ALLEVIATION OF VOLTAGE LIMIT VIOLATION IN POWER NETWORKS

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
Specialization in System Engineering & Operations Research)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work presented in the dissertation entitled, "**ALLEVIATION OF VOLTAGE LIMIT VIOLATION IN POWER NETWORKS**", submitted in partial fulfilment of the requirement for the award of the degree of **Master of Engineering**, in **Electrical Engineering**, with specialization in **System Engineering and Operation Research**, in the Department of Electrical Engineering, University of Roorkee, Roorkee, is an authentic record of my own work, carried out with effect from **July 1997** to **February 1998**, under the guidance of **Dr. H.O. Gupta**, Professor, Department of Electrical Engineering, University of Roorkee, Roorkee.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

23, February, 1998

(ASHISH JAIN)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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ABSTRACT

There is a tendency of power transmission systems of today to operate closer and closer to their physical limit. It is not uncommon that the limiting factor for power transformers in the systems today is the risk of voltage instability. As a consequence, at least some 15 incidents of voltage collapse occurred world wide during the 1970's and 1980's [17]. In the event of an approaching blackout, the disconnection of loads under controlled conditions and/or blocking of the tap changers on transformers and/or routine power generation of the generator buses and switchblade reactors or capacitors can minimise the damage sustained. In the past, operators maintained reliable performance of the power system using their experience and on-the-spot assessment of network conditions. However, power networks are now large, complex and highly interlinked. The increased number of possible operating scenarios can lead to situations where the operator's analytical ability may even fail. The remedy to such situations is the centralized control over power resources and more dependence on computers to assist the operator in system monitoring, control and economic dispatch. Though understanding of bulk power transmission system is essential when it is heavily utilized, to ensure reliable and economic service to customers. As the transmission line become overloaded, the system operators are faced with increasingly difficult reactive and voltage control problems. Voltage related

problems of the power system, if not attended to immediately may prove to be fatal. From a secure operation point of view, the objective of power system operation is to keep bus voltage magnitudes and angles, and the real and reactive power flows in lines within acceptable limits despite changes in load or available resources. Voltage limit violations at the various buses in the system have been alleviated by using the local optimization technique. The local optimization technique is useful because few buses in the vicinity of limit violating buses need to be processed rather than the complete system. It saves lot of computational effort. The controls exercised to alleviate the bus voltage magnitudes are (i) reactive power generation of generator buses (ii) reactive power generation of switchable reactors/capacitors (iii) turns ratio of tap changing transformer and (iv) the load shedding. The above controls lead to minimization of the voltage limit violation at the buses. The problem of alleviation of voltage limit violation has also been formulated as an optimization problem. The objective function to be minimized is taken as the weighted sum of the squares of the limit violation of bus voltages. The voltages at all buses have been considered as dependent variables with a constraint on the upper and lower limit except the slack bus voltage. The independent variables are generator reactive power, generation or absorption of reactive power from the switchable capacitor or reactor, tap changing transformer ratio and load to be shedded. While operating the transformer in the local area, proper care has been taken so that its operation does not deteriorate the bus voltage controlled by it. The continuous variation of transformer tap is assured in the local optimization procedure. The transformers are modelled by their pi-equivalent network. Switchable reactors and capacitors are modelled as reactive power sources varying continuously at the buses to which they are connected.

Conventionally, the optimal operation and planning of power system networks have been on economic criterion. Economic load dispatch (ELD) has been utilized for this purpose and widely accepted by most of the utilities and implemented in their computer aided dispatch centers. As a dispatching tool, the reactive generation requirement and losses in the system are minimized considering it as a optimal power flow problem which can be adopted by utilities for operator guidance to take off line optimal operation decisions. In this part the problem, reactive generation at generator buses and the, losses in the system are minimized by taking the reactive generation at generator buses and the transformer top ratio as an independent variable and the bus voltage magnitude as dependent variable.

Increase loading of power transmission network in recent years has made the problem associated with voltage instability and voltage collapse more important. A good prevention against voltage collapse would require to define and monitor voltage collapse proximity indices, intended to tell operators how far the system is from collapse. The index suggested by Bhanot V. [3] has been calculated at each iteration of load flow. The index named as; diagonal element dependent index-the ratio of maximum diagonal element value to the minimum diagonal element of the Jacobian: allow some obscure properties of the system to appear and thus act

a tool to check the ill conditioning of the network and proximity to collapseof the system..

In the present work the problem of optimal load flow i.e. minimization of reactive generation of generation buses and the losses in the system is taken first. Taking the solution of optimal load flow disturbance is created in the system and voltage limit violation in the system is alleviated using local optimization techniques. After alleviating voltage limit violation the reactive generation and losses in the system are again minimized. The voltage security index is calculated at each iteration for checking secure operation of the system. The algorithm have been tested on 24-bus and 57-bus systems.

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Project seminar & dissertation, which form an integral part of our one and a half year academic program are, according to the popular view, tedious affairs. Contrary to this view, prior to embarking upon this undertaking, much time was devoted towards selecting a suitable project and dissertation, suitable in the sense that it should provide me with an opportunity for applying concepts learnt and should be feasible, considering the limitation on time and resources at our disposal.

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Ashish Jain
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NOMENCLATURE

$A(i)$: Set of buses connected to bus i

BMVA : Base MVA

B_i : Susceptance of shunt capacitor/reactor at the i^{th} load bus

B_{ii} : Sum of self susceptances connected at i^{th} bus

b_{sj} : Susceptance of line between slack bus and j^{th} bus

b_{sg} : Susceptance of line between slack bus and generator bus

b_{ij} : Susceptance of line between buses i and j

$F(X,U)$: Scalar objective function to be minimized (eqn 3.2.1)

G_{ss} : Sum of self conductances connected at slack bus.

$G(X,U)$: Objective function defined in equation (eqn.2.4.1)

g : Set of equality constraints

g_i : Equality constraint equation corresponding to bus i

g_{sj} : Conductance of line between slack bus and j^{th} bus

g_{sg} : Conductance of line between slack bus and generator bus

g_{ij} : Conductance of line between buses i and j.

$g_q(X,U)$: Equality constraint for minimization problem in Chapter 2

I : Iteration count

I_d : Diagonal Element Dependent Index

i-j : Line connected between bus i and j

J : Jacobian matrix

LV : Number of buses at which voltage limits are violated

MW : Megawatt

MVAR : Mega var

MVA : Mega volt-ampere

NB : Total number of buses

NC : Number of control buses

NLB : Total number of load buses

NLO : Number of buses processed for local optimization

NGB : Number of generator buses

NTR : Number of tap changing transformer

OPF : Optimal power flow

PF : Power Factor

PL : Real load

PL_i : Real load at the i^{th} load bus

P_s : Sequence of steps involved in the computation process of alleviation of limit violation problem constituting one pass

PL_s : Real load at the slack bus

PG : Real generation

PG_s : Real generation at the slack bus

PG_i : Real generation at the slack bus

$P_s(V,\theta)$: Net real power injection of all the lines connected at slack bus

p.u. : Per unit

QG_i : Reactive generation at i^{th} generator bus

QG_s : Reactive generation at the slack bus

QL_s : Reactive load at slack bus

QR_i : Reactive generation of switchable capacitor/~~reactor~~ at i^{th} bus

QL_i : Reactive power load at i^{th} bus

Q_i : Net reactive power injection at i^{th} bus ($Q_{Gi} - Q_{Li}$)

$Q_s(V,\theta)$: Net reactive power injection of all the lines connected at slack bus

$TTAP_i$: Tap side of i^{th} transformer

$TIMP_i$: Impedance side bus of i^{th} transformer

TOL : Tolerance

TR_i : Transformer ratio of the i^{th} tap-changing transformer

T_{ij} : Tap ratio of the transformer connected between bus i and j

t_p, t_q : Step size or step length

U : Independent variables or the vector of the control variables

U_j : j^{th} element of vector U

U_j^i : j^{th} element of vector U at i^{th} iteration

V : Vector of bus voltage magnitudes

V_s : Slack bus voltage magnitude

V_g : Generator bus voltage magnitude

V_i : i^{th} element of V

W_i : Weight factors associated with the i^{th} load bus

W_s : Weight factor associated with slack bus power

W_{gi} : Weight factor at i^{th} generator bus

W_r : Weight factor associated with real loss

W_x : Weight factor associated with reactive loss

X : Dependent variables or the state vector

θ : Vector of phase angles of bus voltages

θ_g : Generator bus angle

θ_L : Load bus angle

θ_i : i^{th} element of θ

θ_{sj} : $(\theta_s - \theta_j)$ i.e. difference of bus voltage angles between the slack and j^{th} bus

θ_{sL} : $(\theta_s - \theta_L)$ i.e. difference of bus voltage angles between the slack bus and the load bus.

θ_{sg} : $(\theta_s - \theta_g)$ i.e. difference of bus voltage angles between the slack bus and generator bus

λ : Vector of Lagrangian multipliers

Pre-script Δ	*The increment/small change/amount of limit violation in the corresponding variable*
Pre-script ∇	*The total derivative of corresponding function*
Superscript 'max'	*The upper limit/rating of the corresponding variable*
Superscript 'min'	*The lower limit of the corresponding variable*
Subscript 'old'	*The previous iteration values of the corresponding variable*
Subscript 'new'	*The previous iteration values of the corresponding variable*

INTRODUCTION

The economic recession coupled with environmental and ecological pressures has compelled electric utilities all over the world to serve the increasing load demand without corresponding increase in their transmission and generation facilities. However, under these stressed conditions the utilities are now facing the problem of maintaining required voltages in some parts of the power system network and the increased probability of voltage collapse. Systems in developed countries are heavily compensated, which have proved to be frazile from a voltage stability point of view. What has made the operator's task difficult is the fact that the voltages may appear to be near normal in almost all areas of the power system, even near critical loading.

