadflow equations [29] as

$$S_{rK} = - b_r(B''^{-1}_{I_1,K} - B''^{-1}_{I_2,K}) \tag{7.33}$$

where b_r is the susceptance of line r, I_1 and I_2 are the bus numbers of the end buses of line r, K is the load bus under consideration.

Following reference [135], the probability of failure at bus K is defined by P_K where

$$P_K = \frac{\text{expected value of total duration of load loss}}{\text{total time}}$$

$$= \sum_{i=1}^{I} \sum_{j=0}^{J} p_r(L_i)\, p_r(N_j)\, P_{ijK} \tag{7.34}$$

where

$p_r(L_i)$ is the probability that load state i exists

$p_r(N_i)$ is the probability that network state j exists

I is the number of load states

J is the number of network states

P_{ijK} is the conditional probability that the load at bus K will not be satisfied, conditional on load state i and network state j

The following assumptions reduce eqn. (7.34) to (7.35):

(i) single step representation of load

(ii) voltage criterion is not of interest

$$p_K = \sum_{j=0}^{J} P_r(N_j)\, P_{jK} \qquad (7.35)$$

The objective of eqn. (7.35) is to ensure that the investment in transmission improvements is made at the most desired locations in the system, in terms of an acceptable risk level at the various load points. Since generation availability has previously been assumed, eqn. (7.35) reduces to zero for all generating buses.

The data required for composite reliability studies under the assumptions above include:

(i) All the system data for loadflow analysis.

(ii) Maximum power transfer capability of the transmission lines and transformers.

(iii) Failure rate and repair rate of the lines and transformers.

(iv) Variance of the load and generating units.

(v) Acceptable risk levels of the load points.

(vi) Every line outage is statistically independent and the network is a random variable.

(vii) Daily load cycle.

The flowchart of the program is shown in Fig. 7.6.

7.3.3 Case Study : IEEE 24-bus System

The IEEE 24-bus system designed for expansion in section 7.3 was studied with the following assumptions:

(i) The standard deviation is 10% of the input data.

(ii) Independence of the input data. This is justified as in long-term planning problems, the probabilistic variation of load is generally not one involving time, but instead is associated with load forecasting at a specific time in the future [128].

(iii) Line overloads only.

(iv) Single-step load representation.

(vi) Normal distribution of the input data.

(vii) Acceptable risk level of 0.0075.

Using the above algorithm, risk levels are calculated and lines added between the bus with the most risk level and another with the least risk level. Additional rights-of-way may be created if the one utilized does not reduce the risk level of the bus under consideration. The process is repeated until all the unacceptable risks have been eliminated in the buses affected. Available rights-of-way may be supplied to the planner. From the system diagram (see Fig. 4.2) a reactor of 100 MVAR capability is connected on bus 21, this explains the high risk index of that bus of 0.0130865. Adding lines to the right-of-way 19-21 (from Table 7.1) in turn reduced the risk level to 0.0102269 and 0.0096913 respectively. The acceptable risk level of 0.0075 has not been attained yet.

Instead of adding many 138 kV lines on 19-21, other alternatives which may be considered are:

(i) Addition of 230 kV lines.

(ii) Making use of phase-shifters on the line 19-21.

(iii) Addition of a HVDC link in parallel with the existing 138 kV line in 19-21.

The system planner should consider the following factors before choosing the required alternatives:

(i) Economic factors:

For the first option, a 230/138 kV transformer station would have to be built whereas extension to the existing 138 kV substations would be required if more 138 kV lines are built. The fault clearing duties of existing circuit breakers and switchgears would be increased and some of them may even be replaced if necessary.

The investment on phase-shifters would be included in the decision process if phase-shifters are installed on line 19-21.

HVDC links are usually expensive but for a long-term planning objective, this seems attractive. Availability of VAR supply for the converters would be assured. Depending on the country in question, it may not be necessary to introduce this technology if technicians and engineers with the required background are lacking. However, an extensive training programme may be embarked upon before the commisioning of the equipment.

(ii) Technical factors:

Is the amount of power transferable over the interconnection with some degree of reliability justifiable?

Phase-shifters are required to shift the angles over a small range. Without the fault statistics for the shifters being available, it is assumed that the probability of an outage is zero. With a phase-shifter connected between 19-21 in parallel with the other line, changes within a range of 1-3 degrees reduced the risk level to 0.0013651.

Using a HVDC link raises the transient stability limit. The amount of power depends on the thermal rating of its conductors, converter bridges and terminal equipment. With adequate and available fault statistics,

the required reliability indices would be calculated.

(iii) Environmental and social factors:

How would the pollution be taken? What effects would the new transmission circuit(s) have on the aesthetics of the area?

(iv) Political factors:

Is interconnection possible? Should the system be in synchronism? How would the desired change affect national interest?

7.4 COMPARISON OF METHODS

Network designs using the single line-outage and reliability concepts have been described in the last sections.

Though the design based on reliability criterion is complicated by the effects of the fluctuating weather, overload possibilities on parallel networks and scheduled maintenance of the network, it provides a quantitative measure of system performance. The design based on the single line-outage criterion can result in a higher investment plan particularly if lower reliability values can be tolerated at those points.

The non-availability of comprehensive fault statistics of a network might give rise to conservative evaluation of its performance. The gathering of the required network information may take up to 10 years to gather.

Both designs are supposed to complement each other to achieve maximum security and economy of supply.

7.5 THE ROLE OF THE PLANNER

The power system procedures developed in this chapter are based on analytical methods which define the problem for application of non-linear programming and reliability concepts. This gives rise to the determination of the mathematical optima. However, the economy-quality compromise expected from the system should be compatible with the state of development as well

as that of other industries in the geographical area and the socio-economic and technological background. Hence the need for intuitive developments to be contributed by the experienced system planner through engineering judgement. Consequently the final solution, which is usually a refinement of the mathematical optimum described will be more realistic than a solution obtained using these techniques described above.

Interactive computing methods outlined in chapter 1 would be important and of considerable advantage to the system planner and the prospects for interactive development of the algorithm are:

(i) The choice of α in eqn. (7.5) influences the speed of operation of the program. The value of α guides the planning engineer towards an acceptable network design.

(ii) If the computed rights-of-way in section 7.1.1 are not available in the list provided to the system planning engineer, he can choose the closest to the computer rights-of-way for optimum results.

7.6 CONCLUSION

This chapter has presented a method based on single-stage optimization procedure based on sensitivity analysis and the adjoint network approach using a phase-shifter to transmit power from a new generating station to a loaded AC system. The optimization method was the non-linear programming technique of gradient projection followed by a round-off procedure. The method is fast and computationally less expensive,

the only disadvantage being the round-off procedures to reach integer changes. Integer programming methods based on the branch-and-bound techniques would help to achieve a readily acceptable optimum plan.

The nominal network is tested for security using the single-line outage and reliability criteria and both designs are compared. The quantitative method provides a means of numerically assessing the various reliability characteristics of systems and their constituent parts, thus enabling these to be compared with pre-determined target values. Some or all of the equipment which the network planner intends to use will be new or modified, without empirical performance data. Though extrapolation from existing plant is possible, some information on its probable performance may be determined, though with considerable uncertainty. The results show that the transmission system improvements increase as higher reliability levels are demanded. A fixed contingency criterion like the single-line outage assumed can result in a higher investment plan than required at some locations, particularly if lower reliability values can be tolerated at those points. The selection of an acceptable risk level is a planning decision for which no available values can be utilized in this study.

Further investigations by system utilities have been retarded due to the lack of network data or adequate fault statistics for an existing system. It might take up to 10 years to gather.

Blind use of the mathematical developments above is not envisaged, the system planner is expected to apply some intuitive concern based on engineering judgement to arrive at a system which is not only a near-optimum but satisfies the socio-economic and technological background of the geographical area. For example, it would be expected that the system planner would recommend the utilization of lines of higher voltage instead of large numbers of line additions to a given branch, phase-shifters or even a HVDC link to reinforce a particular branch. Also overloads in underground cables

might be corrected by paralleling lines whereas for overhead lines shifts in the phase-shifter angle or generation rescheduling can be resorted to; this is to preserve the aesthetics of the environment.

In a recent paper [136], Monticelli et al have described an interactive program for long-term transmission system expansion planning based on "least-effort" criterion and sensitivity analysis. All network synthesis is based on the DC power-flow model. The approach presented in this chapter enables qualitative as well as quantitative analyses of network expansion. This is the advantage over previous developments mentioned in the literature.

TABLE 7.7A NODAL DATA

Bus No.	Generated Power (pu)	Real power demand (pu)	Reactive power demand (pu)	Voltage magnitude (pu)
1	0.6	1.25	0.25	1.01
2	-	1.28	0.26	1.0
3	-	1.81	0.37	1.0
4	-	0.74	0.15	1.0
5	-	0.71	0.14	1.0
6	-	1.71	0.35	1.0
7	5.94	2.65	0.54	1.01
8	-	1.94	0.39	1.01
9	4.0	3.33	0.68	1.01
10	3.0	-	-	1.01
11	4.0	-	-	1.0
12	-	-	-	1.0
13	-	-	-	1.0
14	0.43	3.17	0.64	1.01
15	-	-	-	1.0
16	-	-	-	1.0
17	0.40	1.08	0.22	1.01
18	-	1.75	0.36	1.0
19	0.40	0.97	0.20	1.01
20	-	1.95	0.40	1.0
21	-	1.36	0.28	1.0
22	1.55	1.00	0.20	1.01
23	-	1.80	0.37	1.0
24	-	-	-	1.0 (slack)

TABLE 7.7B: REGULATED BUS DATA (Real)

Bus No.	Minimum MW Capability	Maximum MW Capability
1	0.6	3.0
7	1.19	5.94
9	0.8	4.0
10	0.6	3.0
11	0.8	4.0
14	0.43	2.15
17	0.38	1.92
19	0.38	1.92
22	0.31	1.55
24	1.32	6.6

TABLE 7.7C: REGULATED BUS DATA (Reactive)

Bus No.	Minimum MVAr Capability (pu)	Maximum MVAr Capability (pu)
1	0.0	1.80
7	0.0	2.40
8	-0.5	2.0
9	-0.5	2.0
10	-0.6	2.96
11	-0.5	2.10
14	-0.5	1.1
17	-0.5	0.72
19	-0.5	0.72
22	-0.5	0.80
24	-1.25	3.1

TABLE 7.7D: LINE DATA

Line	R (pu)	X (pu)	B/2	Capacity (pu)	λ	μ
17-19	0.0026	0.0139	0.2306	4.0	0.24	16
17-23	0.0546	0.2112	0.0286	3.5	0.51	10
5-17	0.0218	0.0845	0.0115	8.0	0.33	10
4-19	0.0328	0.1267	0.0172	2.5	0.39	10
19-21	0.0497	0.1920	0.0260	1.1	0.48	10
18-23	0.0308	0.1190	0.0161	1.5	0.02	768
12-23	0.0023	0.0839	-	0.7	0.36	10
4-18	0.0268	0.1037	0.0141	10.0	0.34	10
5-20	0.0228	0.0883	0.0120	9.4	0.33	35
20-21	0.0139	0.0605	1.2295	1.8	0.3	10
12-14	0.0067	0.0519	0.0546	1.0	0.44	10
1-6	0.0159	0.0614	0.0083	10.8	0.44	10
6-18	0.0427	0.1651	0.0224	4.4	0.02	768
6-20	0.0427	0.1651	0.0223	2.8	0.02	768
16-18	0.0023	0.0839	-	2.5	0.02	768
13-18	0.0023	0.0839	-	1.0	0.2	768
16-20	0.0023	0.0839	-	5.64	0.4	11
13-20	0.0023	0.0839	-	2.5	0.39	11
7-16	0.0061	0.0476	0.0499	0.9	0.40	11
8-16	0.0054	0.0418	0.0879	4.9	0.52	11
7-13	0.0061	0.0476	0.0499	2.5	0.49	11
13-24	0.0124	0.0966	0.1015	1.0	0.38	11
7-24	0.0111	0.0865	0.0909	0.65	0.33	11
8-22	0.0050	0.0389	0.0409	0.65	0.41	11
14-22	0.0022	0.0173	0.0182	2.0	0.41	11
11-14	0.0031	0.0245	0.1030	7.0	0.41	11
15-22	0.0033	0.0259	0.0273	3.6	0.35	11
3-22	0.0030	0.0231	0.0243	2.0	0.34	11
9-15	0.0018	0.0144	0.0152	2.5	0.32	11
9-11	0.0016	0.0129	0.0545	2.6	0.35	11
10-15	0.0135	0.1053	0.1106	2.5	0.54	11
2-24	0.0014	0.0108	0.0455	8.0	0.35	11
10-11	0.0087	0.0678	0.0712	8.0	0.38	11
2-3	0.0025	0.0198	0.0833	5.0	0.34	11
21-21	-	-	1.00	-	-	-

