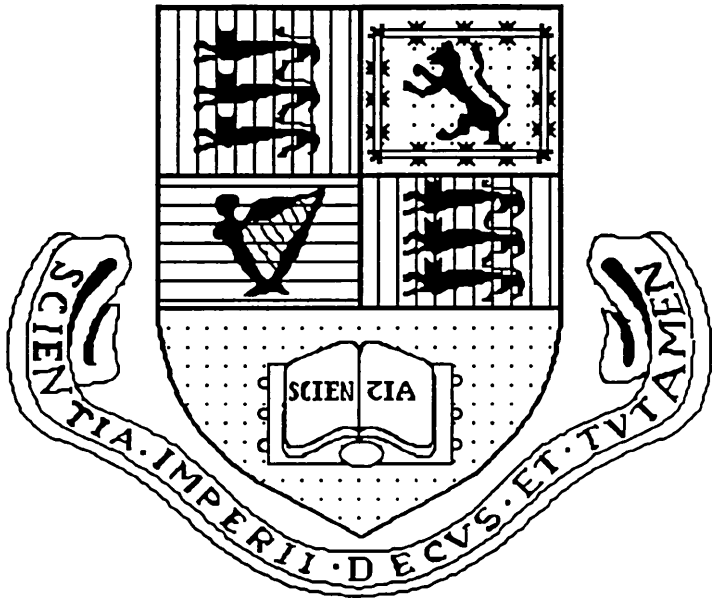
Reactive Reserve Management

in the Operational Planning of Power Systems



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Medicine

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by

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To Jesusa with all my love

Abstract

This thesis is concerned with the steady state reactive power reserve management in the operational planning phase of electrical power systems.

A methodology is proposed to determine the output or setting of existing VAr/voltage control devices so that the allocation of reactive reserves guarantees that the system does not move towards voltage collapse as the demand changes and that it will cope under credible contingency conditions.

To evaluate the proximity of the system to voltage collapse, the network is partitioned into reactive areas by identifying the 'weak' transmission elements which define the boundaries between the areas. 'Vulnerable' nodes are selected for each area and proximity indicators to low voltage and voltage collapse conditions in terms of defined Q-distances are evaluated for them.

Such information (i.e. reactive areas and Q-distances) gives a useful general visualisation of the adequacy of the reserves from the voltage collapse standpoint. Strategies to increase the Q-distances of an area (or areas) can then be found.

To deal with contingencies, a screening algorithm is employed which identifies potentially critical outages, analyzed by an a.c. load flow technique. For each contingency representing a security risk, a reactive power rescheduling is performed to eliminate operational limit violations.

A co-ordination procedure is then applied to bring together all the VAr/voltage control adjustments required to increase the Q-distances of specific areas and to alleviate limit violations for the security risk contingencies. The aim is to maximise the control plan to be implemented in a preventive mode, without violating operational limits on the base case or any security risk contingency conditions.

The proposed global strategy has been prototyped on a computer by integrating algorithmic software and symbolic programming. Although the methodology is basically algorithmic, the use of knowledge-based systems technologies made the prototyping a simple task.

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List of Principal Symbols

P_i	active power injection at bus i
Q_i	reactive power injection at bus i
V_i	voltage magnitude of node i
θ_i	voltage angle of node i
$Y_{ij} = Y_{ij}\underline{/\gamma_{ij}}$	ijth element of the bus admitance matrix
n	number of buses
[H]	submatrix of derivatives of the active powers with respect of the bus voltage angles
[N]	submatrix of derivatives of the active powers with respect to the bus voltage magnitudes
[M]	submatrix of derivatives of the reactive powers with respect to the bus voltage angles
[L]	submatrix of derivatives of the reactive powers with respect to the bus voltage magnitudes
pv	PV buses subscript

pq	PQ buses subscript
g	generation subscript
α	scalar used to identify the weak transmission elements
Δ	incremental operator
$[S_{qpq}^{vpq}]_i$	column vector of sensitivities of the PQ bus voltage magnitudes with respect to a change in the reactive demand at bus *i*
$[S_{qpq}^{qg}]_i$	vector of sensitivities relating changes in the reactive power production at generating stations due to a change in the reactive demand at bus *i*
Qdist-to-VC	indicator of the proximity to voltage collapse conditions
Qdist-to-LV	indicator of the proximity to low voltage conditions
k	factor used in the representation of generators for the 'pseudo-short-circuit' calculation
[B']	nodal matrix for the P-θ part of the fast decoupled load flow model
[B'']	nodal matrix for the Q-V part of the fast decoupled load flow model
sp	specified value superscript
d	demand subscript
o	base case superscript
$\Delta b'$	change of susceptance of the outaged branch (P-θ model) in the contingency screening algorithm
$\Delta b''$	change of susceptance of the outaged branch (Q-V model) in the contingency screening algorithm
$[S_{vpq}^{qg}]$	matrix of sensitivities relating changes in the reactive power production at generators due to changes in the bus voltage magnitudes at PQ nodes
w_{vi}, w_{qi}	weighting factors used in the evaluation of the performance indices
lim	limit superscript
min	lower limit superscript
max	upper limit superscript

$\| \ \|$	absolute value
cg_i	cost associated with adjustments to the voltage of generator i in the reactive rescheduling function
cb_i	penalising factor (i.e. cost) for changes in the susceptance of the switchable shunt capacitor (and/or inductor) bank i in the reactive rescheduling procedure
ct_i	cost penalising adjustments to the tap setting of transformer i in the reactive rescheduling function
$[\Delta V_g]$	vector of voltage adjustments at generating stations obtained from the rescheduling procedure
$[\Delta B]$	vector of susceptance changes caused by the switching of shunt capacitors (or inductors) obtained from the rescheduling procedure
$[\Delta T]$	vector of adjustments in the tap settings of transformers obtained from the rescheduling function
ng	number of generators
nb	number of switchable shunt capacitor (and/or inductor) banks
nt	number of transformers with tap changing facilities
$[S_{vg}^{qg}]$	sensitivity matrices relating changes in the reactive production at
$[S_b^{qg}]$	generating stations due to adjustments in the voltage at generating
$[S_t^{qg}]$	stations, the susceptance of switchable shunt capacitors (and/or inductors) and the tap settings of transformers
$[S_{vb}^{vpq}]$	senstivity matrices relating changes in the voltage magnitudes at PQ
$[S_b^{vpq}]$	buses due to adjustments in the voltage at generating stations, the
$[S_t^{vpq}]$	susceptance of switchable shunt capacitors (and/or inductors) and the tap settings of transformers
$[D]$	submatrix of the derivatives of the active powers with respect to the tap settings of transformers
$[E]$	submatrix of the derivatives of the reactive powers with respect to the

	susceptances of shunt capacitor (and/or inductor) banks
$[F]$	submatrix of the derivatives of the reactive powers with respect to the tap settings of transformers
t	transformer tap setting
$[\Delta u']$	control plan proposed to the co-ordination function
$[\Delta u^{s1}]$	control plan obtained from the first phase of the co-ordination function
$[\Delta u^*]$	control plan obtained from the second step of the co-ordination strategy
$[\Delta u(k)]$	control plan obtained from the reactive power rescheduling function to alleviate limit violations under contingency k operating conditions
pg_i	priority given to the adjustment of generator i voltage in the co-ordination function
pb_i	factor defining the priority associated with the change in the susceptance of the switchable shunt capacitor (or inductor) i in the co-ordination strategy
pt_i	priority assigned to the adjustment of the tap setting of transformer i during the co-ordination procedure
αg_i, γg_i	acceptability factors for the generator i voltage adjustments proposed to the two phases of the co-ordination function
αb_i, γb_i	acceptability factors associated with the changes in the susceptance of the switchable shunt capacitor (or inductor) i proposed to phases I and II of the co-ordination strategy
αt_i, γt_i	factors defining the acceptability of the adjustments of the tap setting of transformer i proposed to the two phases of the co-ordination function
$[S^{qg}_{\alpha g}(bc)]$	sensitivity matrices relating changes in the reactive power production at
$[S^{qg}_{\alpha b}(bc)]$	generating stations (for the base case operating conditions) due to
$[S^{qg}_{\alpha t}(bc)]$	changes in the acceptability factors α of the first phase of the

co-ordination strategy

$[S_{\alpha g}^{vpq}(bc)]$ sensitivity matrices relating changes in the voltage magnitudes at PQ

$[S_{\alpha b}^{vpq}(bc)]$ buses (for the base case operating conditions) due to changes in the

$[S_{\alpha \alpha}^{vpq}(bc)]$ acceptability factors α of phase I of the co-ordination function

$[S_{\gamma g}^{qg}(k)]$ sensitivity matrices relating changes in the reactive power production at

$[S_{\gamma b}^{qg}(k)]$ generating stations (for the contingency k operating conditions) due to

$[S_{\gamma \gamma}^{qg}(k)]$ changes in the acceptability factors γ of the second phase of the co-ordination strategy

$[S_{\gamma g}^{vpq}(k)]$ sensitivity matrices relating changes in the voltage magnitudes at PQ

$[S_{\gamma b}^{vpq}(k)]$ buses (for the contingency k operating conditions) due to changes in the

$[S_{\gamma \gamma}^{vpq}(k)]$ acceptability factors γ of the second phase of the co-ordination function

Corrigenda

Page-line	Details (it is/it should be)
14-23	...flexible operation / ... a flexible operation
16-17	... system does not more / ... system does not move
15-25	... rendersecurity and / ... render security and
20-10	... slots or atributes / ... slots or attributes
37-6	... to a misjudgment / ... to a misjudgement
37-8	... in section 6 of this report / ... in section 2.6 of this chapter
37-12	... the generatator's / ... the generator's
38-3	... in numerical example / ... in the numerical example
42-7	... power form being / ... power from being
50-13	... shunt compontents / ... shunt components
56-18	... is totally outage / ... totally outaged
57-10	... the simplicifcations / ... the simplifications
59-8	... from where / ... from which
62-7	... shown in Figure 5 / ... shown in Figure 3.5
68-11	equation (4.3) $[V_{pq}^{max}] = [V_{pq}^{max}] - [V_{pq}]$ / $[\Delta V_{pq}^{max}] = [V_{pq}^{max}] - [V_{pq}]$

68-17 ... $[Q_g]$ and $[V_{pg}]$ / ... $[Q_g]$ and $[V_{pq}]$

71-14 ... [F] = [∂Q/dT] is / ... [F] = [∂Q/∂T] is

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123-27 ... information form / ... information from

123-31 ... *evaluate_Qreserve_list* / ... *evaluate_Qreserves_list*

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127-41 ... PI_{voo}, IP_{q1}, / ... PI_{voo}, PI_{q1}

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128-11 ... this proceedure can be initalised / ... this procedure can be initialised

128-26 *create_transfer_MM_state_QVbase* / *create_transfer_MM_state_QVdbase*

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Chapter 1

Introduction

1.1. Reactive Power Management

Voltage control in a power system is executed mainly by balancing the demand and production of reactive power. To achieve such a balance is complicated because of the changing requirements of the system due to variation in demand and operating conditions. At peak demand, the required reactive power must be produced in order to maintain an acceptable voltage profile. Yet during light load conditions the reactive power surplus generated by the network has to be consumed to avoid excessive high voltages on the system.

Consideration of contingencies imposes additional requirements. In particular, provision must be made to cater for any reactive power changes following contingencies.

Reactive power management can be classified into the following categories [1]:

Reactive power planning determines the equipment to be installed to enable the power

system to operate flexibly in an acceptable manner from several months to several years in the future, with the objective of minimising the VAr expansion cost.

System operational planning is concerned with studies aimed at achieving satisfactory levels of system security and quality of service making use of existing reactive power equipment and sources for system conditions forecast for the near future (a day, a week, six months ahead, etc.). It is intended to produce coordinated behaviour of the available VAr/voltage devices, taking into account operating and security criteria.

Reactive power dispatch and control determines the actual equipment use and settings. It may be subdivided into **primary** automatic local control (timescale < 1min), **secondary** regional control (timescale > 1 min) which adjusts the primary control reference points within an area, and **tertiary** global control (timescale > 10 min) which performs an overall optimisation at a system level [2,3].

In a report prepared by the IEEE VAr Management Task Force [4], attention was focused on the scheduling, operation and monitoring of VAr production components. Special concern was expressed about the difficulties imposed by the consideration of contingencies.

VAr dispatch is normally performed as a second step after an economic active power generation scheduling.

Optimisation techniques have been used as the basic tool for the scheduling of VAr/voltage control devices. Special consideration has been given to the choice of an adequate objective function.

When system conditions (e.g. a well meshed network and medium demand level) allow flexible operation with adequate margins, economic aspects (e.g. minimisation of the active power losses [5]) may become the main objective of the scheduling.

Under severe conditions (e.g. at peak load level and perhaps considering a set of predefined contingencies) on the other hand, a security-based criterion (e.g. maximising the reactive reserves and distributing them among the generators, proportionate to their ratings [6]) might be more appropriate; however the simple addition of the unused reactive power on the generating units throughout the system is not a meaningful indicator of the reactive reserves. Severe voltage profile degradation and even voltage collapse can be experienced long before the reactive reserves available on all the generating stations can be consumed.

A more objective evaluation of the reactive power reserves is presented in [7]. A distance to voltage collapse in terms of VArs is defined and used as a measure of security. It is suggested to calculate the distance to voltage collapse for each individual node in the network; this would however, produce an overwhelming amount of information.

Although a variety of objectives can be used to deal with different aspects of the VAr/voltage control problem (e.g. minimum active power transmission losses, minimum deviation of voltages from preselected values, minimum weighted reactive power injections, etc.), in this thesis a global methodology for the reactive reserve management in the operational planning phase of power systems, which emphasises security-oriented objectives, is proposed. The primary aim to be achieved is the maintenance of an appropriate voltage profile and adequate reactive reserves support so as to assure the system security under a set of predefined contingencies. The strategy provides an objective measurement of the reactive reserves by considering the effects that the transmission of reactive power may have on the voltage profile. The guarantee that the system will be able to cope with particular contingencies can be provided by dispatching the reactive power in a preventive mode. Short term predictive studies (e.g. one day ahead) can be carried out to assist the operational planning engineers in establishing an operating strategy to rendersecurity and flexibility in performance under varying loading and contingency conditions.

An overview of the proposed methodology is presented in the following section.

1.2. Objectives of the thesis

In this thesis, a global methodology for the steady state reactive reserve management in the operational planning of power systems, is proposed. This strategy, depicted in Figure 1.1, is centred around the two main requirements that have to be taken into consideration when a reactive reserve holding strategy is being determined in the operational planning phase [8], viz:

1) VAr reserves should be allocated in such a way that the system does not more towards Voltage Collapse (VC) as the system demand changes.
2) sufficient VAr reserves should be available to cater for the VAr changes following contingencies.

To deal with the first requirement, the method partitions the system into reactive areas by identifying the weak transmission elements; severe voltage drops would occur if the reactive power transmitted through these elements is increased. Groups of weak transmission elements define then the boundaries between the reactive areas. A 'vulnerable' node is then identified for each reactive area and proximity indicators (Q-distances) to low voltage and voltage collapse conditions are evaluated. This concise information (i.e. Q-distances for the few vulnerable nodes) provides an objective general view of the adequacy of the reactive reserves on the power system. Strategies to increase the reactive strength (Q-distances) of a given area (or areas) are determined.

For the second requirement, a contingency screening and ranking algorithm is employed.

Potentially critical outages are identified, ranked and analysed by an a.c. load flow algorithm to detect the actual voltage security risk contingencies. For each contingency representing a security risk, a reactive power rescheduling technique using LP is employed to alleviate operational limit violations.

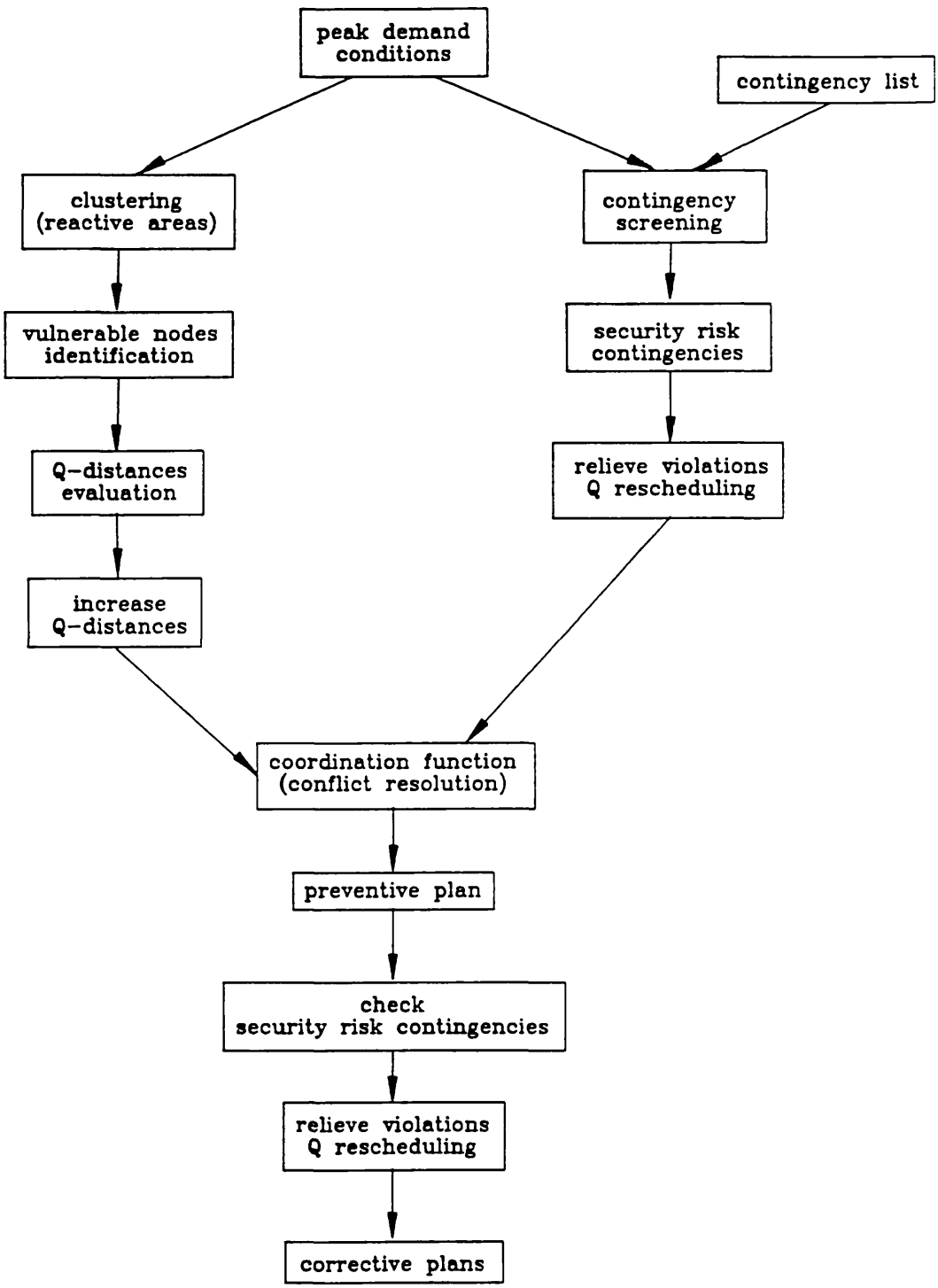


Figure 1.1 Proposed strategy for the reactive reserve management

Finally, the control strategies proposed to relieve limit violations for voltage security risk contingencies and to increase the reactive strength of a given area (or areas), are coordinated using a LP technique. The objective is to maximise the proposed control adjustments to be implemented as preventive strategies without causing any limit violation on the base case of any voltage security risk contingency.

A prototype digital system has been implemented using the ideas explained above. It incorporates logic programming and algorithmic software and although the final strategy is quite algorithmic, the use of knowledge-based systems technologies made the prototyping an easy task.

1.3. Knowledge-based Systems Methodologies

The application of knowledge-based expert systems technologies to power systems is a recent area of research. In this section, knowledge-based systems are briefly described by examining their basic structure, the main knowledge representation schemes and the inference mechanisms. The use of these techniques in power systems is also reviewed.

As a definition, D.A. Waterman [9] states: *"Expert systems are computer programs that manipulate knowledge to solve problems in a narrow problem area. Like human experts, these systems use symbolic logic and heuristics - rules of thumb - to find solutions."* Although the prototype system presented in this thesis may not have the suitable high 'expert' level knowledge to be considered an expert system, substantial benefits may be obtained from such a prototype, purely from the use of these new methodologies.

The two fundamental components of an expert system are its body of knowledge ('**knowledge base**') and a reasoning mechanism ('**inference engine**') that manipulates knowledge to find a solution to the problem posed. The knowledge-based scheme

substitutes the common software development practice of:

data + algorithm = program

with a new structure focused on the knowledge base and the inference engine so that [10]

knowledge + inference = system

The basic structure of a knowledge-based system is depicted in Figure 1.2. The knowledge base contains information (e.g. facts and rules, or other representations) which is used by the system as foundation for decision making. The inference engine performs the reasoning process, using the knowledge in the knowledge base, to lead to the solution of the problem.

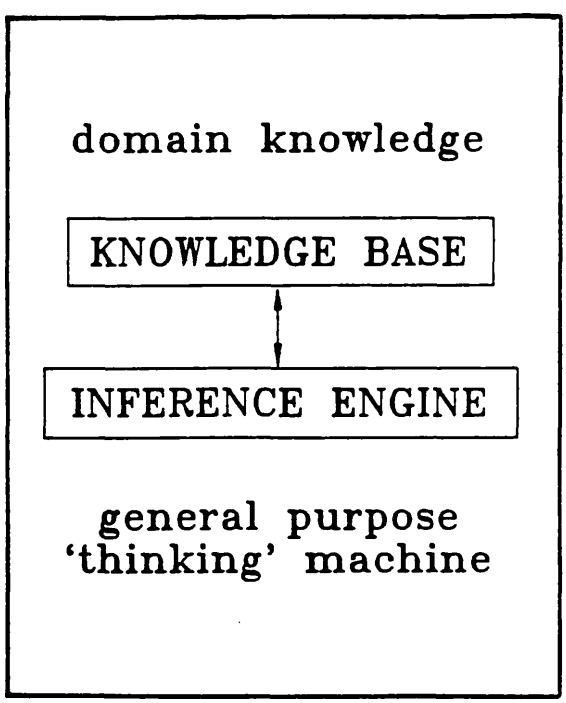


Figure 1.2 Structure of a knowledge-based system [9]

The heart of a knowledge-based system is the knowledge it contains. Some of the most common approaches to knowledge representation are:

Predicate logic. In this scheme knowledge is represented using objects (facts) and relations (rules) between them.

Semantic networks. These are structures used to build hierarchies of concepts. They are based on two fundamental units: nodes and links. Nodes represent objects, concepts or events, and are connected by links describing relations between the nodes. Nodes lower in the network can inherit properties from nodes higher up.

Frames. A frame is a packed data structure used to represent any entity, situation or event. Its characteristics are captured in its slots or atributes. Each slot can have procedures attached to it, executed whenever the information in the slot is stored or retrieved (e.g. the "if-needed", "if-removed" and "if-added" procedures). Frames can be put together hierarchically and inheritance can be exercised.

Production rules. Here, knowledge is represented as a series of If-Then rules.

Objects. In the object-oriented method, knowledge is viewed in terms of a series of items, called objects, which communicate with each other by sending and receiving messages. An object that receives a message, checks its database and decides what action to take.

The two basic forms of inference employed by the reasoning component of knowledge-based systems are [11]:

Forward chaining (data or event-driven reasoning). This style of reasoning works forwards from known facts to other facts which follow from them.

Backward chaining (goal or hypothesis-driven reasoning). In this method of inference,

the system is given a specific goal to prove (hypothesised conclusion) and works backwards to determine what other goals need to be proven to verify the original goal.

Although the application of knowledge-based system technologies to power systems is a recent area of research, growing interest from the industry has been experienced over the last few years [12].

Several working prototypes developed to solve planning, operational planning and real-time control problems have been reported [13].

Fields of application range from EHV networks, to substations and generating stations.

A diversity of knowledge representation schemes (e.g. production rules, predicate logic, frames, objects, semantic networks, etc.) and inference mechanisms (e.g. forward and backward chaining, or a combination of the two) have been employed.

The development tools employed vary from rather sophisticated shells (e.g. KEE, ART, OPS-83, etc.) to simple symbolic languages (e.g. Prolog, Lisp, etc.). The use of knowledge-based systems technologies can accelerate the development process of some power systems applications; in some case (e.g. security assessment), however, the efficiency and procedural functionality of conventional languages (e.g. Fortran, Pascal) can not be replaced.

By integrating knowledge-based systems techniques and conventional software, a powerful programming style providing both ease of expression and efficiency can be obtained [14].

Many traditional power system applications can be enhanced by the use of simple knowledge-based systems methodologies, e.g. by automating, generally tedious and routine activities, which can be described by means of a symbolic programming language (e.g. Prolog), leaving the rest to conventional software and human judgment.

In this research project, a prototype digital system has been developed for the steady state reactive reserve management in the operational planning phase of power systems. Numerical algorithms and logic programming have been integrated into the system.

The symbolic component of the prototype (written in Prolog) determines the sequence with which the different numerical algorithms (written in Pascal and Fortran) are executed to assess and enhance the adequacy of the reactive reserves under certain forecast operating conditions.

The multi-language program development environment POPLOG [15] has been used as the building tool of the prototype.

POPLOG provides a powerful and friendly environment for rapid prototyping. Its three main languages together (POP-11, PROLOG and LISP) provide facilities for list processing, pattern matching, logical inference, and sophisticated control structures.

The core language POP-11 is very similar in power to Lisp, but its appearance is more conventional. Compiled object subroutines written in other languages (e.g. Pascal, Fortran, C) can be linked and applied as built-in primitives of POP-11, Prolog or Lisp. This allows Pascal and Fortran routines to be used for the lowest level algorithms and Prolog rules for the high level knowledge-based programming, getting the best out of the two computational styles and taking advantage of the wealth of algorithmic software normally found in existing data processing environments for power systems.

Further details in the use of this programming environment for the development of the prototype system can be found in chapter 6.

1.4. Outline of the Thesis

In chapter 2 of this thesis, the algorithms for the partitioning of the system into reactive areas, for the identification of vulnerable nodes and for the evaluation of the Q-distances, are presented. The combination of these simple algorithms, provides a quick-scan general perspective of the security of the system from the proximity to voltage collapse standpoint. A particular contribution of this research is the development of the 'pseudo-short-circuit' algorithm, which puts together, in a straight forward manner, the network characteristics and the reactive reserves available at generating stations. This calculation is used to pinpoint the vulnerable nodes in the system and might provide the foundation for a better method for the partition of the network into reactive areas.

Chapter 3 describes the conventional VAr/voltage contingency screening and ranking algorithm implemented to identify potential security risk contingencies. Although the results obtained to date have not been very encouraging, two alternative screening techniques have been proposed and are presented in chapter 3. An improvement in the form of the VAr performance indices is proposed by using non-normalised quantities.

Chapter 4 deals with the reactive power rescheduling function employed to eliminate operational limit violations. Sparse sensitivity matrices and relaxation techniques have been adopted to avoid the rescheduling of practically ineffective VAr/voltage control devices and to reduce the size of the problem. A contribution in this area is the transformation suggested to formulate an equivalent LP problem from the original non-linear optimisation problem (whose objective function involves the absolute values of the control adjustments), so as to allow the use of a conventional library LP routine.

The coordination strategy adopted to bring together all the control adjustments required to increase the reactive strength (Q-distances) of a given area (or areas) and to eliminate operational limit violations for every security risk contingency, is described in chapter 5.

The aim is to maximise the VAr/voltage control adjustments to be implemented in a preventive mode without producing operating constraint violations on the base case or any security risk contingency conditions. It uses LP and relaxation techniques.

The architectural features and functional aspects of the resulting digital prototype system are discussed in chapter 6. The amalgam of algorithmic software and knowledge-based programming rendered a flexible style for software development, which facilitated the implementation of the prototype.

Finally, the conclusions of this research and the areas requiring further study and development are presented in chapter 7.

Chapter 2

Reactive Reserve Evaluation

2.1. Introduction

The simple algebraic sum of the reactive reserves (maximum reactive capability minus actual VAr loading) of all generators on-line, would not provide an objective measure of the reactive reserves on a power system. Severe voltage profile degradation and even voltage collapse might be experienced in heavily loaded systems long before the reactive reserves on all the generators can be used up.

A method which attempts to provide the information required to properly judge the reactive reserves on a power system (location and amount) has been developed and is presented in this chapter. The proposed method partitions the power system into reactive areas by identifying the weak transmission elements (i.e. overhead lines, cables, transformers); severe voltage drops would occur if the reactive power transmitted through these elements is increased. A specified scalar α defines how weak a circuit must be to be identified as a weak connection. Groups of weak transmission elements define then the boundaries between the reactive areas.

A vulnerable node is then identified for each reactive area (using a criterion to be described in this chapter) and the maximum increase of reactive demand is evaluated at the selected vulnerable node, before its voltage violates a specified constraint and before voltage collapse is experienced (distances to low voltage and voltage collapse conditions). Such reactive load increase provides an indication of the reactive strength of the area.

The application of this quick scan technique provides an objective general view of the adequacy of the reactive reserves on a power system.

This chapter establishes the mathematical models of the power system employed in the assessment of the adequacy of the reactive power reserves. The algorithms for the partitioning of the network into reactive areas, for the evaluation of the distances to low voltage and voltage collapse conditions, and for the identification of vulnerable nodes, are also described in this chapter. The application of the methodology to a small power system is presented too.

2.2. Reactive Power Model

Two linearised models that relate reactive injections and voltage magnitudes of the buses of the power system are developed in this section.

Buses are classified according to the specification of their independent variables (i.e. P and V for PV buses, P and Q for PQ buses, and P and θ for the swing bus).