This increased loading of power system and exploitation of transmission system may overlook and jeopardize one of the important aspect of power system, i.e. **Security**. As the system load is increased and operated with a high economic return, the loading and generating margins decrease, thereby creating a less secure system. The Security of power system is its ability to withstand disturbances arising from faults and unscheduled removal of supply, or it is the ability to withstand the impact of sudden changes due to increase in load or equipment outage.

The increase in demand for the real load in interconnected system can be met to some extent, but it may become difficult to meet the increased reactive load requirement. Reactive power problems arise in power systems under a variety of conditions. For lightly loaded systems, too much reactive power may be injected into the network by shunt elements resulting in overlay high voltages at the voltage controlled buses. Alternatively under heavy load conditions there may be insufficient injected reactive power causing the voltages to drop. In some cases for heavily loaded power systems, particularly when the system configuration comprises long transmission lines, the voltage drop caused by dropping of a generator or a transmission line can not be recovered even if the static capacitors at the load ends are switched on. This sort of abnormal voltage drop is called voltage instability or voltage collapse phenomena. Sequence of ~~events~~ violating operating constraints and consequently forcing the load curtailment or system collapse are shown in Fig. 1.1. The gravity and the frequency of occurrence of this phenomena has prompted investigations in a new direction of power system security analysis. Instability and voltage collapse phenomena in interconnected power system has been intensively studied by various investigators.

For heavily loaded systems, a system collapse following a disturbance can often be attributed to large reactive losses produced in the overloaded system. Minimizing the reactive losses in the normal operated system can place the system in a better position for surviving the heavy loading conditions and may reduce

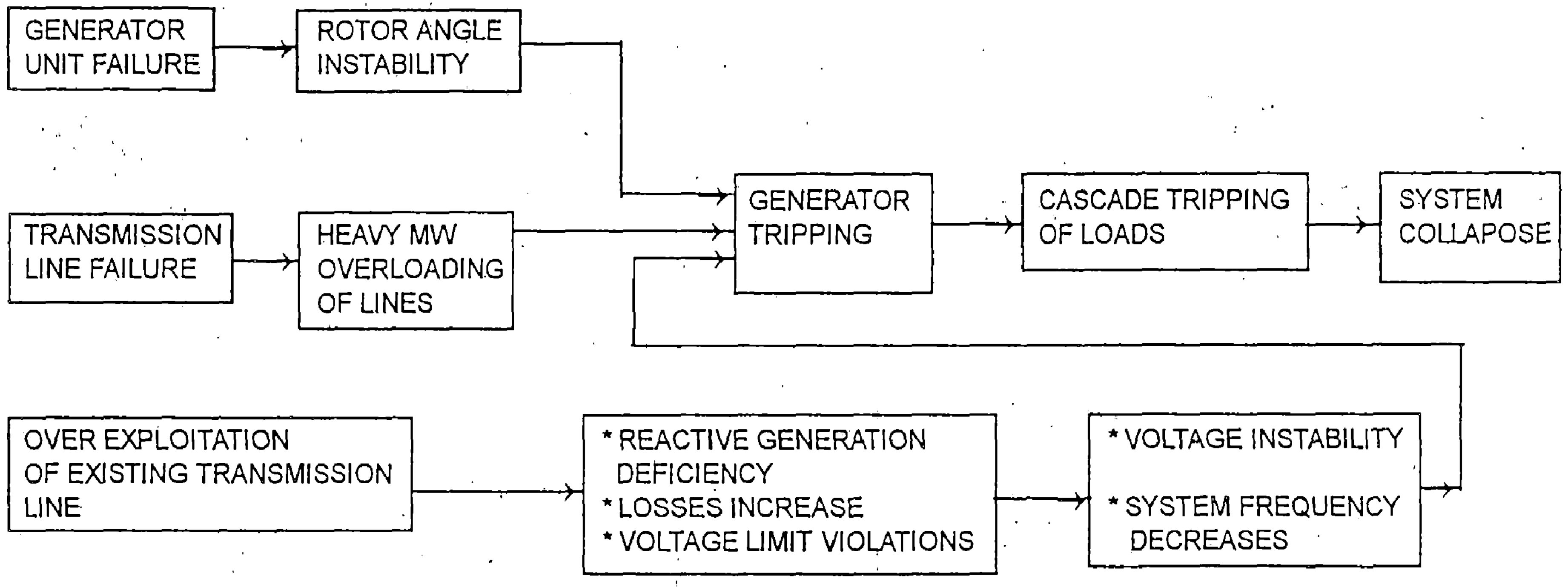


Fig. 1.1 : EVENTS LEADING TO SYSTEM COLLAPSE

the number of shunt capacitors required to prevent the voltage collapse which will ultimately lead to system collapse. Prior to the disturbance, all transmission lines are loaded within their rated capacities. Due to disturbance, there will be sudden increase of series reactive power losses and reduction in the line receiving end voltages. During peak load periods, the summation of the series reactive power losses throughout the network forms a significant part of the overall system reactive power demand. This observation suggests the strategy of minimization of the series reactive power losses.

Presently, many power systems worldwide are undergoing voltage-related problems for more than one reason. A more systematic approach to voltage phenomena is currently needed since new operational strategies directly affecting the system wide voltage profile are taking place. This situation calls for exploring the potential of voltage control measures that are made more flexible to react to changing system conditions. A good voltage profile is important for three reasons : (i) better security, (ii) good quality of supply and (iii) low transmission loss. Hence bus voltages must be maintained in a narrow band around specified value under all operating conditions. This has been recognized as one of the most important operational problems.

Many power systems possess certain amount of reactive power reserves, which if of proper amount and applied at the appropriate time would help in achieving a better voltage profile. Theoretical work underlying this effort is not simple as the comprehensive modelling and solution of operating power system become very complex. Most utilities monitor system wide voltage profile in the Energy Management Systems. This information is used by a human operator to make decisions about setting reference points at particular voltage control locations or for switching reactive power support. Specific voltage control tools for already operational reactive power resources could be equipped with more flexible microprocessor and power electronics-based controls for maintaining desired voltage profile. These tools can be automated or activated manually.

For any given large utility there are multiple objectives to be achieved. In a power system, Security, Economic operation, and Reliability are typical objectives to be satisfied. It may be obvious that trade-off among these objectives are impossible because of their different nature. In other words, it is impossible to treat respective objectives under the identical criterion. In the past, operators maintained reliable performance using experience and on-the-spot assessment of network conditions. However, power networks are now more complex; the increased number of possible operating scenarios can lead to problems beyond the operator's analytical ability. Most utilities, therefore, use computer-aided dispatch to assist the operator in system monitoring, economic dispatch, and voltage security assessment.

In view of the foregoing discussion, present dissertation work has been undertaken and attempted with respect to specific objectives of alleviation of voltage limit violation due to occurrence of disturbance and minimizing the system reactive power generation and losses with optimal use of the available controls so as to save the system from collapse.

1.2 LITERATURE REVIEW

The primary objective of voltage/reactive power control is to maintain voltages and currents within the allowable constraints as ~~operating~~ conditions on the power system change. When the system is subjected to severe disturbances in its inputs and structure, voltage control is considered to be a remedial measure, which together with other controls on the system should act to preserve system integrity and remedy the effects of a disturbance. Many time an experienced operator may successfully select the appropriate remdial action, but in complex operating conditions or in planning studies, it is necessary that the remedial action be computed. A number of research papers are available which directed their efforts in this direction [4, 9]. In his paper [11] N.D. Hatziargyrion presents a method for the adjustment of voltage and reactive power control devices in distribution netwroks based on probabilistic costrained load flow.

The operators and planners of large, interconnected electric power system are seriously concerned with the problem of voltage instability. Due to increasing loads and lack of transmission capability one of the recent concerns that power utilities are facing is to maintain the required system voltage stability margin. In this paper [7] K.N. Srivastava investigates the effect of generation rescheduling in enhancing the overall system voltage stability margin. A new formulation of generation rescheduling in view of minimization of the slack reactive power injection has been suggested in this paper. In addition conventional optimal power flow (OPF) formulations, with their objectives being the minimization of total generation cost and minimization of total system transmission losses, and another formulation of generation rescheduling in view of the maximization of the minimum singular value of power flow Jacobian have been studied in this paper. Ref. [2] presents a prototype of an expert system for monitoring and improving steady state voltage stability in power systems. In the analysis and evaluation of voltage stability, it is necessary to accurately identify the stability margin at each load point under specific system configuration or power balance condition. T. Naga [18] developed static and simulation program for voltage stability studies of bulk power system. With increased interconnections and loadings in the power system networks, utilities face a major challenge to maintain the desired voltage profile which is important to ensure system security, quality of supply to consumers and minimizes transmission loss. The experiences of major voltage collapse incidents have resulted in a strong motivation to alleviate line overloading and voltage limit violation so as to obtain the secure operating point efficiently.