λ = outage rate/year
μ = outage duration (hours)

Where appropriate, some alterations on the network data have been made. The figure of the network is shown in Fig. 4.2

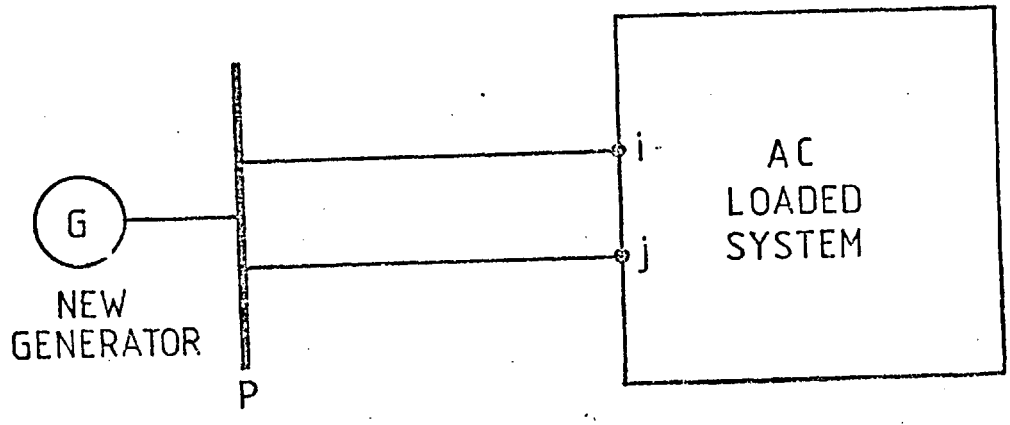


Fig. 7.1 : New network configuration

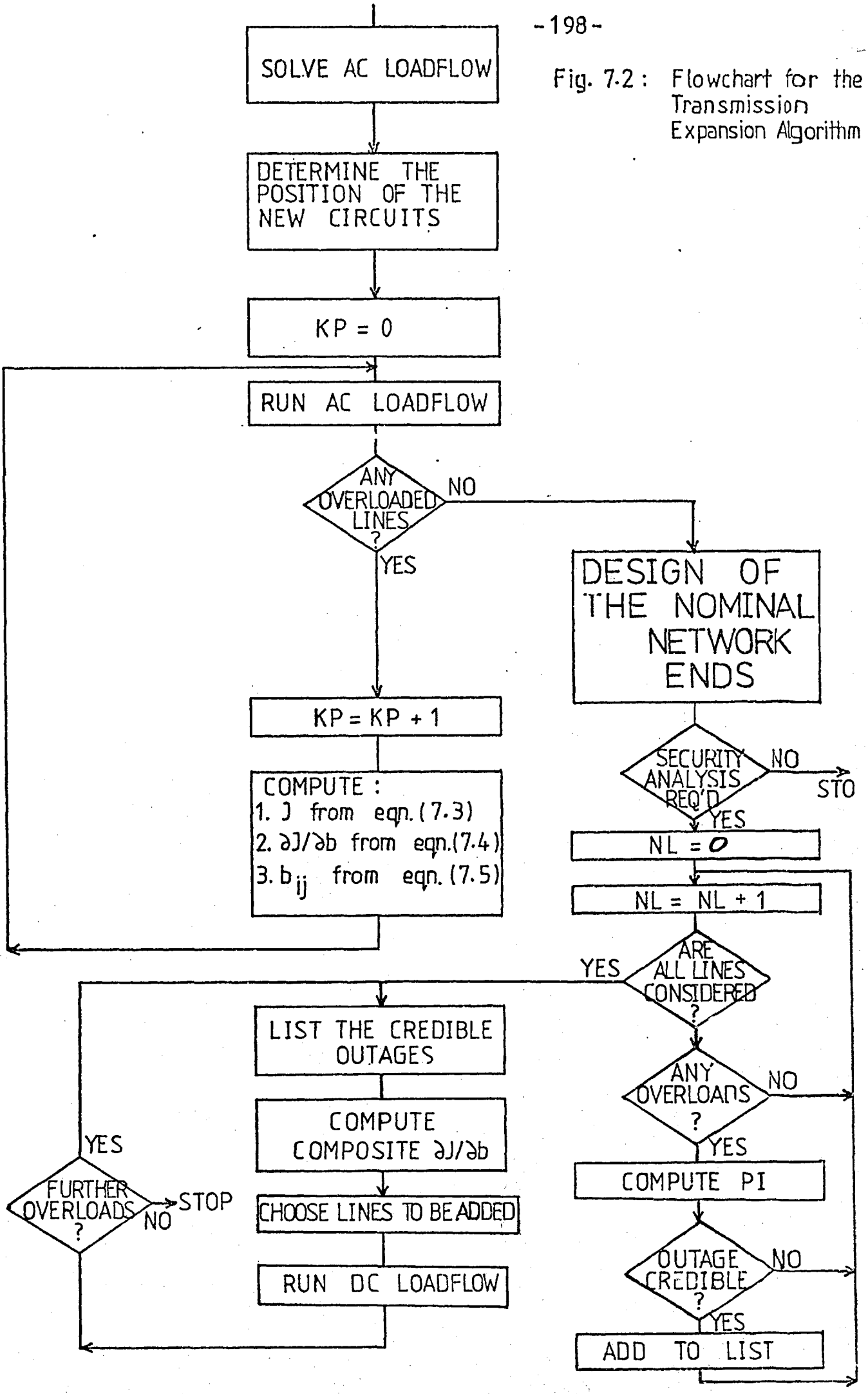


Fig. 7.2 : Flowchart for the Transmission Expansion Algorithm

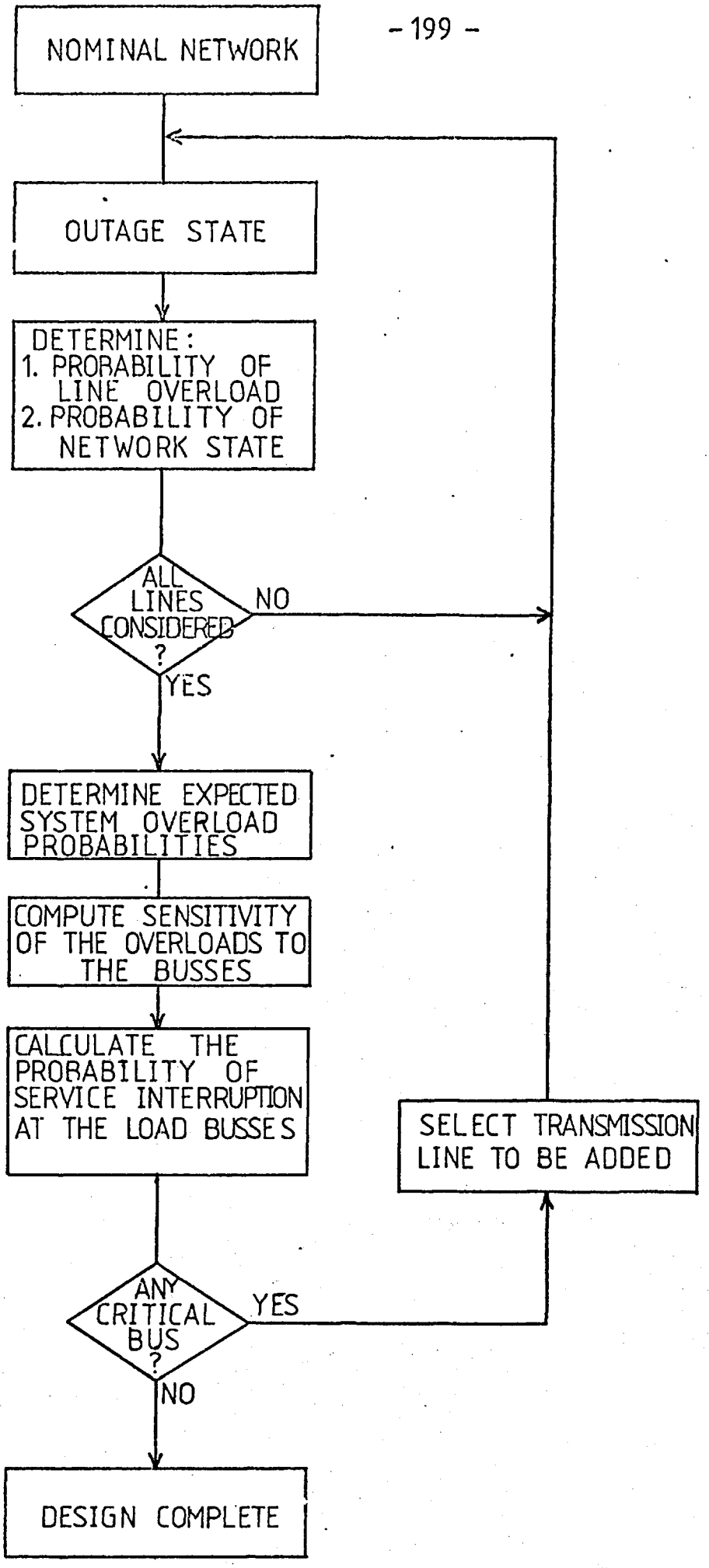


Fig. 7.3 : Flowchart of the program with Reliability Concepts

CHAPTER 8

CONCLUSION

8.1 CONCLUDING REMARKS

Specific conclusions have been given at the end of the respective chapters on the different topics discussed in this thesis.

This final chapter summarises overall comments and conclusions on the general theme of this thesis. The general theme is a study and evaluation of computer methods for steady-state power system security evaluation and transmission system expansion planning. Limitations of the IPSAP package on the present minicomputer are clearly stated and potential extensions of the work are considered.

8.1.1 Computer-aided Dispatch for Security Evaluation

The aim of any utility is to minimize operating costs while maintaining the system in a secure operating condition. However, when an alert state arises, security considerations take precedence and the primary objective becomes restoration to a secure state as rapidly as possible. The system operator, as part of the control system requires suitable input and output facilities. These facilities enable him to construct a scenario of power system operation on the basis of a predicted situation that appears to be credible. Checks must be made that operational limits are satisfied. Hence there is a need for interactive loadflow and fault analysis. The mathematical development of these analyses have been outlined in Chapter 2 and computed results are given in Chapter 3. Colour graphics were used extensively to ensure that the computed results could be presented to an engineer in a more effective manner with the circuit overloading and contingencies clearly high-lighted. More use of colour graphics is envisaged with the decreasing cost of computer software and hardware. The

programs have been written in a user-friendly style such that non-computing personnel can easily handle them, thus providing a much needed improved man/machine interaction.

The interactive loadflow is of considerable interest to utilities. A report by Merlin [137] indicates that out of 26 replies obtained from a questionnaire sent out in 1978 to 13 countries on the use of computer aids in decision-making at European Control Centres, only 3 would not require the interactive loadflow facility by 1990. Concerning interactive short-circuit calculations: about 16 utilities are not considering implementing this program by 1990.

In Chapter 4 methods for security enhancement have been reviewed. A method based on least-squares is proposed and compared with others based on linear and non-linear programming methods. The Decoupled Security Enhancement Algorithm was found to be very fast and would be appropriate for hydro system security scheduling as no direct costs are involved. Some of the control actions include changes in reactive injections and generator terminal voltage magnitudes. The work described in Chapter 4 leads to Chapter 5 where the subject of load-shedding has been investigated in detail and an integer programming method is proposed. The algorithm was extended to include cases of partial loss of generation. The merits of incorporating Taylor's series second order terms were discussed and found to have insignificant effect on the accuracy of the solution. The algorithm proposed would aid the present practice whereby emergency load reduction is achieved by automatic frequency-sensitive relays.

Another investigation of a security enhancement method is described in Chapter 6 using phase-shifters (operated a-priori) for static security control. Two algorithms were developed. The linear programming technique was found to perform better than the alternative based on the least-squares minimization technique. An optimum network design including phase-shifters

was proposed to improve system security as the locations of the phase-shifters considered previously were not the best for alleviating line overloads. The problems of unfeasible solutions would then be avoided. The chapter concludes with an account of the economic benefits of incorporating phase-shifters in system interconnections.