The first step is to linearise the load flow equations

$$P_i = \sum_{j=1}^{n} V_i Y_{ij} V_j \cos(\theta_{ij} - \gamma_{ij}) \tag{2.1}$$

$$Q_i = \sum_{j=1}^{n} V_i Y_{ij} V_j \sin(\theta_{ij} - \gamma_{ij}) \tag{2.2}$$

where n is the number of buses and

$$\mathbf{V}_i = V_i \underline{/\theta_i}, \ \mathbf{Y}_{ij} = Y_{ij} \underline{/\gamma_{ij}} = G_{ij} + jB_{ij}, \ \theta_{ij} = \theta_i - \theta_j$$

Using a Taylor series expansion and neglecting higher order partial derivatives.

$$\begin{bmatrix} [\Delta P_{pv}] \\ [\Delta P_{pq}] \\ [\Delta Q_g] \\ [\Delta Q_{pq}] \end{bmatrix} = \begin{bmatrix} [H_1] & [H_2] & [N_1] & [N_2] \\ [H_3] & [H_4] & [N_3] & [N_4] \\ [M_1] & [M_2] & [L_1] & [L_2] \\ [M_3] & [M_4] & [L_3] & [L_4] \end{bmatrix} \begin{bmatrix} [\Delta\theta_{pv}] \\ [\Delta\theta_{pq}] \\ [\Delta V_g] \\ [\Delta V_{pq}] \end{bmatrix} \tag{2.3}$$

or

$$\begin{bmatrix} [\Delta P_{pv}] \\ [\Delta P_{pq}] \\ [\Delta Q_g] \\ [\Delta Q_{pq}] \end{bmatrix} = \begin{bmatrix} [H] & [N] \\ [M] & [L] \end{bmatrix} \begin{bmatrix} [\Delta\theta_{pv}] \\ [\Delta\theta_{pq}] \\ [\Delta V_g] \\ [\Delta V_{pq}] \end{bmatrix}$$

where the subscripts pv, pq and g refer to PV, PQ and generator (PV and swing) buses respectively, and

$$[H] = \begin{cases} H_{ij} = \dfrac{\partial P_i}{\partial \theta_j} = V_i\, Y_{ij}\, V_j \sin(\theta_{ij} - \gamma_{ij}) \\ H_{ii} = \dfrac{\partial P_i}{\partial \theta_i} = -\sum\limits_{\substack{j=1 \\ j \neq i}}^{n} V_i\, Y_{ij}\, V_j \sin(\theta_{ij} - \gamma_{ij}) \end{cases} \tag{2.4}$$

$$[N] = \begin{cases} N_{ij} = \dfrac{\partial P_i}{\partial V_j} = V_i\, Y_{ij} \cos(\theta_{ij} - \gamma_{ij}) \\ N_{ii} = \dfrac{\partial P_i}{\partial V_i} = \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij}\, V_j \cos(\theta_{ij} - \gamma_{ij}) + 2V_i\, G_{ii} \end{cases} \tag{2.5}$$

$$[M] = \begin{cases} M_{ij} = \dfrac{\partial Q_i}{\partial \theta_j} = -V_i\, Y_{ij}\, V_j \cos(\theta_{ij} - \gamma_{ij}) \\ M_{ii} = \dfrac{\partial Q_i}{\partial \theta_i} = \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} V_i\, Y_{ij}\, V_j \cos(\theta_{ij} - \gamma_{ij}) \end{cases} \tag{2.6}$$

$$[L] = \begin{cases} L_{ij} = \dfrac{\partial Q_i}{\partial V_j} = V_i\, Y_{ij} \sin(\theta_{ij} - \gamma_{ij}) \\ L_{ii} = \dfrac{\partial Q_i}{\partial V_i} = \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij}\, V_j \sin(\theta_{ij} - \gamma_{ij}) - 2V_i\, B_{ii} \end{cases} \tag{2.7}$$

The first model (Model I) is obtained by neglecting the coupling matrices [N] and [M] relating real power injections to voltage magnitudes, and reactive power injections to voltage angles, respectively.

$$\begin{bmatrix} [\Delta Q_g] \\ [\Delta Q_{pq}] \end{bmatrix} = \begin{bmatrix} [L_1] & [L_2] \\ [L_3] & [L_4] \end{bmatrix} \begin{bmatrix} [\Delta V_g] \\ [\Delta V_{pq}] \end{bmatrix} = [L] \begin{bmatrix} [\Delta V_g] \\ [\Delta V_{pq}] \end{bmatrix} \tag{2.8}$$

A non-decoupled reactive power model can be derived from equation (2.3). Set

$$\begin{bmatrix}[\Delta P_{pv}]\\ [\Delta P_{pq}]\end{bmatrix} = [H]\begin{bmatrix}[\Delta \theta_{pv}]\\ [\Delta \theta_{pq}]\end{bmatrix} + [N]\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix} = [0]$$

then

$$\begin{bmatrix}[\Delta \theta_{pv}]\\ [\Delta \theta_{pq}]\end{bmatrix} = -[H]^{-1}\,[N]\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix} \tag{2.9}$$

from equation (2.3),

$$\begin{bmatrix}[\Delta Q_g]\\ [\Delta Q_{pq}]\end{bmatrix} = [M]\begin{bmatrix}[\Delta \theta_{pv}]\\ [\Delta \theta_{pq}]\end{bmatrix} + [L]\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix} \tag{2.10}$$

Substituting (2.9) into (2.10), Model II is obtained

$$\begin{bmatrix}[\Delta Q_g]\\ [\Delta Q_{pq}]\end{bmatrix} = \left[[L] - [M]\,[H]^{-1}\,[N]\right]\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix}$$

$$\begin{bmatrix}[\Delta Q_g]\\ [\Delta Q_{pq}]\end{bmatrix} = \begin{bmatrix}[L_1'] & [L_2']\\ [L_3'] & [L_4']\end{bmatrix}\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix} = [L']\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix} \tag{2.11}$$

2.3. Reactive Areas Determination

The method for determining the reactive areas is a minor modification of the algorithm described in reference [16]. It is a simple algorithm that identifies the weakest transmission elements connected to each bus. A given scalar α defines how weak a circuit must be to be considered as a weak connection. The groups of nodes that remain interconnected after the weak transmission elements are eliminated, define the reactive areas. Thus a reactive area is connected to the rest of the system only through weak transmission elements.

Matrix [L] of the decoupled reactive power Model I (see equation (2.8)) is used in the algorithm

$$\begin{bmatrix} [\Delta Q_g] \\ [\Delta Q_{pq}] \end{bmatrix} = [L] \begin{bmatrix} [\Delta V_g] \\ [\Delta V_{pq}] \end{bmatrix} = \left[\frac{\partial Q}{\partial V}\right] \begin{bmatrix} [\Delta V_g] \\ [\Delta V_{pq}] \end{bmatrix} \tag{2.12}$$

The non-zero off-diagonal elements of [L] correspond to transmission elements (i.e. overhead lines, cables, transformers). From equation (2.7)

$$L_{ij} = \frac{\partial Q}{\partial V_j} = V_i Y_{ij} \sin(\theta_{ij} - \gamma_{ij})$$

it is clear that the elements corresponding to a long transmission line (Y_{ij} small) which is heavily loaded (θ_{ij} large) have small absolute values. At the other extreme, the elements associated with a short lightly loaded circuit (Y_{ij} large and θ_{ij} small) have large absolute values. Thus, the method uses the elements of [L] to identify the weak transmission elements in the network. The main steps of the algorithm are

GIVEN α $(0 \leq \alpha \leq 1)$

FIND $m \leftarrow$ maximum element of $[L]$

SET $\alpha' \leftarrow \alpha * m$

FOR EACH row_i (node i) of the $[L]$ matrix DO

SORT the non-zero off-diagonal elements of the row_i (transmission circuits connected to node i) in ascending order of their absolute value (i.e. build $srow_i \leftarrow$ sorted row_i vector)

FIND the maximum index s such that $srow_i[1] + srow_i[2] + ... + srow_i[s] < \alpha'$, and

DEFINE the corresponding transmission elements (1, 2, ...s) as weak

END FOR EACH

DEFINE as reactive areas the groups of buses that remain interconnected after the weak transmission elements are eliminated

Any transmission element detected as weak at only one of its terminal nodes is reported.

Even when this simple algorithm uses only 'local' information, i.e. line or transformer parameters and state of the element, it highlights the network circuits through which increased reactive transmission can be achieved only at the expense of sacrificing the voltage profile.

As can be seen, the value of the scalar α defines how weak a transmission element must be to be identified as a weak connection. The larger α , the greater number of lines are considered weak and the larger the number of reactive areas defined.

2.4. Proximity Indicators to Low Voltage and Voltage Collapse

Environmental, siting, routing and financial problems force power systems to be operated close to their limits, particularly under critical contingencies at peak demand. Voltage drop may become excessive due to heavy power flows through transmission elements (e.g. after a severe transmission outage) if local reactive support is limited and other sources of reactive power are far (electrically) from loads. Voltage instability may be experienced after a severe contingency due to the lack of adequate reactive power support.

Prevention of voltage collapse (VC) requires the monitoring of indicators which show 'how far' the system is from VC. Steady state methods to evaluate the proximity of a power system to VC fall within two categories [17].

a) Snapshot or local indices. Indices are calculated based on information about the current operating conditions (e.g. sensitivities of load bus voltages and/or total reactive power generation, to variations in the reactive demand at a given node).

b) Global indices. The VC conditions are estimated and distances (e.g. voltage or reactive power margins) to the collapse point are evaluated.

A simple index which expresses the proximity to VC and gives a good insight into the reactive capabilities of the power system is presented here. It falls within the second category, i.e. global index; similarly, a margin indicating the proximity of the system to low voltage (LV) conditions is defined.

Two Q-distances (indices to LV and VC conditions) are defined for any node in the power system. They are depicted in Figure 2.1.

Qdist-to-LV. This Q margin is defined as the maximum reactive power demand that can be added to the node before its voltage drops below a specified minimum value (e.g. 0.90 pu).

Qdist-to-VC. This is the maximum increase of reactive demand at the node that the system can withstand before it becomes voltage unstable.

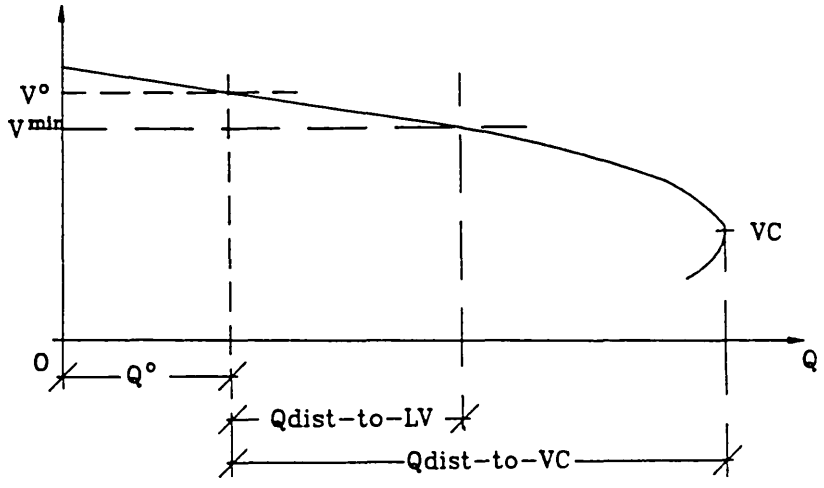


Figure 2.1 Q-distances to LV and VC conditions.

The strength (or weakness) of a node from a voltage/reactive power point of view is defined in terms of its Q-distances. A weak reactive node (or vulnerable node) is defined as a node for which Qdist-to-LV and/or Qdist-to-VC is small. The weakest reactive node (or the most vulnerable node) of a system or area is the node for which Qdist-to-LV and/or Qdist-to-VC has the smallest value. A strong reactive node, on the other hand, is defined as a node for which Qdist-to-LV and Qdist-to-VC are large. The Q-distances might be used to find normalised indicators of the proximity of the system to low voltage and voltage collapse conditions; e.g. in reference [18], a voltage collapse proximity indicator is defined as:

$$VCPI = Q^{o}/(Q^{o} + Qdist - to - VC)$$

The raw Q-distances Qdist-to-LV and Qdist-to-VC expressed in pu or MVAr have been

used in this work.

Specification of the minimum Q-distances to be maintained, would depend on each particular system and on the current operating conditions (i.e. normal or contingency state, peak or low demand level, etc.) [7]; the reactive demand level and importance of the loads in each reactive area should also be taken into consideration.

The evaluation of the Q-distances to low voltage (Qdist-to-LV) and voltage collapse (Qdist-to-VC) conditions for a given node could be carried out using a conventional load flow method. As the system approaches the voltage collapse conditions, however, load flow algorithms tend to oscillate or diverge [7]. An approximate linear technique, which produces good estimates, has been adopted instead. Either of the two linearised reactive power models presented in section 2.2 can be used to evaluate linear sensitivities.
As the voltage of each generating node is assumed to be fixed until the generator reaches its maximum VAr output, then $[\Delta V_g] = [0]$.

The relation between voltage changes at load buses $[\Delta V_{pq}]$ due to a reactive demand change at a given node i, ΔQ_{ipq}, can be found from equation (2.11) as:

$$\left[\Delta V_{pq}\right] = \left[L_4^{'}\right]^{-1} \left[\Delta Q_{pq}\right] = \left[S_{qpq}^{vpq}\right]_i \Delta Q_{ipq} \tag{2.13}$$

where $[S_{qpq}^{vpq}]_i$ is the i-th column of $[L_4']^{-1}$ giving the sensitivities relating changes in the load node voltage magnitudes due to a change in the reactive demand at bus i.

The change in the reactive power production at generating buses $[\Delta Q_g]$ due to a change in the reactive load at bus i can be obtained from equations (2.11) and (2.13) as follows

$$\left[\Delta Q_g\right] = \left[L_2^{'}\right]\left[\Delta V_{pq}\right] = \left[L_2^{'}\right]\left[S_{qpq}^{vpq}\right]_i \Delta Q_{ipq}$$

$$\left[\Delta Q_g\right] = \left[S_{qpq}^{qg}\right]_i \Delta Q_{ipq} \tag{2.14}$$

The Q-distances to low voltage (Qdist-to-LV) and voltage collapse (Qdist-to-VC) for a given node i can be easily calculated as follows

SET $\Sigma\Delta Q_{ipq} \leftarrow 0$

REPEAT

EVALUATE sensitivity vectors $[S_{qpq}^{vpq}]_i$ and $[S_{qpq}^{qg}]_i$

IF NOT voltage-instability THEN (see note 1)

SEARCH minimum ΔQ_{ipq} (see note 2)

UPDATE $[V_{pq}] \leftarrow [V_{pq}] + [S_{qpq}^{vpq}]_i \ \Delta Q_{ipq}$

UPDATE $[Q_g] \leftarrow [Q_g] + [S_{qpq}^{qg}]_i \ \Delta Q_{ipq}$

UPDATE $\Sigma\Delta Q_{ipq} \leftarrow \Sigma\Delta Q_{ipq} + \Delta Q_{ipq}$

IF ($V_{ipq} = V^{min}$) THEN

SET Qdist-to-LV $\leftarrow \Sigma\Delta Q_{ipq}$

END IF

END IF NOT

UNTIL voltage-instability

SET Qdist-to-VC $\leftarrow \Sigma\Delta Q_{ipq}$

Note 1: Voltage instability is detected by checking a change in sign of any element of $[S_{qpq}^{vpq}]_i$ or $[S_{qpq}^{qg}]_i$.

Note 2: Using equations (2.13) and (2.14) the minimum ΔQ_{ipq} that either causes a given maximum voltage deviation at node i, ΔV_{ipq}, or forces a generator to reach its maximum VAr capacity is found as:

$$\Delta Q_{pq} = \text{minimum}\left(\Delta Q'_{ipq}, \Delta Q''_{ipq}\right)$$

where

$$\Delta Q'_{ipq} = \Delta V_{dev}^{max} / \left[S_{qpq}^{vpq}\right]_{ii}$$

$$\Delta Q''_{ipq} = \underset{j}{\text{minimum}} \left\{ (Q_{jg}^{max} - Q_{jg}) / \left[S_{qpq}^{qg}\right]_{ji} \right\}$$

jg = generator (PV or slack)

ΔV_{dev}^{max} is the maximum voltage deviation allowed at node *i* at any given iteration, set to obtain a good compromise between the number of iterations and the accuracy of the Q-distances.

2.5. Identification of Vulnerable Nodes

Even with the use of an approximate fast method, the evaluation of the Q-distances Qdist-to-LV and Qdist-to-VC for every node in a power system would represent a heavy computational burden. This would also produce an overwhelming amount of information.

Instead, for each reactive area, a 'vulnerable' node is detected and the Q-distances are evaluated only for that node in the area. The ideal choice would be to select the node with the minimum value of Qdist-to-LV and Qdist-to-VC (the most vulnerable or 'weakest' node). It may be the case, however, that the node with the minimum Qdist-to-LV is not the same as that with the minimum Qdist-to-VC. This situation is illustrated in Figure 2.2 and would require the selection of two vulnerable nodes for that reactive area; additionally, the operator might want to evaluate the Q-distances for other worrying (based on experience) nodes, e.g. nodes at which the voltage is low.

The precise identification of the most vulnerable node in a reactive area is not possible without the evaluation of the Q-distances for all the nodes in the area; however a 'pseudo-short-circuit' calculation can give an idea of the relative strength (Q-distances) of the nodes in a system or area.

A conventional short-circuit analysis has been used during the selection of 'pilot' nodes for the secondary voltage control in France [19]. Priority is given to the substations with the highest short-circuit capacity, i.e. nodes with the smallest value of the Thevenin or driving point impedance (principal diagonal elements of the [Zbus] matrix). A pilot node is thus selected among those which are closest to the Thevenin voltage source.

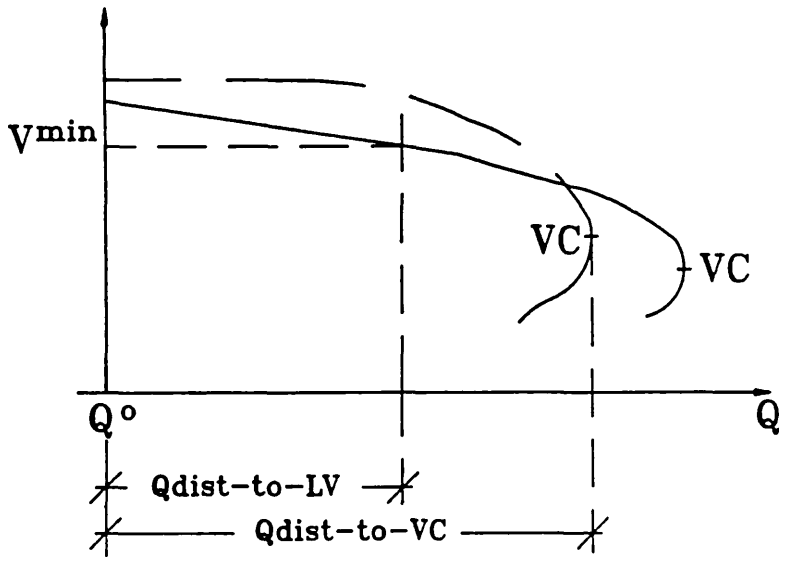
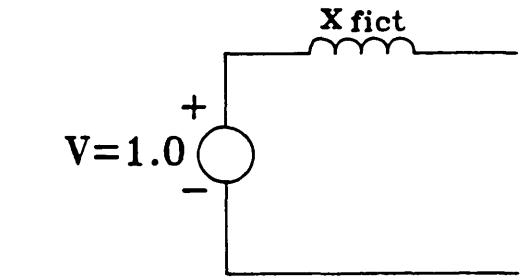


Figure 2.2 Q-distances for nodes with different characteristics

It is intuitively obvious that a quick identification of the vulnerable nodes in a reactive area might be carried out by selecting the nodes with the smallest short-circuit capacity. A conventional short-circuit study; however, would tend to classify nodes close to large generators as being the strongest (because of the small reactances of large generators as compared with those of small generators). This could lead to a misjudgment in a situation in which a large generator is close to its maximum VAr capacity, as illustrated in the example presented in section 6 of this report, where the node to which the largest generator of the system is connected, is found to be among the weakest.

A 'pseudo-short-circuit' calculation is thus carried out to identify the most vulnerable nodes in each of the reactive areas. However, instead of representing a generator as a voltage source behind one of the generatator's reactances (i.e. x"d, x'd, xd), a fictitious reactance which is proportional to the inverse of the VAr reserves of the generator is used as illustrated in Figure 2.3.



$$x_{fict} = k\ (1/Q_{ig}^{res}) = k/(Q_{ig}^{max} - Q_{ig}^{o})$$

Figure 2.3 Equivalent circuit of a generator

The *k* factor represents a kind of 'weight' given to the reactive reserves on the generators. For a small value of *k* (e.g. 0.1 was used in numerical example), the generators with reactive reserves and the nodes close to them would tend to be classified as strong nodes. Nodes far from generating stations (or near only to generators reaching their VAr limits) would appear as weak. This calculation would then pinpoint the nodes which are most vulnerable to low voltage problems.

For a larger *k* (e.g. 1.0 was used in the numerical example), less weight is given to the local reactive reserves and more importance is given to to the transmission facilities connecting a node to remotely located reactive reserves. This calculation would then detect the nodes most vulnerable to voltage collapse.

2.6. Numerical Example

The proposed steps for the evaluation of the reactive reserves have been applied to a small test power system, the 30 Bus New England System [16].

The reactive areas shown in Figure 2.4 were determined for the base case conditions and for $\alpha = 0.10$. If a transmission element (ij) is detected as weak at only one of its terminal nodes (i), it is indicated by an arrow ($i \rightarrow j$). The vulnerable nodes pinpointed by the 'pseudo-short-circuit' calculations ($k = 0.1$ and $k = 1.0$) and their Q-distances (Qdist-to-LV and/or Qdist-to-VC) are shown in Table 2.1; the corresponding Q-V curves are depicted in Figure 2.4. The decoupled Model I was used in the evaluation of the Q-distances.

Figure 2.4 gives a general objective visualisation of the reactive reserve conditions on the system. It provides a good indication of the reactive strength of the reactive areas. The Q-V curves are drawn starting at the base case operating conditions.

The total reactive capability of all generators minus their actual loading (i.e. the total reactive reserve at the generating stations) is 24.55 pu. It can be seen from Table 2.1 that the transmission network is unable to deliver all the reactive reserves available at the generating plants; long before this point is reached, the system will experience severe voltage problems and even voltage collapse.

A conventional short circuit calculation was carried out for this test system. Not surprisingly, node 30 (to which the largest generator in the system is connected) is the node with the largest short circuit capacity. From Table 2.1 on the other hand, it can be seen that node 30 is among the weakest; this is because generator 30 is not far from reaching its maximum VAr output.

Nodes in the reactive area ($\alpha = 0.1$)	Vulnerable nodes $k = 1.0$ (low V)	$k = 0.1$ (VC)	Q-distance at $V_{min}(0.9)$	VC
1	1	1	5.33	8.24
2, 3, 15, 16, 17, 18, 21, 22, 23, 24, 25	18	23	10.51 -	- 13.8
4, 5, 6, 7, 8, 10, 11, 13, 14	7	7	7.75	11.13
9, 30	9	30	5.11 -	- 7.55
12	12	12	3.88	7.02
19, 20	20	20	5.13	9.26
26, 27	27	26	8.54 -	- 12.84
28, 29	28	28	5.44	7.41

Table 2.1 Results of the reactive reserve evaluation ($\Delta V_{dev}^{max} = 0.025$ pu)

The shape of the Q-V curve for a given node *i* is defined by the characteristics and loading conditions of the transmission facilities between the sources of reactive power and node *i*. As an example, Figure 2.5a shows the Q-V curve for node 23. As long as generator 23 remains within its VAr production capabilities, the reactive power is supplied locally, and except for the reactive production of generator 23, there is no change in the operating conditions of the system. When the reactive reserves at generator 23 are exhausted, the main supply of reactive power comes from generator 22 and, because of the strong connection between nodes 22 and 23, the Q-V curve remains fairly flat (i.e there is only a small increase in the reactive power losses). However, as soon as generator 22 reaches its VAr production limits, the slope of the Q-V curve changes abruptly due to the characteristics and operating conditions of the transmission network between other reactive power sources (e.g. generators 19, 2, 6, 10, etc.) and node 23. Figures 2.5b and 2.5c show how the reactive power production of generating stations changes as the reactive demand at node 23 is increased, and Figure 2.5d depicts the increase in the total reactive power generation activated in the system.

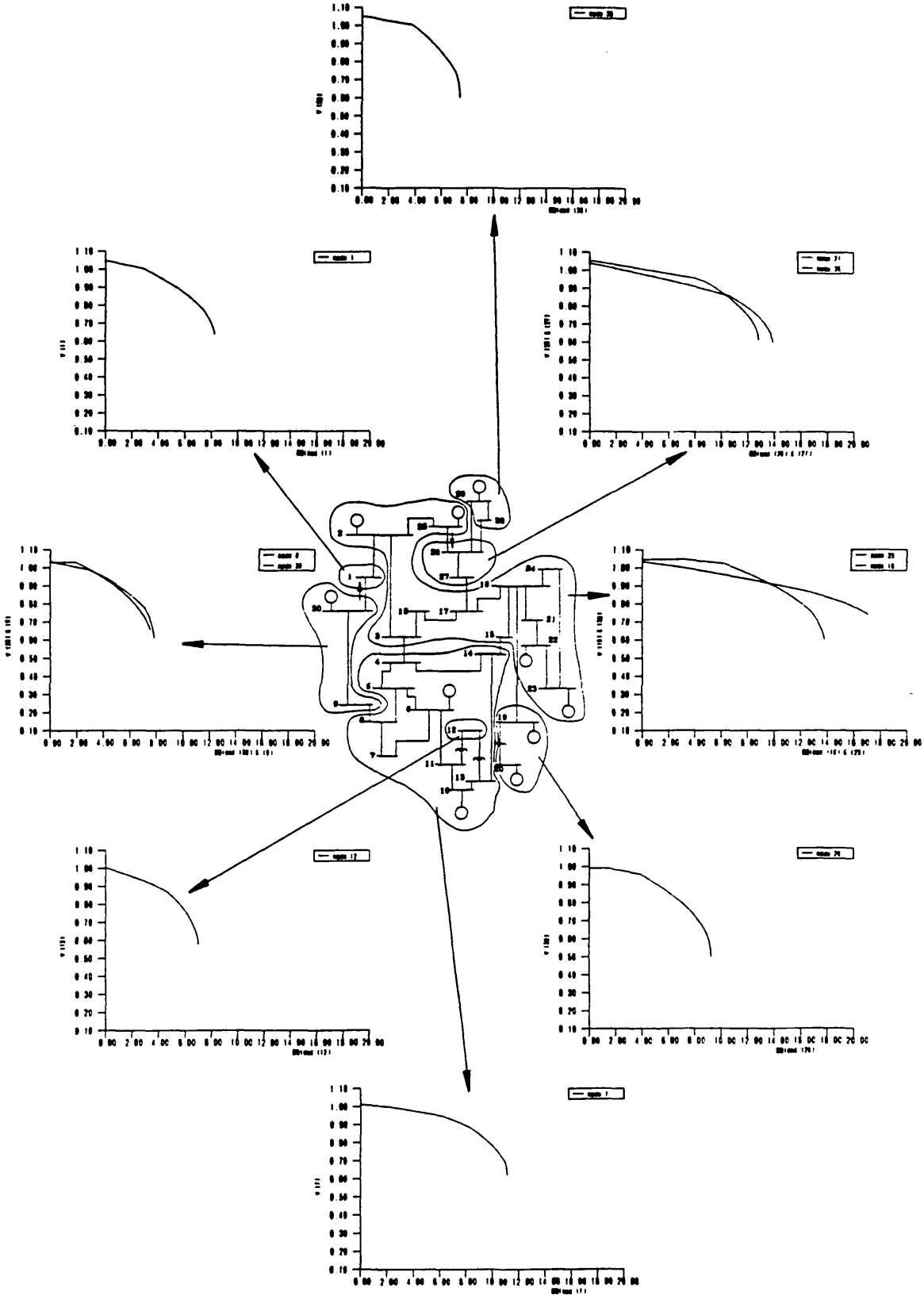


Figure 2.4 30 bus New England system

The change of slope of the line segments which make up the Q-V curve may be used to find strategies to 'move' the Q-V curve to the right, increasing the Q-distance to low voltage and/or voltage collapse conditions. A 'break point' caused by a generator reaching its VAr limits can be 'moved' to the right by increasing the reactive reserves of such a generator (i.e. reducing its reactive power production). A sensitivity calculation might be performed to find a strategy (e.g. switching of capacitors, start up of a generator, etc.) to relieve reactive power form being produced by the generator at which an increase in reactive reserves is required.

Figure 2.6 shows three Q-V curves for node 23:

a) base case (i.e the same Q-V curve as that of Figure 2.5a),

b) after a 3.0 pu capacitor bank is switched in at node 22,

c) after a 3.0 pu capacitor bank is switched in at node 20.

It is obvious that better results are obtained by providing local reactive power support. For case (b) an increase in both Qdist-to-LV and Qdist-to-VC is obtained, while for case (c) only a minor improvement in Qdist-to-VC is achieved. A similar analysis might be carried out to identify locations where reactive power support would be most beneficial to increase the reactive strength of a given area (Qdist-to-LV and/or Qdist-to-VC). Such information could be useful during the VAr expansion planning phase.

To test the accuracy of the proximity indicators to low voltage and voltage collapse conditions, the Q-distances for node 23 were calculated by repetitive a.c. load flow calculations and by the sensitivity technique described in this chapter. Figure 2.7 shows the Q-V curves. The Q-distances evaluated using Model I (decoupled) and Model II (non-decoupled) differ from those calculated with repetitive a.c. load flow calculations by approximately 4.7% and 2.4% (Qdist-to-LV) and 11.5% and 3.4% (Qdist-to-VC) respectively.