A method based on local optimization is developed by Ref. [15] where the alleviation of line over-loads, is solved by using the conjugate gradient technique of Fletcher and Reeves [5]. As stated by Ref. [15], for large scale power system,s the real time solution of the line over-load alleviation problem as an optimization problem, using the P and Q power flow equations, is a practical impossibility. In his paper [8] Mahdi El Arini introduces simple, fast, efficient, reliable and reasonably accurate algorithm to alleviate line overloads by corrective generation rescheduling and significant smaller amount of load sheading. Reference [16] presents an analytical basis and criterion for under voltage load sheding in power systems. If the voltage is unstable, the proposed under voltage load shedding criterion can be used to calculate the amount of load which must be shed to stabilise the voltage magnitude. In Ref. [10] a new method is proposed to approximate a closest loadability limit (CLC), or closest saddle node bifurcation point, using a pair of multiple load flow solution. R.S. Tare [12] presented a new look-ahead approach to loadability (static voltage stability limit) enhancement of power systems.

Given the current operating condition (obtained from the real time data), the near term load demand at each bus (obtained from short term load forecast) and the generation dispatch (based on economic dispatch) Ref. [6] presented a load margin measure (MW and/or MVAR) to access the system's ability to withstand the forecasted load and generation variations. It also presented a method to predict near-term system voltage profiles.

Since the introduction of optimal power flow and dispatching concept, about 35 years ago, several research efforts have been made to improve its formulation and adopt efficient solution techniques. The OPF have been applied for off-line planning studies as well as for closed loop dispatching control. However, many implementation issues specially for its on-line applications, are still unresolved. Ref. [14] presented a survey of literature and highlight some of the new emerging challenges in the optimal power flow formulation and its implementation. In Ref. [19] an effort is made to find the optimal load margin at the buses of the system keeping power factor constant with the objective to maximize the real load at the buses and minimize the reactive power generation, thus satisfying the power balance equations and generator output without violating the limits on bus voltage magnitudes.

(1.3) Present Dissertation

In the present dissertation work the problem of voltage limit violation in power network is studied. An attempt is made to run the system near to the optimal power flow solution. Out of the two subproblems (real and reactive power flow) of OPF only reactive power minimization problem is considered for preseth dissertation work. The problem of voltage limit violation in power network is solved by using local optimization techniques considering local controls available, load shedding and distributed power generation. The formulation of both the problem i.e. alleviation of voltage limit violation and minimization of reactive generation and losses are taken from reference [3]. In the first part of the dissertation reactive generation at generator buses and the losses in the system are minimized. After this,voltage violation are created in the system by considering contingency in the system. Then these violations are alleviated by using local optimization techniques. After alleviating voltage violations in the system reactive generation and losses of the system are again minimized to run the system near to the optimal power flow solution. Voltage security index suggested by reference [3], named as Diagonal Element Dependent Index which is the ratio of maximum diagonol element of power flow Jacobian to the minimum diagonol element of the same, is calculated at each iteration of load flow for checking severe operation of the system and to recognise ill conditioning of the network. The complete algorithem have been sucessfully tested on 24 bus and 57 bus IEEE test system. The data for these systems are given in Appendix-C.

MINIMIZATION OF REACTIVE GENERATION AND LOSSES IN THE SYSTEM

2.1 Introduction

Reactive power/voltage control in a power system received much attention in recent years. In the literature, the reactive power/voltage control problem in the transmission and subtransmission system is usually conducted using optimal power flow program.Control variables such as generator voltages, transformer taps, reactors, reactive generation of generators must be optimized in order to minimize bus voltage variations and transmission losses.

Conventionally, the optimal operation and planning of power system networks have been on economic criterion. Economic load dispatch (ELD) has been utilized for this purpose and widely accepted by most of the utilities and implemented in their computer aided dispatch centres. However, the growing concerns to maintain system security, power quality and clean environment have forced to consider new objectives in the optimal operation of power system such as improvement of system voltage profile, minimum emission dispatch and security constrained dispatch. The optimal power flow has found to major applications.

i) As a tool for taking planning decisions such as unit commitment, generation expansion planning and reactive power planning in the system.

ii) As a power dispatching tool forming part of energy management system.

As a dispatching tool, the OPF has been mostly adopted by utilities for operator guidance to take off-line optimal operating decisions. However, despite number of research efforts in this area, it has found limited application in closed loop dispatching control. Some of the reasons are the time extensive nature of existing models making them unsuitable for on-line applications and inability to consider many physical system constraints and implementation aspects.

Recently, most of the power utilities, world wide, are undergoing a major restructuring. The deregulation of electricity has introduced new open market pricing structure forcing the optimal operation philosophy of generation and transmission network to change.

OPF Formulation

In general, the optimal power flow can be formulated as a nonlinear optimization problem used to minimize objective functions(s).

$$\text{Min. } f(\bar{x},\bar{u}) \quad \ldots\ldots (2.1.1)$$

subject to system equality constraints (usually the power balance equations)

$$h\,(\bar{x},\bar{u}) = 0 \qquad \ldots\ldots (2.1.2)$$

and set of inequality constraints

$$g\,(\bar{x},\bar{u}) \leq 0 \qquad \ldots\ldots (2.1.3)$$

where, $\bar{x}$ is the set of state variables, $\bar{u}$ the control variables.

The conventional OPF is solved for given measured or forecasted values of the disturbance variables, which ar usually the system real and reactive power loads and these values are assumed constant during the optimization. The OPF results provide the optimum settings of the control variables. Based on the decoupling of real and reactive power controls, the OPF can be classified into two broad categories.

i) Active power (P) optimization subproblem.

ii) Reactive power (Q) optimization subproblem.

Some of the objectives, control variables and constraints used in these two subproblems are listed in Table (2.1). Both these decoupled subproblems can be solved simultaneously [3] as coupled OPF problem or can be solved separately or sequentially as decoupled problems [13]. Coupled or full OPF simultaneously determines scheduling of all active and reactive power controls to minimize a global objective. This may be required in some abnormal operations or heavily stressed scenario where cross coupling of the two types of controls can not be ignored. However, for normal operating conditions, it has been shown [1], through extensive testing, that the decoupled formulations produce solutions that are close to the full OPF solutions. The decoupled approach offers the advantages of computational efficiency.

2.2 Problem Statement

For the present dissertation work the optimal power flow problem is formulated considering only reactive power (Q)

Table - 2.1: Active and Reactive Power Subproblems of OPF

Subproblem	Objective Function(s)	Controls	Constraints
Active power optimization subproblem	Minimization of - Fuel cost of thermal plant - Emission of pollutants such as SO_2, NO_x, CO_x - Control shift and number of controls rescheduled.	- Generator's real power output - Setting of phase angle shifters - Tie line power interchange - HVDC line power flow - Real power load shedding.	- System real power balance - Real power output limits of generators - Phase shifter angle limits - Line flow (real power) transfer limit - Turbine response rate or ramp rate - Emission limits - Contingency constraints or security limits
Reactive power optimization subproblem	Minimization of - Real power transmission loss - Bus voltage deviation - Control shift & number of controls rescheduled.	- Generator's terminal voltage settings or reactive power output - Reactive power output of shunt capacitors, reactors and SVC - Transformer OLTC setting - Reactive power load shedding	- System reactive power balance - Limits on reactive power outputs of generators, SVC, shunt capacitors and reactors - Bus voltage limits - Transformer OLTC limits - Line MVAR or MVA flow limit - Security constraints (voltage security limit)

optimization problem. In this problem reactive generation at generator buses and the losses in the system are minimized by taking the reactive generation at generator buses and the transformer top ratio as independent variables and the bus voltage magnitudes as dependent variables.

The modelling of the power system components is briefly discussed in the next section.

2.3 Modelling of Components

The principal components of the power transmission system are transmission lines, on-load tap changing transformers, shunt capacitors or inductors and the load. The transmission lines and the transformers are represented by their pi-equivalent network. Changing a transformer tap basically redistributes reactive power flow and changes the voltage profile throughout the system. Switchable capacitors or inductors are used to supply the reactive power or absorb the excessive reactive power for checking the voltage variations in excess of the permissible values. The load is represented as a lumped load at the respective buses. Detailed representation of these components is given in Appendix-A.

2.4 Problem Formulation

The formulation of problem is taken from reference [3]. The objective function for minimizing the reactive generation and losses in the system is given as,

$$\text{Minimize } G(X,U) = \sum_{i=1}^{NGB} W_{gi}.(QG_i)^2 + W_{fqgs} \times [(QG_s - QL_s - Q_s(v,\theta)]^2$$

$$+ W_r \sum_{i=1}^{NB} \Bigl[\sum_{j=i+1}^{NB} \bigl[(-g_{ij}).\bigl[(V_i - V_j)^2 + V_i.V_j.(\theta_i - \theta_j)^2\bigr] \bigr] \Bigr]$$

$$+ W_x \sum_{i=}^{N} \Bigl[\sum_{j=i+1}^{NB} \bigl[b_{ij}. \bigl[(V_i - V_j)^2 + V_i.V_j.(\theta_i - \theta_j)^2 \bigr] \bigr] \Bigr]$$

$$+ W_x. \sum_{i=1}^{NB} \Bigl[\sum_{j=i+1}^{NB} \bigl[b_{ij}.\bigl[\bigl[2.V_i.V_j/T_{ij}\bigr].\mathrm{Cos}\theta_{ij} - \bigl[V_i^2/T_{ij}^2\bigr] - V_j^2\bigr]\bigr] \Bigr] \qquad \ldots(2.4.1)$$

Where

$$Q_s(V,\theta) = V_s. \sum_{j=1} V_j.(g_{sj}.\ \mathrm{Sin}\theta_{sj} - b_{sj}.\ \mathrm{Cos}\theta_{sj}) \qquad \ldots(2.4.2)$$

QG_i = Reactive generation at i^{th} generator bus.