The phase-shifter capability in alleviating line overloads, discussed in Chapters 4 and 6, gave rise to the idea of extending this work to transmission system expansion planning treated in Chapter 7. This work is summarised briefly in the next section here.

8.1.2 Transmission System Expansion Planning

A review of procedures for transmission system expansion planning was presented in Chapter 7. A method of reinforcing a loaded ac system has been proposed. The effect has been investigated on system power flows of including phase-shifters in new lines being added to the network. Using the adjoint network formulation and the steepest-descent technique, a performance index was optimised with respect to the changes in the admittance in each right-of-way. Reinforcements for improved security were considered using the single-line outage and reliability criteria. These enabled qualitative and quantitative methods of system expansion to be compared.

8.1.3 Computing Systems Used

Two types of computing systems were used for the work described in this thesis: a dedicated minicomputer (the PDP 11) and a large mainframe installation (the Imperial College CDC Cyber system). The advantages derived from the dedicated minicomputer include:

(a) very fast turnaround times, since the minicomputer is dedicated entirely to the interactive process;

(b) an extremely high communication speed between the computer and the graphical display;

(c) requires no specialised computer operating staff. Hence it is very economical to use.

The disadvantages of the minicomputer are:

(a) smaller memory (the PDP 11 used in this research had a capacity of only 32K). This need not be a disadvantage in future. 64K chips are now available, and 256K are being designed;

(b) higher solution times (see Table 8.1). Faster microprocessors with hardware multiply are coming soon.

Table 8.1: Comparison of the solution times (in seconds) for the fast decoupled loadflow

	5-bus network	9-bus network	14-bus IEEE system	24-bus IEEE system	30-bus IEEE system
Dedicated minicomputer (PDP-11)	1.82	7.52	42.74	88.04	171.70
Cyber 164	.026	0.104	0.561	0.933	2.242

The variation of log t against log (NB) is shown in Fig. 8.1 where NB is the number of buses.

The time for the Cyber depends on the number of users connected to the system at any one moment.

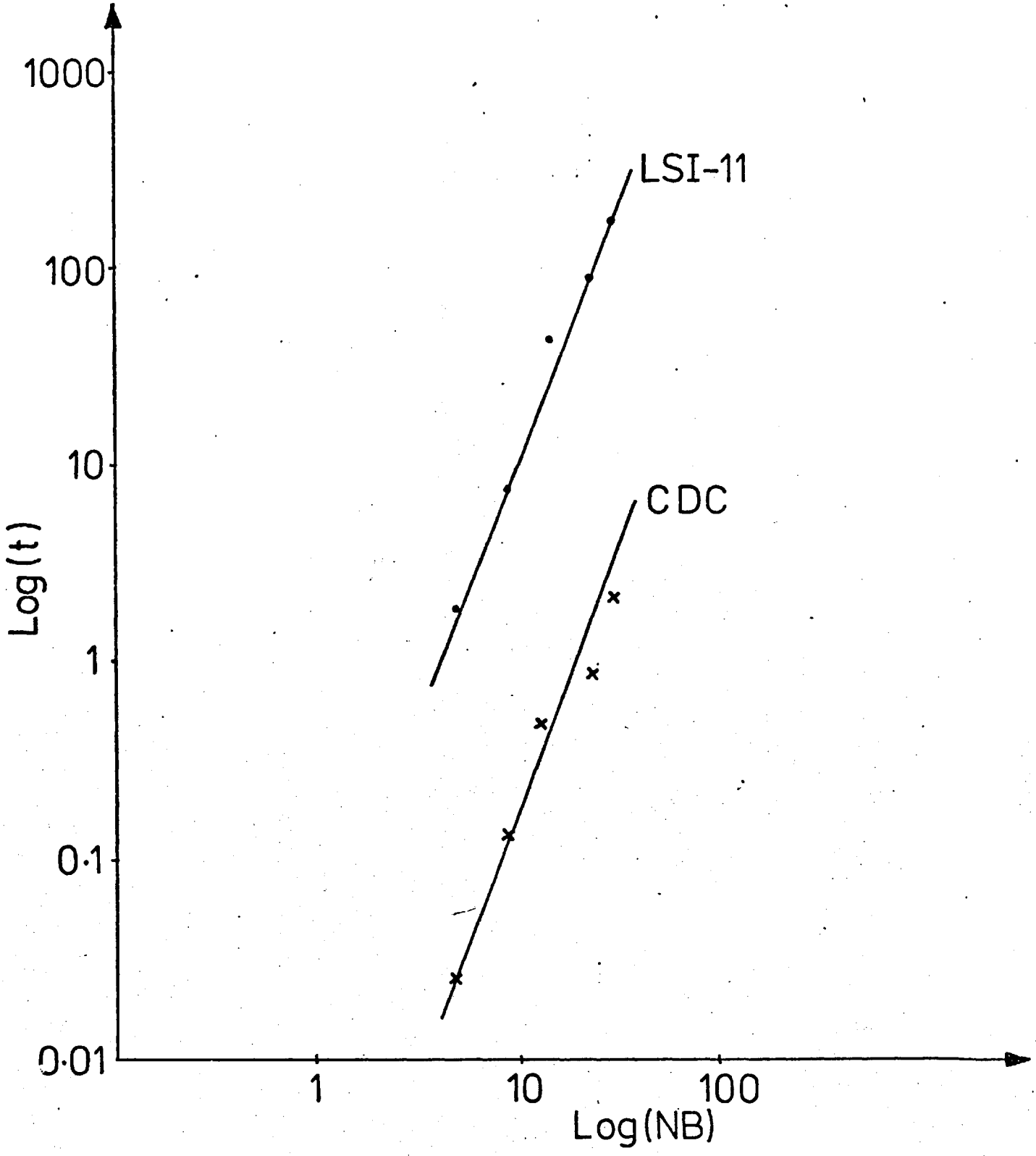


Fig. 8.1 : Graph of $\log_{10}(t)$ versus $\log_{10}(NB)$

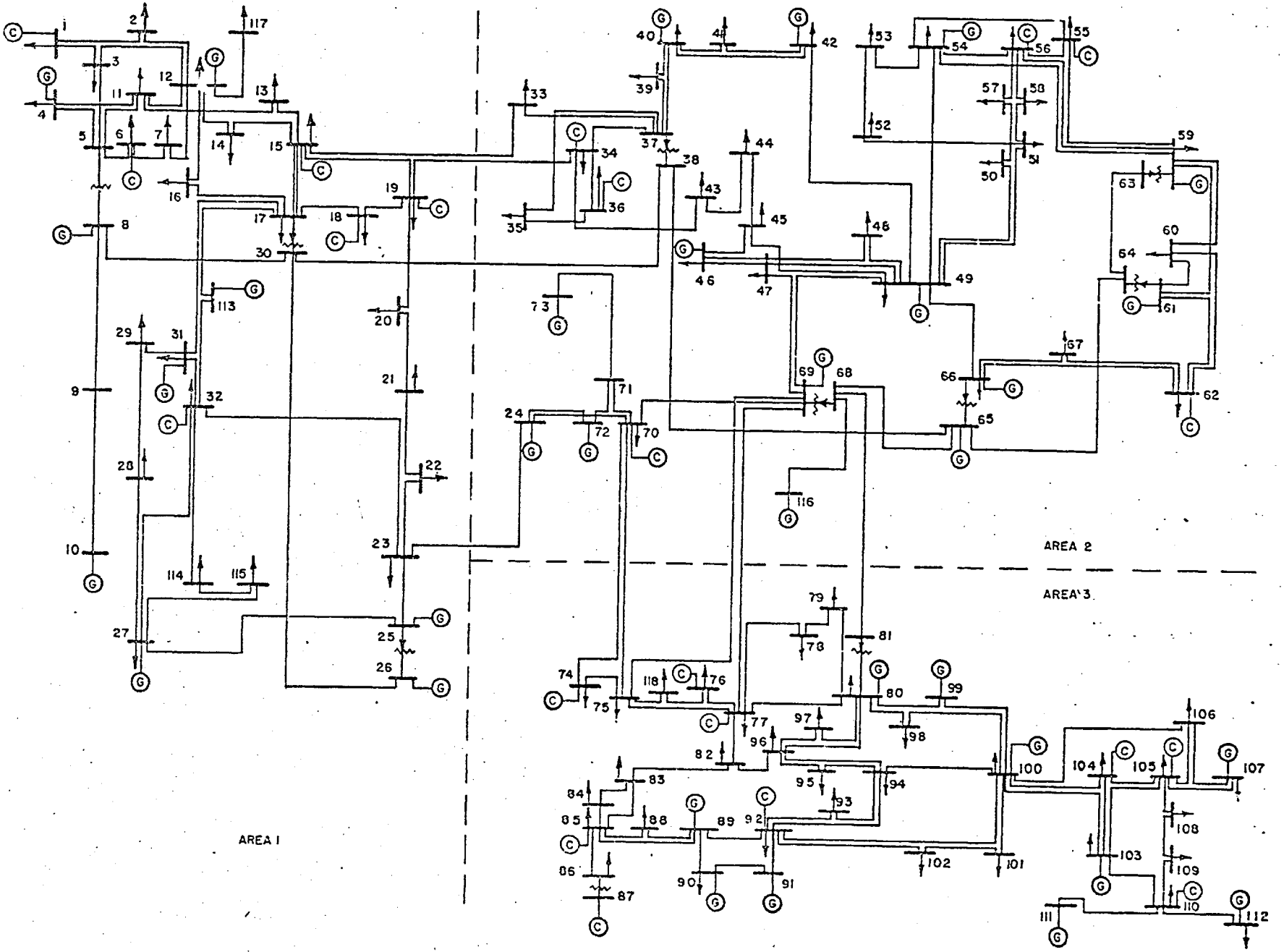


Fig. 8.2: The Standard IEEE 118 bus test system.

8.2 PRACTICAL LIMITATIONS OF ~~IDSAP~~ IPSAP AND METHODS FOR FUTURE EXTENSION

The present size of the network that can be displayed is limited by:

(a) size of the TV monitor screen

(b) capacity of the minicomputer.

The programs are dimensioned for 19-bus and 30 lines. So far only the IEEE 14-bus network with 17 lines and 3 transformers is the largest that has been solved in this research. The security analysis program contains 25.7 K words whereas the fault analysis program contains 25.9 K words. Sparsity techniques were not used for the Fault Analysis program. Both programs have been configured with the numerical files and the graphics information combined. However, they have an immediate application in post-graduate teaching and possibly also for undergraduate experiments in the near future.

The capabilities of these programs can be extended by using diakoptic techniques, as explained by Happ in [138] and Brameller et al in [139] and by using the extended-Ward equivalents developed by Monticelli et al in [140]. The IEEE 118-bus test system [141] shown in Fig. 8.2 can be solved using network equivalents as follows:

The system is divided as shown into areas. Let area 2 be the internal system A with two external systems B and C, Areas 1 and 3 respectively. This can be represented as shown in Fig. 8.3.