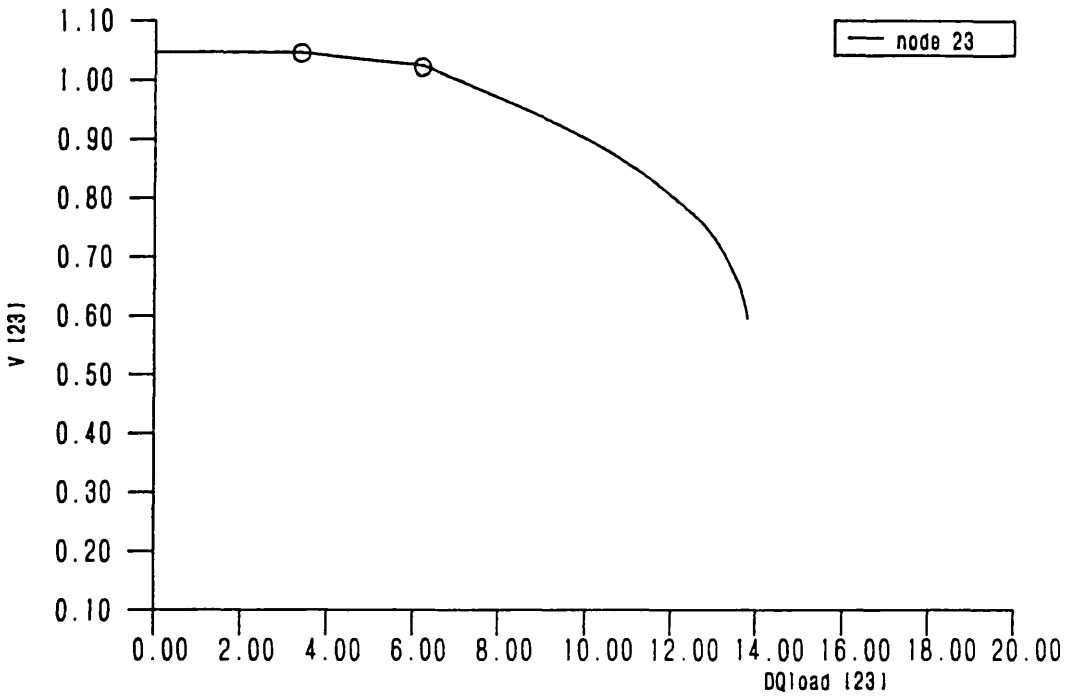


Figure 2.5a Q-V curve for node 23

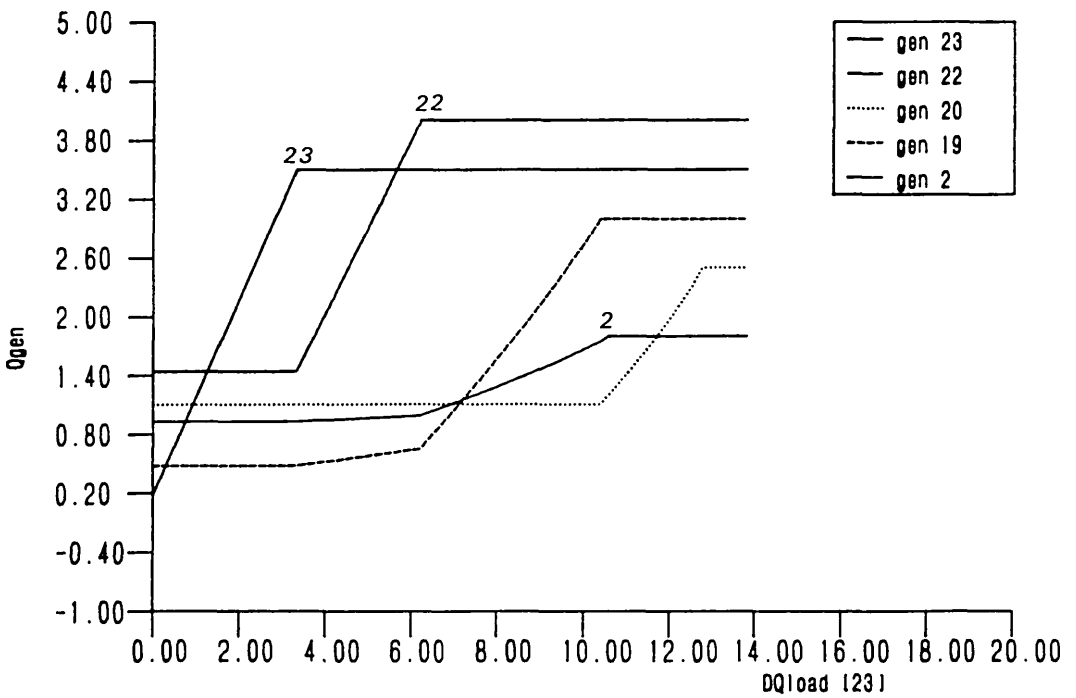


Figure 2.5b Reactive power production at generators 2, 19, 20, 22 and 23

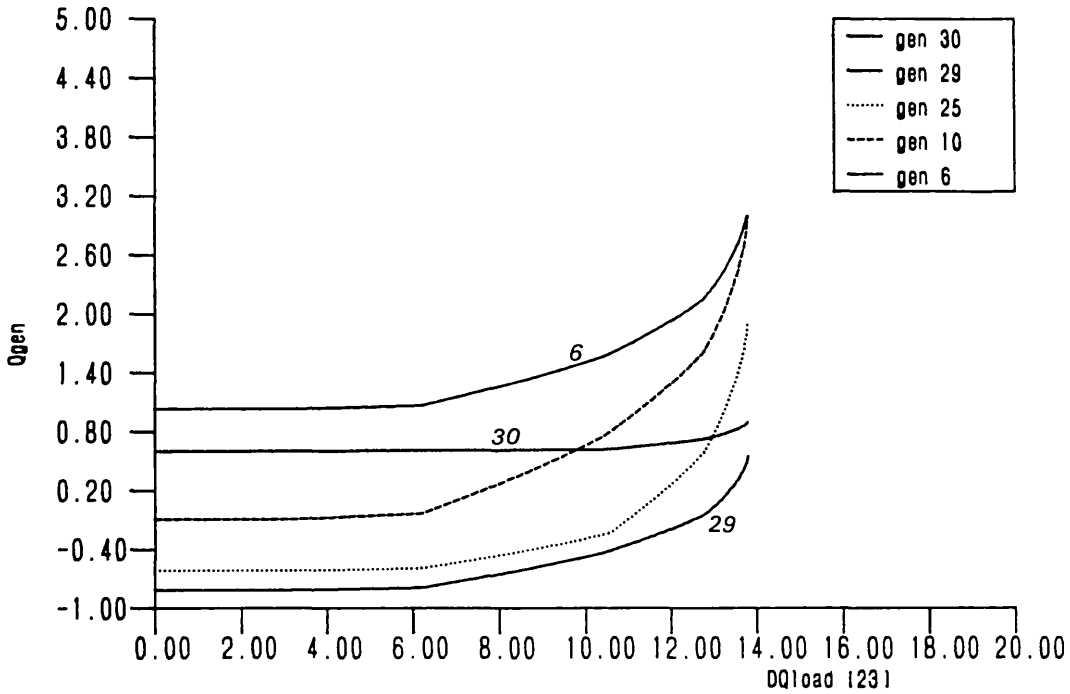


Figure 2.5c Reactive power production at generators 6, 10, 25, 29 and 30

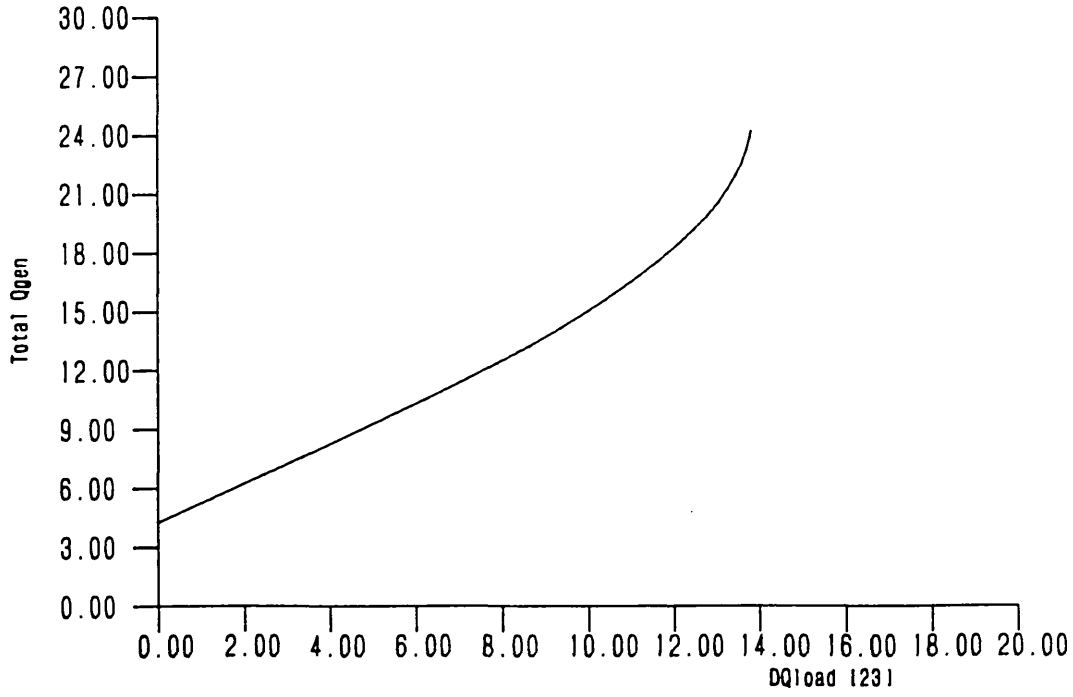


Figure 2.5d Total reactive power production activated in the system

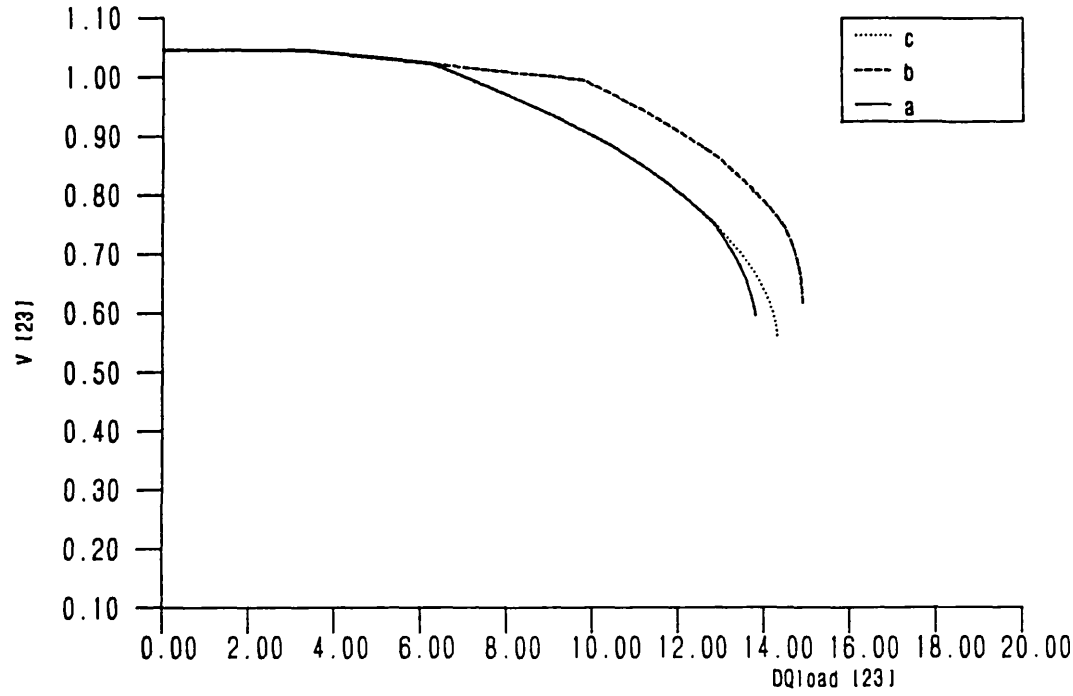


Figure 2.6 Increasing the Q-distances to LV and/or VC

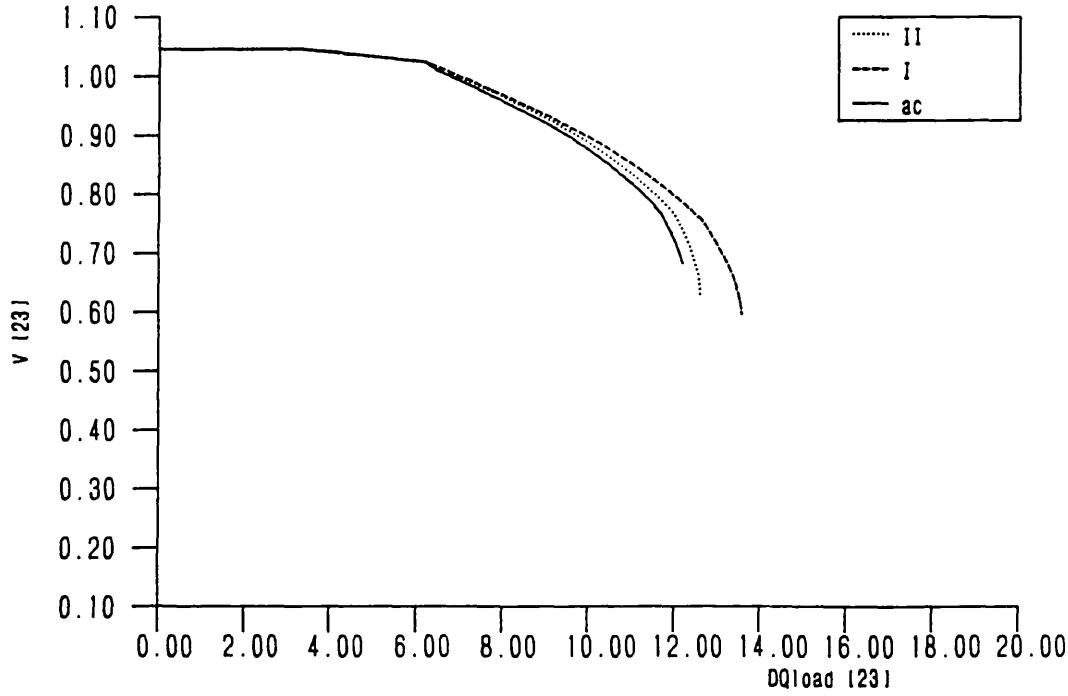


Figure 2.7 Q-V curves for node 23 by a.c., model I and model II ($\Delta V_{dev}^{max} = 0.01$)

Chapter 3

VAr/Voltage Contingency Selection

3.1. Introduction

When assessing the security of a power system, it is hardly feasible to carry out an accurate exhaustive testing to determine how well the system can withstand, at given operating conditions, the contingencies in the contingency list, so the contingency analysis procedure is divided into two main stages: contingency selection and contingency evaluation.

The contingency selection procedure is used in the operational planning phase of power systems to quickly scan a large number of contingencies to identify those which may cause serious limit violations and also to evaluate the severity of such violations. Contingencies are ranked according to the severity of their impacts on the power system, so that only the most critical cases at the top of the list need to be studied in detail. The reduced list of contingencies, identified as potentially critical, is called the **worst case list** [20].

The contingency evaluation procedure consists of detailed analysis by means of full a.c. load flow calculations, of the worst case list. The contingency selection algorithms are

classified as performance index (PI) based ranking techniques and screening methods.

PI ranking algorithms place contingencies in approximate order of severity, based on the change of value of a scalar PI which provides a measure of the impact of each contingency. The sensitivities of the PI with respect to outages are evaluated and the contingencies are ordered in decreasing order of relative severity according to the value of such sensitivities [21].

Screening techniques use approximate network solutions to identify contingencies causing limit violations; and although ranking is not strictly necessary, it may be done based on the approximate solutions, so that the a.c. load flow calculations are carried out starting with the most severe cases at the top of the list.

A conventional contingency screening and ranking algorithm for the selection of branch outages causing reactive power/voltage problems [22,23] has been implemented and is presented in this chapter. Four PIs employed to completely describe the severity of the violations caused by a contingency are established. Two alternative screening techniques are also described, although the results obtained to date have not been very encouraging. Finally, the application of the conventional screening method to a small power system is shown.

3.2. Contingency Screening of Branch Outages Causing VAr/Voltage Problems

An approximate network solution (to be described) is carried out to estimate the system variables for every outage in the contingency list. Potentially critical cases (i.e. those causing limit violations) are identified and performance indices which provide a measure of the impact of each of these contingencies are evaluated. The potentially critical

contingencies are then sorted in decreasing order of severity according to the magnitude of their PIs, and analysed by a full a.c. load flow technique starting with the most severe outages at the top of the worst case list.

For the approximate network solution a conventional contingency screening approach for the selection of branch outages causing VAr/voltage problems, consists of a single iteration of the fast decoupled load flow [24] equations (*1P-1Q*) for each outage in the contingency list [22, 23]. This is given by

$$\begin{bmatrix} B' \end{bmatrix} \begin{bmatrix} \begin{bmatrix} \Delta\theta_{pv} \end{bmatrix} \\ \begin{bmatrix} \Delta\theta_{pq} \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} \Delta P_{pv}/V_{pv} \end{bmatrix} \\ \begin{bmatrix} \Delta P_{pq}/V_{pq} \end{bmatrix} \end{bmatrix}$$

$$\begin{bmatrix} B' \end{bmatrix} \begin{bmatrix} \Delta\theta \end{bmatrix} = [\Delta P/V] \tag{3.1}$$

$$\begin{bmatrix} B'' \end{bmatrix} \begin{bmatrix} \Delta V_{pq} \end{bmatrix} = \begin{bmatrix} \Delta Q_{pq}/V_{pq} \end{bmatrix}$$

$$\begin{bmatrix} B'' \end{bmatrix} [\Delta V] = [\Delta Q/V] \tag{3.2}$$

where

$$\Delta P_i/V_i = \left(P_i^{sp} - \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\theta_{ij} - \gamma_{ij}) \right) / V_i \tag{3.3}$$

for all *PV* and *PQ* nodes, and

$$\Delta Q_i/V_i = \left(Q_i^{sp} - \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\theta_{ij} - \gamma_{ij}) \right) / V_i \tag{3.4}$$

for all *PQ* nodes,

$$P_i^{sp} = P_g^{sp} - P_d^{sp}, \qquad Q_i^{sp} = Q_g^{sp} - Q_d^{sp}$$

where the superscript *sp* means a fixed specified value, and the subscripts *g* and *d* stand for generation and demand respectively.

During the first half iteration (*1P*), $[\Delta\theta]$ are calculated using compensation techniques [25] and equation (3.1) to give

$$[\Delta\theta] = \left[[B']^{-1} - c_1 [B']^{-1} [M'] [M']^t [B']^{-1}\right] [\Delta P/V] \tag{3.5}$$

$$c_1 = \left(\Delta b'^{-1} + [M']^t [B']^{-1} [M']\right)^{-1} \tag{3.6}$$

where $[M']$ is a column vector which is null except for $M'_i = 1$ and $M'_j = -1$; i and j are the terminal nodes of the outaged line. If one of the terminal nodes of the branch (i or j) is the slack, then $[M']$ will have only one element different from zero.

If $1/c_1 = 0$, then the circuit outage splits the network; $\Delta b'$ is the change of suceptance (P-θ model) of branch ij, i.e. $\Delta b' = -1/x_{ij}$.

The $[\Delta P/V]$ vector in equation (3.5) is sparse with non-zero elements:

$$\Delta P_i/V_i = P_{ij}^o/V_i^o \qquad \text{if } i \neq \text{slack}$$

$$\Delta P_j/V_j = P_{ji}^o/V_j^o \qquad \text{if } j \neq \text{slack}$$

were the superscript *o* indicates base case values. Bus voltage angles can be updated after equation (3.5) is solved as

$$[\theta] = [\theta^o] + [\Delta\theta] \tag{3.7}$$

In the second half iteration (*1Q*) of the conventional *1P-1Q* screening technique, the estimated bus voltage angles $[\theta]$ are used to evaluate the vector of the reactive power

mismatches at PQ buses $[\Delta Q/V]$, (see equation (3.4)), to give

$$\Delta Q_i/V_i = \left(Q_i^{sp} - \sum_{j=1}^{n} V_i^o V_j^o Y_{ij} \sin(\theta_{ij} - \gamma_{ij})\right)/V_i^o$$

Applying compensation techniques and equation (3.2), changes in PQ bus voltage magnitudes are then calculated as

$$[\Delta V] = \left[\left[B''\right]^{-1} - c_2\left[B''\right]^{-1}\left[M''\right]\left[M''\right]^t\left[B''\right]^{-1}\right][\Delta Q/V] \qquad (3.8)$$

where $[M'']$ is a sparse column vector with non-zero elements, $M''_i = 1/t$ and $M''_j = -1$; t is the tap position if the outaged branch is a transformer with off-nominal tap setting or 1.0 otherwise. If i and/or j are PV or slack, the $[M'']$ is null or has only one element different from zero. c_2 is found from

$$c_2 = \left(\Delta b''^{-1} + \left[M''\right]^t\left[B''\right]^{-1}\left[M''\right]\right)^{-1} \qquad (3.9)$$

where $\Delta b''$ is the change of susceptance (Q-V model) at branch ij, i.e. $\Delta b'' = b_{ij}$, $y_{ij} = g_{ij} + jb_{ij}$. The simulation of effects of branch outages on the matrix $[B'']$ excludes the removal of the shunt compontents [26]. Bus voltage magnitudes at PQ nodes are updated after equation (3.8) is solved.

$$[V] = \left[V^o\right] + [\Delta V] \qquad (3.10)$$

Changes in the reactive power production at generating stations (PV nodes and slack) can then be estimated as

$$\left[\Delta Q_g\right] = \left[S_{vpq}^{qg}\right][\Delta V] \qquad (3.11)$$

where $[S_{vpq}^{qg}]$ is a matrix of sensitivities relating changes in the reactive production at generators (*PV* and slack nodes) due to changes in bus voltage magnitudes at load (*PQ*) nodes. The elements of $[S_{vpq}^{qg}]$ are

$$\left[S_{vpq}^{qg}\right]_{ij} = \frac{\partial Q_g}{\partial V_{jpq}} = V_i\, Y_{ij} \sin(\theta_{ij} - \gamma_{ij})$$

where *i* is *PV* or slack and *j* is *PQ*. The estimated reactive power at generating stations is:

$$\left[Q_g\right] = \left[Q_g^o\right] + \left[\Delta Q_g\right] \tag{3.12}$$

The estimated system variables $[V]$ and $[Q_g]$ are then used to evaluate the performance indices described in the next section. The main steps of the conventional *1P-1Q* contingency screening algorithm are summarised in Figure 3.1.

3.3. Performance Index

The performance index (PI) is a single-valued function whose magnitude is intended to reflect the severity of limit violations on bus voltage and output of reactive power sources for a given contingency. A contingency is considered to be severe if it causes a limit violation larger than a given threshold, or the summation of all limit violations is greater than a predefined tolerance.

To detect system wide as well as local problems, and to avoid mixing different variables in the same performance index, four PIs are defined to completely describe the system abnormalities due to VAr/voltage violations caused by a given contingency [20].

FOR each circuit ij IN contingency list DO

MODIFY admittance matrix to reflect the outage

EVALUATE $1/c_1$

$$1/c_1 \leftarrow \Delta b'^{-1} + [M']^t [B']^{-1} [M']$$

IF $1/c_1 = 0$ THEN

SEND warning message 'outage splits the network'

ELSE

EVALUATE $[\Delta P/V]$

$$\Delta P_i/V_i \leftarrow P^o_{ij}/V^o_i, \quad \Delta P_j/V_j \leftarrow P^o_{ji}/V^o_j$$

$$\Delta P_k/V_k \leftarrow 0 \text{ for } k \neq i,j$$

EVALUATE $[\Delta\theta]$

$$\left[\Delta\theta\right] \leftarrow \left[\left[B'\right]^{-1} - c_1 \left[B'\right]^{-1} \left[M'\right] \left[M'\right]^t \left[B'\right]^{-1}\right] [\Delta P/V]$$

UPDATE $[\theta]$

$$[\theta] \leftarrow [\theta^o] + [\Delta\theta]$$

EVALUATE $[\Delta Q/V]$

$$\Delta Q_k/V_k \leftarrow \left(Q^{sp}_k - \sum_{l=1}^{n} V^o_k \; V^o_l \; Y_{kl} \sin(\theta_{kl} - \gamma_{kl})\right) \Big/ V^o_k$$

EVALUATE $[\Delta V]$

$$[\Delta V] \leftarrow \left[\left[B''\right]^{-1} - c_2 \left[B''\right]^{-1} \left[M''\right] \left[M''\right]^t \left[B''\right]^{-1}\right] [\Delta Q/V]$$

UPDATE $[V]$

$$[V] \leftarrow [V^o] + [\Delta V]$$

EVALUATE $[\Delta Q_g]$

$$\left[\Delta Q_g\right] \leftarrow \left[S^{qg}_{vpq}\right] [\Delta V]$$

UPDATE $[Q_g]$

$$\left[Q_g\right] \leftarrow \left[Q^o_g\right] + \left[\Delta Q_g\right]$$

EVALUATE performance indices

$$PI_{v1}, PI_{v\infty}, PI_{q1}, PI_{q\infty}$$

END ELSE

END FOR

Figure 3.1 *1P-1Q* contingency screening algorithm

$$PI_{v1} = \sum_{\mu} w_{vi} \left| V_i - V_i^{lim} \right| \tag{3.13}$$

$$PI_{v\infty} = max \left(w_{vi} \left| V_i - V_i^{lim} \right| \right) \quad i\epsilon\mu \tag{3.14}$$

$$PI_{q1} = \sum_{\psi} w_{qi} \left| Q_g - Q_g^{lim} \right| \tag{3.15}$$

$$PI_{q\infty} = max \left(w_{qi} \left| Q_g - Q_g^{lim} \right| \right) \qquad i\epsilon\psi \tag{3.16}$$

where μ is the set of buses at which the voltage magnitude is outside specified limits, and ψ is the set of generating units at which the reactive power injection is outside production capabilities; V_i^{lim} (V_i^{min} or V_i^{max}) and Q_{ig}^{lim} (Q_{ig}^{min} or Q_{ig}^{max}) represent the violated limits. The value given to the tuning parameters w_{vi} and w_{qi} depends on experience and on the relative importance given to different limit violations. An additional parameter that may be used to fully describe the severity of a contingency is the number of potential violations.

Note that the PIs involve out-of-limits quantities only. A common form of PI_{q1} and $PI_{q\infty}$ involves the relative value of the VAr source limit violations, i.e. [20, 21, 23]

$$w_{qi} \left| (Q_{ig} - Q_g^{lim}) / Q_g^{lim} \right|$$

So each VAr limit violation is accounted for with the same importance, regardless of the size of the reactive power source. While this may be correct when seen from an individual generator's viewpoint, the PI_{q1} and $PI_{q\infty}$ are intended to indicate system wide problems. In other words, while a given VAr production limit violation$|(Q_{ig} - Q_{ig}^{lim}) / Q_{ig}^{lim}|$ relative to the limit of the generator, may be equally damaging to any generator, large or small, the same violation would represent a more severe problem for the system if it involves a large

generator because it would constitute a large deficit of reactive power which has to be

supplied from other sources. As a consequence, the form of the PI_{q1} and $PI_{q\infty}$ of equations (3.15) and (3.16) is considered to be more appropriate in ranking lists.

3.4. Alternative Screening Methods

After an outage, the excitation on the generating stations will change to maintain the voltage profile of the system. Sometimes, however, there are contingencies for which some generators reach the limit of their VAr production capabilities; a deviation from the scheduled voltage would be experienced at such generating buses.

Some misrankings may then occur when the conventional *1P-1Q* contingency screening method is applied, because it does not recognise generation VAr limits. The performance indices PI_{q1} and $PI_{q\infty}$ are intended to alleviate such misrankings. Severe VAr contingencies may be flagged by analysing the contingencies for which the value of PI_{q1} and/or $PI_{q\infty}$ is larger than a specified threshold. However, the actual impact caused by a generator reaching its VAr production limit, will depend on the location (and amount) of other sources of reactive power. The same numerical value of a generator VAr limit violation when PI_{q1} and $PI_{q\infty}$ are evaluated in the *1P-1Q* method, may well represent different conditions (i.e. secure/insecure) for different contingencies.

Two alternative approaches have been implemented in an attempt to provide a better estimate of the network behaviour and hence better contingency screening and ranking. The algorithms are described in the following sections, although the results obtained to date have not been encouraging.

3.4.1. *1P-nQ* screening algorithm

This method is a small modification of the conventional *1P-1Q* algorithm. It uses the first half iteration (*1P*) of the fast decoupled load flow and compensation techniques to estimate the changes in the bus voltage angles [$\Delta\theta$] (see equations (3.5)-(3.7)).