QG_s = Reactive generation at the slack bus.

QL_s = Reactive load at slack bus.

$Q_s(V,\theta)$ = Net reactive power injection of all the lines connected at slack bus.

W_{gi} = Weight factor at i^{th} generator bus

W_s = Weight factor associated with slack bus power

W_x = Weight factor associated with reactive loss

W_r = Weight factor associated with real loss

NGB = Number of generator buses

The third, fourth and fifth terms in equation (2.4.1) represent the real power loss, reactive power loss and the loss in the line having transformer respectively. The objective function of equation (2.4.1) is subjected to the following constraints.

$$g_q \; (X,U) \;=\; 0 \qquad \ldots(2.4.3)$$

$$U^{min} \;\le\; U \;\le\; U^{max} \qquad \ldots(2.4.4)$$

Where

X = Dependent variable or the State vector consisting of the voltage magnitudes

U = Independent variables or the vector of the Control variables available to the operator consisting of generator reactive generation and the turns ratio of the transformer.

Equation (2.4.3) represents the usual load flow equation and equation (2.4.4) represents the limitations on the control variables.

2.5 STEP-WISE SOLUTION PROCEDURE

The flow chart for the step-wise solution procedure for solving this problem is shown in figure (2.1) evaluation of the partial derivatives of the objective functions given by equation the(2.4.1) and equality constraints given by equation (2.4.3) w.r.t the dependent and independent variables are given in Appendix D.The description of the software package 'MINIMIZE' is given in Appendix-E.

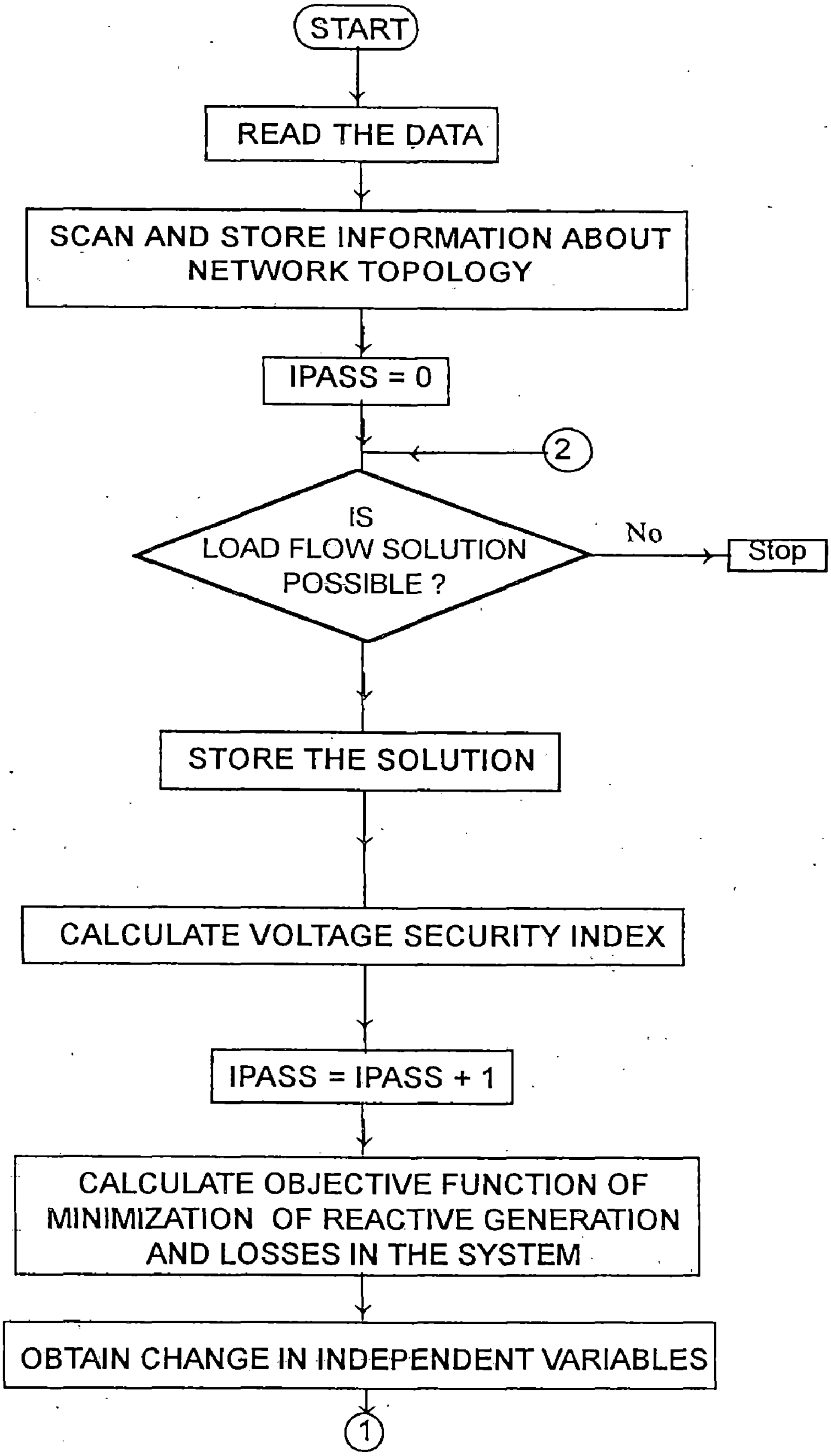
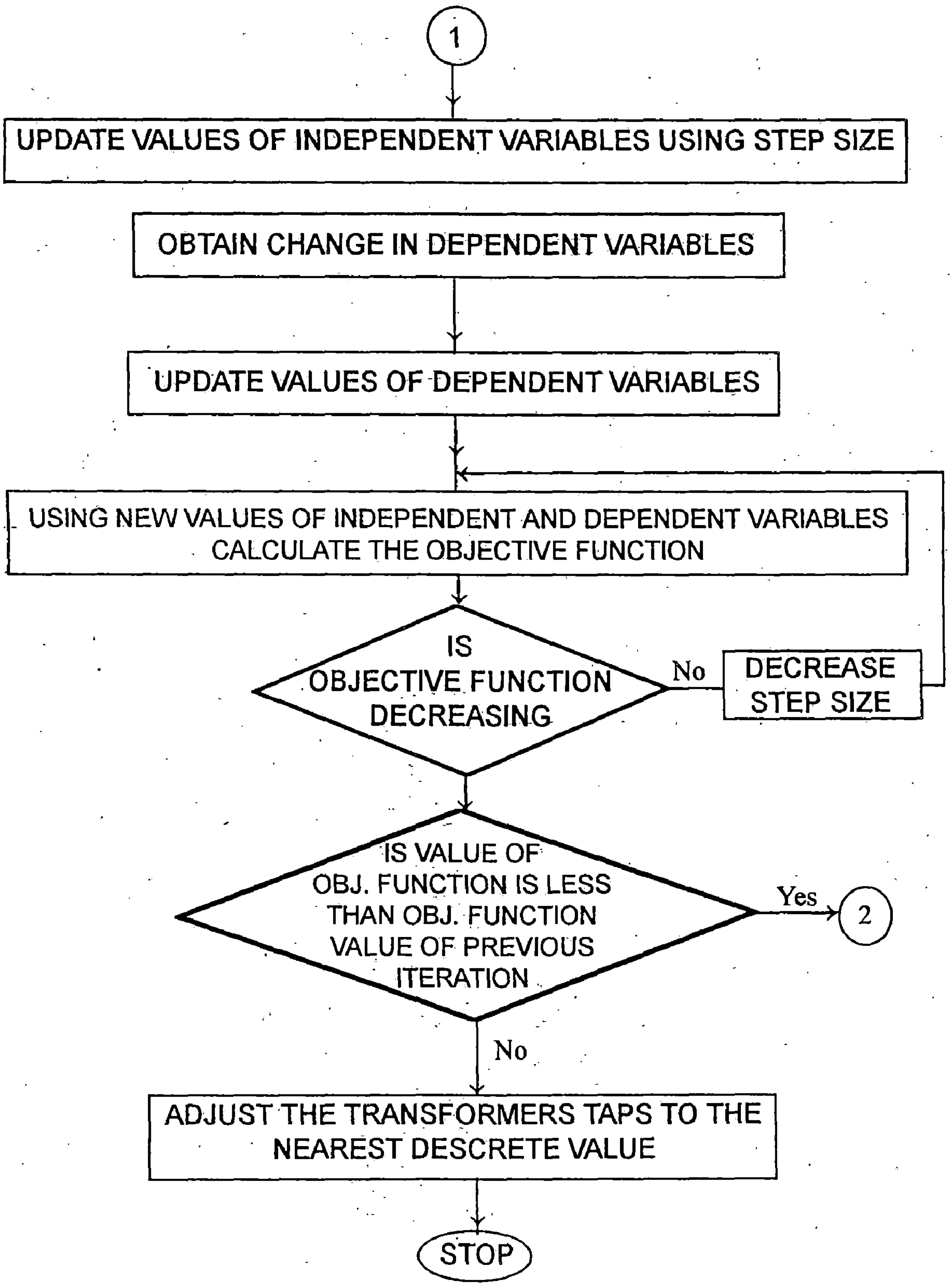


Fig. 2.1.Flow chart for minimization of reactive generation and losses in the system

Contd.