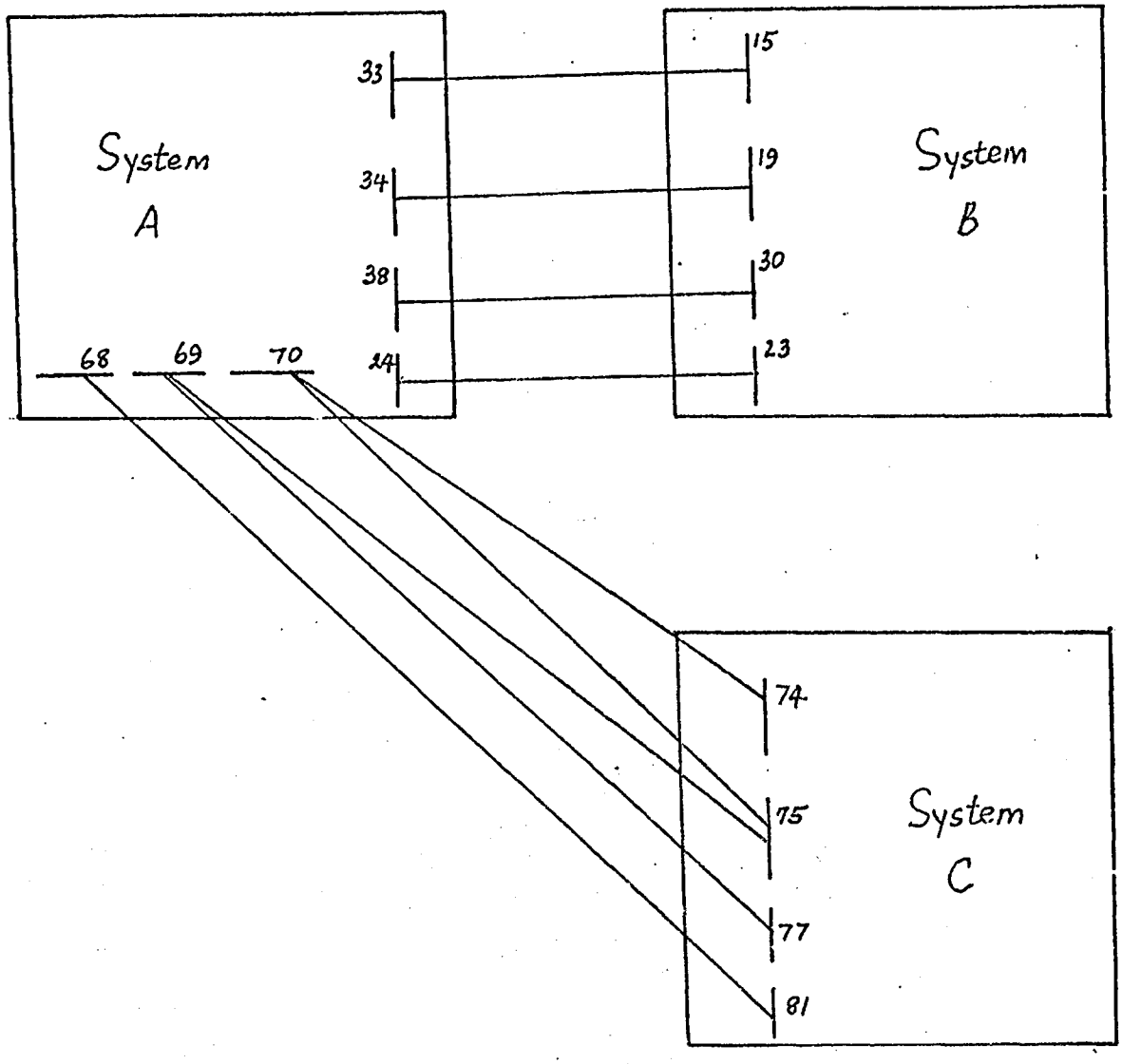


Fig. 8.3: Network equivalents of the 118 IEEE system

The boundary buses are 33, 34, 38 and 24 and 68, 69 and 70 for systems B and C respectively.

Other practical methods for solving large scale power systems are:

(a) to have the numerical information separated from the graphics. This requires the intermittent transfer of results from disks;

(b) Using a "zooming" action to display parts of the networks.

With the decreasing cost of computer hardware there is little doubt that the minicomputer capacity can be increased to handle larger systems.

The interactive package(IPSAP) when fully developed would be used by:

(a) operators responsible for security monitoring and system control;

(b) planning engineers responsible for system maintenance and expansion;

(c) teaching and research. Already two 3rd year undergraduate projects are in progress to develop power system experiments for the benefit of future final-year students.

8.3 SUGGESTIONS FOR FUTURE DEVELOPMENT

Further work should be undertaken in the following areas:

(a) Transient security analysis [142] could be included in IPSAP so as to enable the operator to make use of more efficient computing tools.

(b) "Non-converged" solutions in IPSAP should be handled by including algorithms developed by Brameller and Denmead in [143].

(c) The security analysis algorithms developed in Chapters 4, 5 and 6 should be compared with those of Vervloet and Brameller in [79].

(d) The effects of undesirable bus voltages should be

(i) included in the algorithm developed in Chapter 7 by making use of a non-linear ac loadflow program;

(ii) the integer-programming based branch-and-bound technique could be used in Section 7.1.2;

(iii) a general interactive development of the algorithms: This would improve the efficiency of planning procedures.

REFERENCES

1. Dopazo, J.F., Dunlop, R.D., Maliszewski, R.M., Overly, T.L. and Sasson, A.M. "Enhanced Security Assessment and Control Project". IEE International Conference on Power Systems Monitoring and Control, London. June 1980, pp. 94-100.

2. Undrill, J.M., de Mello, F.P., Kostyniak, T.E. and Mills, R.J. "Interactive Computation in Power System Analysis". IEEE Proceedings, Vo. 62, No. 7, July 1974, pp. 1009-1018.

3. Adams, R.N. and Laughton, M.A. "On-line Interactive Computing for Electrical Power System Planning and Design". IEE Conference on Computer Aided Design, Southampton, publication No. 86, April 1972, pp. 51-56.

4. Short, M.J., "Interactive Computer Studies of the Dynamic Modelling of Multi-Machine Power Systems". 7th Universities Power Engineering Conference (UPEC), Bradford, January 1972, pp. 23-28.

5. Hirsch, P.M., "Interactive Graphics for Load-Flow". Proceedings of the 1977 Power Industry Computer Applications Conference (PICA), pp. 159-165.

6. Carter, G.K., Grems, M.D. and Happ, H.H. "Interactive Loadflow and Stability Computations for Power System Studies". Proceedings of the 1975 PICA, pp. 89-95.

7. Stagg, G.W. "Interactive Computing for Real-time and General Purpose Computer Systems". Proceedings of the 5th Power System Computational Conference (PSCC), Cambridge, Vol. 2, Paper No. 4.2/3, September 1975, pp. 1-21.

8. Ben-Yaacov, G.Z., Israel, T. and Mijne, G. "Integrated Program Package for Power System Studies". Proceedings of the 1979 PICA Conference, pp. 115-123.

9. Dechamps, C., Fuchsova, J. and Jamoulle, E. "An Integrated Hardware/Software Package for Power System Planning". 1981, PSCC, Lausanne, pp. 108-109.

10. Lynch, C.A. "Interactive Design and Operation of Power Systems". Ph.D. thesis, University of Manchester, May 1977.

11. Lynch, C.A. and Efthymiadis, A.E. "Network Graphics based Interactive Power System Analysis". IEEE Winter power meeting, New York. Paper No. A79018-1, February 1979, pp. 1-6.

12. Lynch, C.A., Smith, A.A. and Efthymiadis, A.E. "Use of Interactive Network Graphics Based Power System Analysis in Distribution Network Operation". IEE Conference on Power System Monitoring and Control, June 1980, pp. 175-180.

13. Khan, A.M.M. and Bickford, J.P. "Interactive Calculation of Power System Transients. IEE Proceedings, Vol. 127, Part C, No. 1, January 1980, pp. 41-43.

14. Ekwue, A.O. and Short, M.J. "Interactive Computer Graphics for Power System Analysis". Proceedings of the second International Conference and Exhibition on "ENGINEERING SOFTWARE", London, March 1981, pp. 673-683.

15. Talukdar, S.N. and Wu, F.F. "Computer-Aided-Dispatch for Electric Power Systems". Proceedings of the IEEE, Vol. 69, No. 10, October 1981, pp. 1212-1231.

16. Dy Liacco, T.E. "Real-Time Computer Control of Power Systems". Proceedings of the IEEE, Vol. 62, No. 7, July 1974, pp. 884-891.

17. Prada, R.B. "Security in the Economic Operation of Power Systems". Ph.D. thesis, University of London, July 1980.

18. Fink, L.H. and Carlsen, K. "Operating under Stress and Strain". IEEE Spectrum, March 1978, pp. 48-53.

19. Knight, U.G. "Emergency Control of Power Systems". Lecture delivered on 28 April 1981 at the IEE, Savoy Place, London under the auspices of the Power Division.

20. Cadogan, J.B. and Eisenberg, L. "Sulphur Oxide Emissions Management for Electric Power Systems". IEEE Trans. on PAS-96, No. 2, March/April 1977, pp. 393-401.

21. Ellert, F.J. and Hingorani, N.G. "HVDC for the Long Run". IEEE Spectrum, August 1976, pp. 37-42.

22. Roy, J. "Evaluation of EHV Transmission Options". Proceedings of the International Conference on HVDC and/or AC Power Transmission organised by the IEE, November 1973, pp. 318-322.

23. Hardy, J.E., Turner, F.P.P., Zimmermann, L.A. "AC or DC? One Utility's Approach". Proceedings of the IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November/December 1981, pp. 241-246.

24. Endrenyi, J. "Reliability Modelling in Electric Power Systems". John Wiley Publications, 1978.

25. Debs, A.S. and Benson, A.R. "Security Assessment of Power Systems". Proceedings Engineering Foundation Conference on Systems Engineering for Power : Status and Prospects. Henniker, August 1975, pp. 144-176.

26. Stott, B. "Review of Loadflow Calculation Methods". Proceedings IEEE, July 1974, Vol. 62, No. 7, pp. 916-929.

27. Pang, C.K., Prabhakara, F.S., El-Abiad, A.H. and Koivo, A.J. "Security Evaluation in Power Systems using Pattern Recognition". IEEE Trans. on PAS, Vol. 93, May/June 1974, pp. 969-976.

28. Ejebe, G.C. and Wollenberg, B.F. "Automatic Contingency Selection". IEEE Trans. on PAS, Vol. 98, No. 1, January/February 1979, pp. 97-109.

29. Stott, B. and Alsac, O. "Fast-decoupled Loadflow". IEEE Trans. on PAS, Vol. 93, May/June 1974, pp. 858-869.

30. Brameller, A., Allan, R.N. and Haman, Y.M. "Sparsity". Pitman, 1976.

31. Tinney, W.F. and Walker, J.W. "Direct Solutions of Sparse Network Equations by Optimally Ordered Triangular Factorization". Proceedings, IEEE, Vol. 55, 1967, pp. 1801-1809.

32. Stott, B. and Hobson, E. "Solution of Large Power System Networks by Ordered Elimination : A Comparison of Ordered Schemes". Proceedings, IEE , Vol. 118, No. 1, January 1971.

33. Winokur, M. "Interactive Loadflow Solutions for Systems with Multiple Outages". Imperial College Power System Report No. 104, October 1980.

34. Irisarri,G., Sasson, A.M. and Levner, D. "Automatic Contingency Selection for On-line Security Analysis - Real-time Tests". IEEE Trans. on PAS, Vol. 98, No. 5, Sept/Oct. 1979, pp. 1552-1559.

35. Irisarri, G. and Sasson, A.M. "Automatic Contingency Selection Method for On-line Security Analysis". IEEE Trans. on PAS, Vol. 100, No. 4, April 1981, pp. 1838-1844.

36. Albuyeh, F. "Automatic Contingency Selection by Sensitivity Matrices". Paper No. A80060-4 presented at the IEEE PES winter meeting, New York, February 1980, pp. 1-4.

37. Mikolinnas, T.A. and Wollenberg, B.F. "An Advanced Contingency Selection Algorithm". IEEE Trans. on PAS, Vol. 100, No. 2, February 1981, pp. 608-617.

38. Brown, H.E., Person, C.E., Kirchmayer, L.K. and Stagg, G.W. "Digital Calculation of Three-phase Short Circuits by Matrix Method". Trans. AIEE, Vol. 79, February 1961, pp. 1277-1282.

39. Elgerd, O.I. "Electric Energy Systems Theory : An Introduction". Tata McGraw-Hill, 1971.

40. Laughton, M.A. "Analysis of Unbalanced Polyphase Networks by the Method of Phase Coordinates Part 1 : System Representation in Phase Frame of Reference". Proceedings IEE, Vol. 115, No. 8, August 1968, pp. 1163-1172.

41. Laughton, M.A. "Analysis of Unbalanced Polyphase Networks by the Method of Phase Coordinates Part II: Fault Analysis". Proceedings IEE, Vol. 116, No. 5, May 1969, pp. 857-865.

42. Laughton, M.A. and Saleh, A.O.M. "Unified Phase-coordinate Loadflow and Fault Analysis of Polyphase Networks". International Journal of Electric Power and Energy Systems, Vo. 2, No. 4, October 1980, pp. 181-192.

43. Saleh, A.O.N. and Laughton, M.A. "Phase-coordinate Loadflow and Fault Analysis Program". Ibid, pp. 193-200.

44. Reitan, D.K. and Kruempel, K.C. "Modification of the Bus Impedance Matric for System Changes involving Mutual Couplings". Proceedings IEEE, Vol. 57, August 1969, pp. 1432-1433.

45. Reitan, D.K. "A New Method using the Bus-Impedance Matrix Model for Short-Circuit Calculations". Proceedings, IEEE, Vol. 68, August 1980, pp. 1027-1030.