To carry out the second step (*nQ*) of the proposed screening procedure, the vector of reactive power mismatches at PQ buses [$\Delta Q/V$] is evaluated using the estimated bus voltage angles [θ]. The vector of PQ bus voltage magnitude changes

$$[\Delta V] = \left[\left[B''\right]^{-1} - c_2 \left[B''\right]^{-1} \left[M''\right]\left[M''\right]^t \left[B''\right]^{-1}\right] [\Delta Q/V]$$

is expressed as

$$[\Delta V] = \left[\Delta V^1\right] + c_2 \left[\Delta V^2\right] \tag{3.17}$$

where

$$\left[\Delta V^1\right] = \left[B''\right]^{-1} [\Delta Q/V]$$

$$\left[\Delta V^2\right] = -\left[B''\right]^{-1} \left[M''\right]\left[M''\right]^t \left[B''\right]^{-1} [\Delta Q/V]$$

$$c_2 = \left(\Delta b''^{-1} + \left[M''\right]^t \left[B''\right]^{-1} \left[M''\right]\right)^{-1}$$

Changes in the reactive power production at generating stations can be evaluated as

$$\left[\Delta Q_g\right] = \left[S^{qg}_{vpq}\right] [\Delta V] = \left[S^{qg}_{vpq}\right] \left[\left[\Delta V^1\right] + c_2\left[\Delta V^2\right]\right] \tag{3.18}$$

For a given generator, say *k*,

$$\Delta Q_{kg} = \left[S_{vpq}^{qg}\right]^{k} \left[\left[\Delta V^{1}\right] + c_2\left[\Delta V^{2}\right]\right] \tag{3.19}$$

where $[S_{vpq}^{qg}]^k$ is a row vector (row k of matrix $[S_{vpq}^{qg}]$) of sensitivities relating the change in reactive power production of generator k due to voltage magnitude changes at PQ nodes. Equation (3.19) can be rewritten as

$$\Delta Q_{kg} = S_{kg}^{1} + c_2\, S_{kg}^{2}$$

$$\Delta Q_{kg} = S_{kg}^{1} + S_{kg}^{2} / \left(\Delta b''^{-1} + \left[M''\right]\left[B''\right]^{-1}\left[M''\right]\right) \tag{3.20}$$

where

$$S_{kg}^{1} = \left[S_{vpq}^{qg}\right]^{k}\left[\Delta V^{1}\right]$$

$$S_{kg}^{2} = \left[S_{vpq}^{qg}\right]^{k}\left[\Delta V^{2}\right]$$

From equation (3.20) it is possible to determine the change of suceptance (Q-V model) $\Delta b''$ that causes generator k to reach its maximum VAr production capacity, given by

$$\Delta b_k'' = \left(\frac{S_{kg}^{2}}{Q_g^{max} - Q_{kg} - S_{kg}^{1}} - \left[M''\right]\left[B''\right]^{-1}\left[M''\right]\right)^{-1} \tag{3.21}$$

The minimum reduction in the line suceptance $\Delta b''$ that either causes the circuit to be totally outaged (i.e. $b'' = 0$), or forces a generating unit to reach its maximum VAr production capability, is determined; c_2 is then calculated and the changes in the PQ bus voltage magnitudes and reactive power production at generators, are evaluated.

This completes a Q iteration of the proposed *1P-nQ* screening algorithm. Further *Q* iterations are carried out until the circuit is totally outage (i.e. $b'' = 0$).

A generator reaching its VAr production limit is changed from being a PV node to a PQ node in the following iteration.

The main steps of the proposed algorithm are summarised in Figure 3.2.

The results obtained to date by applying the *1P-nQ* screening algorithm have not been encouraging. The estimated bus voltage magnitudes do not represent a noticeable improvement upon those found with the conventional *1P-1Q* method.

The suspected reason for the poor performance of the *1P-nQ* algorithm is the network model adopted. The contingency situations under which generators reach their maximum VAr production capabilities, are usually adverse conditions, e.g. very heavily loaded systems. Hence the simplicifcations and assumptions made in the fast decoupled load flow formulation are no longer completely valid.

Furthermore, while the compensation calculation used to estimate $[\Delta\theta]$ (P-θ model) is carried out in one step (*1P*), the simulation of the circuit outage to evaluate $[\Delta V]$ (Q-V model) is performed in several compensation steps (*nQ*) using the same estimated $[\theta] = [\theta^o] + [\Delta\theta]$ in all of them.

FOR each circuit ij IN contingency list DO

MODIFY admittance matrix to reflect the outage

EVALUATE $[\Delta P/V]$

$$\Delta P_i/V_i \leftarrow P^{o}_{ij}/V^{o}_{i},\ \Delta P_j/V_j \leftarrow P^{o}_{ji}/V^{o}_{j}$$

$$\Delta P_k/V_k \leftarrow 0 \text{ for } k \neq i,j$$

EVALUATE $[\Delta\theta]$

$$\left[\Delta\theta\right] \leftarrow \left[\left[B'\right]^{-1} - c_1 \left[B'\right]^{-1} \left[M'\right] \left[M'\right]^{t} \left[B'\right]^{-1}\right] [\Delta P/V]$$

UPDATE $[\theta]$

$$[\theta] \leftarrow [\theta^{o}] + [\Delta\theta]$$

REPEAT

EVALUATE $[\Delta Q/V]$

$$\Delta Q_k/V_k \leftarrow \left(Q_k^{sp} - \sum_{l=1}^{n} V_k\, V_l\, Y_{kl} \sin\left(\theta_{kl} - \gamma_{kl}\right)\right) \Big/ V_k$$

EVALUATE $[\Delta V^1]$ and $[\Delta V^2]$

$$[\Delta V^1] \leftarrow [B'']^{-1}\,[\Delta Q/V]$$

$$\left[\Delta V^2\right] \leftarrow -\left[B''\right]^{-1} \left[M''\right] \left[M''\right]^{t} \left[B''\right]^{-1} [\Delta Q/V]$$

FOR each generator k DO

EVALUATE $\Delta b''_k$

$$\Delta b''_k \leftarrow \left(S^2_{kg}/\left(Q^{max}_{kg} - Q_{kg} - S^1_{kg}\right) - \left[M''\right]^{t} \left[B''\right]^{-1} \left[M''\right]\right)^{-1}$$

END FOR

SEARCH minimum $\Delta b''$

EVALUATE c_2

$$c_2 \leftarrow \left(\Delta b''^{-1} + \left[M''\right]^{t} \left[B''\right]^{-1} \left[M''\right]\right)^{-1}$$

UPDATE $[V]$

$$[V] \leftarrow [V] + [\Delta V^1] + c_2\,[\Delta V^2]$$

UPDATE $[Q_g]$

$$Q_{kg} \leftarrow Q_{kg} + S^1_{kg} + c_2\, S^2_{kg}$$

UNTIL total outage

EVALUATE PI_{v1} and $PI_{v\infty}$

END FOR

Figure 3.2 *1P-nQ* contingency screening algorithm

3.4.2. Gauss-Seidel approach

This screening technique (*1P-1GS*) carries out one iteration of the hybrid fast decoupled load flow model [27]. It applies compensation techniques and the real part of the fast decoupled load flow (*1P*) to evaluate $[\Delta\theta]$ (see equations (3.5)-(3.7)).

To estimate the bus voltage magnitudes, it uses a Gauss-Seidel-like formula derived from the reactive part of the bus power equation:

$$Q_i = V_i \sum_{j=1}^{n} V_j \, (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \tag{3.22}$$

from where

$$V_i = \left(-Q_i / V_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} V_j \, (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \right) / B_{ii} \tag{3.23}$$

The VAr production limits of generators are taken into consideration as follows:

If the calculated Q_i exceeds the maximum production capability Q_i^{max} then Q_i^{max} is taken as the reactive power at the bus and the corresponding voltage magnitude is evaluated from equation (3.23).

The sequence of steps required to perform the *1P-1GS* screening algorithm is shown in Figure 3.3.

Poor estimates of the voltage magnitudes $[V]$ have been obtained with the *1P-1GS* algorithm. The number of GS iterations was increased (*1P-nGS*) in an attempt to get a more accurate solution; however, an extremely slow convergence rate was obtained, which seems to be a usual problem with Gauss-Seidel methods [20,28].

FOR each circuit ij IN contingency list DO

MODIFY admittance matrix to reflect the outage

EVALUATE $[\Delta P/V]$

$$\Delta P_i/V_i \leftarrow P^{\circ}_{ij}/V^{\circ}_i,\ \Delta P_j/V_j \leftarrow P^{\circ}_{ji}/V^{\circ}_j$$

$$\Delta P_k/V_k \leftarrow 0 \text{ for } k \neq i,j$$

EVALUATE $[\Delta\theta]$

$$[\Delta\theta] \leftarrow \left[[B']^{-1} - c_1 [B']^{-1} [M'] [M']^t [B']^{-1}\right] [\Delta P/V]$$

UPDATE $[\theta]$

$$[\theta] \leftarrow [\theta^{\circ}] + [\Delta\theta]$$

FOR each node k DO

IF node k IS slack or PV THEN

EVALUATE Q_k

$$Q_k \leftarrow V_k \sum_{l=1}^{n} V_l \left(G_{kl} \sin\theta_{kl} - B_{kl} \cos\theta_{kl}\right)$$

IF $Q_k > Q_k^{max}$ THEN

SET $Q_k \leftarrow Q_k^{max}$

EVALUATE V_k

$$V_k \leftarrow \left(-Q_k/V_k + \sum_{\substack{l=1 \\ l \neq k}}^{n} V_l \left(G_{kl} \sin\theta_{kl} - B_{kl} \cos\theta_{kl}\right)\right)/B_{kk}$$

END IF

END IF

ELSE (i.e. node is PQ)

EVALUATE V_k

$$V_k \leftarrow \left(-Q_k/V_k + \sum_{\substack{l=1 \\ l \neq k}}^{n} V_l \left(G_{kl} \sin\theta_{kl} - B_{kl} \cos\theta_{kl}\right)\right)/B_{kk}$$

END ELSE

END FOR

EVALUATE PI_{v1} and $PI_{v\infty}$

END FOR

Figure 3.3 *1P-1GS* contingency screening algorithm

3.5. Numerical Example

The 6 bus system [20] shown in Figure 3.4, has been used to illustrate the application of the method.

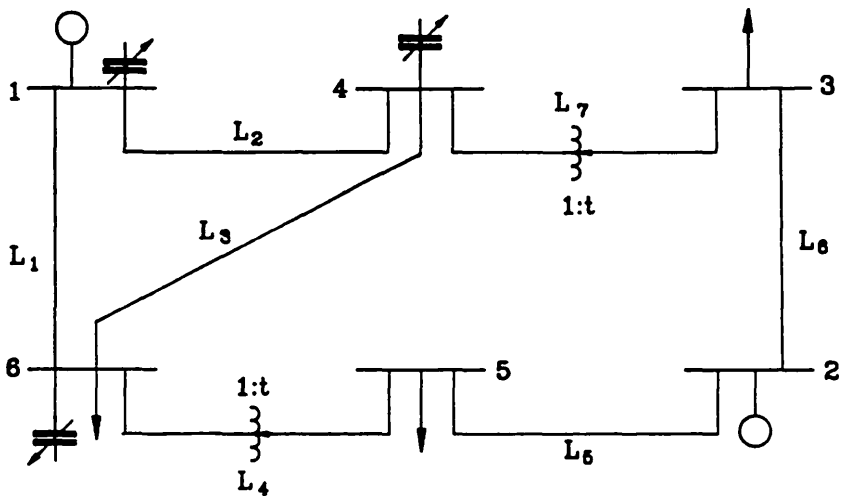


Figure 3.4 Diagram of the 6 bus system

The base case (i.e. intact system) operating conditions and the operational limits are shown in Table 3.1 and Table 3.2 respectively.

Bus No./type	Voltage p.u.	Angle degrees	Generation MW	Generation MVAr	Load MW	Load MVAr	Shunt Cap. B (p.u.)
1 swing	1.050	0.00	17.64	19.87	-	-	0.0339
2 PV	1.100	10.29	50.00	-0.08	-	-	-
3 PQ	1.067	-1.70	-	-	22.50	6.50	-
4 PQ	0.993	-1.20	-	-	-	-	0.0293
5 PQ	0.994	0.68	-	-	15.00	9.00	-
6 PQ	0.994	-1.83	-	-	25.00	2.50	0.0350

tap settings $t_{4\text{-}3} = 1.10$ $t_{6\text{-}5} = 1.025$

Table 3.1 Intact system operating conditions

Reactive power	Q_1	-20.00	100.00
generation (MVAr)	Q_2	-20.00	100.00
Load bus	V_3 V_4 V_5 V_6	0.975	1.10
voltage (p.u.)			

Table 3.2 Operational limits

Given the intact system operating conditions and the contingency list { L_1, L_2, L_3, L_4, L_5, L_6, L_7}, the contingency screening procedure generates the results shown in Figure 5. The exact solutions, obtained by performing an a.c. load flow calculation for each contingency case, are presented in Figure 3.6.

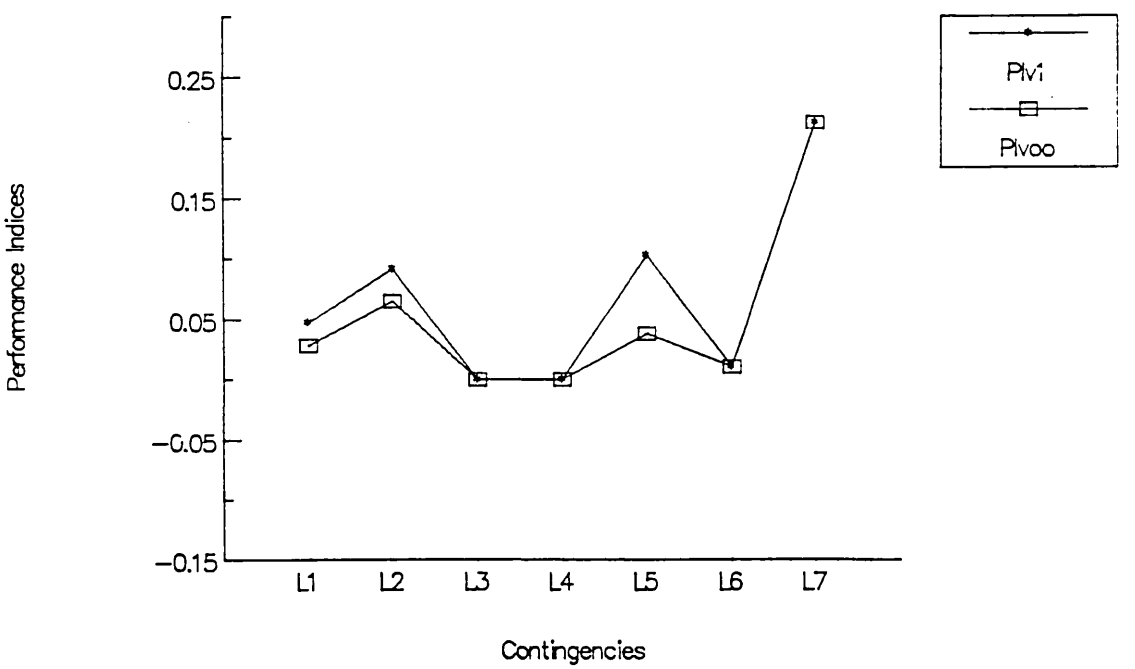


Figure 3.5 *1P-1Q* contingency screening results

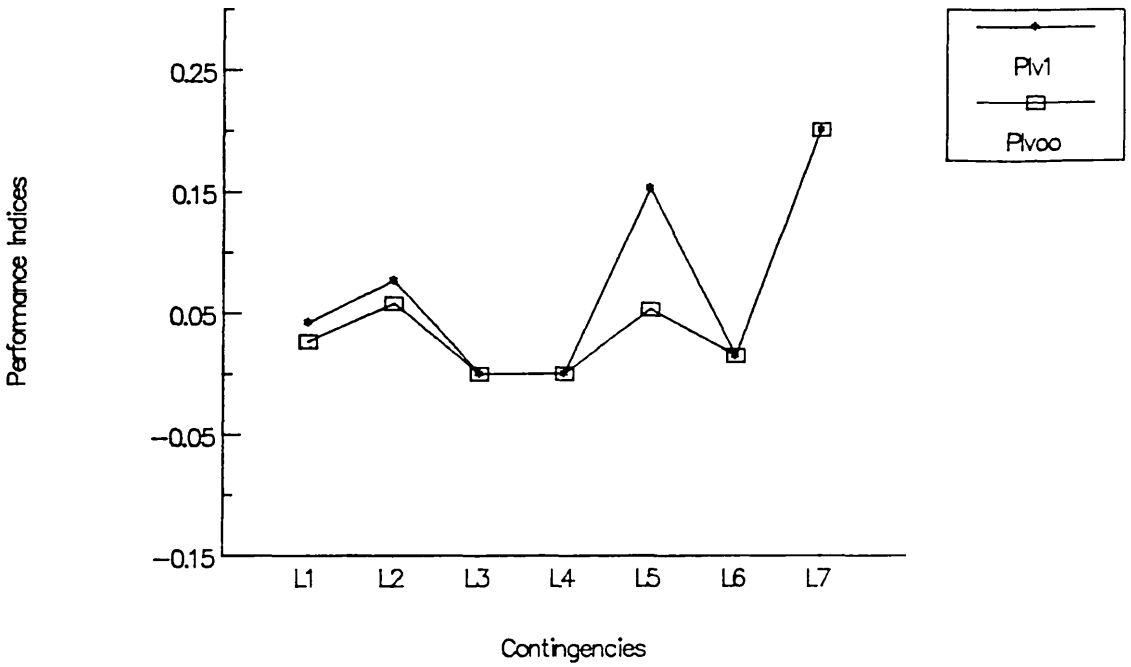


Figure 3.6 Exact a.c. load flow solution

Although some discrepancy exists between the results produced by the screening technique and those generated by the a.c. load flow calculations, all the contingencies are correctly classified by the *1P-1Q* algorithm, i.e. no misses or false alarms were found. Furthermore, the ranking of the contingencies, when sorted in decreasing order of severity according to the value of their PIs, is the same for both the exact and the approximate solutions. Figures 3.7 and 3.8 show the worst case list, classified using the performance indices PI_{v1} and $PI_{v\infty}$ respectively; the two solutions (i.e. approximate and exact) are presented.

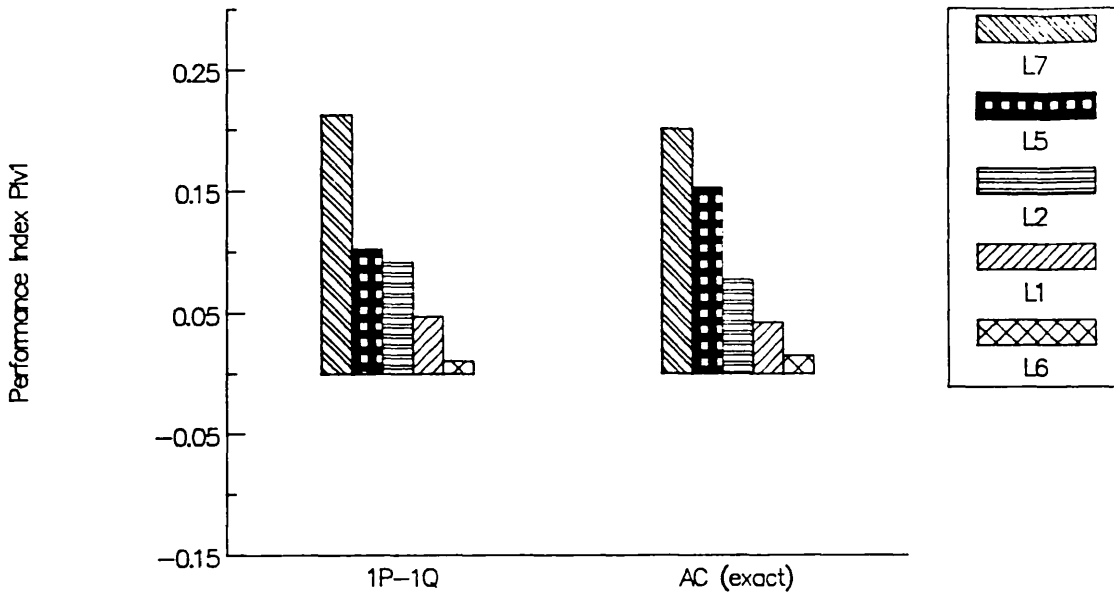


Figure 3.7 Worst case list sorted according to PI_{v1}

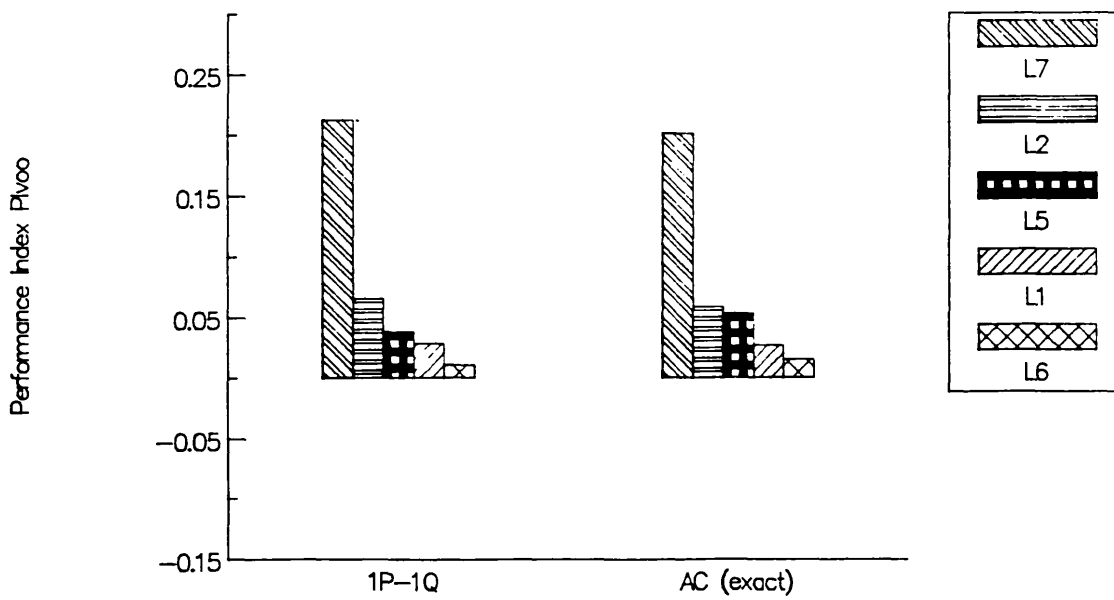


Figure 3.8 Worst case list classified according to $PI_{v\infty}$

Chapter 4

Reactive Power Rescheduling

4.1. Introduction

This chapter is concerned with the use of linear programming (LP) for the reactive power rescheduling problem. An algorithm is presented for determining the required adjustments of the settings of devices that affect the generation and flow of reactive power in the power system, in order to relieve limit violations. Generator terminal voltages, switchable shunt capacitors and inductors, and transformer tap settings are adjusted to alleviate over-voltages, under-voltages and generator VAr production limit violations.

Linear sensitivities are used to formulate an optimisation problem which is solved by a linear programming technique. Repeated model linearisations and LP optimisations are carried out until all limit violations are eliminated.

The reactive power rescheduling is mathematically formulated as an optimisation problem aiming at the minimisation of the amount of control adjustment required to relieve

operational limit violations. The objective function is formulated, and the constraints, dependent and control variables are identified. Accurate Q-V sensitivities are obtained by implicitly representing the voltage angles. The application of the rescheduling function to a small power system is also presented.

4.2. Problem Formulation

The objective of the reactive power rescheduling function described in this chapter is to alleviate voltage and generator VAr limit violations with an overall minimal adjustment (positive or negative) to the control devices. Accordingly, the objective function is mathematically formulated as [29]:

$$\text{Minimise} \sum_{i=1}^{ng} cg_i \, |\Delta V_i| + \sum_{i=1}^{nb} cb_i \, |\Delta B_i| + \sum_{i=1}^{nt} ct_i \, |\Delta T_i| \qquad (4.1)$$

where

cg_i is the cost associated with adjustments to the voltage of the generator i

cb_i is a penalising factor (i.e. cost) for changes in the susceptance of the switchable shunt capacitor (or inductor) i

ct_i is the cost penalising adjustments to the tap setting of transformer i

$|\Delta V_i|$ is the absolute value of the voltage adjustment at generating station i

$|\Delta B_i|$ is the absolute value of the susceptance change caused by the switching of capacitors (or inductors) at node i

$|\Delta T_i|$ is the absolute value of the adjustment in the tap setting of transformer i

ng is the number of generators

nb is the number of switchable shunt capacitor (and/or inductor) banks

nt is the number of transformers with tap changing facilities.

By assigning large values to the corresponding penalising factors, adjustments to certain control variables can be avoided or minimised. On the other hand, higher priority can be given to some control devices by assigning low values to their cost factors, e.g. adjustments which the operator can make easily and quickly on selected devices might be preferred.

Limits on the control variables can be expressed by inequality constraints, given as:

$$\begin{aligned} [\Delta V_g^{min}] \le [\Delta V_g] \le [\Delta V_g^{max}] \\ [\Delta B^{min}] \le [\Delta B] \le [\Delta B^{max}] \\ [\Delta T^{min}] \le [\Delta T] \le [\Delta T^{max}] \end{aligned} \tag{4.2}$$

where

$$\begin{aligned} [\Delta V_g^{min}] &= [V_g^{min}] - [V_g] \\ [\Delta V_g^{max}] &= [V_g^{max}] - [V_g] \\ [\Delta B^{min}] &= [B^{min}] - [B] \\ [\Delta B^{max}] &= [B^{max}] - [B] \\ [\Delta T^{min}] &= [T^{min}] - [T] \\ [\Delta T^{max}] &= [T^{max}] - [T] \end{aligned}$$

Here $[V_g^{min}]$, $[V_g^{max}]$ and $[V_g]$ are vectors of the minimum and maximum limits and the actual value of the voltage at generating stations. $[B^{min}]$, $[B^{max}]$ and $[B]$ are vectors of minimum, maximum and present value of the susceptance of switchable shunt capacitor (and/or inductor) banks. $[T^{min}]$, $[T^{max}]$ and $[T]$ are vectors specifying the minimum and maximum limits and the current operating settings of the transformer taps.

Adjustments of the VAr control devices (i.e. $[\Delta V_g]$, $[\Delta B]$ and $[\Delta T]$), will affect the load bus voltages $[V_{pq}]$ and the reactive power production at generating stations $[Q_g]$.

Operating limits on $[V_{pq}]$ and $[Q_g]$ (dependent variables) can be observed by the inequality constraints:

$$\begin{aligned}
\left[\Delta Q_g^{min}\right] &\le \left[S_{vg}^{qg}\right]\left[\Delta V_g\right] + \left[S_b^{qg}\right]\left[\Delta B\right] + \left[S_t^{qg}\right]\left[\Delta T\right] \le \left[\Delta Q_g^{max}\right] \\
\left[\Delta V_{pq}^{min}\right] &\le \left[S_{vg}^{vpq}\right]\left[\Delta V_g\right] + \left[S_b^{vpq}\right]\left[\Delta B\right] + \left[S_t^{vpq}\right]\left[\Delta T\right] \le \left[\Delta V_{pq}^{max}\right]
\end{aligned} \tag{4.3}$$

where

$$\begin{aligned}
\left[\Delta Q_g^{min}\right] &= \left[Q_g^{min}\right] - \left[Q_g\right] \\
\left[\Delta Q_g^{max}\right] &= \left[Q_g^{max}\right] - \left[Q_g\right] \\
\left[\Delta V_{pq}^{min}\right] &= \left[V_{pq}^{min}\right] - \left[V_{pq}\right] \\
\left[V_{pq}^{max}\right] &= \left[V_{pq}^{max}\right] - \left[V_{pq}\right]
\end{aligned}$$

Here $[Q_g^{min}]$, $[Q_g^{max}]$ and $[Q_g]$ are vectors of minimum and maximum limits and the actual production of reactive power at generating stations. $[V_{pq}^{min}]$, $[V_{pq}^{max}]$ and $[V_{pq}]$ are vectors of the minimum and maximum limits and the current value of the voltage at load (PQ) buses.

$[S_{vg}^{qg}]$, $[S_b^{qg}]$, $[S_t^{qg}]$, $[S_{vg}^{vpq}]$, $[S_b^{vpq}]$ and $[S_t^{vpq}]$ are sensitivity matrices relating changes in the dependent variables $[Q_g]$ and $[V_{pg}]$ (i.e. reactive production at generating stations and voltage at load buses) due to adjustments in the control variables $[V_g]$, $[B]$ and $[T]$ (i.e. voltage at generating stations, susceptance of switchable shunt capacitors and/or inductors, and tap settings of transformers). The linearised model used to evaluate the sensitivity matrices is presented in the next section.

4.3. Linear Sensitivities

To calculate the sensitivity matrices required in the formulation of the reactive power rescheduling problem, a linearised model of the network is developed in this section.