Fig.2.1. Continued



ALLEVIATION OF VOLTAGE LIMIT VIOLATION USING LOCAL OPTIMIZATION

3.1 INTRODUCTION

Today's electric power systems are highly interconnected. As these systems continue to grow, the problem of maintaining voltage tolerances at various locations in the transmission network becomes complex. If the generation facilities are adjacent to load centers, the real and reactive power can be supplied by the generating units. However, in many cases the generation facilities are located at long distances from the loads, and with this comes the need for compensation of voltage drop along the transmission line and for provision of voltage support at the load areas for both normal and abnormal conditions.

As the gap between the generation and load in the power system increases, it may become difficult to operate the power system in secure mode. Voltage security of large modern power systems which are interconnected is becoming an increasing concern to both system operators and planners. There are two contributing factors for this trend. First, as power systems are being operated closer to their limits, voltage control problems are becoming of relevance. Second, analytical tools to deal with voltage security are not as well developed.

Primarily there are three reasons for control of voltages, (i) to prevent damage to components of power system (ii) to prevent damage or malfunctioning of consumer goods and (iii) to reduce system losses. Most control strategies for voltage control under difficult operating conditions are a combination of preventive actions planned for off-line and operator decision. Though a rapid predictive capability for voltage limit analysis is difficult to achieve due to the highly nonlinear nature of the problem and computational complexity, the subject of on-line voltage security analysis is gaining attention. There are three basic elements of on-line security analysis and control, namely Monitoring, Assessment and Control. On-line tuning of power system enhances its security from the point of view of prominent contingencies, and results in economic operation by co-ordinating the corrective control actions consisting of adjustment of transformer tap settings, switching of capacitors or reactors, generation rescheduling, adjustment of angles of phase shifter, reconfiguration of system and if necessary load shedding.

There are numerous automatic control within a power system. Some regulate the voltage level through reactive power output of the rotating units or static voltage compensators. Other controls maintain the balance between the generator real power outputs and the system load. As long as a co-ordinated functioning of these automatic controls prevail, a power system can be operated effectively. A loss of co-ordination among these controls may lead to a system collapse. To be effective, the system should maintain a continuing balance between the supply and demand of both real and reactive power. The emphasis these days is to make the controls and the resources more adaptive to unexpected situations. It is believed that more adaptive voltage control design could improve the voltage profile as the operating conditions change, and slow down a rather expensive trend towards implementing excessive amounts of reactive power support on the system.

The primary objective of voltage/reactive power control is to maintain voltages and currents within the allowable constraints as operating conditions on the power system change. Under normal operating conditions, voltage control is expected to improve the system wide voltage profile so that energy cost is ~~minimized~~. When the system is subjected to severe disturbances in input variables and/or structure, voltage control is considered to be a remedial measure, which together with other controls on the system should act to preserve system integrity and remedy the effects of a disturbance. Many times an experienced operator may successfully select the appropriate remedial action, but in complex operating conditions or in planning studies, it is necessary that the remedial action be computed.

The experiences of major voltage collapse incidents have resulted in strong motivation to alleviate line overloading and voltage limit violation so as to obtain the secure operating point efficiently. Alleviation of voltage limit violation at certain critical buses is a serious problem in the interconnected power system when a heavily loaded line is tripped or some of the lines carry power in excess of their capability. In this Chapter an attempt is made to alleviate the voltage limit violations under heavy loading conditions using the concept of local optimization. Using this technique, the alleviation of voltage limit violations are corrected by coordinating controls at the local level during any severe disturbance to avoid the disintegration of the power system.

3.2 ALLEVIATION OF VOLTAGE LIMIT VIOLATION USING LOCAL OPTIMIZATION AS AN INDEPENDENT PROBLEM

3.2.1 Problem formulation

The problem of alleviation of voltage limit violation is formulated as an optimization problem [3]. The objective function to be minimized is taken as the weighted sum of the squares for the limit violation of bus voltages. Two sets of variables are defined. The first set consists of the dependent variables (X), representing voltages at all the buses except slack bus with a constraint on the upper and lower limit. The other set is of the independent variables (U), which controls the generator reactive power, generation or absorption of reactive power from the switchable capacitor/reactor, tap-changing transformers ratio and the load shedding.

The objective function, f(X,U) to be minimized is expressed as,

$$\text{Minimize } f(X,U) = \sum_{i \in LV} (\Delta V)_i^2 \qquad \ldots(3.2.1)$$

Where

$f(X,U)$ = Scalar objective function to be minimized

LV = Set of buses at which voltage limits are violated

$$\Delta V_i = \begin{cases} V_i - V_i^{max} & \text{if } V_i > V_i^{max} \\ V_i^{min} - V_i & \text{if } V_i < V_i^{min} \end{cases} \qquad \ldots(3.2.2)$$

is magnitude of voltage limit violation.

The objective function (3.2.1) is subjected to the following constraints -

(i) $g(X,U) = 0$ ...(3.2.3)

(ii) $X^{min} \le X \le X^{max}$ ...(3.2.4)

(iii) $U^{min} \le U \le U^{max}$ ...(3.2.5)

Where

$g(X,U)$ = Set of equality constraints

X = State vector (dependent variable) of the power system consisting of bus voltages for all buses except the slack bus

U = Vector of control variables (independent) available to the operator consisting of :

(a) Reactive power generation of generator buses.

(b) Reactive power generation of switchable reactors or capacitors.

(c) Transformer ratio of tap changing transformers.

(d) Load shedding at the load buses.

Less sensitive controls are neglected to limit the corrective actions. As far as possible, load shedding is avoided and the other three controls are used for providing the necessary corrective action.

Equation (3.2.3) represents the reactive power balance. Equations (3.2.4) and (3.2.5) represent the system operating constraints, i.e. minimum and maximum values of bus voltages and the limits on the control variables respectively. Two independent variables representing the generator reactive power and the transformer tap ratio, separated from the set of independent variables U are given as,

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}$$

$$TR_i^{min} \leq TR_i \leq TR_i^{max}$$

Where

Q_{Gi} = Reactive power generation of the i^{th} generator

TR_i = Transformer ratio of the i^{th} tap-changing transformer

While calculating the objective function, two terms corresponding to the violation of reactive power generation of the generator and the transformer tap limit with proper weightage are also added.

3.2.1.1 Local Optimization

The objective function given as the weighted sum of squares of the voltage limit violation is minimized using the local optimization method . In this method, few buses in the vicinity of the buses having voltage limit violations are processed for local optimization; irrespective of the size of the system under study. Local optimization method is useful because few buses in the vicinity of limit violated buses are to be processed and terminal buses are also handled without any difficulty. The buses for local optimization are selected on the basis of prespecified step length, i.e. N step length means buses up to N lines away from the terminal buses at which limits are violated. In our case a step length of 1 or 2 has worked well. This has drastically reduced the complexity of the problem as few buses in the vicinity of limit violating buses are sufficient for providing the necessary control action.

The alleviation of limit violation of voltage is minimized using the Conjugate Gradient Technique, which is simple, efficient, robust and requires less storage space. The method is efficient and robust in comparison with the existing methods, as the new secure operating point is obtained with minimum control actions.

3.2.1.2 Transformer and Switchable Reactor/Capacitor Modelling

While operating the transformers in the local area, proper care is taken so that voltage profile of any bus is not deteriorated. The transformer may be fixed-tap or tap-changing type. In the local optimization procedure, a very small step size is assumed for transformer taps, so that continuous variation in the transformer ratios is allowed. In the global solution, the tap position is adjusted to the nearest available discrete value. The transformers are modelled by their pi-equivalent network.

Switchable reactors and capacitors are normally used to absorb the excessive reactive power, or supply reactive power to maintain the system voltage profile. They are modelled as reactive power sources varying continuously at the buses to which they are connected. In the global solution, the reactive power supplied is rounded off to the nearest permissible discrete value. Switchable shunt capacitors/reactors at the load buses are represented by susceptance B_i calculated at the voltage in the base case load flow.