46. Podmore, R. "General Method for Unbalanced Faults". 1973 PICA, pp. 56-62.

47. Reichert, K. and Hager, H. "Fast Evaluation of Short-Circuit Levels in Power Systems". 6th PSCC Darmstadt, August 1978, pp. 666-678.

48. Takahashi, K., Fagan, J. and Chen, M. "Formation of a Sparse Bus Impedance Matrix and its Application to a Short-circuit Study". 1973, PICA Conference, pp. 63-69.

49. Gross, G. and Hong, H.W. "Short-circuit Calculations using Matrix Modification Techniques". 1981 PSCC Lausanne, pp. 915-920.

50. Brown, H.E. "Solution of Large Networks by Matrix Methods". Chapter 7, Wiley publication, 1975.

51. Anderson, P.M. "Analysis of Faulted Power Systems". Iowa State University Press, 1973.

52. Battlebury, D.R. and Ham, D.E. "Display Requirements and Techniques for System Control". IEE Conference on "On-line Operating and Optimization of Transmission and Distribution Systems", London, June 1976, pp. 78-82.

53. Ekwue, A.O. "Interactive Power System Analysis Programs (IPSAP) : User's Manual". Imperial College Power System Research Report No. 105, November 1981.

54. Ekwue, A.O. "Interactive Power System Analysis Programs (IPSAP): Documentation and Listings". Imperial College Power System Research Report No. 106, November 1981.

55. Medicherla, T.K.P., Billinton, R. and Sachdev, M.S. "Generation Rescheduling and Load Shedding to Alleviate Line Overloads : Analysis". IEEE Trans. on PAS 98, No. 6, Nov/Dec. 1979, pp. 1876-1884.

56. Medicherla, T.K., Billinton, R. and Sachdev, M.S. "Generation Rescheduling and Load Shedding to Alleviate Line Overloads : System Studies". IEEE Trans. on PAS 100, No. 1, January 1981, pp. 36-42.

57. Freris, L.L. and Sasson, A.M. "Investigation of the Load Flow Problem". Proceedings IEE, Vol. 115, No. 10, 1968, pp. 1459-1469.

58. Sasson, A.M. "Interactive and Non-linear Programming Techniques applied to the Solution of Power System Problems". Ph.D. Thesis, University of London, 1968.

59. Dommel, H.W. and Tinney, W.F. "Optimal Power Flow Solutions". IEEE Trans. on PAS, Vol. 87, No. 10, October 1968, pp. 1866-1876.

60. Laughton, M.A. "Optimal Power System Operation - Analytical Formulation". Proceedings of the Symposium on Optimal Power System Operation, U.M.I.S.T., September 1969.

61. Brameller, A. and Lo, K.L. "A Review of Minimization Techniques with Reference to Power System Engineering". Proceedings of the Symposium on Real-time Control of Electric Power Systems, Brown Boveri and Co. Ltd., Baden, Switzerland, 1971, pp. 81-102.

62. Prada, R.B. and Cory, B.J. "On-line Secure and Economic Dispatch". EPSR 2 (1979), pp. 189-198.

63. Shen, C.M. and Laughton, M.A. "Power System Load Scheduling with Security Constraints using Dual Linear Programming". Proceedings IEE, Vol. 117, No. 11, November 1970, pp. 2117-2127.

64. Wu, F.F., Gross, G., Luini, J.F. and Looks, P.M. "A 2-stage Approach to Solving Large Scale Optimal Power Flows". 1979 PICA Conference, pp. 126-136.

65. Aschmoneit, F.C., Ruhose, K.H. and Wagner, G.G. "Steady-state Sensitivity Analysis for Security Enhancement". 5th PSCC Darmstadt, August 1978, pp. 481-484.

66. Stott, B. and Hobson, E. "Power System Security Control Calculations using Linear Programming Parts 1 and II". IEEE Trans. on PAS, Vol. 97, No. 5, Sept/October 1978, pp. 1713-1731.

67. Chan, S.M. and Schweppe, F.C. "A Generation Reallocation and Load Shedding Algorithm". January/Fenruary 1979, pp. 26-34.

68. Stott, B., Marinho, J.L. and Alsac, O. "Review of Linear Programming applied to Power System Rescheduling". 1979 PICA Conference, pp. 142-154.

69. Lo, K.L. and Amokaha, J. "Active Power Rescheduling with Line Limits Security". Paper No. A2.5, 1981, UPEC Sheffield, April, pp-1-6.

70. Nabona, N. and Freris, L.L. "Optimization of Economic Dispatch through Quadratic and Non-linear Programming". Proceedings IEE, Vol. 120, No. 5, May 1973, pp. 514-580.

71. Strang, G. "Linear Algebra and its Applications". Chapter 3, Academic Press, 1980.

72. Ekwue, A.O. and Short, M.J. "Power System Security Enhancement by Sensitivity Analysis and its Interactive Implementation". 1981 UPEC Sheffield, Paper No. A2.1, April, pp. 1-6.

73. Ejebe, G.C., Puntel, W.A. and Wollenberg, B.F. "A Load Curtailment Algorithm for the Evaluation of Power Transmission System Adequacy". IEEE Power Engineering Society summer meeting, July 1977, Paper No. A77505-1, pp. 1-5.

74. Hano, I., Tamura, Y., Narita, S. and Matsumoto, K. "Real-time Control of System Voltage and Reactive Power". IEEE PAS, Vol. 88, No. 10, October 1969, pp. 1544-1559.

75. Kishore, A. and Hill, E.F. "Static Optimization of Reactice Power Sources by use of Sensitivity Parameters". IEEE Trans. on PAS, Vol. 90, 1971, pp. 1166-1173.

76. Thanikachalam, A. and Tudor, J.R. "Optimal Rescheduling of Power for System Reliability". IEEE Trans. on PAS, Vol. 90, Sept/Oct. 1971, pp. 2186-2192.

77. Shoults, R.R. and Chen, M. "Reactive Power Control by Least-Squares Minimization". IEEE Trans. on PAS, Vol. 95, No. 1, Jan/Feb. 1976, pp. 325-334.

78. IEEE Reliability Test System. IEEE Trans. on PAS, Vol. 98, No. 6, Nov/Dec. 1979, pp. 2047-2054.

79. Vervloet, F.G. and Brameller, A. "AC Security Assessment". Proc. IEEE, Vol. 122, No. 9, September 1975. pp. 897-902.

80. Carpentier. J. "Optimal Power Flows". International Journal of Electric Power and Energy Systems, Vol. No. 1, April 1979, pp. 3-15.

81. Hajdu, L.P., Peschon, J., Tinney, W.F. and Piercy, D.S. "Optimum Load-shedding Policy for Power Systems". IEEE Trans. on PAS-87, No. 3, March 1968, pp. 784-795.

82. Subramanian, D.K. "Optimum Load-shedding through Programming Techniques". IEEE Trans. on PAS-90, No. 1, Jan/Feb. 1971, pp. 89-95.

83. Ghoneim, M.Z., Saleh, M.H., Askourah, M.A.N. and Rahman, S.A. "Estimation of Optimum Load-shedding in Transmission Systems using Mathematical Programming Techniques". Paper No. A77595-2 presented at the IEEE summer meeting, Mexico, July 1977, pp. 1-7.

84. Allwright, J.C. Personal communication, May 1981.

85. Greenberg, H. "Integer Programming". Mathematics in Science and Engineering No. 76, Academic Press London and New York, 1971.

86. Sachdev, M.S. and Medicherla, T.K.P. "A Second Order Loadflow Technique". IEEE Trans. on PAS-96, No. 1, Jan/Feb. 1977, pp. 189-197.

87. Medicherla, T.K.P. and Sachdev, M.S. "A Second Order Decoupled Loadflow Technique". Paper No. A76491-1 presented at the 1976 summer Power Engineering Society meeting Portland, OR July 1976, pp. 1-7.

88. Lokay, H.E. and Burtnyk, V. "Application of Underfrequency Relays for Automatic Load-shedding". IEEE Trans. on PAS, Vol. 87, No. 3, March 1968, pp. 776-783.

89. Thanikachalam, A., Sulzberger, V.T., Olinda, P.V. and Wrubel, J.N. "On-line Operation of Phase-shifters using Energy Control Centre Computers". IEEE Trans. on PAS-93, Sept./Oct. 1974, pp. 1563-1571.

90. Ku, W.S. and Olinda, P.V. "Security and Voltage Applications of the Public Service Dispatch Computer". Proceedings of the 1969 PICA, pp. 201-209.

91. El-Abiad, A.H. and Stagg, G.W. "Automatic Evaluation of Power System Performance - Effect of Line and Transformer Outages". AIEE Trans. PAS, February 1963, pp. 712-716.

92. Rubino, L.J. and Tishniski, W.J. "System Interconnection using Special Phase-shifting Transformers". Proceedings of the International Conference on HVDC and/or AC Power Transmission organised by the IEE, November 1973, pp. 183-188.

93. Cory, B.J., Ekwue, A., Prada, R.B., Meisel, J. and Gilles, M. "Secure Operational Studies of Multi-terminal High Voltage DC Systems embedded in AC Networks". Proceedings of the International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission organised by the IEE, Nov./Dec. 1981, pp. 149-153.

94. Ekwue, A.O. and Short, M.J. "Interactive Security Evaluation in Power System Operation", submitted to the IEE, Part C, March 1982.

95. Mathur, R.M. and Sharaf, A.M. "Thyristor Controlled Phase-shifters". International Conference on Thyristor and Variable Static Equipment for AC and DC TRansmission, organised by the IEE Nov./Dec. 1981, pp. 73-76.

96. Sasson, A.M. and Merrill, H.M. "Some Applications of Optimization Techniques to Power System Problems". Proceedings IEEE Vol. 62, No. 7. July 1974, pp. 959-972.

97. Kaltenbach, J., Peschon, J. and Gehrig, E.H. "A Mathematical Optimization Technique for the Expansion of Electric Power Transmission Systems". IEEE Trans. on PAS-89, No. 1, January 1970, pp. 113-119.

98. Garver, L.L. "Transmission Network Estimation using Linear Programming". IEEE Trans. on PAS-89, No. 7, Sept/Oct. 1970, pp. 1688-1697.

99. Deif, M.K. and Adams, R.N. "Transmission Network Planning using a New Generalized Current Injection Model". Proceedings of the 15th UPEC, University of Leicester, March 1980, pp. 1-6.

100. Adams, R.N. and Deif, M.K. "General LP Model for Transmission Planning". 1981 PSCC, Lausanne, pp. 55-60.

101. Puntel, W.R., Reppen, N.D., Ringlee, R.J., Platts, J.E., Ryan, W.A. and Sullivan, P.J. "An Automated Method for Long-range Planning of Transmission Networks". Proceedings of the 1973 PICA, Minneapolis, pp. 36-46.

102. Sullivan, R.L. "Power Systems Planning". McGraw-Hill publications, 1977, Chapter 7.

103. Püttgen, H.B. "Applications of Sensitivity Analysis to Power Systems". 1980 IEEE International Symposium in Circuits and Systems, Houston, Texas, pp. 74-78.

104. Director, S.W. and Rohrer, R.A. "The Generalised Adjoint Network and Network Sensitivities". IEEE Trans. on Circuit Theory, Vol. 16, No. 3, August 1969, pp. 318-323.

105. Calahan, D.A. "Computer-aided Network Design". McGraw-Hill publications 1972, Chapter 5.

106. Dusonchet, Y.P. and El-Abiad, A.H. "Transmission Planning using Dynamic Optimization Method". IEEE Trans. on PAS-92, July/August 1973, pp. 1358-1371.

107. Lee, S.T.Y., Hicks, K.L. and Hnyilicza, E. "Transmission Expansion by Branch-and-bound Integer Programming with Optimal Cost-capacity Curves". IEEE Trans. on PAS-93, 1974, pp. 1390-1400.

108. Koglin, H.J. and Müller, H. "Overload Reduction through Corrective Switching". IEE Power System Monitoring and Control Conference publication No. 187, June 1980, pp. 159-164.

109. Koglin, H.J. and Müller, H. "First Experience with Computer-aided Corrective Switching". Proc. of the 1981 PSCC, Lausanne, pp. 474-481.

110. Koglin, H.J. and Müller, H. "Corrective Switching - a New Dimension in Optimal Loadflow",submitted for publication in the Electrical Power and Energy Systems, 1981.

111. Ekwue, A.O. and Short, M.J. "Optimum Design of a Network Structure using Phase-shifters to reinforce a Loaded AC System", accepted for the 1982 UPEC, Manchester, March/April.