The load flow equations are linearised using a Taylor series expansion and neglecting higher order derivatives.

$$P_i = \sum_{j=1}^{n} V_i Y_{ij} V_j \cos(\theta_{ij} - \gamma_{ij}) = \sum_{j=1}^{n} V_i V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \qquad (4.4)$$

$$Q_i = \sum_{j=1}^{n} V_i Y_{ij} V_j \sin(\theta_{ij} - \gamma_{ij}) = \sum_{j=1}^{n} V_i V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \qquad (4.5)$$

n is the number of buses, and

$$\mathbf{V}_i = V_i \angle\theta_i, \qquad \mathbf{Y}_{ij} = Y_{ij} \angle\gamma_{ij} = G_{ij} + jB_{ij}, \qquad \theta_{ij} = \theta_i - \theta_j$$

$$\begin{bmatrix} [\Delta P_{pv}] \\ [\Delta P_{pq}] \\ [\Delta Q_g] \\ [\Delta Q_{pq}] \end{bmatrix} = \begin{bmatrix} [H_1] & [H_2] & [N_1] & [N_2] & [C_1] & [D_1] \\ [H_3] & [H_4] & [N_3] & [N_4] & [C_2] & [D_2] \\ [M_1] & [M_2] & [L_1] & [L_2] & [E_1] & [F_1] \\ [M_3] & [M_4] & [L_3] & [L_4] & [E_2] & [F_2] \end{bmatrix} \begin{bmatrix} [\Delta\theta_{pv}] \\ [\Delta\theta_{pq}] \\ [\Delta V_g] \\ [\Delta V_{pq}] \\ [\Delta B] \\ [\Delta T] \end{bmatrix}$$

or

$$\begin{bmatrix} [\Delta P_{pv}] \\ [\Delta P_{pq}] \\ [\Delta Q_g] \\ [\Delta Q_{pq}] \end{bmatrix} = \begin{bmatrix} [H] & [N] & [C] & [D] \\ [M] & [L] & [E] & [F] \end{bmatrix} \begin{bmatrix} [\Delta \theta_{pv}] \\ [\Delta \theta_{pq}] \\ [\Delta V_g] \\ [\Delta V_{pq}] \\ [\Delta B] \\ [\Delta T] \end{bmatrix} \tag{4.6}$$

the subscripts pv, pq and g refer to PV, PQ and generator (PV and swing) buses respectively. The dimension of $[H]$, $[N]$, $[M]$ and $[L]$ is (n-1) x (n-1), (n-1) x n, n x (n-1) and n x n respectively and their elements are evaluated as:

$$[H] = \begin{cases} H_{ij} = \dfrac{\partial P_i}{\partial \theta_j} = V_i\, Y_{ij}\, V_j \sin(\theta_{ij} - \gamma_{ij}) \\ H_{ii} = \dfrac{\partial P_i}{\partial \theta_i} = -\sum\limits_{\substack{j=1 \\ j \neq i}}^{n} V_i\, Y_{ij}\, V_j \sin(\theta_{ij} - \gamma_{ij}) \end{cases} \tag{4.7}$$

$$[N] = \begin{cases} N_{ij} = \dfrac{\partial P_i}{\partial V_j} = V_i\, Y_{ij} \cos(\theta_{ij} - \gamma_{ij}) \\ N_{ii} = \dfrac{\partial P_i}{\partial V_i} = \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij}\, V_j \cos(\theta_{ij} - \gamma_{ij}) + 2V_i\, G_{ii} \end{cases} \tag{4.8}$$

$$[M] = \begin{cases} M_{ij} = \dfrac{\partial Q_i}{\partial \theta_j} = -V_i\, Y_{ij}\, V_j \cos(\theta_{ij} - \gamma_{ij}) \\ M_{ii} = \dfrac{\partial Q_i}{\partial \theta_i} = \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} V_i\, Y_{ij}\, V_j \cos(\theta_{ij} - \gamma_{ij}) \end{cases} \tag{4.9}$$

$$[L] = \begin{cases} L_{ij} = \dfrac{\partial Q_i}{\partial V_j} = V_i\, Y_{ij} \sin(\theta_{ij} - \gamma_{ij}) \\ L_{ii} = \dfrac{\partial Q_i}{\partial V_i} = \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij}\, V_j \sin(\theta_{ij} - \gamma_{ij}) - 2V_i\, B_{ii} \end{cases} \tag{4.10}$$

From equation (4.4), it can be deduced that $[C] = [\partial P/\partial B]$ is a (n-1) x nb null matrix, which is obvious because pure capacitor (and/or inductor) banks are considered.

$$[C] = [\partial P/\partial B] = [0] \tag{4.11}$$

$[E] = [\partial Q/\partial B]$ is a n x nb sparse matrix with only one non-zero element per column, corresponding to the node at which the switchable capacitor (and/or inductor) bank is connected. From equation (4.5), the value of such an element can be evaluated as (e.g. for a bank connected to node i):

$$\frac{\partial Q_i}{\partial B_i} = -V_i^2 \tag{4.12}$$

$[D] = [\partial P/\partial T]$ is a (n-1) x nt sparse matrix with two non-zero elements per column, corresponding to the terminal nodes of the transformer associated with that column. If one of the terminal buses of the transformer is the slack, then $[D]$ has only one element different to zero in the corresponding column. Similarly, $[F] = [\partial Q/dT]$ is a n x nt matrix with two non-zero elements per column.

To determine the non-zero elements of the $[D]$ and $[F]$ matrices, consider the equivalent π circuit used to represent a transformer with off-nominal tap setting, shown in Figure 4.1 [30].

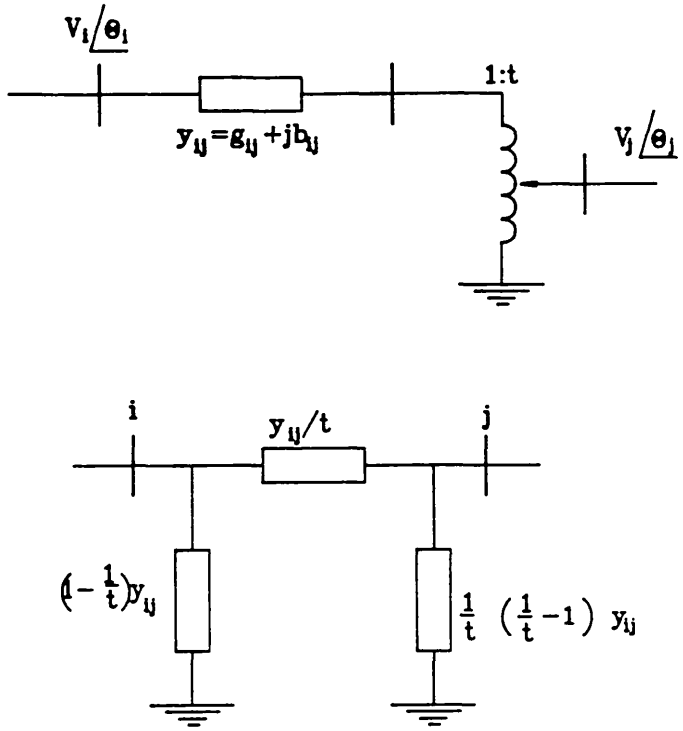


Figure 4.1 Representation of a transformer with off-nominal tap setting

The flow through the equivalent circuit of the transformer can be expressed as

$$P_{ij} - jQ_{ij} = V_i^2 y_{ij} - \frac{1}{t} y_{ij} V_i V_j \underline{/-\theta_{ij}} \tag{4.13}$$

$$P_{ji} - jQ_{ji} = \frac{1}{t^2} V_j^2 y_{ij} - \frac{1}{t} y_{ij} V_i V_j \underline{/\theta_{ij}} \tag{4.14}$$

Using the real part of equations (4.13) and (4.14), the two non-zero elements of the $[D]$ matrix column can be evaluated as

$$\frac{\partial P_i}{\partial t} = \frac{\partial P_{ij}}{\partial t} = \frac{1}{t^2} V_i V_j (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) \tag{4.15}$$

$$\frac{\partial P_j}{\partial t} = \frac{\partial P_{ji}}{\partial t} = -\frac{2}{t^3} V_j^2 g_{ij} + \frac{1}{t^2} V_i V_j (g_{ij} \cos\theta_{ij} - b_{ij} \sin\theta_{ij}) \tag{4.16}$$

If i or j is the slack then the corresponding column in the $[D]$ matrix has only one non-zero element.

Similarly, using the imaginary part of equations (4.13) and (4.14), the two non-zero elements of the column associated with the transformer in matrix $[F]$ are calculated as

$$\frac{\partial Q_i}{\partial t} = \frac{\partial Q_{ij}}{\partial t} = -\frac{1}{t^2} V_i V_j (b_{ij} \cos\theta_{ij} - g_{ij} \sin\theta_{ij}) \tag{4.17}$$

$$\frac{\partial Q_j}{\partial t} = \frac{\partial Q_{ji}}{\partial t} = \frac{2}{t^3} V_j^2 b_{ij} - \frac{1}{t^2} V_i V_j (b_{ij} \cos\theta_{ij} + g_{ij} \sin\theta_{ij}) \tag{4.18}$$

Having defined the elements of the sub-matrices of equation (4.6), the sensitivities relating changes in the dependent variables (i.e. $[\Delta V_{pq}]$ and $[\Delta Q_g]$) due to adjustments in the control devices (i.e. $[\Delta V_g]$, $[\Delta B]$ and $[\Delta T]$) are evaluated as follows:

After a converged a.c. load flow solution, the active power injections are held constant (except at the slack bus). From equation (4.6), it follows that

$$\begin{bmatrix} [\Delta P_{pv}] \\ [\Delta P_{pq}] \end{bmatrix} = [H] \begin{bmatrix} [\Delta \theta_{pv}] \\ [\Delta \theta_{pq}] \end{bmatrix} + [N] \begin{bmatrix} [\Delta V_g] \\ [\Delta V_{pq}] \end{bmatrix} + [0]\,[\Delta B] + [D]\,[\Delta T] = [0]$$

from which

$$\begin{bmatrix} [\Delta \theta_{pv}] \\ [\Delta \theta_{pq}] \end{bmatrix} = -[H]^{-1} \left[[N] \begin{bmatrix} [\Delta V_g] \\ [\Delta V_{pq}] \end{bmatrix} + [D]\,[\Delta T] \right] \tag{4.19}$$

From equation (4.6)

$$\begin{bmatrix}[\Delta Q_g]\\ [\Delta Q_{pq}]\end{bmatrix} = [M]\begin{bmatrix}[\Delta\theta_{pv}]\\ [\Delta\theta_{pq}]\end{bmatrix} + [L]\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix} + [E]\,[\Delta B] + [F]\,[\Delta T] \qquad (4.20)$$

Substituting (4.19) into (4.20)

$$\begin{bmatrix}[\Delta Q_g]\\ [\Delta Q_{pq}]\end{bmatrix} = \left[[L] - [M]\,[H]^{-1}\,[N]\right]\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix} + [E]\,[\Delta B] + \left[[F] - [M]\,[H]^{-1}\,[D]\right][\Delta T]$$

or

$$\begin{bmatrix}[\Delta Q_g]\\ [\Delta Q_{pq}]\end{bmatrix} = \begin{bmatrix}[L_1'] & [L_2']\\ [L_3'] & [L_4']\end{bmatrix}\begin{bmatrix}[\Delta V_g]\\ [\Delta V_{pq}]\end{bmatrix} + \begin{bmatrix}[E_1]\\ [E_2]\end{bmatrix}[\Delta B] + \begin{bmatrix}[F'_1]\\ [F_2']\end{bmatrix}[\Delta T] \qquad (4.21)$$

Since the reactive power injections at PQ buses are held constant

$$[\Delta Q_{pq}] = [L_3'][\Delta V_g] + [L_4'][\Delta V_{pq}] + [E_2]\,[\Delta B] + [F_2']\,[\Delta T] = [0]$$

then

$$[\Delta V_{pq}] = [S_{vg}^{vpq}][\Delta V_g] + [S_b^{vpq}]\,[\Delta B] + [S_t^{vpq}]\,[\Delta T] \qquad (4.22)$$

where

$$[S_{vg}^{vpq}] = -[L_4']^{-1}[L_3'] \qquad (4.23)$$

$$[S_b^{vpq}] = -[L_4']^{-1}[E_2] \qquad (4.24)$$

$$[S_t^{vpq}] = -[L_4']^{-1}[F_2'] \qquad (4.25)$$

From equation (4.21)

$$[\Delta Q_g] = [L_1'][\Delta V_g] + [L_2'][\Delta V_{pq}] + [E_1][\Delta B] + [F_1'][\Delta T] \quad (4.26)$$

Substituting (4.22) into (4.26)

$$[\Delta Q_g] = [S_{vg}^{qg}][\Delta V_g] + [S_b^{qg}][\Delta B] + [S_t^{qg}][\Delta T] \quad (4.27)$$

where

$$[S_{vg}^{qg}] = [L_1'] + [L_2'][S_{vg}^{vpq}] \quad (4.28)$$

$$[S_b^{qg}] = [E_1] + [L_2'][S_b^{vpq}] \quad (4.29)$$

$$[S_t^{qg}] = [F_1'] + [L_2'][S_t^{vpq}] \quad (4.30)$$

In order to avoid the rescheduling of practically ineffective devices (e.g. a large adjustment in a control variable for a minimal improvement in an inequality violation), the sensitivity matrices of equations (4.23)-(4.25) and (4.28)-(4.30) are constructed neglecting those elements whose absolute value is smaller than a given threshold. The criterion suggested by Mota-Palomino and Quintana [31] has been adopted. That is, if the change (absolute value) in a dependent variable (e.g. $|\Delta V_{ipq}|$, $|\Delta Q_{ig}|$), caused by the maximum feasible adjustment in a control device (e.g. ΔV_{jg}, ΔB_j, ΔT_j) is smaller than a specified threshold, then the corresponding element *ij* in the sensitivity matrix is neglected. The maximum feasible adjustment in a control device used to build the sparse sensitivity matrices, is the difference between the maximum and the minimum limits of the corresponding control variable.

4.4. Solution Methodology

The objective function (equation (4.1)), the limit constraints on the control variables (equation (4.2)), and the sensitivity-based constraints on the dependent variables (equation (4.3)) constitute an optimisation problem whose solution provides the adjustments on the VAr control devices required to alleviate limit violations. The optimisation problem can be shown in an integrated form as follows:

Minimise

$$\sum_{i=1}^{ng} cg_i \,|\Delta V_i| + \sum_{i=1}^{nb} cb_i \,|\Delta B_i| + \sum_{i=1}^{nt} ct_i \,|\Delta T_i|$$

subject to

$$\begin{aligned}
\left[\Delta V_g^{min}\right] &\le \left[\Delta V_g\right] \le \left[\Delta V_g^{max}\right] \\
\left[\Delta B^{min}\right] &\le [\Delta B] \le \left[\Delta B^{max}\right] \\
\left[\Delta T^{min}\right] &\le [\Delta T] \le \left[\Delta T^{max}\right] \qquad (4.31)
\end{aligned}$$

$$\left[\Delta Q_g^{min}\right] \le \left[S_{vg}^{qg}\right]\left[\Delta V_g\right] + \left[S_b^{qg}\right]\left[\Delta B\right] + \left[S_t^{qg}\right]\left[\Delta T\right] \le \left[\Delta Q_g^{max}\right]$$

$$\left[\Delta V_{pq}^{min}\right] \le \left[S_{vg}^{vpq}\right]\left[\Delta V_g\right] + \left[S_b^{vpq}\right]\left[\Delta B\right] + \left[S_t^{vpq}\right]\left[\Delta T\right] \le \left[\Delta V_{pq}^{max}\right]$$

To reduce the size of the problem, a relaxation technique has been adopted [31]. Only detected violations and the set of controls effective on them, plus other potential violations (i.e. non- violated dependent variables which are sensitive to those controls) are considered when the optimisation problem (4.31) is formulated.

The solution of the optimisation problem (4.31) is used to update the set points of the VAr

control devices. An a.c. load flow calculation is then carried out to verify the effectiveness of the proposed adjustments.

If there are no limit violations in the new system state, then the problem is solved. Otherwise, existing violations, effective controls and potential violations are identified and a new optimisation problem is formulated and solved.
These iterations are repeated until all limit violations are alleviated or an infeasible solution of the optimisation problem is obtained, in which case, the best approximation to the desired constraint problem is provided [32].

The optimisation problem formulated as shown in equation (4.31), can not be solved by means of a conventional linear programming (LP) technique, because the objective function is not linear, as it involves the absolute values of the control adjustments. Nevertheless, the optimisation problem of equation (4.31) can be rewritten as an equivalent LP problem applying the transformation next described.

Consider the following optimisation problem.

Minimise

$$\sum_{i=1}^{n} c_i \, |x_i|$$

subject to

$$\left[X^{min}\right] \leq [X] \leq \left[X^{max}\right]$$

$$\left[Z^{min}\right] \leq [A]\,[X] \leq \left[Z^{max}\right]$$

The solution of this optimisation problem is the same as that of an equivalent LP problem formulated as [33]:

Minimise

$$\sum_{i=1}^{n} c_i \, y_i$$

subject to

$$\left[X^{min}\right] \leq [X] \leq \left[X^{max}\right]$$

$$\left[Z^{min}\right] \leq [A]\,[X] \leq \left[Z^{max}\right]$$

$$-[Y] \leq [X] \leq [Y]$$

$$[Y] \geq [0]$$

Note that a set of n variables $[Y]$ and two sets of constraints have been introduced to formulate the LP problem. However, as only existing violations, effective controls and other potential violations are considered when the problem is formulated (relaxation and sparse sensitivity matrices), the LP problem remains small and computationally economical.

4.5. Numerical Example

The proposed reactive power rescheduling methodology has been tested using the 6 bus system [20] shown in Figure 4.2.

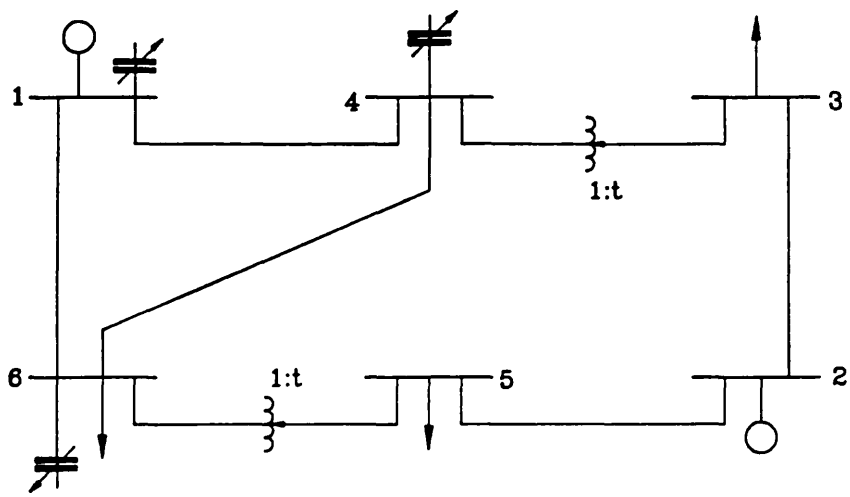


Figure 4.2 6 bus sample system

The initial operating conditions and the operational limits are shown in Table 4.1 and Table 4.2 respectively.

From Tables 4.1 and 4.2 it is seen that the voltage magnitude at buses 4, 5 and 6 (i.e. V_4, V_5 and V_6) is outside operational limits. The proposed reactive power rescheduling function has been used to alleviate such under-voltages.

Bus No./type	Voltage p.u.	Angle degrees	Generation MW	Generation MVAr	Load MW	Load MVAr	Shunt Cap. B (pu)
1 swing	1.050	0.00	84.18	39.67	-	-	0.033898
2 PV	1.100	-1.78	50.00	17.47	-	-	-
3 PQ	1.009	-10.86	-	-	45.00	13.00	-
4 PQ	0.941	-8.20	-	-	-	-	0.029326
5 PQ	0.922	-11.12	-	-	30.00	18.00	-
6 PQ	0.926	-11.16	-	-	50.00	5.00	0.035088

Tap settings $t_{4\text{-}3} = 1.10$ $t_{6\text{-}5} = 1.025$

Table 4.1 Initial operating conditions

	Variable	Lower limit	Upper limit
Control devices			
Generator	V_1	0.95	1.10
voltage (pu)	V_2	0.95	1.15
Capacitor	B_1	0.00	0.05
bank B (pu)	B_4	0.00	0.05
	B_6	0.00	0.05
Tap	$T_{4\text{-}3}$	0.90	1.10
setting	$T_{6\text{-}5}$	0.90	1.10
Dependent variables			
Reactive power	Q_1	-20.00	100.00
generation (MVAr)	Q_2	-20.00	100.00
Load bus	V_3, V_4, V_5, V_6	0.975	1.10
voltage (pu)			

Table 4.2 Operational limits

Table 4.3 and Figures 4.3 and 4.4 depict the results obtained. Cases 3 and 4 show how adjustments to certain control devices may be avoided by assigning large values to the

corresponding cost factors. Case 2, on the other hand, shows that high priority can be given to some control devices by assigning low values to their penalising factors.

	Variable	Initial state	Final state case 1	case 2	case 3	case 4
	V_3	1.009	1.073	1.076	1.062	1.074
Load bus	V_4	0.941	0.999	1.002	1.001	1.000
voltage (pu)	V_5	0.922	0.987	0.987	0.987	0.987
	V_6	0.926	0.987	0.989	0.987	0.988
Reactive power						
	Q_1	39.67	36.77	33.81	36.13	36.15
generation (MVAr)						
	Q_2	17.47	15.01	14.72	16.10	14.94

Table 4.3 Reactive power rescheduling - dependent variables

In order to account for the inaccuracies introduced by the linearisation process; when the optimisation problem of equation (4.31) is formulated, the operational limits on the dependent variables $[V_{pq}]$ and $[Q_g]$ (sensitivity-based constraints) are slightly narrowed, e.g.

$$V_{ipq}^{max} = V_{ipq}^{max} - Tol* \left(V_{ipq}^{max} - V_{ipq}^{min}\right)$$

$$V_{ipq}^{min} = V_{ipq}^{min} + Tol* \left(V_{ipq}^{max} - V_{ipq}^{min}\right)$$

Tol has been set equal to 0.1 for all the dependent variables $[V_{pq}]$ and $[Q_g]$. In the four cases, the reactive power rescheduling procedure required only one iteration to relieve all the operating limit violations.

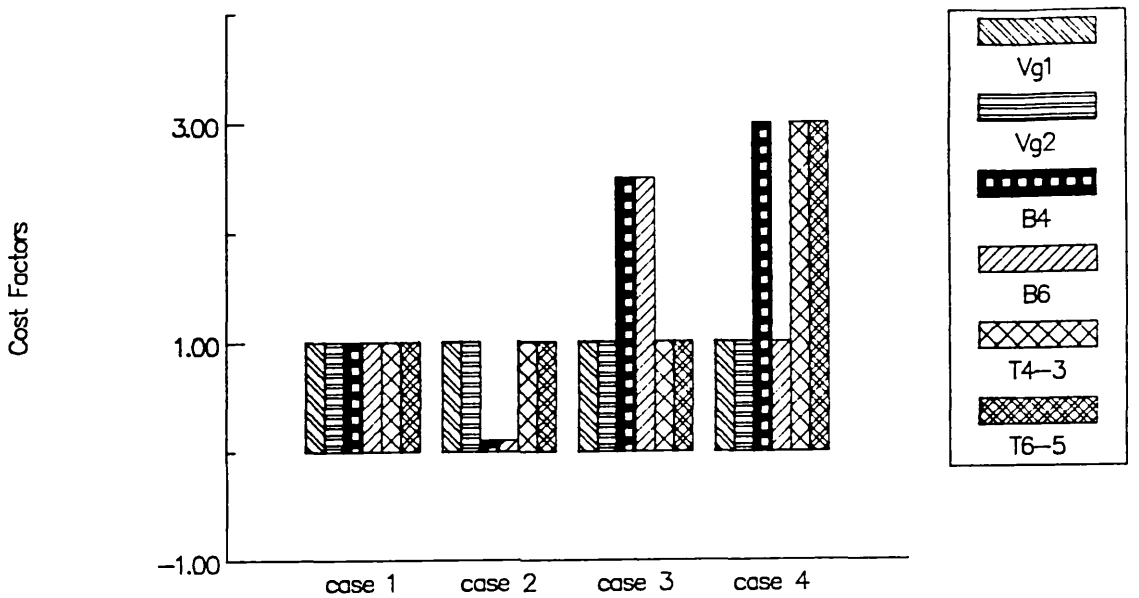


Figure 4.3 Cost factors associated with the control devices

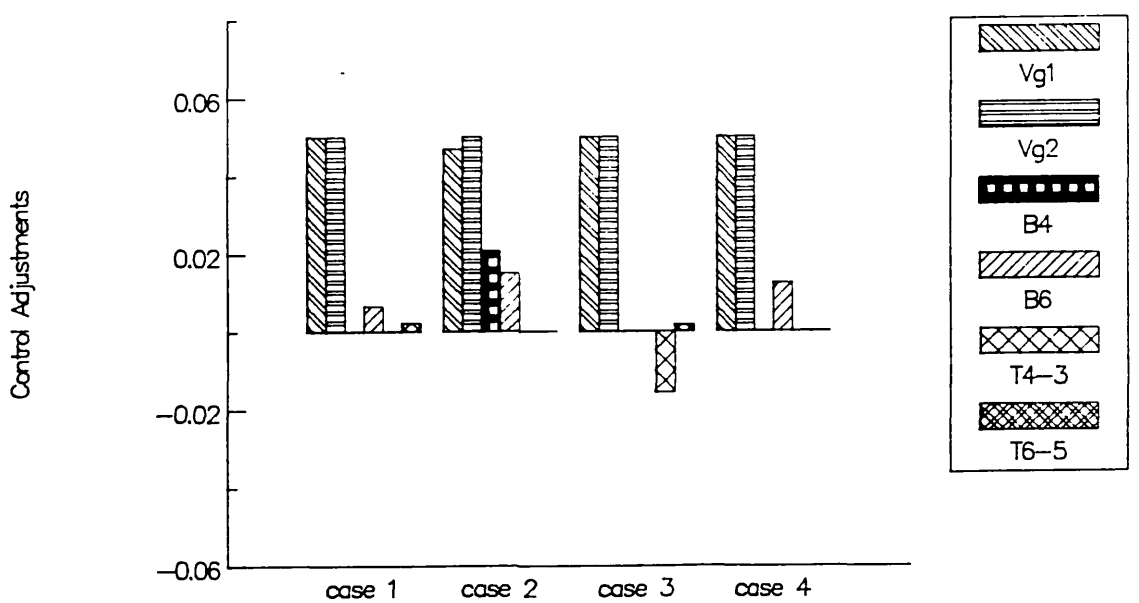


Figure 4.4 Reactive power rescheduling - control adjustments

Chapter 5

Co-ordination Strategy

5.1. Introduction

The adjustments of VAr/voltage control devices, proposed to relieve limit violations for security risk contingencies and to increase the reactive strength (Q-distances) of a given area (or areas), are co-ordinated using a linear programming technique.

The algorithm for the evaluation of the Q-distances to low voltage and voltage collapse conditions, and a procedure to increase such Q-distances are presented in chapter 2 of this thesis. The contingency screening and ranking technique employed to detect those contingencies representing potential security risks, is described in chapter 3 and chapter 4 deals with the reactive power rescheduling function used to alleviate operational limit violations.

This chapter presents the strategy used to collect and organise all the VAr/voltage control adjustments needed to eliminate operational limit violations for each security risk contingency, and to increase the Q-distances of specified areas. The mathematical formulation of the strategy as a two-phase optimisation problem is described, and its

application to a small test power system is also shown.

As the philosophy of operation of the CEGB (and perhaps of most electricity companies) is to implement as much preventive control as possible (within defined utility constraints), initially all the control adjustments are proposed to what is called here the **co-ordination function**, as desirable preventive strategies. The objective of the co-ordination function is thus to maximise the proposed control adjustments to be implemented in a preventive mode without causing any limit violation on the base case or any VAr/voltage security risk contingency. It is emphasised that such adjustments are to be carried out using available controls for the operational planning phase.

5.2. Global Methodology

The methodology adopted to bring together all the control adjustments required to alleviate limit violations for each voltage security risk contingency, and to increase the reactive strength of a given area (or areas), is depicted in Figure 5.1. The objective is to maximise the control shifts to be executed as a preventive plan, without producing operating constraint violations on the base case or any voltage security risk contingency conditions [20].

The co-ordination function is carried out in two steps. In the first step, the effects of the proposed control shifts on the base case conditions are evaluated. All violations are included in the constraints set and an upper-bound LP problem is formulated and solved. Adjustments which over constrain the co-ordination problem are detected, dropped and proposed as corrective strategies for the corresponding contingencies.

In the second phase of the co-ordination function, the effects of the control adjustments proposed by the first phase on the voltage security risk contingencies are determined. All

detected violations are included in the constraints set and a new upper-bound LP problem is formulated and solved.

Before the first phase of the co-ordination function is carried out, conflicting adjustments are detected for each control device (i.e. $[V_g]$, $[B]$, $[T]$), e.g. if $\Delta T_1\ (k) > 0$ and $\Delta T_1\ (l) < 0$ for $l \neq k$, then the adjustment on T_1 proposed by the contingency k reactive power rescheduling $\Delta T_1\ (k)$, is a conflicting adjustment. Contingencies involving conflicting control adjustments are identified and for each of such contingencies a reactive power rescheduling is performed, penalising heavily the conflicting controls so as to avoid them.