3.2.2 SOLUTION PROCEDURE

The complete solution procedure for this problem is take from reference [3]. Only some important points are presented here. The reactive power balance for the i^{th} bus is expressed as,

$$g_i = Q_{Gi} - Q_{Li} - Q_i = 0$$

Where

g_i = Equality constraint equation corresponding to i^{th} bus

Q_{Li} = Reactive load at i^{th} bus

Q_i = Net reactive power injection at i^{th} bus, i.e. $(Q_{Gi} - Q_{Li})$

$$= \left[\sum_{j\in A(i)} (g_{ij}.\mathrm{Sin}(\theta_i - \theta_j) - b_{ij}.\mathrm{Cos}(\theta_i - \theta_j)).V_j\right].V_i$$

$$g_i = \left[(B_i).V_i^2\right] - \left[\sum_{j\in A(i)} (g_{ij}.\mathrm{Sin}(\theta_i - \theta_j) - b_{ij}.\mathrm{Cos}(\theta_i - \theta_j)).\ V_j\right].V_i + (Q_{Gi} - Q_{Li}) = 0$$

Or,

$$g_i = \left[B_i + \sum_{j\in A(i)} b_{ij}\right].\ V_i^2 - \left[\sum_{j\in A(i)} (g_{ij}.\mathrm{Sin}(\theta_i - \theta_j) - b_{ij}.\mathrm{Cos}(\theta_i - \theta_j)).V_j\right].V_i + (Q_{Gi} - Q_{Li}) = 0, \quad i = 1,\ NLO \qquad \ldots(3.2.6)$$

Where

B_i = Susceptance of shunt capacitor/reactor at the i^{th} load bus.

b_{ij} = Susceptance of line between buses i and j.

g_{ij} = Conductance of line between buses i and j.

NLO = Number of buses processed for local optimization.

Equation (3.2.6) can be written in a simple quadratic form as,

$$g_i = AA.V_i^2 + BB.V_i + CC = 0 \qquad \ldots(3.2.7)$$

where constants AA, BB and CC of the equation (5.7) are given below.

$$AA = B_i + \sum_{j \in A(i)} b_{ij} \qquad \ldots(3.2.8)$$

$$BB = - \sum_{j \in A(i)} V_j . \left\{ g_{ij}.\mathrm{Sin}(\theta_i - \theta_j) - b_{ij}.\mathrm{Cos}(\theta_i - \theta_j) \right\} \qquad \ldots(3.2.9)$$

$$CC = \left[Q_{Gi} - Q_{Li} \right] \qquad \ldots(3.2.10)$$

The solution of equation (3.2.7) can be written as,

$$V_i = \frac{-BB \pm \sqrt{(BB)^2 - 4.AA.CC}}{2.AA} \qquad \ldots(3.2.11)$$

The negative sign of the square root satisfies the system operating constraints.

In local optimization procedure, equation (3.2.11) has been used for calculation of the objective function and its derivatives. The calculation procedure of the solution assumes following assumptions :

(i) $V_i \approx V_j = 1.0$

(ii) $\text{Cos}(\theta_i - \theta_j) = 1.0$

(iii) $g_{ij}\ \text{Sin}(\theta_i - \theta_j) < b_{ij}$

(iv) In the local optimization iterations, bus voltage angles are constant.

These approximations in the calculation of derivatives work very well. No convergence problem was observed when testing the method with 24 and 57 bus IEEE test systems.

The partial derivatives of objective function and equality constraints given by equations (3.2.1) and (3.2.3) w.r.t. the dependent (X) and independent (U) variables in local optimization procedure are given in Appendix-D from equation (D.8.) to (D.34).

3.2.3 Step Wise Solution

The complete flow chart for step wise solution is shown in figure (3.1). The detailed description of the software package

'ALLEVIATION' is shown in Appendix - F.

3.3 VOLTAGE SECURITY INDEX

The study of voltage instability has become an important area of research in the field of power system engineering. The main thrust of research has been to arrive at an accurate and reliable indicator of the proximity of a system to collapse. Such an index would be useful to utilities in operating their systems with maximum economy and reliability. For on line applications, there is a need for tools which can quickly identify potentially dangerous condition and provide the operator with guidance to steer the system away from voltage collapse. Many investigators have proposed the use of indices to estimate how far a given operating condition is from the stability limit. These measures of indices, in order to be useful, should have certain qualities, namely:

i) The indices should be roughly a linear function of the controllable parameters especially as stability boundaries are approached.

ii) There should be corrective measures that can be derived from the indices.

iii) The measure should be robust to model uncertainties.

iv) They should be computationally efficient and easy to understand.

Three voltage security indices have suggested by Bhanot V. [3] namely diagonal element dependent index (I_d), maximum row sum ~~dependent~~ index (I_r) and Euclidean norm dependent index (I_e) based on power flow Jacobian matrix and its inverse at the

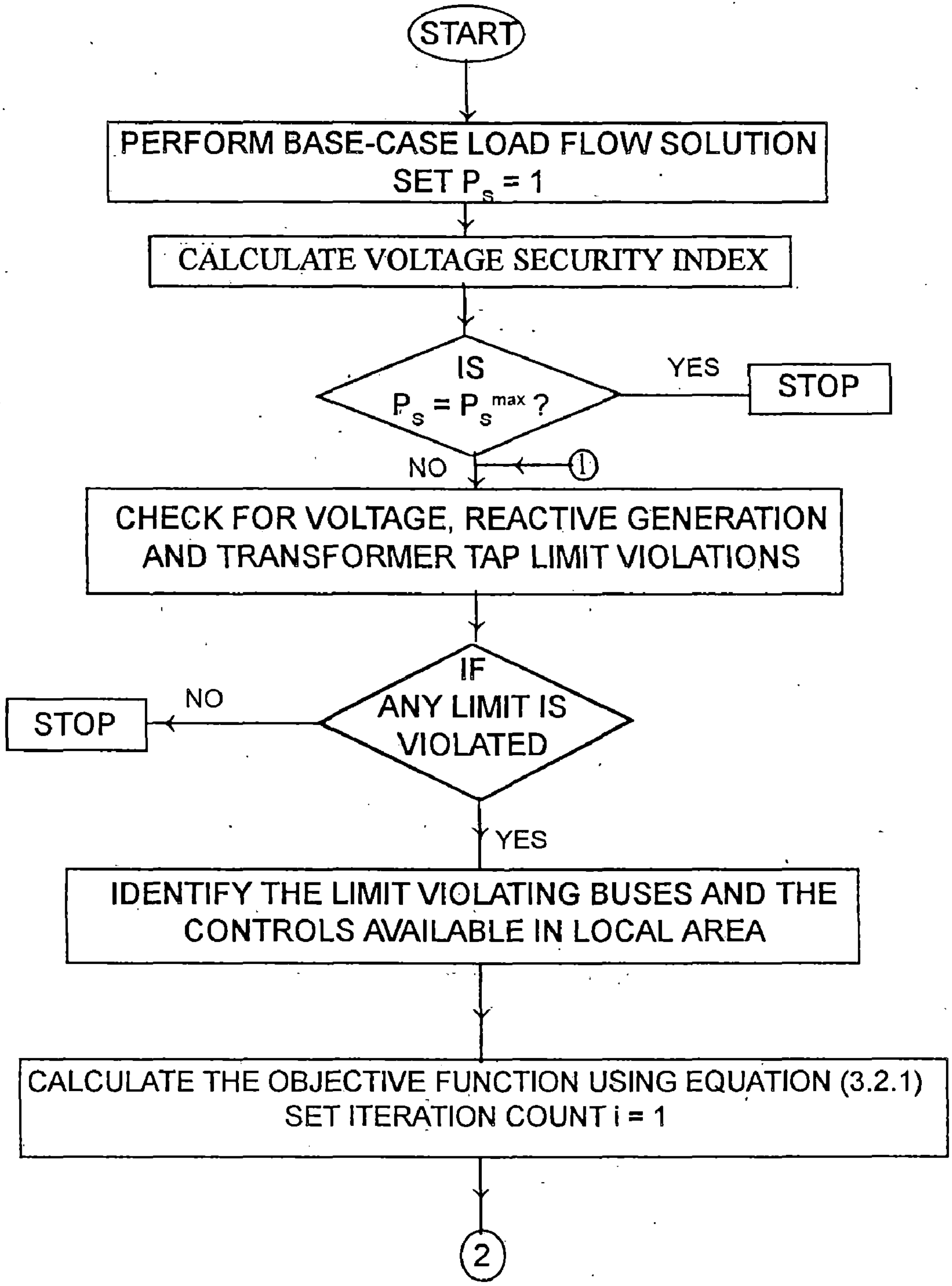
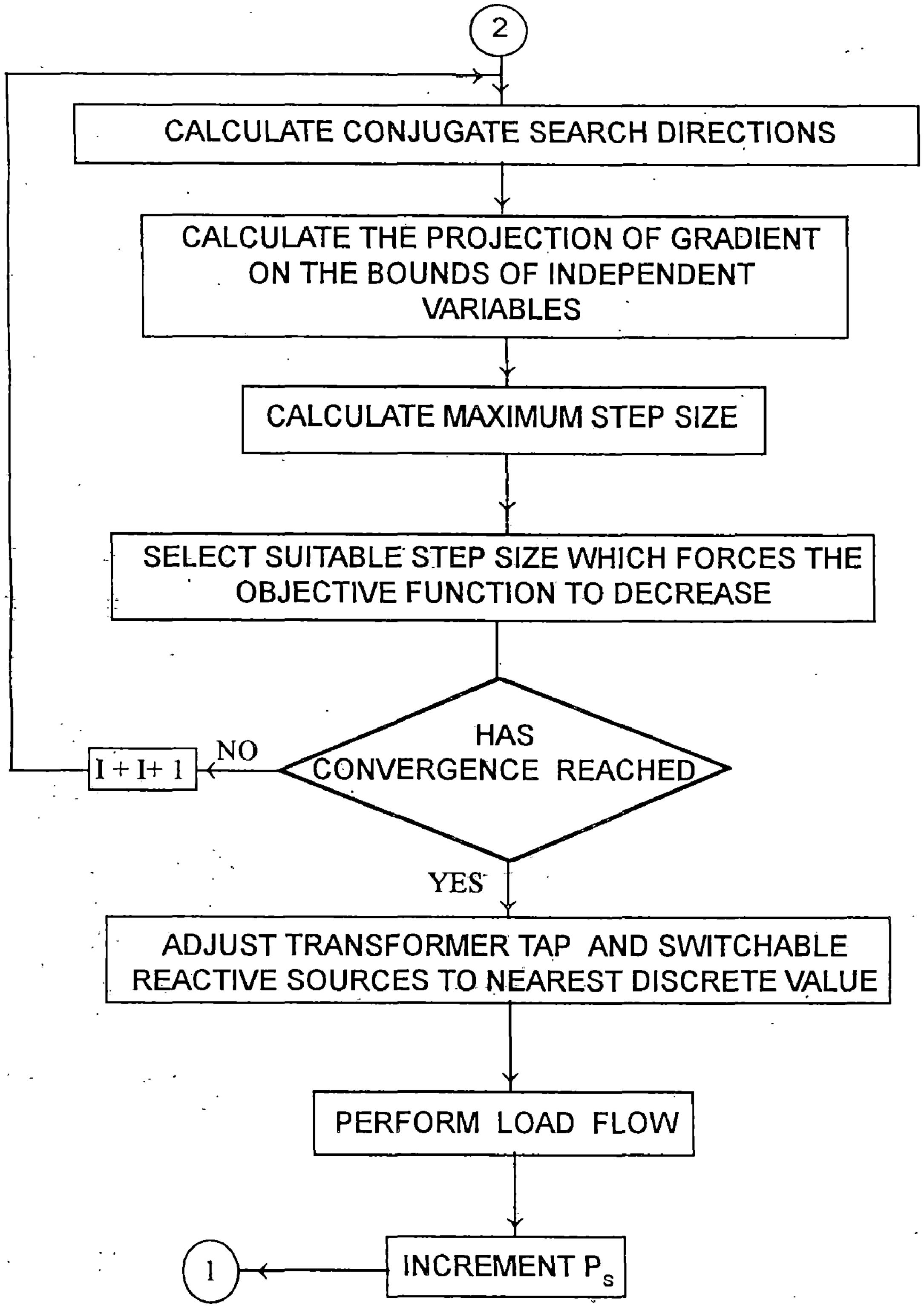