112. Knight, U.G., Booth, R.R., Mallard, S.A. and Lewis, D.M. "Computers in Power System Planning". Proc. of the IEEE, Vol. 62, July 1974, pp. 872-883.

113. Fernando, P.N. "The Planning of Electrical Power System Generation and Transmission using Integer Programming and Reliability Concepts". Ph.D. thesis, University of Londor, September 1976.

114. Induruwa, A.S. "Power System Generation and Transmission Planning using Probability Methods". Ph.D. thesis, University of London, January 1980.

115. Billinton, R. "Composite System Reliability Evaluation". IEEE Trans. on PAS-88, No. 4, April 1969, pp. 276-281.

116. Billinton, R. "Power System Reliability Evaluation". Gordon and Breach, Science publishers, 1970.

117. Billinton, R. and Bhavaraju, M.P. "Transmission Planning using a Reliability Criterion, Part 1 : Reliability Criterion". IEEE Trans. on PAS-89, No. 1, January 1970, pp. 28-34.

118. Bhavaraju, M.P. and Billinton, R. "Transmission Planning using a Reliability Criterion, Part 2: Transmission Planning". IEEE Trans. on PAS-90, No. 1, Jan/Feb. 1971, pp. 70-78.

119. Billinton, R., Medicherla, T.K.P. and Sachdev, M.S. "Composite Generation and Transmission System Reliability Evaluation". Paper No. A78 237-0 presented at the IEEE Power Engineering Society winter meeting 1978, pp. 1-7.

120. Billinton, R., Medicherla, T.K.P. and Sachdev, M.S. "Adequacy Indices for Composite Generation and Travsmission System Reliability Evaluation". Paper No. A79024-1, IEEE winter Power meeting, New York, February 1979.

121. Billinton, R. and Medicherla, T.K.P. "Overall Approach to the Reliability Evaluation of Composite Generation and Transmission Systems". IEE Proceedings, Part C, No. 2, March 1980, pp. 72-81.

122. Dandeno, P.L., Jorgensen, G.E., Puntel, W.R. and Ringlee, R.J. "Program for Composite Bulk Power Electric System Adequacy Evaluation". IEE Conference on Reliability of Power Supply Systems, publication No. 148, 1977.

123. Borkowska, B., "Probabilistic Load Flow". IEEE Trans. on PAS-93, May/June 1974, pp. 752-759.

124. Allan, R.N., Borkowska, B. and Grigg, C.H. "Probabilistic Analysis of Power Flows". Proc. IEE, Vol. 121, December 1974, pp. 1551-1556.

125. Allan, R.N. and Al-Shakarchi, M.R.G. "Probabilistic AC Loadflow". Proceedings IEE, Vol. 123, June 1976, pp. 531-536.

126. Allan, R.N. and Al-Shakarchi, M.R.G. "Probabilistic Techniques in AC Loadflow Analysis". Proceedings, IEE, Vol. 124, February 1977, pp. 154-160.

127. Allan, R.N., Grigg, C.H. and Al-Shakarchi, M.R.G. "Numerical Techniques in Probabilistic Load Flow Problems". International Journal for Numerical Methods in Engineering, Vol. 10, No. 4, 1976, pp. 853-860.

128. Dopazo, J.F., Kliten, O.A. and Sasson, A.M. "Stochastic Load Flows". IEEE Trans. on PAS-94, March/April 1975, pp. 299-309.

129. Allan, R.N. and Al-Shakarchi, M.R.G. "Linear Dependence between Nodal Powers in Probabilistic AC Loadflow". Proceedings, IEE, Vol. 124, No. 6, June 1977, pp. 529-534.

130. Aboytes, F. and Cory, B.J. "An Alternative Formulation of the Stochastic Load Flow Method". Proceedings of the 1975 PICA Conference, pp. 209-215.

131. Aboytes, F. "Stochastic Contingency Analysis". IEEE Trans. on PAS-97, March/April 1978, pp. 335-341.

132. Allan, R.N., Grigg, C.H. and Prato-Garcia, J.A. "Effect of Network Outages in Probablistic Loadflow Analysis". Paper No. A79032-4, IEEE Power Engineering Society winter meeting, New York, February 1979, pp. 1-7.

133. Prada, R.B. and Cory, B.J. "Stochastic Security Analysis". Proceedings of the 14th UPEC, Loughborough, March 1979.

134. Papoulis, A. "Probability Random Variables and Stochastic Processes". McGraw-Hill Book Company, New York, 1965.

135. Hayes, T.P., Webb, R.P. and Day, J.T. "A Quantitative Method for Transmission System Reliability Calculations". Paper No. A78566-2, IEEE Power System summer Engineering meeting, Los Angeles, July 1978, pp. 1-8.

136. Monticelli, A., Santos, A. (Jnr.), Pereira, M.V.F., Cunha, S.H., Parker, B.J. and Praca, J.C.G. "Interactive Transmission Network Planning using a Least-effort Criterion". Paper No. 82 WM 160-0 presented at the Winter Power Engineering Society meeting, New York, February 1982.

137. Merlin, A. "State-of-the-Art of Use of Computer Aids for Decision-making in Control Centres". Proceedings of the International Journal of Electric Power and Energy Systems, Vol. 3, No. 2, April 1981.

138. Happ, H.H. "Diakoptics - the Solution of System Problems by Tearing". Proc. of the IEEE, Vol. 62, No. 7, July 1974, pp. 930-940.

139. Brameller, A., John M.N. and Scott, M.R. "Practical Diakoptics for Electrical Networks". Chapman and Hall publications, 1969.

140. Monticelli, A., Deckmann, S., Garcia, A. and Stott, B. "Real-time External Equivalents for Static Security Analysis". IEEE Trans. PAS-98, March/April 1979, pp. 498-508.

141. "IEEE 118 Test System". Systems Engineering for Power Emergency Operating State Control. Davos, Switzerland. Section 1, Sept./Oct. 1979, pp. 117.

142. Rudnick, H. and Brameller, A. "Transient Security Assessment Methods". Proc. IEE, Vol. 125, No. 2, February 1978.

143. Brameller, A. and Denmead, J.K. "Some Improved Methods for Digital Network Analysis". Proc. of the IEE, February 1962, pp. 109-116.

APPENDIX 1

IPSAP's USER'S MANUAL [53]

A.1 SYSTEM OVERVIEW

A.1.1 Booting up Procedure

(i) Switch the BOOT switch on

(ii) Reply DYØ when the sign * appears on the VDU

(iii) Boot up requires the following files on the system disk:

SWAP.SYS , RT11SJ.SYS , TT.SYS

STARTS.COM , SDATE.SAV

A.1.2 Physical Device Names of Hardware

(i) DY Double density floppy disk - RXØ2 or the CRDS (Charles River Data System)

(ii) LP Line printer output device (logical unit 6)

(iii) TT Console terminal (logical unit 5 and 7)

A.1.3 Logical Device Names

(i) SY System volume: where the monitor programs, compilers, linker, utility programs are stored;

(ii) DK disk storage volume: where the user developed programs are stored. This is the default device for most commands.

A.1.4 Name Extensions in Files

To indicate the file type. Here is a list of the commonly used extensions:-

(i) .BAD File with bad blocks. Created by INITALIZE/BAD

(ii) .BAK Editor backup file. Created by EDIT command

(iii) .COM Indirect command file. Used in this package for linking of programs

(iv) .DAT Fortran data file

(v) .FOR Fortran source file

(vi) .LST Listing file. Created by FORTRAN/LIST

(vii) .MAP Map file. Created by LINK/MAP

(viii) .OBJ Relocatable binary file. Created by the FORTRAN compiler

(ix) .SAV Memory image. Created by LINK command

(x) .SYS System files and handlers

A.1.5 Management and Maintenance of Files

(i) R FRMTDY: Formats a new disk for single or double density. Assumes that FRMTDY is on DYØ

(ii) INITIALIZE/BAD DY1: To start a new disk or "clean up" an old disk

(iii) DELETE DY1: Filename: deletes the file, Filename from the disk DY1

(iv) SQUEEZE DY1: To squeeze a disk so that no gaps are left on disk DY1

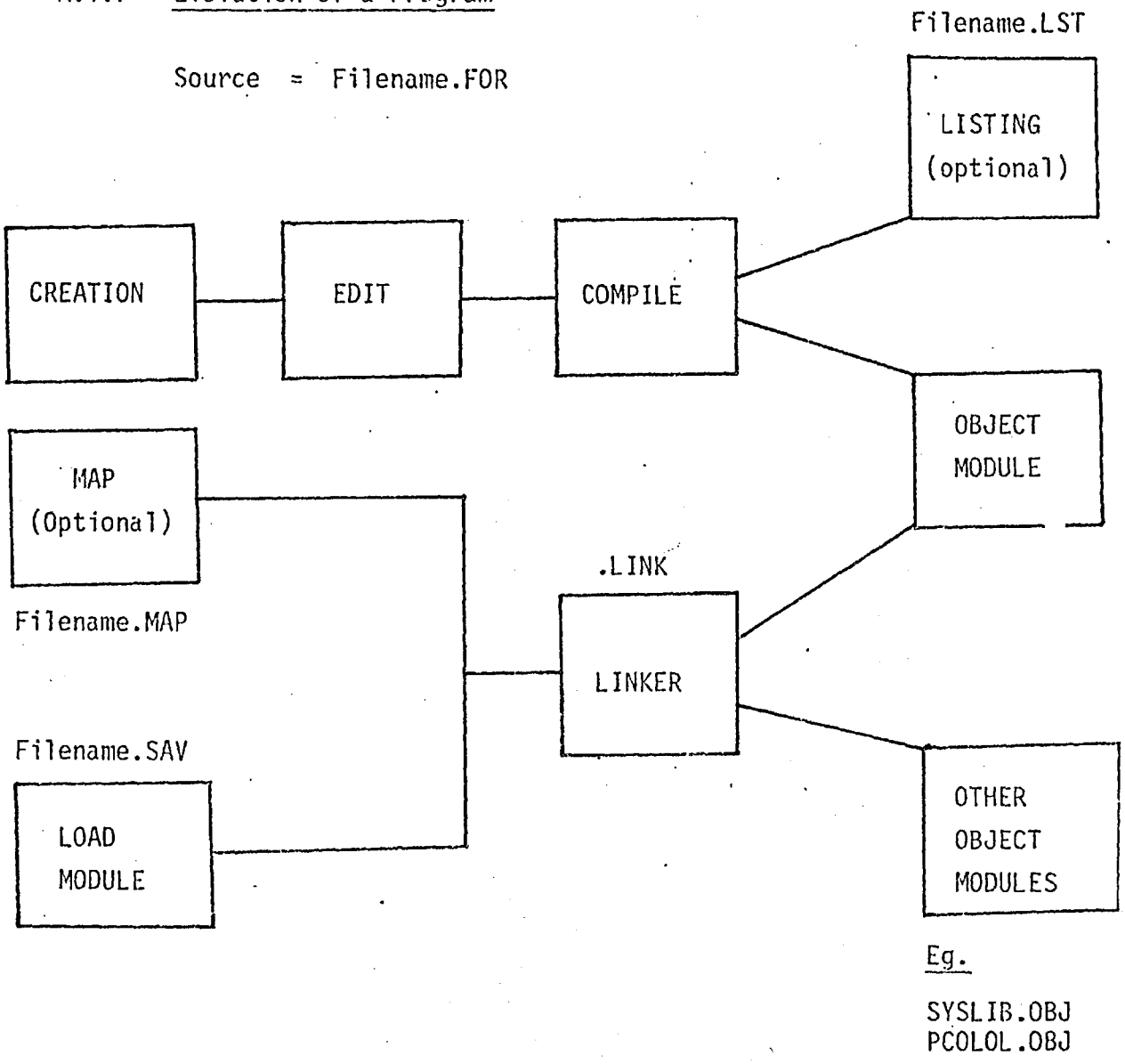
(v) COPY DY1: Filename DYØ: Copies the file Filename from the disk volume to the system volume with the same name

(vi) COPY/BOOT DY1: RT11SJ.SYS DY1: To bootstrap information onto DY1: These commands require the system files:

A.1.6 Necessary System Files:

(i)	SYSLIB.OBJ	(vii)	FORTRA.SAV	(xiii)	PCOLOL.OBJ
(ii)	FRMTDY.SAV	(viii)	TT.SYS	(xiv)	DUP.SAV
(iii)	SWAP.SYS	(ix)	LS.SYS	(xv)	PCOLOL.OBJ
(iv)	RT11SJ.SYS	(x)	LINK.SYS	(xvi)	DIR.SAV
(v)	SDATE.SAV	(xi)	PIP.SAV		
(vi)	STARTS.COM	(xii)	EDIT.SAV		

A.1.7 Evolution of a Program



A.1.8 Creating and Editing a File

To create a new program with the name Filename, enter the following:

.EDIT/CREATE Filename .FOR	To start the edit program
*I (followed by Text)	I for inserting text

----------	
*(ESC) (ESC)	To terminate the last command
*EX(ESC)(ESC)	To close the file and exit from edit

To edit an existing program with the name: filename

.EDIT Filename .FOR	
*R(ESC)(ESC)	To read file into text buffer

A.1.9 Log-in Procedure

The RETURN Key is required for each command.