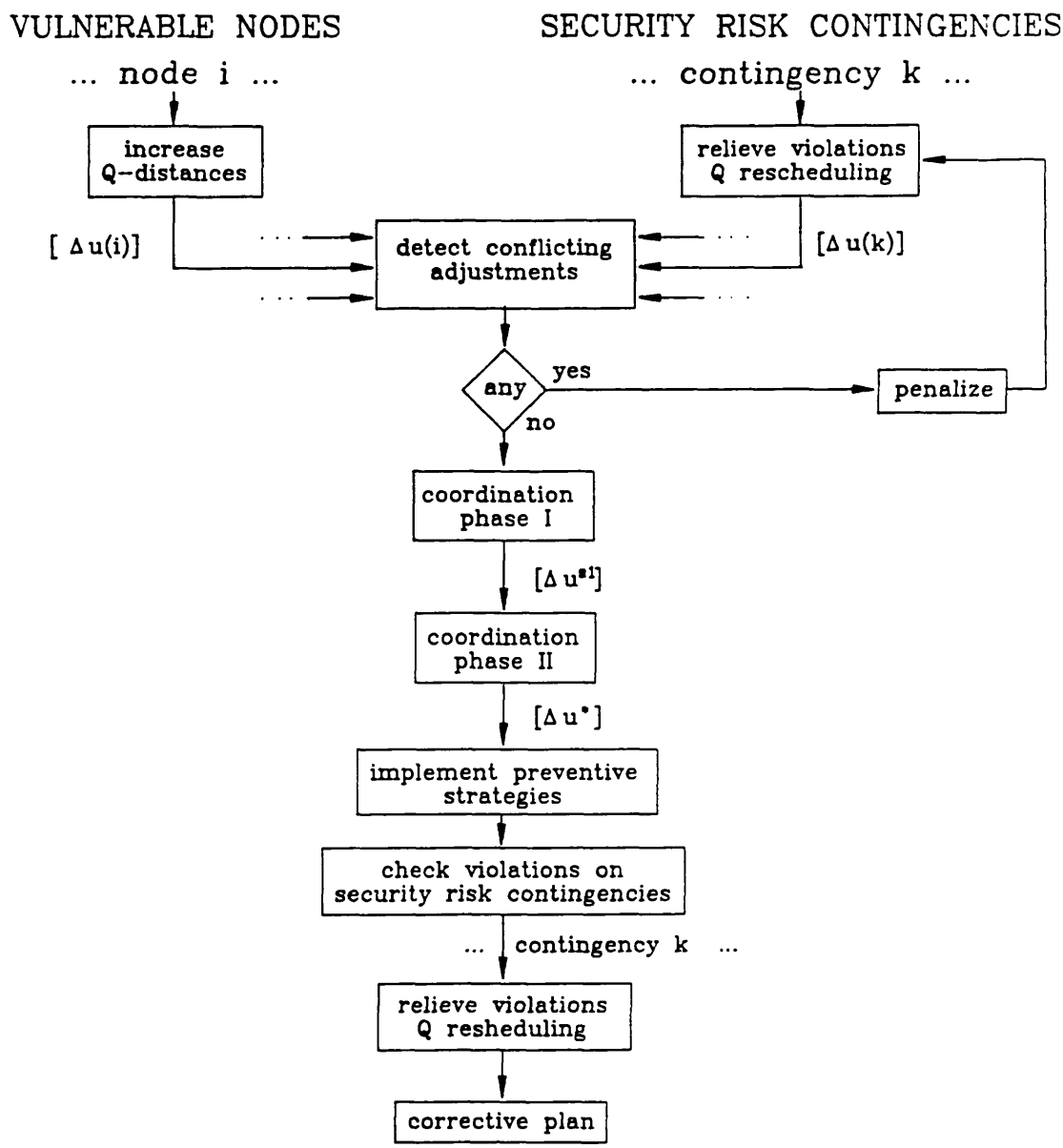


Figure 5.1 Co-ordination Strategy

5.3. Co-ordination Function - Phase I

After conflicting control adjustments have been eliminated, the maximum adjustment proposed for each control device is determined

$$\left[\Delta u^{'}\right] = \begin{bmatrix} \left[\Delta V_g^{'}\right] \\ \left[\Delta B^{'}\right] \\ \left[\Delta T^{'}\right] \end{bmatrix} = \begin{bmatrix} \Delta V_1^{'} \\ \vdots \\ \Delta V_{ng}^{'} \\ \Delta B_1^{'} \\ \vdots \\ \Delta B_{nb}^{'} \\ \Delta T_1^{'} \\ \vdots \\ \Delta T_{nt}^{'} \end{bmatrix} \tag{5.1}$$

e.g.

$$\Delta B_i^{'} = \Delta B_i\,(k)$$

where k is such that

$$|\Delta B_i\,(k)| = \underset{j}{\text{maximum}}\left(|\Delta B_i\,(j)|\right) \qquad j \epsilon \Omega$$

Ω is the set of voltage security risk contingencies and vulnerable nodes; j thus refers either to a security risk contingency for which $\Delta B_i(j)$ is part of a scheme proposed by the Q rescheduling function to alleviate limit violations, or to a vulnerable node for which $\Delta B_i(j)$ is part of a strategy devised to increase its reactive strength (Q-distances).

The control adjustments proposed by the first phase of the co-ordination function $[\Delta u^{s1}]$ can be expressed as a fraction of the maximum adjustments $[\Delta u']$ by defining a set of scalar multipliers α, such that

$$[\Delta u^{s1}] = \begin{bmatrix} [\Delta V_g^{s1}] \\ [\Delta B^{s1}] \\ [\Delta T^{s1}] \end{bmatrix} = \begin{bmatrix} \alpha g_1 \ \Delta V_1' \\ \vdots \\ \alpha g_{ng} \ \Delta V_{ng}' \\ \alpha b_1 \ \Delta B_1' \\ \vdots \\ \alpha b_{nb} \ \Delta B_{nb}' \\ \alpha t_1 \ \Delta T_1' \\ \vdots \\ \alpha t_{nt} \ \Delta T_{nt}' \end{bmatrix} \tag{5.2}$$

and

$$0 \le \alpha g_i \le 1.0 \qquad i = 1, ..., ng$$

$$0 \le \alpha b_i \le 1.0 \qquad i = 1, ..., nb$$

$$0 \le \alpha t_i \le 1.0 \qquad i = 1, ..., nt$$

Ideally all α factors would be equal to unity, i.e. $[\Delta u^{s1}] = [\Delta u']$. The objective of the first phase of the co-ordination function is to maximise the control adjustments to be implemented as preventive strategies without causing limit violations on the base case operating conditions. Accordingly, the objective function is mathematically formulated as:

Maximise

$$\sum_{i=1}^{ng} pg_i \ \alpha g_i + \sum_{i=1}^{nb} pb_i \ \alpha b_i + \sum_{i=1}^{nt} pt_i \ \alpha t_i \tag{5.3}$$

where

pg_i is a priority factor associated with the adjustment of generator i voltage

pb_i is a factor defining the priority given to the change in the susceptance of the switchable shunt capacitor (or inductor) i

pt_i is the priority associated with the change in the tap setting of transformer i

Higher priority can be given to certain control adjustments (e.g. those associated with high risk contingencies), by assigning large values to their priority factors.

The effects of implementing $[\Delta u^{s1}]$ on the dependent variables $[V_{pq}]$ and $[Q_g]$ for the base case (bc) operating conditions, can be evaluated using linear sensitivities:

$$\left[\Delta Q_g(bc)\right] = \left[\left[S_{vg}^{qg}(bc)\right]\left[S_b^{qg}(bc)\right]\left[S_t^{qg}(bc)\right]\right]\begin{bmatrix} \alpha g_1 & \Delta V_1' \\ & \vdots \\ \alpha g_{ng} & \Delta V_{ng}' \\ \alpha b_1 & \Delta B_1' \\ & \vdots \\ \alpha b_{nb} & \Delta B_{nb}' \\ \alpha t_1 & \Delta T_1' \\ & \vdots \\ \alpha t_{nt} & \Delta T_{nt}' \end{bmatrix}$$

$$\left[\Delta V_{pq}(bc)\right] = \left[\left[S_{vg}^{vpq}(bc)\right]\left[S_b^{vpq}(bc)\right]\left[S_t^{vpq}(bc)\right]\right]\begin{bmatrix} \alpha g_1 & \Delta V_1' \\ & \vdots \\ \alpha g_{ng} & \Delta V_{ng}' \\ \alpha b_1 & \Delta B_1' \\ & \vdots \\ \alpha b_{nb} & \Delta B_{nb}' \\ \alpha t_1 & \Delta T_1' \\ & \vdots \\ \alpha t_{nt} & \Delta T_{nt}' \end{bmatrix} \quad (5.4)$$

Eliminating the control adjustments from these equations, it can be seen that the operating limits on $[V_{pq}]$ and $[Q_g]$ (dependent variables) for the base case conditions, can be observed by introducing the following inequality constraints:

$$\left[\Delta Q_g^{\min}(bc)\right] \le \left[\left[S_{\alpha g}^{qg}(bc)\right]\left[S_{\alpha b}^{qg}(bc)\right]\left[S_{\alpha t}^{qg}(bc)\right]\right]\begin{bmatrix}[\alpha g]\\ [\alpha b]\\ [\alpha t]\end{bmatrix} \le \left[\Delta Q_g^{\max}(bc)\right]$$

$$\left[\Delta V_{pq}^{\min}(bc)\right] \le \left[\left[S_{\alpha g}^{vpq}(bc)\right]\left[S_{\alpha b}^{vpq}(bc)\right]\left[S_{\alpha t}^{vpq}(bc)\right]\right]\begin{bmatrix}[\alpha g]\\ [\alpha b]\\ [\alpha t]\end{bmatrix} \le \left[\Delta V_{pq}^{\max}(bc)\right] \quad (5.5)$$

where

$[\alpha g]$, $[\alpha b]$ and $[\alpha t]$ are column vectors of dimension ng, nb and nt respectively, and whose elements are the scalar multipliers α defined in equation (5.2).

$[S_{\alpha g}^{qg}(bc)]$, $[S_{\alpha b}^{qg}(bc)]$, $[S_{\alpha t}^{qg}(bc)]$, $[S_{\alpha g}^{vpq}(bc)]$, $[S_{\alpha b}^{vpq}(bc)]$ and $[S_{\alpha t}^{vpq}(bc)]$ are sensitivity matrices relating changes in the dependent variables $[Q_g]$ and $[V_{pq}]$ due to changes in the α factors. They are evaluated using the sparse sensitivity matrices $[S_{vg}^{qg}(bc)]$, $[S_b^{qg}(bc)]$, $[S_t^{qg}(bc)]$, $[S_{vg}^{vpq}(bc)]$, $[S_b^{vpq}(bc)]$ and $[S_t^{vpq}(bc)]$calculated after a converged a.c. load flow solution defining the base case operation conditions, and the maximum control adjustments proposed $[\Delta V'_g]$, $[\Delta B']$ and $[\Delta T']$; e.g. (see equations (5.4) and (5.5))

$$\left[S_{ab}^{vpq}(bc)\right] = \left[S_b^{vpq}(bc)\right]\begin{bmatrix}\Delta B'_1 & 0 & \cdots & 0\\ 0 & \Delta B'_2 & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & \Delta B'_{nb}\end{bmatrix}$$

To summarise, the first step of the co-ordination function is shown in a compiled form as follows:

Maximise

$$\sum_{i=1}^{ng} pg_i\ \alpha g_i + \sum_{i=1}^{nb} pb_i\ \alpha b_i + \sum_{i=1}^{nt} pt_i\ \alpha t_i$$

subject to

$$\left[\Delta Q_g^{\min}(bc)\right] \le \left[\left[S_{\alpha g}^{qg}(bc)\right]\left[S_{\alpha b}^{qg}(bc)\right]\left[S_{\alpha t}^{qg}(bc)\right]\right]\begin{bmatrix}[\alpha g]\\ [\alpha b]\\ [\alpha t]\end{bmatrix} \le \left[\Delta Q_g^{\max}(bc)\right]$$

$$\left[\Delta V_{pq}^{\min}(bc)\right] \le \left[\left[S_{\alpha g}^{vpq}(bc)\right]\left[S_{\alpha b}^{vpq}(bc)\right]\left[S_{\alpha t}^{vpq}(bc)\right]\right]\begin{bmatrix}[\alpha g]\\ [\alpha b]\\ [\alpha t]\end{bmatrix} \le \left[\Delta V_{pq}^{\max}(bc)\right] \quad (5.6)$$

$$[0] \le \begin{bmatrix}[\alpha g]\\ [\alpha b]\\ [\alpha t]\end{bmatrix} \le [1]$$

where [0] and [1] are $(ng + nb + nt)$ column vectors of 0's and 1's respectively.

When formulating the upper-bound LP problem of equation (5.6), a relaxation technique has been adopted. The effects of implementing $[\Delta u']$ (i.e. all α factors equal to 1.0) on the base case operating conditions are evaluated using linear sensitivities and only detected violations are included in the constraints set.

The solution of the first step of the co-ordination problem (i.e. the α factors) defines the adjustment for each control device (see equation (5.2)) that can be implemented on the

intact system (base case) conditions without violating any operating constraint. For example, $\alpha t_i = 1.0$ indicates that the maximum adjustment proposed for the transformer tap i ($\Delta T_i^{s1} = \Delta T'_i$) can be executed without introducing any limit violation on the base case conditions. At the other extreme, $\alpha g_i = 0.0$ means that no adjustment is feasible for the generator i voltage ($\Delta V_i^{s1} = 0.0$). An intermediate value defines the amount of adjustment which is implementable (e.g. $\Delta B_i^{s1} = \alpha b_i \Delta B'_i$) on the intact system . The shadow prices (Lagrange multipliers) at the solution of the LP problem of equation (5.6), measure the increment in the cost function (i.e. the amount of control adjustments to be implemented as preventive strategies and thus enforcement of system security) due to small changes in the limits of the constraints. So, operating limits on the intact system conditions, which prevent the implementation of control adjustments as preventive strategies, can be detected and expanded whenever they are acceptable, in order to increase security [20].

5.4. Co-ordination Function - Phase II

In the second step of the co-ordination problem, the effects of the control adjustments proposed by the first phase [Δu^{s1}], on the security risk contingencies, are accounted for.

The control adjustments proposed by the Q rescheduling function to relieve violations on a given contingency (e.g. k) conditions [$\Delta u\ (k)$], can be expressed as a function of the adjustments postulated by the first phase of the co-ordination function [Δu^{s1}], by defining a set of scalar multipliers ϕ such that

$$\left[\Delta u(k)\right] = \begin{bmatrix} \Delta V_1(k) \\ \vdots \\ \Delta V_{ng}(k) \\ \\ \Delta B_1(k) \\ \vdots \\ \Delta B_{nb}(k) \\ \\ \Delta T_1(k) \\ \vdots \\ \Delta T_{nt}(k) \end{bmatrix} = \begin{bmatrix} \phi g_1^k \ \Delta V_1^{s1} \\ \vdots \\ \phi g_{ng}^k \ \Delta V_{ng}^{s1} \\ \\ \phi b_1^k \ \Delta B_1^{s1} \\ \vdots \\ \phi b_{nb}^k \ \Delta B_{nb}^{s1} \\ \\ \phi t_1^k \ \Delta T_1^{s1} \\ \vdots \\ \phi t_{nt}^k \ \Delta T_{nt}^{s1} \end{bmatrix} \tag{5.7}$$

from where

$$\phi g_i^k = \Delta V_i(k)/\Delta V_i^{s1} \qquad i = 1, \ldots, ng$$

$$\phi b_i^k = \Delta B_i(k)/\Delta B_i^{s1} \qquad i = 1, \ldots, nb$$

$$\phi t_i^k = \Delta T_i(k)/\Delta T_i^{s1} \qquad i = 1, \ldots, nt$$

Similarly, the control adjustments proposed by the second phase of the co-ordination problem $[\Delta u^*]$ can be expressed as fractions of those postulated by the first step $[\Delta u^{s1}]$, by introducing a set of scalar multipliers γ

$$\left[\Delta u^*\right] = \begin{bmatrix} \left[\Delta V_g^*\right] \\ \\ \left[\Delta B^*\right] \\ \\ \left[\Delta T^*\right] \end{bmatrix} = \begin{bmatrix} \gamma g_1 \ \Delta V_1^{s1} \\ \vdots \\ \gamma g_{ng} \ \Delta V_{ng}^{s1} \\ \gamma b_1 \ \Delta B_1^{s1} \\ \vdots \\ \gamma b_{nb} \ \Delta B_{nb}^{s1} \\ \gamma t_1 \ \Delta T_1^{s1} \\ \vdots \\ \gamma t_{nt} \ \Delta T_{nt}^{s1} \end{bmatrix} \tag{5.8}$$

where

$$0 \leq \gamma g_i \leq 1.0 \qquad i = 1, \ldots, ng$$

$$0 \leq \gamma b_i \leq 1.0 \qquad i = 1, \ldots, nb$$

$$0 \leq \gamma t_i \leq 1.0 \qquad i = 1, \ldots, nt$$

In an ideal situation, all the γ factors would be equal to unity, i.e. $[\Delta u^*] = [\Delta u^{s1}]$. An objective function similar to (5.3) can be formulated for the second step of the co-ordination function:

Maximise

$$\sum_{i=1}^{ng} pg_i \, \gamma g_i + \sum_{i=1}^{nb} pb_i \, \gamma b_i + \sum_{i=1}^{nt} pt_i \, \gamma t_i \tag{5.9}$$

For each VAr/voltage security risk contingency (e.g. k), the difference between $[\Delta u^*]$ and the adjustments postulated by the rescheduling procedure to eliminate violations on the contingency conditions $[\Delta u\,(k)]$, is evaluated and expressed as a function of $[\Delta u^{s1}]$ (see equations (5.7) and (5.8)), as:

$$\left[\Delta u^{*-k}\right] = \begin{bmatrix} \left[\Delta V_g^{*-k}\right] \\ \left[\Delta B^{*-k}\right] \\ \left[\Delta T^{*-k}\right] \end{bmatrix} = \begin{bmatrix} (\gamma g_1 - \phi g_1^k) & \Delta V_1^{s1} \\ \vdots & \\ (\gamma g_{ng} - \phi g_{ng}^k) & \Delta V_{ng}^{s1} \\ (\gamma b_1 - \phi b_1^k) & \Delta B_1^{s1} \\ \vdots & \\ (\gamma b_{nb} - \phi b_{nb}^k) & \Delta B_{nb}^{s1} \\ (\gamma t_1 - \phi t_1^k) & \Delta T_1^{s1} \\ \vdots & \\ (\gamma t_{nt} - \phi t_{nt}^k) & \Delta T_{nt}^{s1} \end{bmatrix} \tag{5.10}$$

As the implementation of $[\Delta u\,(k)]$ does not cause any violation in the contingency k conditions (as a matter of fact, it constitutes the control plan obtained from the rescheduling

procedure to alleviate limit violations in the contingency k operating conditions), then it is necessary only to check if the implementation of $[\Delta u^{*-k}]$ produces any violation in the contingency k conditions.

Operating limits on $[V_{pq}]$ and $[Q_g]$ for the contingency k conditions, can be observed by introducing the following inequality constraints:

$$\left[\Delta Q_g^{min}(k)\right] \le \left[\left[S_{vg}^{qg}(k)\right]\left[S_b^{qg}(k)\right]\left[S_t^{qg}(k)\right]\right]\begin{bmatrix}\left[\Delta V_g^{*-k}\right]\\ \left[\Delta B^{*-k}\right]\\ \left[\Delta T^{*-k}\right]\end{bmatrix} \le \left[\Delta Q_g^{max}(k)\right]$$

$$\left[\Delta V_{pq}^{min}(k)\right] \le \left[\left[S_{vg}^{vpq}(k)\right]\left[S_b^{vpq}(k)\right]\left[S_t^{vpq}(k)\right]\right]\begin{bmatrix}\left[\Delta V_g^{*-k}\right]\\ \left[\Delta B^{*-k}\right]\\ \left[\Delta T^{*-k}\right]\end{bmatrix} \le \left[\Delta V_{pq}^{max}(k)\right] \quad (5.11)$$

Substituting equation (5.10) into equation (5.11), the constraints on the dependent variables can be rewritten as functions of the $\gamma$and ϕ factors as:

$$\left[\Delta Q_g^{min}(k)\right] \le \left[\left[S_{\gamma g}^{qg}(k)\right]\left[S_{\gamma b}^{qg}(k)\right]\left[S_{\gamma t}^{qg}(k)\right]\right]\begin{bmatrix}\left[\gamma g\right]-\left[\phi g\right]\\ \left[\gamma b\right]-\left[\phi b\right]\\ \left[\gamma t\right]-\left[\phi t\right]\end{bmatrix} \le \left[\Delta Q_g^{max}(k)\right]$$

$$\left[\Delta V_{pq}^{min}(k)\right] \le \left[\left[S_{\gamma g}^{vpq}(k)\right]\left[S_{\gamma b}^{vpq}(k)\right]\left[S_{\gamma t}^{vpq}(k)\right]\right]\begin{bmatrix}\left[\gamma g\right]-\left[\phi g\right]\\ \left[\gamma b\right]-\left[\phi b\right]\\ \left[\gamma t\right]-\left[\phi t\right]\end{bmatrix} \le \left[\Delta V_{pq}^{max}(k)\right] \quad (5.12)$$

where $[\gamma g]$ and $[\phi g]$, $[\gamma b]$ and $[\phi b]$, and $[\gamma t]$ and $[\phi t]$ are column vectors of dimension ng,

nb and *nt* respectively and whose elements are the scalar multipliers γ and ϕ defined in equations (5.7) and (5.8).

$[S^{qg}_{\gamma g}(k)]$, $[S^{qg}_{\gamma b}(k)]$, $[S^{qg}_{\gamma t}(k)]$, $[S^{vpq}_{\gamma g}(k)]$, $[S^{vpq}_{\gamma b}(k)]$ and $[S^{vpq}_{\gamma t}(k)]$ are evaluated using the sparse sensitivity matrices $[S^{qg}_{vg}(k)]$, $[S^{qg}_{b}(k)]$, $[S^{qg}_{t}(k)]$, $[S^{vpq}_{vg}(k)]$, $[S^{vpq}_{b}(k)]$ and $[S^{vpq}_{t}(k)]$ (calculated after a converged a.c. load flow solution defining the contingency *k* operating conditions), and the adjustments proposed by the first step of the co-ordination function $[\Delta V_g^{s1}]$, $[\Delta B^{s1}]$ and $[\Delta T^{s1}]$, e.g. (see equations (5.10) to (5.12)).

$$\left[S^{qg}_{\gamma t}(k)\right] = \left[S^{qg}_{t}(k)\right] \begin{bmatrix} \Delta T_1^{s1} & 0 & \dots & 0 \\ 0 & \Delta T_2^{s1} & \dots & 0 \\ \vdots & \vdots & & \\ 0 & 0 & \dots & \Delta T_{nt}^{s1} \end{bmatrix}$$

Defining

$$\left[D^{qg}(k)\right] = \left[\left[S^{qg}_{\gamma g}(k)\right]\left[S^{qg}_{\gamma b}(k)\right]\left[S^{qg}_{\gamma t}(k)\right]\right] \begin{bmatrix} [\phi g] \\ [\phi b] \\ [\phi t] \end{bmatrix}$$

$$\left[D^{vpq}(k)\right] = \left[\left[S^{vpq}_{\gamma g}(k)\right]\left[S^{vpq}_{\gamma b}(k)\right]\left[S^{vpq}_{\gamma t}(k)\right]\right] \begin{bmatrix} [\phi g] \\ [\phi b] \\ [\phi t] \end{bmatrix}$$

the second phase of the co-ordination is formulated as an upper-bound LP problem and is shown in an integrated form as follows:

Maximise

$$\sum_{i=1}^{ng} pg_i \gamma g_i + \sum_{i=1}^{nb} pb_i \gamma b_i + \sum_{i=1}^{nt} pt_i \gamma t_i$$

subject to

$$\begin{bmatrix} \Delta Q_g^{min}(k) \\ + \\ D^{qg}(k) \end{bmatrix} \leq \left[\left[S_{\gamma g}^{qg}(k) \right] \left[S_{\gamma b}^{qg}(k) \right] \left[S_{\gamma t}^{qg}(k) \right] \right] \begin{bmatrix} [\gamma g] \\ [\gamma b] \\ [\gamma t] \end{bmatrix} \leq \begin{bmatrix} \Delta Q_g^{max}(k) \\ + \\ D^{qg}(k) \end{bmatrix}$$

$$\begin{bmatrix} \Delta V_{pq}^{min}(k) \\ + \\ D^{vpq}(k) \end{bmatrix} \leq \left[\left[S_{\gamma g}^{vpq}(k) \right] \left[S_{\gamma b}^{vpq}(k) \right] \left[S_{\gamma t}^{vpq}(k) \right] \right] \begin{bmatrix} [\gamma g] \\ [\gamma b] \\ [\gamma t] \end{bmatrix} \leq \begin{bmatrix} \Delta V_{pq}^{max}(k) \\ + \\ D^{vpq}(k) \end{bmatrix} \tag{5.13}$$

$$[0] \leq \begin{bmatrix} [\gamma g] \\ [\gamma b] \\ [\gamma t] \end{bmatrix} \leq [1]$$

$k \varepsilon$ voltage security risk contingency set.

To reduce the size of the upper-bound LP problem (5.13), only detected violations are included in the constraints set, i.e. all non-violated operating constraints are relaxed. Furthermore, as the objective is to maximise the amount of control to be implemented in a preventive mode, the detection of limit violations is carried out only for the case when all the γ factors are equal to unity, i.e. $[\Delta u^*] = [\Delta u^{sl}]$.

Rigorously, when detecting violations on a given contingency (e.g. k) state, due to the implementation of $[\Delta u^*]$, the worst possible circumstances should be considered, e.g. assume that operating limit violations are being checked for V_{ipq} in the contingency k state; when the lower limit $\Delta V_{ipq}^{min}(k)$ is considered, then

$$\text{If } \left[S_{\gamma g}^{vpq}(k)\right]_{ij} \geq 0.0 \text{ then assume } \gamma g_j = 0.0$$

$$\text{If } \left[S_{\gamma g}^{vpq}(k)\right]_{ij} < 0.0 \text{ then assume } \gamma g_j = 1.0$$

$$j = 1, \ldots, ng$$

Similarly, when the upper limit $\Delta V_{ipq}^{max}(k)$ is checked.

$$\text{If } \left[S_{\gamma g}^{vpq}(k)\right]_{ij} \geq 0.0 \text{ then assume } \gamma g_j = 1.0$$

$$\text{If } \left[S_{\gamma g}^{vpq}(k)\right]_{ij} < 0.0 \text{ then assume } \gamma g_j = 0.0$$

$$j = 1, \ldots, ng$$

Similar checks should be made for $[S_{\gamma b}^{vpq}]_{ij}$ $(j = 1, ..., nb)$ and $[S_{\gamma t}^{vpq}]_{ij}$ $(j = 1, ..., nt)$.

This procedure might, however, detect too many potential violations, including all the operating limits violated in all the security risk contingencies before any control adjustment is implemented. It would certainly complicate unnecessarily the LP problem (5.13), as the implementation of the control adjustments proposed by the rescheduling function for a given contingency (e.g. k) $[\Delta u\ (k)]$ would obviously cause no constraint violations for such contingency k conditions. Furthermore, as the ideal result of the second step of the co-ordination function would be to have all the γ factors equal to unity (i.e. $[\Delta u^*] = [\Delta u^{s1}]$), it is considered reasonable to check for constraint violations only for such circumstances (i.e. all γ factors equal to 1.0).

5.5. Numerical Example

The 6 bus system [20] shown in Figure 5.2, has been used to illustrate the application of the methodology.

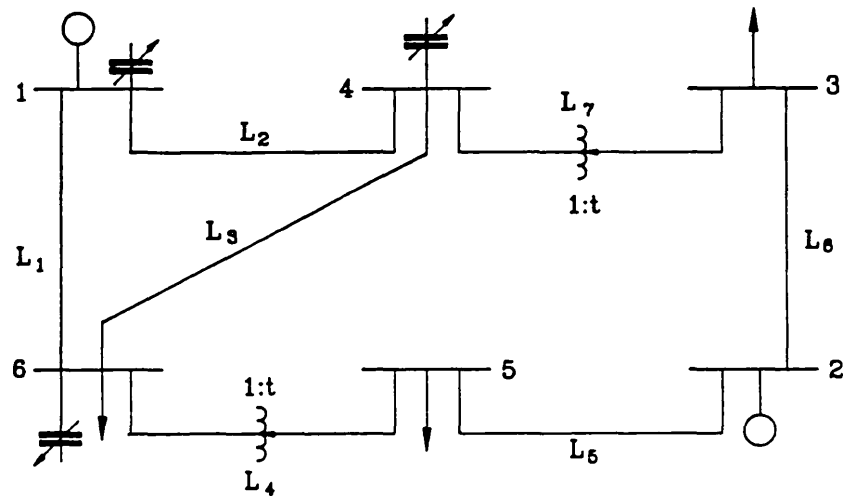


Figure 5.2 Diagram of the 6 bus system

The base case (i.e. intact system) operating conditions and the operational limits are shown in Table 5.1 and Table 5.2 respectively.

Given the intact system operating conditions and the contingency list $\{L_1, L_2, L_3, L_4, L_5, L_6, L_7\}$, the contingency screening procedure (described in chapter 3) generates the results shown in Figure 5.3. Contingencies for which any potential limit violation is identified (i.e. $PI_{v1} > 0.0$), are considered as possible security risks (i.e. they form the worst case list).

Execution of the a.c. load flow for such contingency cases verifies that effectively, under the current operating conditions (base case), contingencies L_1, L_2, L_5, L_6, and L_7 represent voltage security risks.

Bus No./type	Voltage p.u.	Angle degrees	Generation MW	Generation MVAr	Load MW	Load MVAr	Shunt Cap. B (p.u.)
1 swing	1.050	0.00	17.64	19.87	-	-	0.0339
2 PV	1.100	10.29	50.00	-0.08	-	-	-
3 PQ	1.067	-1.70	-	-	22.50	6.50	-
4 PQ	0.993	-1.20	-	-	-	-	0.0293
5 PQ	0.994	0.68	-	-	15.00	9.00	-
6 PQ	0.994	-1.83	-	-	25.00	2.50	0.0350

tap settings $t_{4\text{-}3} = 1.10$ $t_{6\text{-}5} = 1.025$

Table 5.1 Intact system initial operating conditions

		Variable	Lower limit	Upper limit
Control devices				
	Generator	V_1	0.95	1.10
	voltage (p.u.)	V_2	0.95	1.15
	Capacitor	B_1	0.00	0.05
	bank B (p.u.)	B_4	0.00	0.05
		B_6	0.00	0.05
	Tap	$T_{4\text{-}3}$	0.90	1.10
	setting	$T_{6\text{-}5}$	0.90	1.10
Dependent variables				
	Reactive power	Q_1	-20.00	100.00
	generation (MVAr)	Q_2	-20.00	100.00
	Load bus	V_3 V_4 V_5 V_6	0.975	1.10
	voltage (p.u.)			