Fig.3.1. Flow chart for Alleviation of Limit Violations of voltage, Reactive Generation and Transformer Tap Ratio.

Fig. 3.1. continued......



solution point. Out of these, diagonal element dependent index (I_d) is most easy to calculate. For my dissertation work I used it as a voltage security index.

3.3.1 Diagonal Element Dependent Index (I_d)

This index (I_d) is most easy to calculate and is given by the ratio of the maximum to minimum value of the Jacobian diagonal elements. As the extreme loading conditions are approaching or any disturbance occur in the system, a sudden increase in the value of this index occurs, acting as an alarm for the system operator to avoid the voltage collapse. Beyond the collapse point no convergence is possible. This index is calculated as

$$I_d = \left| \frac{\text{Maximum diagonal element value of Jacobian}}{\text{Minimum diagonal element value of Jacobian}} \right|$$

This index is a pre indicator of the health of the system, the computation of I_d which is the simplest and the fastest, may be used for on line voltage securing assessment. A sample calculation of the diagonal element dependent index. I_∂ is given in Appendix-B.

3.4 ALLEVIATION OF VOLTAGE LIMIT VIOLATION PROBLEM COMBINED WITH MINIMIZATION OF REACTIVE GENERATION AND LOSSES PROBLEM

For the present dissertation work problem of minimization of reactive generation of generator buses (minimization sub routine) and alleviation of voltage limit violation (alleviation subroutine) are connected with following objectives:

i) To operate the system as close as possible to optimal power flow solution and to guide operator to take offline operating decisions.

ii) To recover the normal operating conditions i.e. secure and stable operation of the system following a major or little contingency by alleviating voltage limit violation at the disturbed buses. Also again to operate the system near to optimal power flow solution.

With these objectives, firstly the reactive generation of generator buses and losses in the system are minimized to operate the system close to optimal power flow solution. Then a disturbance is created in the system (such as any loaded line in the system is removed) and observe on which buses voltage limit/reactive power generation limits are violated and on which transformer taps limits are violated in the system. Then these violation are removed by local optimization technique. Then after alleviating voltage limit/reactive power generation violation an attempt is made to run the system again close to optimal load flow solution.

Flow chart of the complete algorithm is shown in Fig. (3.2). The solution procedure is explained in the following section.

3.4.1 Stepwise Solution

Step - 1:

Minimize the objective function consisting of reactive generation of the generator buses and losses in the system following the steps as described in section (2.5).

Step - 2:

If the function is not minimized go to step 1.

Step - 3:

Calculate voltage security index and create the contingency in the system.

Step - 4:

Alleviate the voltage limit violation/generators reactive generation violation and transformers tap ratio violation due to the creation of contingency, following the steps described in section (3.2.3).

Step - 5:

Calculate voltage security index.

Step - 6:

Minimize the objective function consisting of reactive generation of the generator buses and losses in the system following the steps as described in section (2.5).

Step - 7:

If the function is not minimized go to step 6.

Step - 8:

Calculate voltage security index and stop.

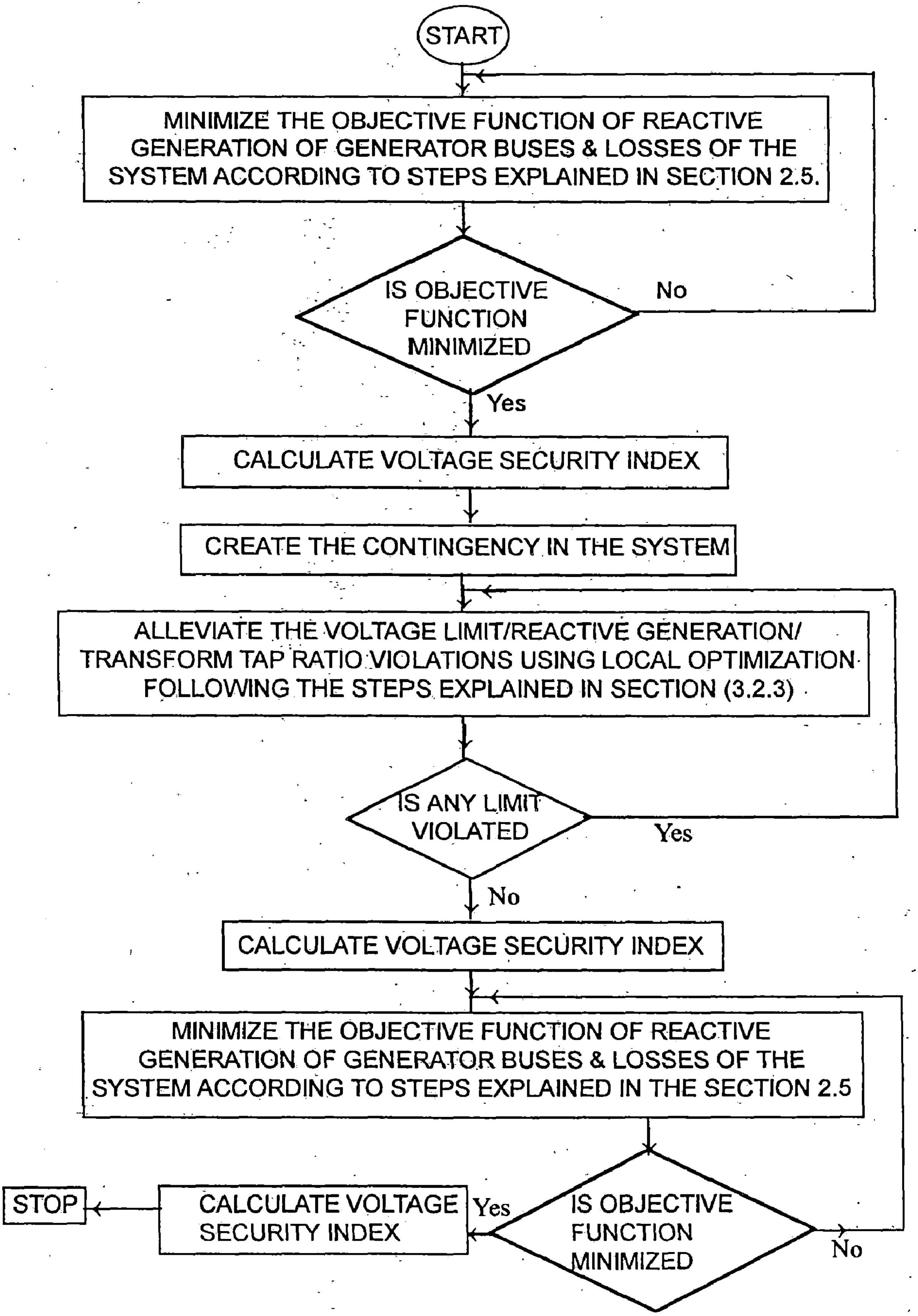


Fig. 3.2. Flow Chart for alleviation of voltage limit violations combined with minimization of reactive generation and losses

RESULTS AND DISCUSSION

4.1 RESULTS OF ALLEVIATION OF VOLTAGE LIMIT VIOLATION

To demonstrate the robustnesses of the method as described in section (3.2) large voltage violations are induced by creating the critical contingency on 24 bus IEEE (RTS) and 57 bus IEEE systems. The results of the proposed method for alleviation of voltage limit violation as applied to two different test systems are presented in this section. The new secure operating points after an outage has occured is efficiently obtained under steady state conditions. The four different cases of the two test systems show in figure (4.1 to 4.4) are as follows.