Step 1: Switch on the minicomputer, VDU, monitor and the line-printer respectively. Ensure that the baud rate of 9600 is maintained for both the VDU and the line printer.

Step 2: With the system disk in DYØ and the user's in DY1, boot-up the system according to section A.1.1. If the date is correct, go to step 3, otherwise set the correct date.

Step 3: Assign the logical unit 6 to the VDU by .ASS TT: 6:
Assign DK to DY1 as .ASS DY1: DK:

Step 4: The programs are now ready to be assessed as shown in the section A.2.

A.1.10 Network Drawing and Data Entry

The commencement of the computations require the drawing of the network diagram (graphical information) and the supply of the system data.

The network diagrams are drawn by entering the appropriate mnemonic code via the keyboard. For example the letter B if typed with the cursor positioned on the screen anywhere a busbar is required can have a generator attached to it by typing the letter G. Generally by controlling the cursor, all the circuit elements can be draw. A subroutine "HELP" shown in Fig. 3.2 has been created to help in drawing the symbols. The graphical representations are shown below:

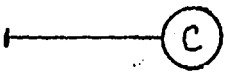
(i) B for a busbar representation



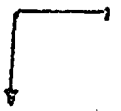
(ii) G for a generator on a bus



(iii) C for a synchronous compensator



(iv) S for a load representation

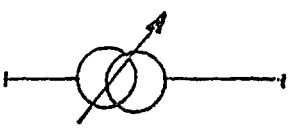


(v) L for a line representation (locate the origin by entering "0" and then "L" at the end bus)

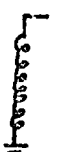
(vi) V for the above sequence should be followed by entering V to obtain a "bent" line representation

(vii) N requests for the name of the busbar where the cursor is positioned; a maximum of 2 figures is allowed

(viii) T displays the transformer symbol. (use the command "0" as in (v) above.)



(ix) Y for the reactor representation



(x) D for a capacitor



(xi) E escapes from the graphics routine and requests for the name of the new graphical file to be stored on the disk.

The system data can either be entered through the terminal during the program execution or through a file previously created for the purpose. For both cases, the "free format" has been used for ease of data entry.

A.2 INTERACTIVE POWER SYSTEM ANALYSIS PROGRAMS

FILE5 is an interactive program for the security analysis of power systems and considers (i) base loadflow study and (ii) line-outage contingencies and INFAL is for three-phase fault analysis and single-line-to-ground studies.

After the log-in procedures of section A.1.9 have been completed, the user can now run the programs as described below.

A.2.1 FILE5

.RUN FILE5

This displays the IPSAP header on the video monitor after initialising the screen. The sequence of instructions and results are shown for any network. The network and graphical files should be given at this stage.

After the base loadflow analysis, automatic contingency analysis is carried out with no solution option when the required number of iterations for the fast decoupled loadflow technique is up to 10 iterations or when there is a generator isolation.

A Summary of the results is presented.

A.2.2 INFAL

.RUN INFAL

The positive and zero sequence network data are stored on files as required during the interactive sequence.

Various displays are shown for different network configurations.

A.3 OVERLAYING OF IPSAP

An overlay structure divides the program into segments. For each overlaid program there is one root segment and a number of overlay segments. Each overlay segment is assigned to a particular area of available memory called an overlay region. More than one overlay segment can be assigned to

a given overlay region. However, each region of memory is occupied by one (and only one) of its assigned segments at a time. The other segments assigned to that region are stored on the disk. They are brought into memory when called, replacing the segment previously stored in that region. The root segment, on the other hand, contains those parts of the program that must always be memory resident. Therefore the root is never overlaid; the main program and the system routines of IPSAP are placed in the root segment,hence not overlaid.

The linking procedures for the FILE5 and INFAL programs are shown below. The linker calculates the size of any region to be the size of the largest segment assigned to that region. Thus to reduce the size of a program (that is the amount of memory it needs) one should concentrate on reducing the size of the largest segment in each region.

```
DK:FILE5[240],DL1:FILE5=FILE,DL1:INITT,SY:DLTCOL,DK:SYMBOL/P:400//
START/O:1
FILE1/O:1
FILE2/O:1
FILE3/O:1
PSGRA/O:1
FLOAC/O:1
CHED/O:1
AUSTR1/O:1
AUTSEL/O:1
FILE4/O:2
DISVOL/O.2
AUSTR2/O:2
AUSTR3/O:2
CIRDRA/O:2
CREATE/O:2
HELP/O:2
GRAOUT/O:2
DIREC/O:2
```

Linking of FILE5

```
DK:INFAL[200],DL1=INFAL=INFAL,SY:PLTCOL,DL1:SYSCL2/P:400,DL1:INITT,DK:SYMBOL
PSGRA/O:1
TRSTOE/O:1
DIREC/O:1
SYST/O:1
POSIT/O:1
BROWN/O:1
START/O:1
SINC/O:1
YBUS/O:1
TRAOUT/O:2
HELP/O:2
FAUANL/O:2
GRAOUT/O:2
SINGPH/O:2
BYSTIE/O:2
POINT/O:2
YSTORE/O:2
BUSADD/O:2
DISVOL/O:3
CATS/O:3
CIRDRA/O:3
```

Linking of INFAL

These subroutines are described in [54].

APPENDIX 2 [55]

LINEAR RELATIONSHIP BETWEEN LINE CURRENT AND STATE VARIABLES

The current flowing in a transmission line from bus p to q in terms of the magnitudes and phase angles of bus voltages and the parameters of the transmission line is defined by equation (A.1.1). The current I_{pq} is, therefore, a function of magnitudes and phase angles of the voltages at buses p and q.

$$I_{pq} = [(V_p \cos \delta_p - V_q \cos \delta_q) G_{pq} - (V_p \sin \delta_p - V_q \sin \delta_q) B_{pq} - B_c V_p \sin \delta_p] + j[(V_p \sin \delta_p - V_q \sin \delta_q) G_{pq} + (V_p \cos \delta_p - V_q \cos \delta_q) B_{pq} + V_p B_c \cos \delta_p] \quad (A.2.2)$$

$$= I_r + jI_j$$

where

I_{pq} is the current flowing in the transmission line connecting buses p and q

$G_{pq}+jB_{pq}$ is the series admittance of the line connecting buses p and q

B_c is half of the line charging admittance, and

I_r, I_j are the real and imaginary parts of I_{pq}

The current I_{pq} is the square root of the sum of the squares of I_r and I_j. Using this relationship, the partial derivatives of I_{pq} are as follows:

$$\frac{\partial I_{pq}}{\partial \delta_p} = \frac{I_r}{I_{pq}} [- G_{pq} V_p \sin \delta_p - B_{pq} V_p \cos \delta_p - B_c V_p \cos \delta_p] + \frac{I_j}{I_{pq}} G_{pq} V_p \cos \delta_p - B_{pq} V_p \sin \delta_p - B_c V_p \sin \delta_p] \quad (A.2.3)$$

$$\frac{\partial I_{pq}}{\partial \delta_p} = \frac{I_r}{I_{pq}} [G_{pq} V_q \sin \delta + B_{pq} V_q \cos \delta_q]$$

$$+ \frac{I_j}{I_{pq}} [- G_{pq} V_q \cos \delta_q + B_{pq} V_q \sin \delta_q] \qquad \text{(A.2.4)}$$

$$\frac{\partial I_{pq}}{\partial V_p} = \frac{I_r}{I_{pq}} [G_{pq} \cos \delta_p - B_{pq} \sin \delta_p - B_c \sin \delta_p] +$$

$$\frac{I_j}{I_{pq}} [G_{pq} \sin \delta_p + B_{pq} \cos \delta_p + B_c \cos \delta_p] \qquad \text{(A.2.5)}$$

$$\frac{\partial I_{pq}}{\partial V_q} = \frac{I_r}{I_{pq}} [- G_{pq} \cos \delta_q + B_{pq} \sin \delta_q] +$$

$$\frac{I_j}{I_{pq}} [-G_{pq} \sin \delta_q - B_{pq} \cos \delta_q] \qquad \text{(A.2.6)}$$

APPENDIX 3 [71]

PHYSICAL MEANING OF LEAST-SQUARES

Consider the equation of a physical system

$$AX = b \tag{A.3.1}$$

where A is a matrix of order m by n with $m > n$. It is expected that the equation is inconsistent. However; the solution of equation (A.3.1) exists though not unique, hence pseudo-inverse techniques can be used.

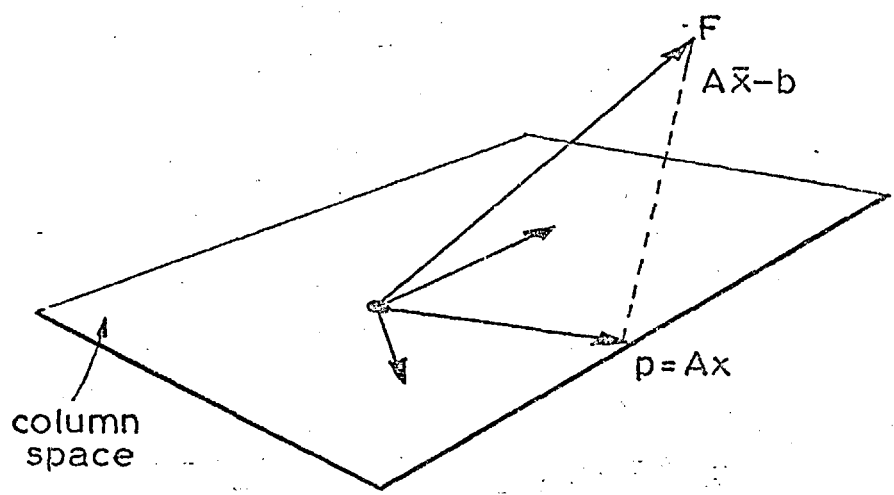


Fig. A.3.1: Physical Interpretation of Least-Squares

The least-squares approach is equivalent to finding a point in a subspace of the n sample space, where the distance to the tip of F is a minimum. The error is given by

$$E = \| A\bar{X} - b \| \tag{A.3.2}$$

Since $p = A\bar{X}$ is the projection of b onto the n space, the error vector must be perpendicular to that space. Each vector in the column space of A is a linear combination of the columns with more coefficients $y_1, y_2 \ldots, y_n$, i.e. it is a vector Ay. For all choice of y, these vectors in the plane must be perpendicular to the error vector E:

$$\left.\begin{array}{l} (Ay)^T (A\bar{X} - b) = \phi.\phi \\ \text{or} \\ y^T [A^T A\bar{X} - A^T b] = \phi.\phi \end{array}\right\} \qquad (A.3.3)$$

hence the least-squares solution to an inconsistent system AX-b of m equations in n unknown variables satisfies

$$A^T A\bar{X} = A^T b \qquad (A.3.4)$$

If the columns of A are linearly independent

$$\bar{X} = (A^T A)^{-1} A^T b \qquad (A.3.5)$$

This is the left pseudo-inverse equation.

Similarly for $n > m$, the right pseudo-inverse equation becomes:

$$\bar{X} = A^T (AA^T)^{-1} b \qquad (A.3.6)$$

APPENDIX 4

FORMULATION OF THE LOAD SHEDDING PROBLEM FOR INTEGER PROGRAMMING TO BE USED BY THE NAG ROUTINE

As previously stated, the problem formulated in equations (5.2) and (5.3) cannot be solved with the NAG standard routine for integer programming in its present form. Hence the modification suggested by Allwright [84] and shown below was made to arrive at a solution.