Table 5.2 Operational limits

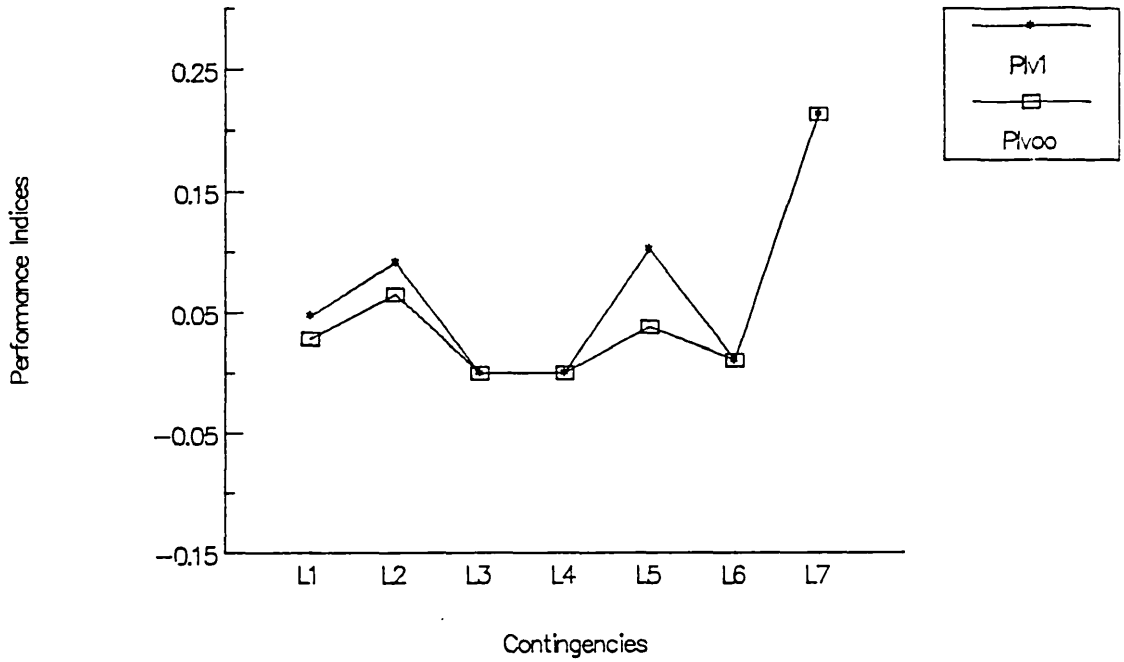


Figure 5.3 Contingency screening results

For each security risk contingency, a reactive power rescheduling (described in chapter 4) is carried out to relieve operating constraint violations. The proposed adjustments to the VAr/voltage control devices are depecited in Figure 5.4.

The results of the reactive power rescheduling function showed that for the contingency L_7 operating conditions, no control plan capable of removing an under-voltage at bus 3 exists. The control scheme illustrated in Figure 5.4 ($\Delta V_2(L_7) = 0.05$) constitutes the best approximation of the desired solution, i.e. the minimum sum of infeasibilities [32]. The low voltage at node 3 ($V_3 = 0.861$) is due to the large power transfer through the longest transmission line (L_6) in the system after the transformer L_7 is outaged. An obvious remedy to correct this problem is to apply shunt compensation at bus 3; the solution should, however, be determined in the VAr expansion planning phase [20].

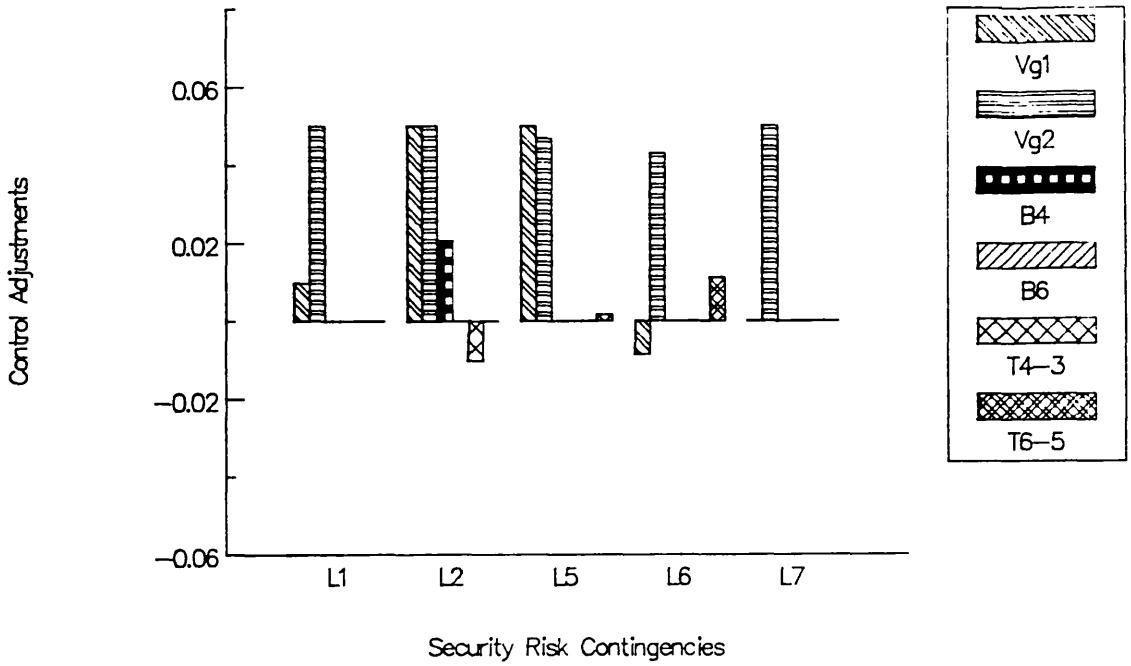


Figure 5.4 Control adjustments from the reactive power rescheduling procedure

As far as the co-ordination strategy is concerned, the control plan for contingency L_7 is included in the proposal made in the first phase, but contingency L_7 is excluded from the security risk contingency list in the second phase.

The control plan given by the rescheduling procedure to alleviate limit violations in the contingency L_6 conditions, involves a conflicting control adjustment, $\Delta V_1(L_6) < 0.0$ and $\Delta V_1(L_i) > 0.0$ for $i = 1, 2, 5$. A new reactive power rescheduling is thus carried out for contingency L_6, penalising heavily the conflicting control device ($cg_1 = 10$) and giving higher priority to other non-conflicting devices ($cg_2 = cb_6 = ct_{6\text{-}5} = 0.5$) and ($cb_4 = ct_{4\text{-}3} = 1$). The results are shown in Figure 5.5.

The conflicting adjustment $\Delta V_1(L_6)$ has been eliminated in the new control scheme for contingency L_6; however, another conflict is introduced, $\Delta B_4(L_6) < 0.0$ and $\Delta B_4(L_2) > 0.0$. This time the conflicting adjustment is avoided by executing a reactive rescheduling

for contingency L_2, assigning a large value to the cost factor of the conflicting control (cb_4 = 10) and ($cg_1 = cg_2 = cb_6 = ct_{4\text{-}3} = ct_{6\text{-}5}$ = 1). Figure 5.5 shows the control adjustments proposed to the first phase of the co-ordination function, after the conflicts have been eliminated.

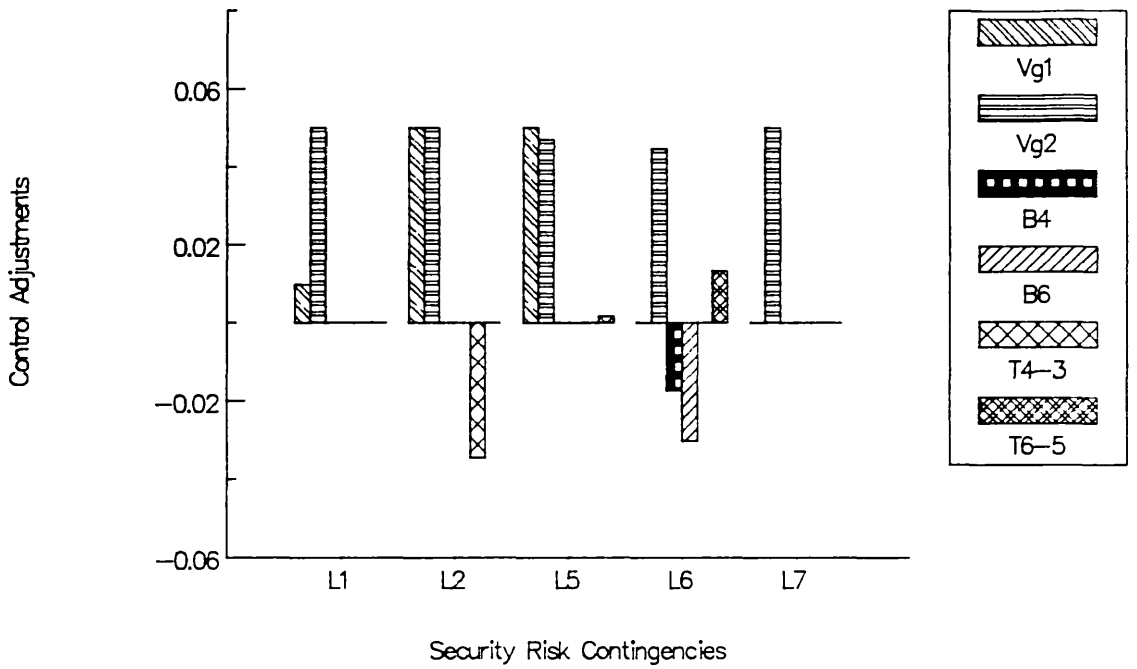


Figure 5.5 Control adjustments after conflict resolution

The maximum adjustment proposed for each VAr/voltage control device is determined. The results are illustrated in Figure 5.6. The effects of implementing [$\Delta u'$] on the intact system operating conditions are then evaluated using linear sensitivities and it is found that no constraint violations are caused, so all α factors are equal to unity. From equation (5.2) then [Δu^{s1}] = [$\Delta u'$].

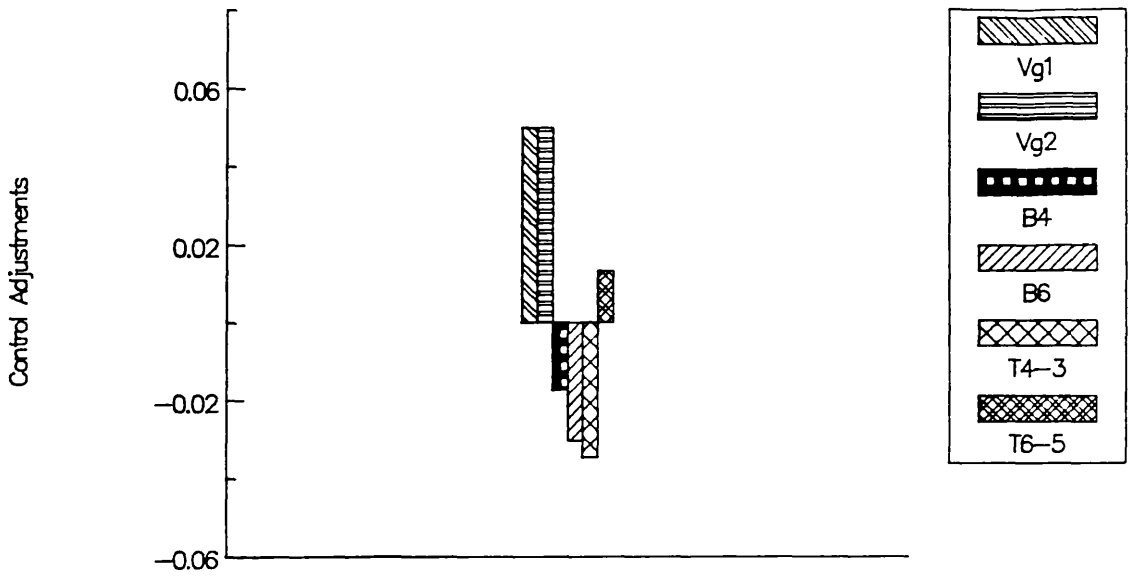


Figure 5.6 Co-ordination function - phase I $[\Delta u^{s1}] = [\Delta u']$

The effects of implementing $[\Delta u^{s1}]$ - $[\Delta u(k)]$ on the voltage security risk contingencies (i.e. $k\varepsilon\{L_1, L_2, L_5, L_6\}$) are taken into consideration in the second phase of the co-ordination strategy. Figure 5.7 shows $[\Delta u^{s1}]$ - $[\Delta u(k)]$; note that contingency L_7 has been dropped from the security risk contingency list. The effects of $[\Delta u^{s1}]$ - $[\Delta u(k)]$ on the contingency k operating conditions are evaluated using linear sensitivities. Any detected violation is included in the constraints set and the upper-bound LP problem of equation (5.13) is formulated and solved. The solution is shown in Table 5.3 and in the rightmost set of Figure 5.8.

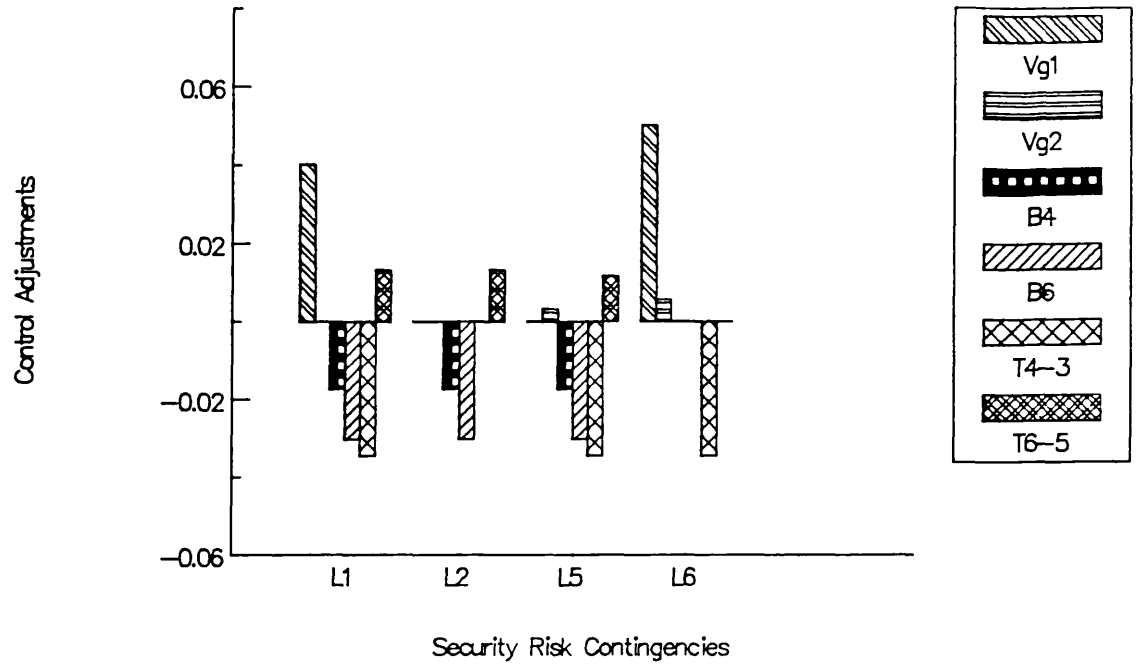


Figure 5.7 Co-ordination function - phase II $[\Delta u^{s1}]$ - $[\Delta u(k)]$

Variable	Value	Constraint	Lagrange multiplier
γ_{g1}	0.76	c_1	210.3
γ_{g2}	1.0	c_2	-107.0
γ_{b4}	0.0		
γ_{b6}	0.61	c_1 related to $V_4^{min}(L_2)$	
$\gamma_{4\text{-}3}$	1.0		
$\gamma_{6\text{-}5}$	1.0	c_2 related to $V_3^{max}(L_6)$	

Table 5.3 Co-ordination function - phase II results

The acceptability factors for the VAr/voltage control devices adjustments proposed to the two phases of the co-ordination strategy, are illustrated in Figure 5.9.

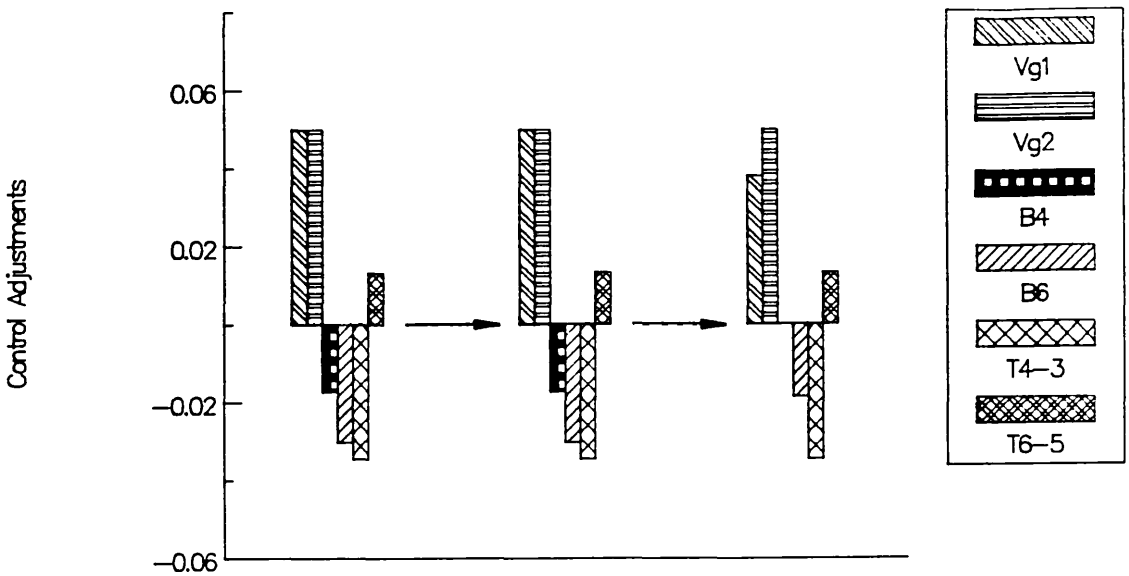


Figure 5.8 Co-ordination function $[\Delta u'] \rightarrow [\Delta u^{s1}] \rightarrow [\Delta u^*]$

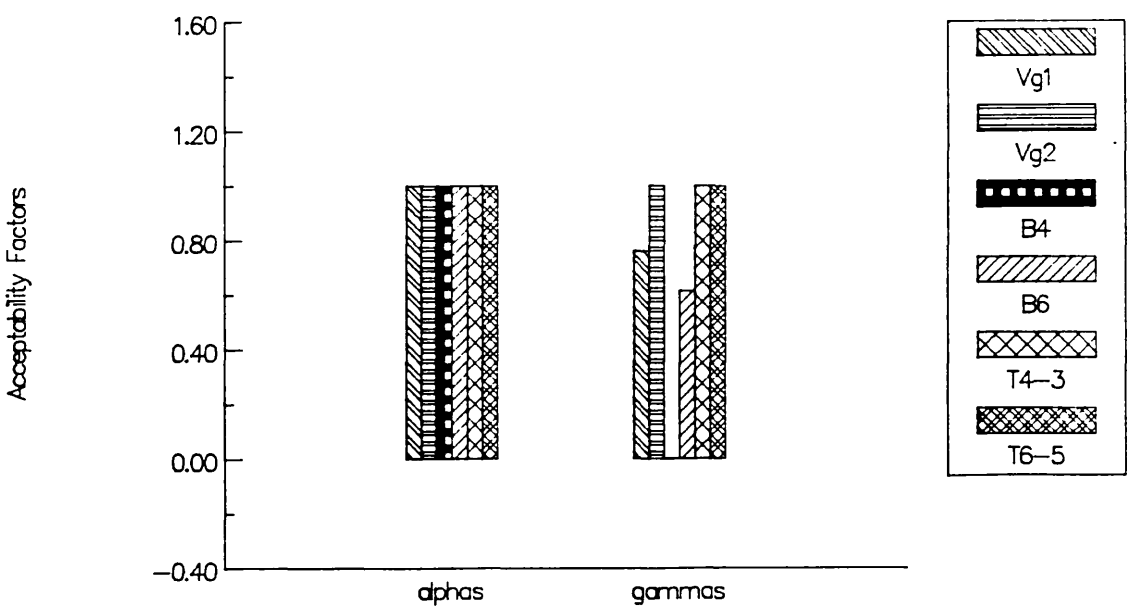


Figure 5.9 Co-ordination function α and γ factors

An ideal solution was obtained in the first phase of the co-ordination strategy (i.e. all α factors are equal to 1.0 and thus $[\Delta u^{s1}] = [\Delta u']$), because the implementation of $[\Delta u']$ does not cause any operating constraint to be violated on the base case conditions.

In the second phase, however, the observance of V_4^{min} and V_3^{max} for the contingency L_2 and L_6 conditions respectively (c_1 and c_2), restricts the implementation of some of the control adjustments in a preventive mode ($\gamma g_1 = 0.76$, $\gamma b_4 = 0.0$, $\gamma b_6 = 0.61$). An obvious way to increase the acceptability (γ) factors is to expand V_4^{min} (the largest Lagrange multiplier corresponds to c_1). A slight reduction in V_4^{min} would be considered acceptable because node 4 is not loaded.

Such limit expansion was proved to be unnecessary. The implementation of the preventive control scheme represented by the rightmost set of Figure 5.8 makes the system steady state secure for the base case operating conditions and in the event of any contingency in the set $\{L_1, L_2, L_5, L_6\}$. The fact that the implementation of only part of the control plan proposed to phase II makes the system secure against all contingencies considered in phase II (i.e. $\{L_1, L_2, L_5, L_6\}$) is due to the narrowing of the operational limits when the reactive rescheduling (described in chapter 4) is carried out for each security risk contingency. In other words, the adjustments given by the Q rescheduling function for a given contingency k, would move all the dependent variables $[V_{pq}]$ and $[Q_g]$ well within their operational limits, e.g. if $V_{ipq}^{min} = 0.975$ and $V_{ipq}^{max} = 1.1$, then the implementation of $[\Delta u(k)]$ would bring V_{ipq} to be $0.9875 \lesssim V_{ipq} \lesssim 1.0875$. This limit shrinking technique used in the Q rescheduling thereby increases the feasibility of obtaining a preventive plan which makes the system contingency secure, even when non-ideal solutions are found in any of the two phases of the co-ordination function (i.e. α and/or γ factors $\neq 1$).

Table 5.4 shows the final operating conditions after the preventive plan proposed by the co-ordination function is implemented. Under these conditions, the contingency screening function (described in chapter 3) produces the results shown in Figure 5.10. As mentioned before, the under-voltage at node 3 for the contingency L_7 conditions has to be considered

in the VAr expansion planning phase to determine the alterations that should be made to alleviate such violation [20].

Bus No./type	Voltage p.u.	Angle degrees	Generation MW	Generation MVAr	Load MW	Load MVAr	Shunt Cap. B (p.u.)
1 swing	1.088	0.00	17.04	17.41	-	-	0.0339
2 PV	1.150	9.17	50.00	1.92	-	-	-
3 PQ	1.089	-1.49	-	-	22.50	6.50	-
4 PQ	1.041	-1.10	-	-	-	-	0.0293
5 PQ	1.051	0.59	-	-	15.00	9.00	-
6 PQ	1.035	-1.68	-	-	25.00	2.50	0.0165

tap settings $t_{4\text{-}3} = 1.065$, $t_{6\text{-}5} = 1.038$

Table 5.4 Intact system final operating conditions

Execution of the a.c. load flow shows that the slight potential violation detected for contingency L_2 represents a false alarm, i.e. no limit violation actually exists under the contingency L_2 operating conditions.

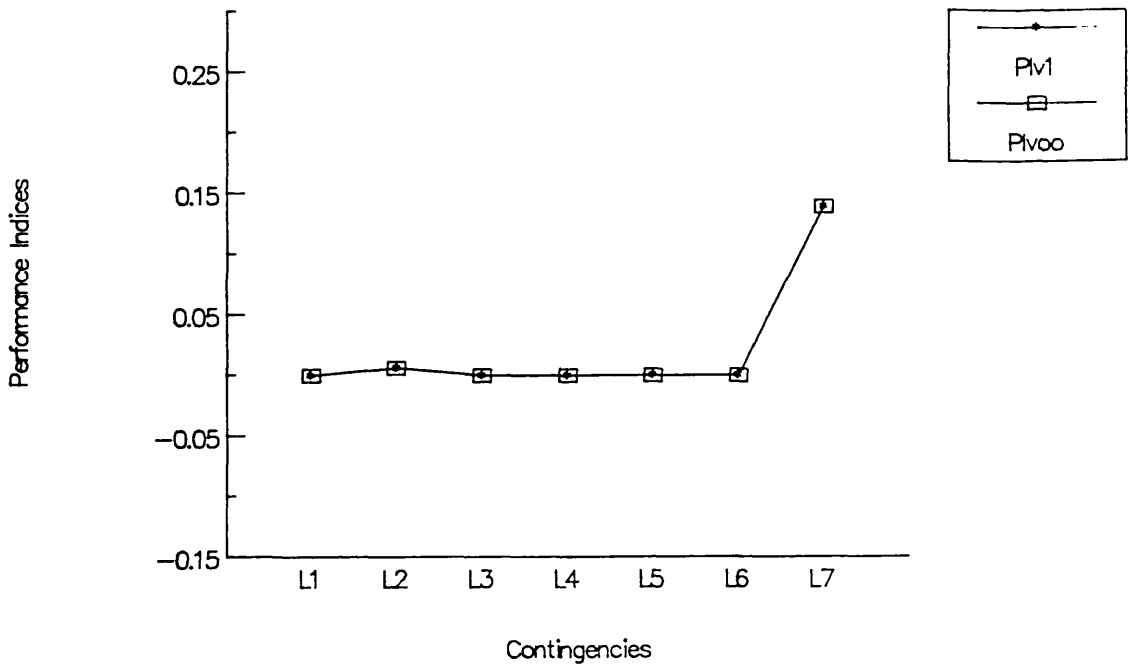


Figure 5.10 *PI*s for the final operating conditions

Chapter 6

Prototype System

6.1. Introduction

A prototype system for the reactive reserve management in the operational planning phase of power systems has been implemented, and is described in this chapter.

The system integrates algorithmic software and symbolic programming and although the final strategy is quite algorithmic, the use of knowledge-based system technologies has made the prototyping an easy task. Attention has been focussed on fast prototyping, ignoring efficiency considerations. The system runs comparatively slowly, mainly because the pattern matching mechanism to search through the knowledge base (symbolic component) is itself a slow process. The system architecture, the numerical (algorithmic) and symbolic components and the means of communication between them, are described in this chapter.

6.2. Overview of the System

The structure of the system is shown schematically in Figure 6.1. The contrasting nature of the tasks involved (knowledge-based programming/numerical procedures) strongly supports the use of a multilanguage programming environment as the building tool. Different activities are best served by different languages. Heavy numerical computations (e.g. load flow, contigency analysis, etc.) can be done more efficiently in a conventional language (e.g. Pascal, Fortran, etc.); on the other hand, knowledge-based programming (e.g. rules, inference, etc.) is much more easily written in a symbolic language (e.g. Prolog, Lisp, etc.). These arguments led to the selection of POPLOG [15] as the means for the development of the system.

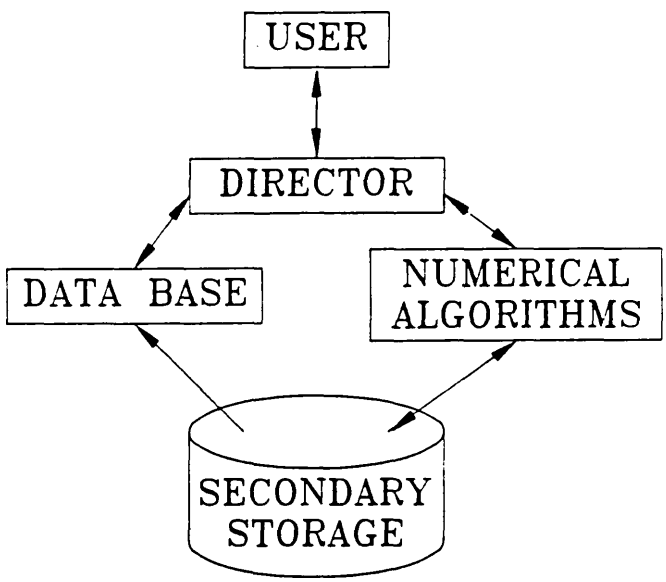


Figure 6.1 Block diagram of the prototype system

Several 'high level' procedures have been written in Prolog to facilitate the handling of the data base (working memory) and the numerical algorithms form the Prolog top-level mode [15]. They are grouped in a module called the 'Director', which acts as a manager of the numerical procedures and controls their application, e.g. it sets up the reactive rescheduling function, restricting or prioritising some control devices in such a way that some specific operational policy is reflected.

The data base of facts (written in Prolog) contains the information provided by the numerical algorithms and the characteristics and operational limits of the elements of the power system under study.

The numerical algorithms have been programmed in Pascal and all of them work on the same dynamically created data structure [34]. Once this structure is built, any algorithm can be called and the solution is held in the structure (i.e. main memory) until it is specifically modified (e.g. by calling another algorithm) with any kind and amount of activity in the Prolog top-level system taking place in between. This is very useful because unnecessary calculations can be avoided. This could be seen as having a 'main program' written in Prolog with the 'subroutines' written in Pascal being able to perform any activity in the Prolog top-level system between calls to the Pascal subroutines, without losing the information contained in the data structure on which the Pascal subroutines work.

Secondary storage is used to keep the data of several test systems. It is also used as a communication channel between the numerical algorithms and the data base when the amount of information to be transferred is large (e.g. the state of the power system); when only a small amount of data is required to be sent (e.g. Q-distances for a given node) the Director is used as the information exchange route.

6.3. Algorithmic Software

The mathematical models and algorithms on which the reactive reserve management strategy is based, are described in previous chapters.

Except for the algorithm to partition the system into reactive areas (described in chapter 2), which for simplicity was written in Prolog, all the numerical algorithms have been programmed in Pascal and all of them work on the same main data structure. Special data structures (arrays) are used by the NAG library LP routine [32] in the reactive rescheduling and co-ordination functions (described in chapters 4 and 5 respectively).

The algorithmic component of the system is divided into several modules, each containing a group of coherent routines. Pascal was chosen for the implementation of the numerical procedures because it facilitates the writing of highly structured and easily understandable programs.

The essential features of the main data structure are depicted in the diagram of Figure 6.2. It consists of a singly linked list of 'buses' (Pascal records) which have pointers to the 'lines' (Pascal records) connected to them. The structure is created 'dynamically' as the input data is read from files or interactively supplied by the user. The storage for each individual record is allocated (i.e. a 'new' record is created) as required and the new record is joined to the rest of the structure, so the data structure 'grows' as the program executes. The access to the structure is through a pointer to the first element of the list. A set of routines for the manipulation (create, eliminate, modify, etc.) of the data structure is available.

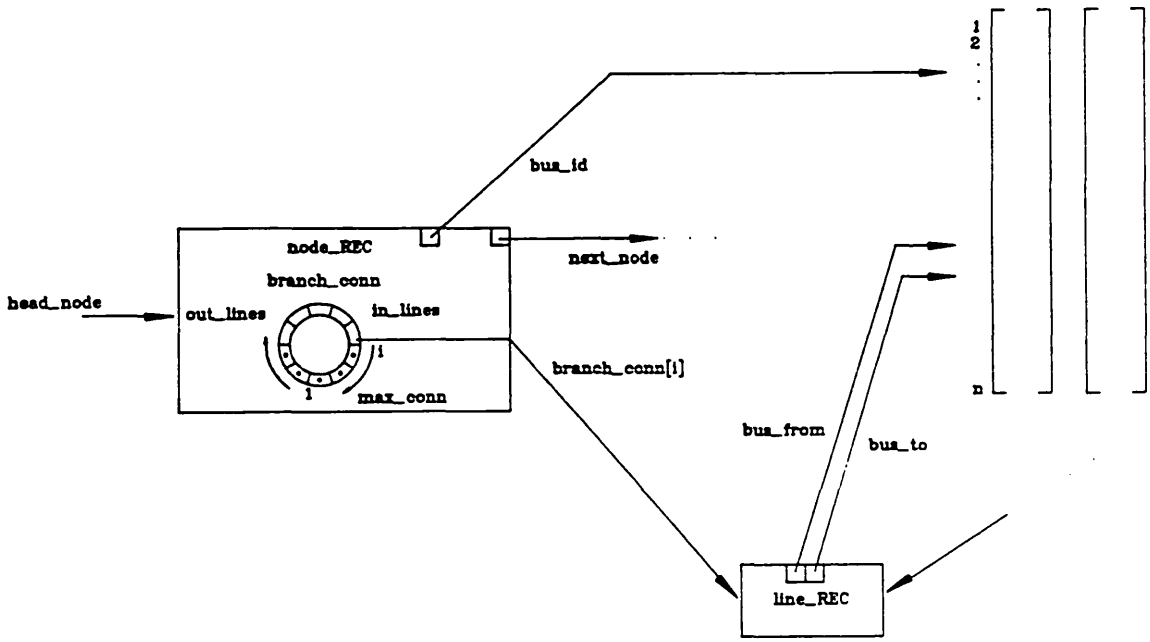


Figure 6.2 Dynamic data structure

6.4. Symbolic Component

The logic programming language Prolog has been used in the implementation of the symbolic component of the prototype system reported here. The essential elements of this conversational language are briefly described.

Programming in **Prolog** consists of declaring **facts** and **rules** about objects and their relations, and asking **queries** about them [35]. Prolog programs can be seen as a powerful extension of the relational data base model [36], because of the ability to define rules [37].

Facts are means of defining relations between objects. The collection of facts in a program can be thought of as the **data base** of the program [38]. Queries are means by which to **interrogate** the data base; when a query is produced, Prolog will search through the data base to determine if the query (goal) is a logical consequence of the data base. **Rules** are means of expressing new or complex relations using a group of other relations.

When handling a conjunction of goals, Prolog tries to satisfy each goal in turn working from left to right, invoking a **backward chaining** use of the rules to interrogate the data base. If a goal cannot be satisfied Prolog **goes back** (left) and tries to **resatisfy** the last goal for which there are untried facts (or rules) [35, 37, 38] (i.e. the evaluation **backtracks**).

The essential types of facts containing the permanent characteristics and operational limits of the power system are:

- For each VAr/voltage control device

  control_characteristics (Type, Location, Response, Lower_limit, Upper_limit).

where Type ε {lVlgen, shunt, tap}, Response ε {slow, fast}; the variables have been given self – explanatory names.

- For each load bus

load_limitsV (Node, Vmin, Vmax).

- For each generator

generator_limitsQ (Node, Qmin, Qmax).

Similarly, the sets of facts describing the operating conditions of the power system have the following structures:

control_state (Type, Location, Set_point).
load_stateV (Node,V).
generator_stateQ (Node, Qgen).

The topology of the power system is described by a set of facts of the form:

has_neighbours (N, [I, J, ..., K]).

There is one of such facts for each node in the network; N is the node identifier and [I, J, ..., K] is the set of buses directly connected to it.

The 'Director', written in Prolog, contains procedures which make it capable of interacting with and controlling the numerical calculations, written in Pascal and Fortran. A conceptual description of some of these 'hihg-level' routines is included in section 6.5 of this chapter.

The information provided by the numerical algorithms and the communication mechanisms between the number-crunching and the symbolic components of the system are also

described in section 6.5.

6.5. Communication

Mechanisms have been implemented for the integration of the number-crunching algorithms (written in Pascal and Fortran) and the knowledge-based component (written in Prolog) of the system. The flow of information between the symbolic component, the data structures on which the numerical algorithms work, and the user, becomes an easy task.

Examples are given of the existing paths of communication between dissimilar languages.

The prototype system has been implemented on a micro VAX computer running under VMS operating system. The user-system interaction takes place at the Prolog top-level mode [15], which can be accessed by typing the DCL command:

$ prolog

The reactive reserve management prototype is then set up by typing:

?-['start QV.pl'].
?-setup_QV_prototype.

This instruction 'loads' the Prolog modules which make up the symbolic component of the system, and 'links' the complied object modules containing the number-crunching algorithms; it also loads some system support libraries.

A power system can then be analysed giving the command:

?-hl_retrieve_existing_system.

A list of stored power system networks is displayed and the user is requested to select one of them. The dynamic data structure (see Figure 6.2) is built as the data is read from secondary storage and the data base of facts describing the permanent characteristics, operational limits and topology of the power system, is loaded into the knowledge-based component.

The base case operating conditions can be evaluated and displayed by specifying the following goals:

```
?-hl_fast_decoupled,
  create_transfer_MM_state_QVdbase,
  display_QVstate.
```

The first instruction initiates an a.c. load flow calculation using the fast decoupled model [24]. The definition of this command is:

```
hl_fast_decoupled :-
      dopop ('fast_decoupled (0, false)').
```

where *fast_decoupled* is a Pascal procedure with no input/output parameters, which belongs to the number-crunching component of the system. This illustrates the simplest kind of interaction between dissimilar languages, a Pascal routine with no parameters is called directly from the Prolog system:

Prolog → Pascal

It is only necessary to ensure that the data structure on which the Pascal procedure works, already exists. The results of this algorithm are held in the data structure. The second command creates (from the data structure to secondary storage) and loads (from secondary storage to the knowledge-based system) the portion of the data base describing the state of the power system:

Prolog ← file ← Pascal

The effects of the last command are obvious.

The following conjunction of goals carries out the partition of the power system into reactive areas (see chapter 2):

```
?-create_transfer_MM_dQZdV_facts,
 find_wlines (Alfa),
 find_Qareas.
```

The first instruction creates and loads (data structure → file → knowledge-based system) a set of facts specifying the [L] = [∂Q/∂V] matrix on which the method for the partition of the system into reactive areas is based. For each bus, a fact giving the value of the corresponding diagonal element ∂Qi/∂Vi, has the following structure:

```
dQiZdVi (I, Value).
```

Similarly, for each line the value of the corresponding off-diagonal elements are given by two facts of the type:

```
dQiZdVj (I, J, Value).
dQiZdVj (J, I, Value).
```

The algorithm for the identification of the weak transmission elements is described in the following 'rules':

```
find_wlines (Alfa):-
        fast_setof (AVal, (dQiZdi (K, Val),
                           AVal is abs (Val)),
                Diag),
        sort (Diag, SDiag),
        Bst is last (SDiag),
        AlfaBst is Alfa*Bst,
        not (find_wlines_node_by_node (AlfaBst)),
        listing (weakQ_line).
```

```
find_wlines_node_by_node (Alfa):-
        dQiZdVi (I,_),
        fast_setof ([AVal, I, J],
                (dQiZdVj (I, J, Val),
                AVal is abs (Val)),
                Row I),
        keysort (RowI, SRowI),
        get_wlines_at_node (SRowI, Alfa, O.O),
        fail.

get_wlines_at_node ([], _, _):-!.

get_wlines_at_node ([[Val, I, J]|RowI], Alfa, Acc):-
        AcctVal is Acc + Val,
        AcctVal > Alfa, !.

get_wlines_at_node ([[Val, I, J]|RowI], Alfa, Acc):-
        AcctVal is Acc + Val,
        assertz (weakQ_line ([I, J]),
        get_wlines_at_node (RowI, Alfa, AcctVal).
```

After the *wlines (Alfa)* goal has been satisfied, the data base will contain a series of facts defining the weak transmission elements identified. The structure of such facts is:

```
weakQ_line ([I, J]).
```

The groups of buses that remain interconnected after the weak transmission elements are eliminated (i.e. the reactive areas), are found with the following rules:

```
find_Qareas:-
        fast_setof ([I, J] , weakQ_line ([I, J]),
                WeakQ_lines),
        all_nodes (Nodes),
        get_Qareas (Nodes, WeakQ_lines),
        listing (reactive_area),!.

get_Qareas ([], WeakQ_lines) :-!.

get_Qareas ([N|Nodes], WeakQ_lines) :-
        stiffly_conn_group ([N], [N], Group, [], WeakQ_lines),
        sort (Group, QArea),
        assertz (reactive_area (QArea) ),
        diff_set (Nodes, Group, Nodes_Group),
        get_Qareas (Nodes_Group, WeakQ_lines).

stiffly_conn_group ([], Seen, Group, Acc, WeakQ_lines) :-
        Group = Acc, !.
```

```
stiffly_conn_group ([Q|Qs], Seen, Group, Acc, WeakQ_lines) :-
        has_neighbours (Q, QNs) ,
        once
        (   fast_setof  (N, (member (N, QNs) ,
                             not (member ([Q,N], WeakQ_lines) ),
                             not (member ([N,Q], WeakQ_lines) )
                                 ),
            RealQNs ) ;
          RealQNs = []
        ),
        diff_set (RealQNs, Seen, UnSeenQNs),
        append (UnSeenQNs, Seen, SeenNew),
        append (Qs, UnSeenQNs, QsNew),
        stiffly_conn_group (QsNew, SeenNew, Group, [Q|Acc],
                WeakQ_lines).
```

Once the *find_Qareas* goal is satisfied, a set of facts defining the partition of the power system into reactive areas, will be contained in the data base. The structure of such facts is:

```
reactive_area ([I,J,K,...L]).
```

The identification of the vulnerable nodes for each of the reactive areas is carried out by specifying the following commands:

```
?-create_transfer_MM_Zth_facts (Kfactor),
  find_vulnerable_nodes.
```

The first instruction creates and loads (data structure → secondary storage → data base) a set of facts specifying the results of the 'pseudo-short-circuit' calculation. The elements of the principal diagonal of the 'pseudo-[Zbus]-matrix' are defined by facts of the form:

```
zth (I, Zmag, Ztheta).
```

The second goal is defined as:

```
find_vulnerable_nodes:-
        nl, write ('Area - Vulnerable node'), nl,
        reactive_area (Group),
        fast_setof ([Scc,I], (member (I, Group),
                                        zth (I, Z, _),
                                        Scc is 1.0/Z),
                ZGroup),
        keysort (ZGroup, SGroup),
        [_,Vul ] is hd (SGroup),
        write (Group), write ('-'), write (Vul), nl,
        fail.
```

The evaluation of the Q-distances to low voltage and voltage collapse conditions (i.e. Qdist-to-LV and Qdist-to-VC) for the vulnerable nodes, can be performed by specifying:

```
?-evaluate_Qreserves_list (Ns).
```

where *Ns* is the list of vulnerable nodes, and the command is defined as:

```
evaluate_Qreserves_list ([]):-!.

evaluate_Qreserves_list([N|Ns]) :-
        evaluate_Qreserve (N),
        evaluate_Qreserves_list (Ns).
```

The subgoal *evaluate_Qreserve (N)* has the following form:

```
evaluate_Qreserve (Bus) :-
        prolog_setq (pbus_id, Bus),
        dopop ('evaluate_Qreserve_pop (pbus_id) '),
        prolog_eval (valof (pVmin), Vmin),
        prolog_eval (valof (pQresVmin) , QresVmin),
        prolog_eval (valof (pEQgenVmin), EQgenVmin),
        prolog_eval (valof (pVVC), VVC),
        prolog_eval (valof (pQresVC), QresVC),
        prolog_eval (valof (pEQgenVC), EQgenVC),
        assertz (qreserve (Bus,Vmin,QresVmin,EQgenVmin,VVC,QresVC,
                EQgenVC) ).
```

where *evlauate_Qreserve_pop* is a POP-11 procedure [39] (POP-11 is the core language of the POPLOG system):

```
define evaluate_Qreserve_pop (bus_id) ;
lvars id ;
        initint32(1)          →        id                    ;
        bus_id                →        id(1)                 ;
        consdfloat (0,0)      →        pddVmin               ;
        consdfloat (0,0)      →        pddQresVim            ;
        consdfloat (0,0)      →        pddEQgenVmin          ;
        consdfloat (0,0)      →        pddVVC                ;
        consdfloat (0,0)      →        pddQresVC             ;
        consdfloat (0,0)      →        pddEQgenVC            ;
        evaluate_Qreserve_pas
                (id,pddVmin,pddQresVmin,pddEQgenVmin,pddVVC,
                pddQresVC, pddEQgenVC, 7,false);
        dd_value(pddVmin)          → pVmin          ;
        dd_value(pddQresVmin)      → pQresVmin      ;
        dd_value(pddEQgenVmin)     → pEQgenVmin     ;
        dd_value(pddVVC)           → pVVC           ;
        dd_value(pddQresVC)        → pQresVC        ;
        dd_value(pddEQgenVC)       → pEQgenVC       ;
endefine;
```

evaluate_Qreserve_pas is a Pascal procedure for the evaluation of the Q-distances to low voltage and voltage collapse conditions. These procedures illustrate the mechanisms used for the communication between the numerical and symbolic components of the system, when parameter passing is required:

Prolog → POP-11 → Pascal

Prolog ← POP-11 ← Pascal

as opposed to the case when no parameters are needed, and the information form the data structure is transmitted to the knowledge-based system through secondary storage:

Prolog → Pascal

Prolog ← file ←Pascal

After the *evaluate_Qreserve_list(Ns)* is satisfied, the database contains a set of facts giving the Q-distances for the vulnerable nodes. The form of such facts is:

qreserve (N, Vmin, QdistLV, EQgLV, VVC, QdistVC, EQgVC).

where

N	is the bus identifier
Vmin	is a specifiend minimum value for the voltage magnitude
QdistLV	is the distance to low voltage conditions (i.e. Qdist-to-LV)
EQgLV	is the additional reactive power generation activated in the network from the base case to the low voltage conditions
VVC	is the node N voltage magnitude at the voltage collapse point
QdistVC	is the distance to voltage collapse (i.e Qdist-to-VC)
EQgVC	is the total additional reactive generation activated in the system

The second major component of the number-crunching subsystem is the VAr/voltage contingency screening algorithm (described in chapter 3), which can be activated by typing the goal:

```
?-screening_1P1Q_list (Lines).
```

where *Lines* is the contingency list, and the command is defined as:

```
screening_1P1Q ([]):-!.

screening _1P1Q_list ([[F,T]/Lines]) :-
        screening_1P1Q (F,T),
        screening_1P1Q_list (Lines).
```

Each circuit in the contingency list is processed by a Pascal contingency screening procedure. The two parameters (i.e. the terminal nodes of the circuit) are passed to the number-crunching component by a POP-11 routine and the solution of the algorithm is transferred from the data structure to the symbolic subsystem through secondary storage, i.e.

Prolog → POP-11 → Pascal

Prolog ← file ← Pascal

Once the *screening_1P1Q_list (Lines)* goal has been satisfied, the database will hold the approximate network solutions carried out to estimate the network variables. For every outage in the contingency list, the corresponding approximate solution is given by a fact of the form:

screen_1P1Q_estimates (Oloc, S, Vl_set, Vg_set, Qg_set).

where

Oloc	= [F,T] specifies the location of the outage (i.e. the terminal nodes of the circuit)
S	ε{split, non_split} indicates if the outage splits the network
Vl_set	is the set of estimated load bus voltage magnitudes
Vg_set	contains the voltage magnitudes of generators
Qg_set	is the set of estimated reactive power production at generating stations

The evaluation of the PIs is described by the following rules:

```
find_PIs_1P1Q :-
        not (get_PIs_one_by_one).

get_PIs_one_by_one :-
        screen_1P1Q_estimates (Oloc, non_split, Vl_set, Vg_set, Qg_set),
        get_PIvs (Vl_set, Vg_set, PIv1, PIvoo),
        get_PIqs (Qg_set, PIq1, PIqoo),
        assertz (performance_index_1P1Q (Oloc, PIv1, PIvoo, PIq1, PIqoo)),
        fail.
```

```
get_PIvs (Vl_set, Vg_set, PIv1, PIvoo):-
    once
    (
        fast_setof
        (    DV,
             (
                 (
                     member ([L,Vapx], Vl_set),
                     load_limitsV (L, Vmin, Vmax),
                     (   (   Vapx < Vmin,
                             D is (Vapx - Vmin),
                             DV is abs (D)
                         );
                         (   Vapx > Vmax,
                             D is (Vapx - Vmax),
                             DV is abs (D)
                         )
                     )
                 );
                 (
                     member ([G, Vapx], Vg_set),
                     control_characteristics (IVlgen, G, _, Vmin, Vmax),
                     (   (   Vapx < Vmin,
                             D is (Vapx - Vmin),
                             DV is abs (D)
                         );
                         (   Vapx > Vmax,
                             D is (Vapx - Vmax),
                             DV is abs (D)
                         )
                     )
                 )

             ),
             DVs
        )
        ;
        DVs = []
    ),
    once
    (
        (    DVs=[], PIv1 = 0.0, PIvoo = 0.0)
        ;
        (    not (DVs=[]), find_EDs (DVs, 0.0, PIv1),
             sort (DVs, DVsorted), PIvoo is last (DVsorted)
        )
    ) .
```

```
get_PIqs (Qg_set, PIq1, PIqoo):-
    once
    (
        fast_setof
        ( DQ
            (
                member ([G, Qapx], Qg_set),
                generator_limitsQ (G, Qmin, Qmax),
                (   (   Qapx < Qmin),
                        D is (Qapx - Qmin),
                        DQ is abs (D)
                    );
                    (   Qapx > Qmax,
                        D is (Qapx - Qmax),
                        DQ is abs (D)
                    )
                )
            ),
            DQs
        )
        ;
        DQs = []
    ) ,
    once
    (
        (   DQs=[], PIq1 = 0.0, PIqoo = 0.0)
        ;
        (   not (DQs=[]),find_EDs (DQs, 0.0, PIq1),
            sort (DQs, DQsorted), PIqoo is last (DQsorted)
        )
    ).


find_EDs ([], Acc, Sum) :-
    Sum is Acc.


find_EDs ([D|Ds], Acc, Sum) :-
    NewAcc is Acc + D,
    find_EDs (Ds,NewAcc,Sum).
```

So, the performance indices PI_{v1}, $PI_{v\infty}$, PI_{q1} and $PI_{q\infty}$ can be evaluated by typing the goal:

```
?-find_PIs_1P1Q.
```

which will bring to the database a series of facts specifying the *PIs* for each circuit in the contingency list. The form of such facts is:

```
performance_index_1P1Q (Oloc, PIv1, PIvoo, IPq1, PIqoo).
```

The Prolog library routine sort (or keysort) can then be used to rank the contingencies according to the value of one of their *PIs*.

Contingencies considered to be severe (i.e.the worst case list) are analysed by a full a.c. load flow calculation. The goal:

?-ac_contingency (From, To).

trips out the circuit *From-To*, carries out an a.c. load flow calculation, and creates, loads and displays the facts describing the operating conditions after the outage.

If it is found that the outage represents a VAr/voltage security risk, a reactive power rescheduling (see chapter 4) is performed.

The reactive power rescheduling function is the third major component of the number-cruching subsystem. A step of this proceedure can be initalised by specifying the command:

?-qrescheduling_step.

which is defined as follows:

```
qrescheduling_step :-
    detect_existing_violations,
    evaluate_transfer_MM_sens_matrix,
    construct_sparse_sens_matrix,
    find_effective_controls,
    detect_potential_violations,
    setup_LP_problem,
    dopop ('solve_LP_Qrescheduling_pas (0,false)'),
    display_proposed_control_adjs,
    implement_proposed_adjustments,
    dopop ('uninitialised_fast_decoupled (0,false)'),
    create_transfer_MM_state_QVbase,
    display_QVstate.
```

Existing violations, effective controls and potential violations are identified and an optimisation problem is formulated and solved. The solution is then used to update the settings of the VAr/voltage control devices and an a.c. load flow calculation is performed to verify the effectiveness of the proposed control adjustments.

If no limit violations are detected in the new system state, then the rescheduling problem is solved; otherwise, another *qrescheduling_step* is carried out.

```
?-cf_store_state (Ncond, Oloc).
```

where *Ncond* ε {base_case, contingency} specifies the system conditions (*Ncond* = contingency in this case) and *Oloc* ε {[From, To], []} defines the location of the outage (if any); backs up into the database the current operating conditions, the sparse sensitivity matrices and the control adjustments used to relieve limit violations (this information is requried by the co-ordination function). It also resets the VAr/voltage control devices to their base case set points, and reconnects the outaged circuit. Another circuit in the worst case list can then be analysed using the *ac_contingency (From,To)* command.

The last main element of the algorithmic subsystem is the co-ordination function (described in chapter 5). Its first step is described by the rule:

```
coordina_step1(Contingencies, Nodes_incr_Qdist) :-
        find_maximum_adjustments (Contingencies, Nodes_incr_Qdist),
        check_for_limit_violations_bc,
        cf_setup_LP_problem, !,
        dopop ('solve_LP_coordination_pas (0, false)'),
        cf_display_max_adj_possible.
```

where *Contingencies* is the set of line outages for which control adjustments are proposed by the rescheduling function to eliminate limit violations, and *Nodes_incr_Qdist* is the set of nodes for which adjustments are being proposed to increase their Q-distances.

The maximim adjustment proposed for each VAr/voltage control device is determined (i.e. [Δu']) and the effects of implementing [Δu'] on the base case conditions are evaluated using

linear sensitivites. All violations are included in the constraints set and an upper-bound LP problem is formulated and solved. The solution of this first step defines the adjustments that can be implemented on the base case conditions without violating any operational limit (i.e.[Δu^{s1}]). the second step of the co-ordination strategy is defined by the following rule:

```
coordina_step2 (Contingency_list) :-
    check_violations_continglist (Contingency_list),
    cf_setup_LP_problem, !,
    dopop ('solve_LP_coordination_pas (0, false)'),
    cf_display_max_adj_possible.
```

The effects of [Δu^{s1}] on the security risk contingencies (i.e. *Contingency_list*) are accounted for. Detected violations are included in the constraints set and a new LP problem is formulated and solved. The solution of the second step thus represents the control adjustments that can be implemented in a preventive mode.

Chapter 7

Conclusions

The steady state reactive reserve management problem was analysed from the viewpoint of the operational planning of power systems.

The basic problem consists of the appropriate use of the available VAr/voltage control devices in order to maintain adequate reactive reserves (i.e. large enough and correctly spread throughout the power system) to preserve system security.

In this thesis, a global methodology for the reactive reserve management in the operational planning phase of power systems has been proposed. The objective of the strategy is to determine the settings of existing VAr/voltage control devices to allocate the reactive reserves in such a way as to ensure that the system does not move towards voltage collapse as the demand changes, and that sufficient reserves are available to cater for the reactive power changes following contingencies.

Several algorithms based on fairly simple models of the power system have been used to deal with different aspects of the problem.

To assess the proximity of the system to voltage collapse conditions, the network is divided

into reactive areas by identifying the weak transmission elements (which define the boundaries between the areas). A 'vulnerable' node is then pinpointed for each reactive area by means of an algorithm which combines, in a very simple way, two of the most critical factors defining the Q-V curves of the buses in the system, i.e. the transmission network and the reactive reserves available at generating stations. Proximity indicators to low voltage and voltage collapse conditions are evaluated for the vulnerable nodes. This information (i.e. reactive areas and Q-distances) provides an objective general view of the adequacy of the reserves from the voltage collapse proximity viewpoint. Strategies to increase the reactive strength (Q-distances) of an area can then be determined.

Contingencies are accounted for as follows: a contingency screening and ranking algorithm is used to identify the potentially critical cases which are further analysed by an AC load flow method. For each security risk contingency a LP reactive power rescheduling is carried out to relieve operational limit violations.

A LP coordination function is then employed to bring together all the VAr/voltage control adjustments proposed to increase the strength (Q-distances) of a given area (or areas) and to alleviate limit violations for security risk contingencies. The objective is to maximise the adjustments to be implemented in a preventive mode, without violating operational limits on the base case or any security risk contingency conditions.

The proposed methodology has been prototyped by integrating algorithmic software and logic programming, and although the final strategy is basically algorithmic, the use of Expert System technologies has made the prototyping an easy task.

The symbolic component of the system (written in PROLOG) acts as a manager of the numerical procedures (written in PASCAL and FORTRAN) and controls their application, e.g. it sets up the LP reactive rescheduling function, restricting or prioritising some control devices in such a way that some specific operational policy is reflected.

Attention has been focused on fast prototyping, ignoring efficiency considerations. The system runs relatively slowly, mainly because the pattern matching mechanism to search through the knowledge base is a slow process.

The modularity of the prototype digital system is such that further refinements to enhance its performance can be easily added without altering its basic structure and functionality. Although the mathematical models and algorithms involved are fairly simple, the prototype constitutes a valuable tool for the assessment and enhancement of the reactive reserve conditions on a power system. It can be used to gain understanding of the complexity involved in the management of the reactive reserves.

Alternative operational polices can be quickly explored through rules which utilise and control existing number-crunching algorithms, specifying parameters (e.g. threshold, cost factors, etc.) so that a given strategy is represented.

The work presented on this thesis has given rise to a number of areas requiring further research and development. Some of the most relevant are given below.

Partitioning of the system into reactive areas. Because the algorithm employed to divide the network into reactive areas uses only 'local' information, i.e. circuit parameters and state, it does not show, for a given node, which sources can provide reactive support, e.g. a particular bus may get more aid from generators outside its reactive area than from those belonging to the same area. The 'pseudo-short-circuit' calculation, which combines both the transmission network characteristics and the reactive reserves available at generating stations, may provide the basis for an alternative method. The components of the 'pseudo-short-circuit' current for a given node can provide a good insight into the reactive support that the node can receive from each generating station.

Evaluation of the distances to low voltage and voltage collapse. The distances to low voltage and voltage collapse conditions (Qdist-to-LV and Qdist-to-VC) for

a given node are evaluated by incrementing its reactive demand. A more realistic increase in the demand (e.g. augmenting all the loads - with constant power factor - in the system) should be considered; this would, however, produce a global indicator for the whole system, making the detection of specific weak reactive areas a very difficult task. A combination of the two approaches might also be explored.

The simulation of the behaviour of automatic on-load tap changing transformers when the Q-distances are evaluated, is considered a priority for further developments.

VAr/voltage contingency selection. Experiments carried out to date have shown that the conventional 1P-1Q screening technique provides a good estimate of the network behaviour as long as the generators remain within their reactive production capabilities.

Two alternative screening methods which take into consideration the generator's VAr production limits were proposed in Chapter 3. However, the results obtained to date with the two algorithms (1P-nQ and 1P-1GS) have not been very encouraging; nevertheless exhaustive testing should be carried out before they can be discarded. A better Q-V model of the network (e.g. CRIC[20]) is also under consideration. The bus voltage angle changes estimated with the first half itertion (1P) of the fast decoupled load flow and compensation techniques were found to be accurate enough, but efforts to include generation VAr limits should be continued. Generator outages should be included in the contingency list as well as some high probability double contingencies based on engineering judgment and experience.

Reactive power rescheduling. Account should be taken of the discrete nature of the transformer taps and shunt capacitor/inductor banks (e.g. by using mixed integer linear programming techniques). A limit in the number of control adjustments (not too many) should also be considered, especially when the reactive rescheduling function is used to propose corrective plans to alleviate operational limit violations under contingency conditions.

Coordination function - conflict resolution. A sound strategy is required to eliminate conflicting control adjustments, rather than the trial and error method used to date to tune the cost factors associated with the adjustments of VAr/voltage control devices.

Finally, although the prototype digital program is easy to operate from the Prolog top-level mode, the man-machine interface should be enhanced (e.g. graphics, explanation facilities, etc.).

To date, the methodology presented in this thesis has been used only on small sample systems. The application of the software and principles developed in this research to large networks (e.g. part of the CEGB grid) is under consideration for the near further. The prototype system is being transferred to the CEGB National Control Centre's computer to be explored on an informal trial basis.

To conclude, although several areas needing further analysis and development were identified, the main contributions of this research project are summarised as follows:

- The proposal of a simple and global strategy for the management of the reactive reserves, which encompasses the two major aspects of the steady state VAr/voltage security : contingencies and proximity to voltage collapse.

- The development of the 'pseudo-short-circuit' algorithm which combines the transmission network characteristics and the reactive reserves available at the generators, in a single calculation. It has been used to identify the vulnerable nodes in the system and could be the basis for an alternative method for the partitioning of the network into reactive areas.

- The improvement in the form of the VAr performance indices PI_{q1} and $PI_{q\infty}$ by considering non-normalised violations.

- The development of a transformation applied to reformulate the non-linear reactive rescheduling problem (the objective function involves absolute values) as an equivalent LP problem. An accurate Q-V model of the network was obtained by implicitly representing the voltage angles.

- The application of a co-ordination strategy which reflects the operating philosophy of the CEGB, and perhaps of most electricity utilities, i.e. dispatch the reactive power in a preventive mode as far as defined utility constraints allow. In practice, control adjustments might have to be implemented as corrective measures under specific conflicting contingency conditions.

- The implementation of a rapid prototype digital system in which all the above mentioned algorithms are manipulated by a high-level knowledge-based component of the system, to assess and enhance the adequacy of the reactive power reserves, under specific forecast operating conditions. The system offers a flexible environment to quickly explore alternative reactive reserve management policies.

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