The problem:

maximize

$$\left.\begin{array}{l} \sum_{i=1}^{N} C_i X_i \\ \\ \text{subject to} \\ \\ Ax \leq b \\ \\ X_i \geq \phi \end{array}\right\} \qquad \text{(A.4.1)}$$

where N is the number of variables can be transformed into

minimize

$$\left.\begin{array}{l} \sum_{i=1}^{N} C_i Y_i \\ \\ \text{subject to} \\ \\ Ay \geq b' \\ \\ \text{and} \\ \\ Y_i \geq \phi \end{array}\right\} \qquad \text{(A.4.2)}$$

and then solved using the NAG routine.

Proof:

$$\max \sum_{i=1}^{N} C_i X_i \quad \Longleftrightarrow \quad \min \sum_{i=1}^{N} -C_i X_i \tag{A.4.3}$$

Have some $\hat{X}$ so that

$$d = \sum_{i=1}^{N} C_i \hat{X}_i \tag{A.4.4}$$

and

$$\hat{X}_i > X_i$$

$$\left.\begin{array}{ll} \min \sum_{i=1}^{N} -C_i X_i & \Longleftrightarrow \quad \min d - \sum_{i=1}^{N} C_i X_i \\ Ax \leq b & Ax \leq b \\ X \geq \phi & X \geq \phi \end{array}\right\} \tag{A.4.5}$$

$$\Longrightarrow \quad \min \sum_{i=1}^{N} C_i (X_i - X_i)$$

$$Ax \leq b$$

$$X \geq \phi$$

$$\text{Define } (\hat{X}_i - X_i) = Y_i > \phi \Longrightarrow X_i = \hat{X}_i - Y_i \tag{A.4.6}$$

Then equation (A.3.5) becomes:

$$\min \sum_{i=1}^{N} C_i Y_i \tag{A.4.7}$$

subject to

$$\left.\begin{array}{l} Ax \leq b \iff A(\hat{x} - y) \leq b \\ \\ -Ay \leq b - A\hat{x} \leq b' \end{array}\right) \qquad (A.4.8)$$

where

$$b - A\hat{x} = b'$$

Then

$$Ay \geq b'$$

and

$$Y_i \geq \phi$$

is the form required.

APPENDIX 5

DEVELOPMENT OF THE ADJOINT NETWORK OF CIRCUITS [105]

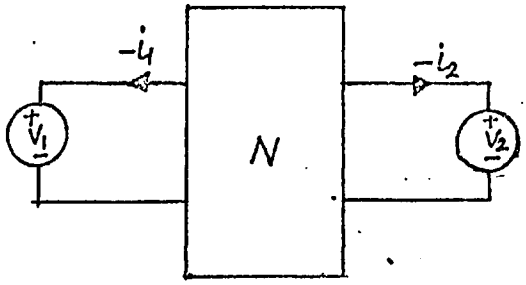


Fig. A.5.1

A two-port network

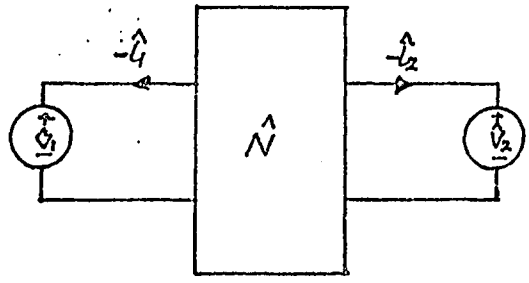


Fig. A.5.2

Its adjoint network

Consider the linear resistive network of Fig. A.4.1 described by

$$\underset{\sim}{G} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad \text{or} \quad \underset{\sim\sim}{G}\underset{\sim}{v} = \underset{\sim}{i} \tag{A.5.1}$$

where $\underset{\sim}{G}$ = short-circuit conductance matrix. The Tellegen summation for the entire network including the sources V_1 and V_2 must be zero. In addition each term of the sum must vanish for every branch within the two figures, provided that N has no internal parameters. This leaves only the terms which must then sum pair-wise to zero. The terms in the Tellegen summation for the sources are

$$(-\hat{i}_1)\, dV_1 - \hat{V}_1 d(-i_1) + (-\hat{i}_2)\, dV_2 - \hat{V}_2 d(-i_2)$$

$$= -[\hat{i}_1 \hat{i}_2]\, d\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} + [\hat{V}_1 \hat{V}_2]\, d\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{A.5.2}$$

$$= - \hat{\underset{\sim}{i}}^T \, d\underset{\sim}{v} + \hat{\underset{\sim}{v}}^T \, d_i \qquad (A.5.3)$$

$$= - \hat{\underset{\sim}{i}}^T \, d\underset{\sim}{v} + \hat{\underset{\sim}{v}}^T \, \underset{\sim}{G} \, d\underset{\sim}{v} \qquad (A.5.4)$$

$$= (-\hat{i}^T + \hat{\underset{\sim}{v}}^T G) \, d\underset{\sim}{v} \qquad (A.5.5)$$

where it is assumed that $d\underset{\sim}{G} = O$ This expression can be made zero by setting

$$\hat{\underset{\sim}{i}}^T = \hat{\underset{\sim}{v}}^T \underset{\sim}{G} \Longleftrightarrow \hat{\underset{\sim}{i}} = \underset{\sim}{G}^T \hat{\underset{\sim}{v}} \qquad (A.5.6)$$

It is concluded that N is described by a port matrix G that is the transpose of $\underset{\sim}{G}$, i.e.

$$\hat{\underset{\sim}{G}} = \underset{\sim}{G}^T \qquad (A.5.7)$$

APPENDIX 6

PROBLEM FORMULATION OF THE ADJOINT NETWORK EQUATIONS FOR POWER SYSTEM TRANSMISSION PLANNING [102]

Problem Formulation

A DC loadflow model of a network can be represented by

$$P_i = \sum_{\substack{j=1 \\ j\neq i}} |V_i||V_j|B_{ij}(\delta_i-\delta_j) \quad \text{for } i = 1,2,\ldots N$$

$$= \Sigma P_m \qquad m = \text{elements incident on bus } i \tag{A.6.1}$$

where

$$P_m = |V_i||V_j|B_{ij}(\delta_i - \delta_j) \tag{A.6.2}$$

$$\left.\begin{aligned} &= B_{ij}(\delta_i - \delta_j) \\ &= B_{ij}\,\delta_{ij} = Bm\delta m \end{aligned}\right) \tag{A.6.3}$$

since the voltage profile is normally assumed flat and equal to 1.0 per unit.

The problem of transmission expansion planning as a static optimization becomes

$$\min J = \tfrac{1}{2}G'(X)WG(X) \tag{A.6.4}$$

subject to the constraint that

(i) the DC load flow equations are satisified

(ii) $\underline{B} \leq B \leq B^{max}$

For simplicity, it is assumed that the performance index is a weighted error-squared-type index in which the error is the difference between the line loadings I_{ij} and the capacity I_{ij}^{max}.

$$G(X) = \begin{bmatrix} I_1 - I_1^{max} \\ \vdots \\ I_L - I_L^{max} \end{bmatrix} \qquad (A.6.5)$$

for L overloaded lines.

Determining the Gradient Vector

Applying Tellegen's theorem explained in the previous Appendix with the network defined by equations (A.6.1 - A.6.3)

$$\sum_{n=L+1}^{E} \Delta\delta_n \tilde{P}_n - \tilde{\delta}_n \Delta P_n + \sum_{m=2}^{L} \Delta\delta_m \tilde{P}_m - \tilde{\delta}_m \Delta P_m + \Delta\delta_1 \tilde{P}_1 - \tilde{\delta}_1 \Delta P_1 = 0 \qquad (A.6.6)$$

From equation (A.6.3)

$$\left.\begin{aligned} \Delta P_m &= B_m \Delta\delta_m + \delta_m \Delta B_m \qquad m = 2, \ldots L \\ \text{and} \\ \Delta\delta_1 &= 0 \\ \Delta P_n &= 0 \qquad n = L+1, \ldots, E \end{aligned}\right\} \qquad (A.6.7)$$

Equation (A.5.6) becomes

$$\sum_{n=L+1}^{E} \Delta\delta_n \tilde{P}_n + \sum_{m=2}^{L} \left(\frac{\tilde{P}_m}{B_m} - \tilde{\delta}_m\right) \Delta P_m - \tilde{\delta}_1 \Delta P_1$$

$$= \sum_{m=2}^{L} \frac{\delta_m \tilde{P}_m}{B_m} \Delta B_m \qquad \text{(A.6.8)}$$

Setting $\tilde{P}_n = 0$, $n = L + 1, \ldots, E$ and $\tilde{\delta}_1 = 0$ define

$$\frac{\tilde{P}_m}{B_m} - \tilde{\delta}_m = \frac{\partial J}{\partial P_m} = g_m(P_m) W_{mm} \qquad \text{(A.6.9)}$$

or

$$\left.\begin{aligned} \tilde{P}_m &= B_m\tilde{\delta}_m + B_m g_m (P_m) W_{mm} \\ &= B_m\tilde{\delta}_m + B_m(I_m - J_m^{max}) W_{mm} \end{aligned}\right\} \qquad \text{(A.6.10)}$$

Substituting equation (A.6.9) into equation (A.6.8) with $\tilde{P}_n = 0$ and $\tilde{\delta}_1 = 0$ to obtain

$$\sum_{m=2}^{L} g_m(P_m) W_{mm} \Delta P_m = \sum_{m=2}^{L} \frac{\delta_m \tilde{P}_m}{B_m} \Delta B_m \qquad \text{(A.6.11)}$$

Defining

$$\frac{\partial J}{\partial B_m} = \frac{\partial_m \tilde{P}_m}{B_m} \qquad m = 2, \ldots L \qquad \text{(A.6.12a)}$$

$$= \frac{\partial_m}{B_m} \left[B_m\tilde{\delta}_m + B_m(I_m - I_m^{max}) W_{mm}\right] \qquad \text{(A.6.12b)}$$

$$= \partial_m\tilde{\partial}_m + \partial_m (I_m - I_m^{max}) W_{mm} \qquad \text{(A.6.12c)}$$

From equation (A.5.12), the gradient of the performance index with respect to B is

$$\frac{\partial J}{\partial B} = \begin{bmatrix} \partial_2 \tilde{\partial}_2 + \partial_2 (I_2 - I_2^{max}) W_{22} \\ \vdots \\ \partial_L \tilde{\partial}_L + \partial_L (I_L - I_L^{max}) W_{LL} \end{bmatrix} \qquad \text{(A.6.13)}$$

Including the cost of line additions equations (A.5.4) and (A.5.13) become

$$J = \tfrac{1}{2} G'(X)\, WG(X) + K'X \qquad \text{(A.6.14)}$$

where K is the vector of unit line costs

$$\frac{\partial J}{\partial B} = \begin{bmatrix} \partial_2 \tilde{\partial}_2 + \partial_2 (I_2 - I_2^{max}) W_{22} + \delta_2 K_2 \\ \vdots \\ \partial_L \tilde{\partial}_L + \delta_L (I_L - I_L^{max}) W_{22} + \partial_L K_L \end{bmatrix} \qquad \text{(A.6.15)}$$

APPENDIX 7

TABLE OF ERROR FUNCTIONS [134]

$$\operatorname{erf} x = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-y2/3}\, dv$$

x	erf x	x	erf x
0.05	0.01994	1.55	0.43943
0.10	0.03983	1.60	0.44520
0.15	0.05962	1.65	0.45053
0.20	0.07926	1.70	0.45543
0.25	0.08971	1.75	0.45994
0.30	0.11791	1.80	0.46407
0.35	0.13683	1.85	0.46784
0.40	0.15542	1.90	0.47128
0.45	0.17364	1.95	0.47441
0.50	0.19146	2.00	0.47725
0.55	0.20884	2.05	0.47982
0.60	0.22575	2.10	0.48214
0.65	0.24215	2.15	0.48422
0.70	0.25804	2.20	0.48610
0.75	0.27337	2.25	0.48778
0.80	0.28814	2.30	0.48928
0.85	0.30234	2.35	0.49061
0.90	0.31594	2.40	0.49180
0.95	0.32894	2.45	0.49286
1.00	0.34134	2.50	0.49379
1.05	0.35314	2.55	0.49461
1.10	0.36433	2.60	0.49534
1.15	0.37493	2.65	0.49597
1.20	0.38494	2.70	0.49653
1.25	0.39435	2.75	0.49702
1.30	0.40320	2.80	0.49744
1.35	0.41149	2.85	0.49781
1.40	0.41924	2.90	0.49813
1.45	0.42647	2.95	0.49841
1.50	0.43319	3.00	0.49865