* 24 Bus IEEE test system: Line No. 26 removed (Fig. 4.1)

** 57 Bus IEEE test system: Line No. 10 removed (Fig. 4.2)

*** 57 Bus IEEE test system: Line No. 32 removed (Fig. 4.3)

**** 57 Bus IEEE test system: Line No. 33 removed (Fig. 4.4)

4.1.1 24 Bus IEEE System

In the case of 24 bus system line number 10 is removed. 24 Bus system with line 10 removed is shown in Fig. (4.1), the area processed for local optimization is marked in the figure. The buses at which voltage limits are violated are also marked in figure. The results for alleviation of voltage limit violation in this case are presented in table 4.1. In this case generator

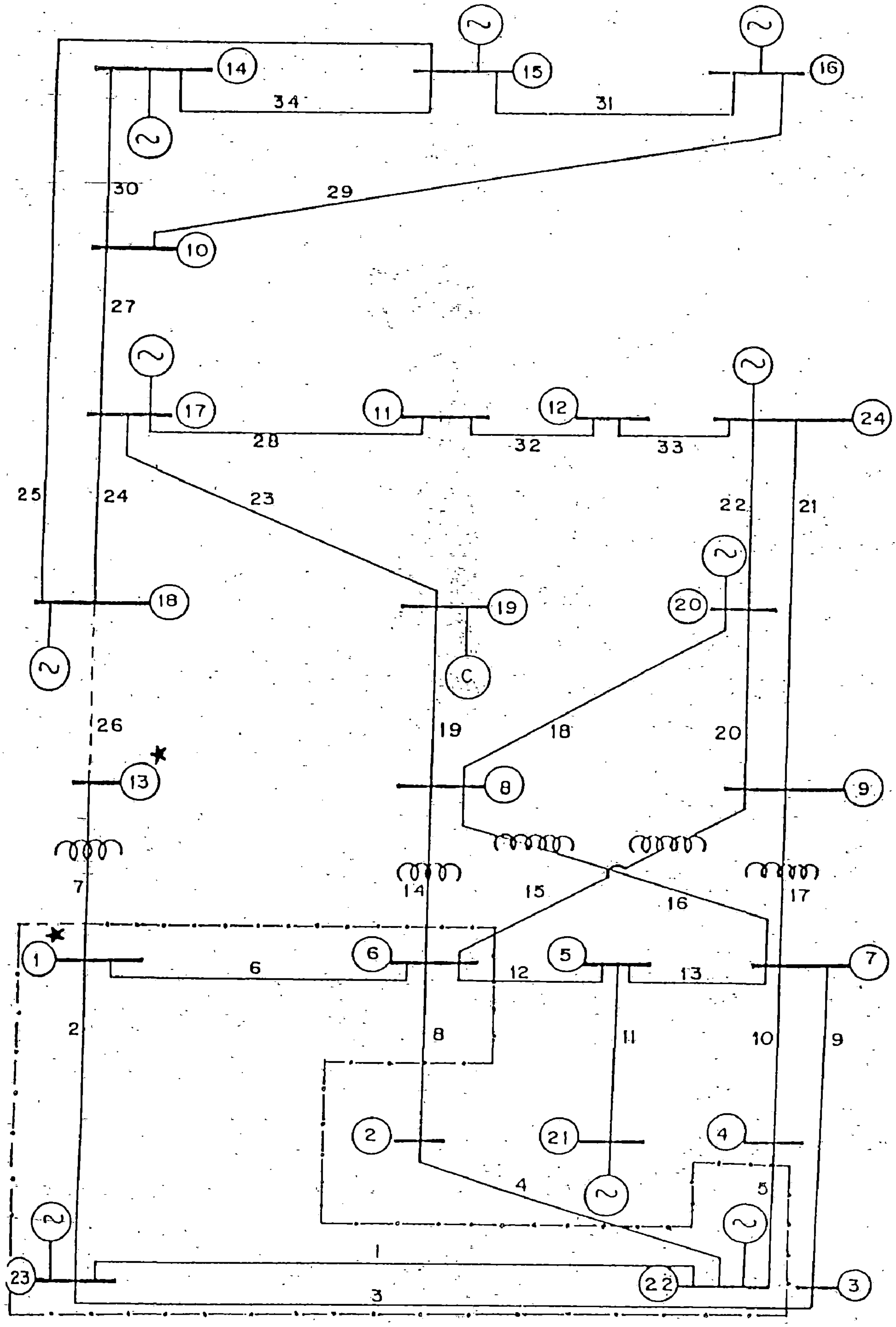


FIG. (4.1) 24 - BUS IEEE TEST SYSTEM : Line No. 26 Removed

* : Buses at Which Voltage Limits Are Violated

-·-·-·- : Area Processed For Local Optimization

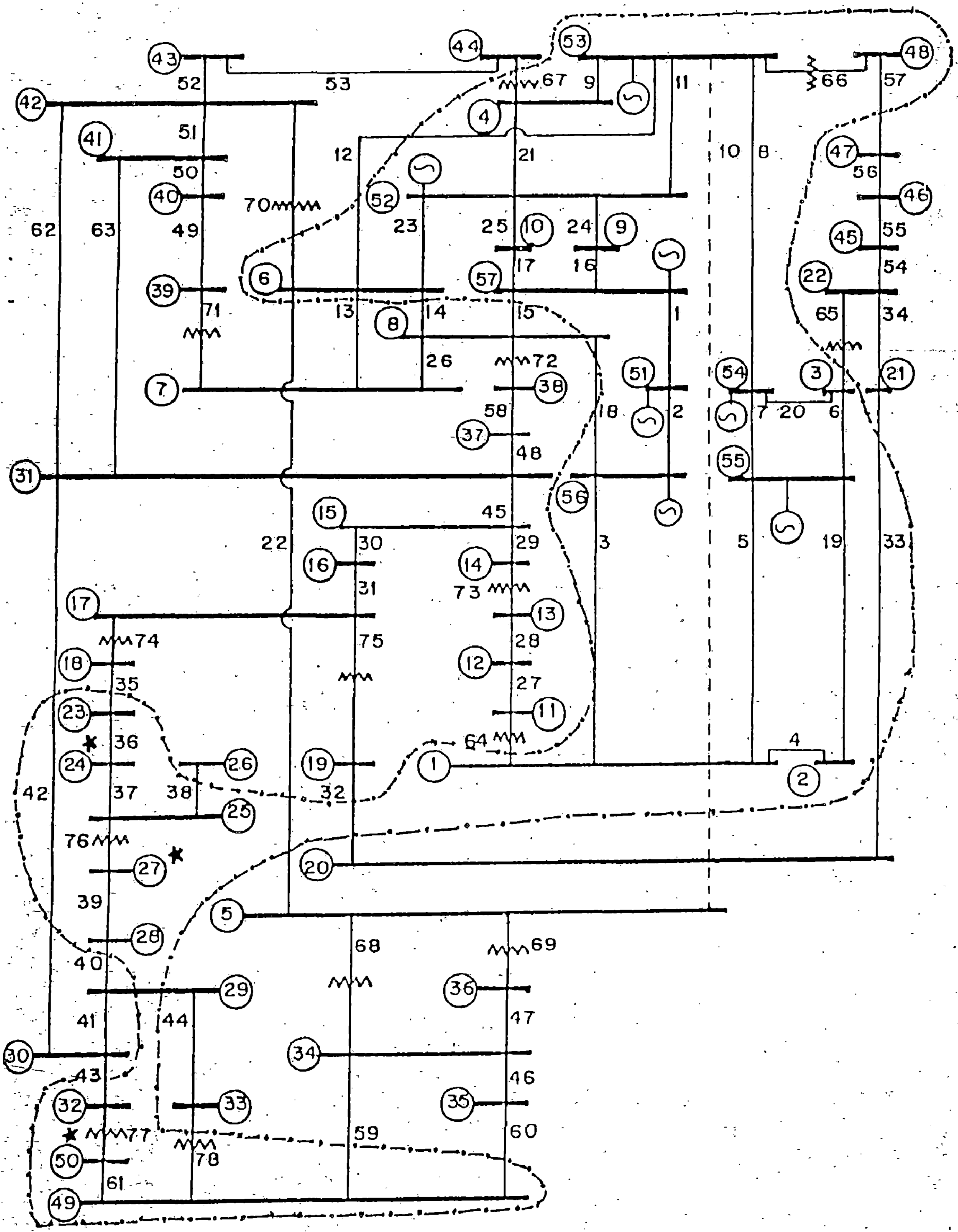


FIG (4.2) 57 - BUS IEEE TEST SYSTEM :Line No. 10 Removed

* : Buses at Which Voltage Limits Are Violated

-·-·- : Area Processed For Local Optimization

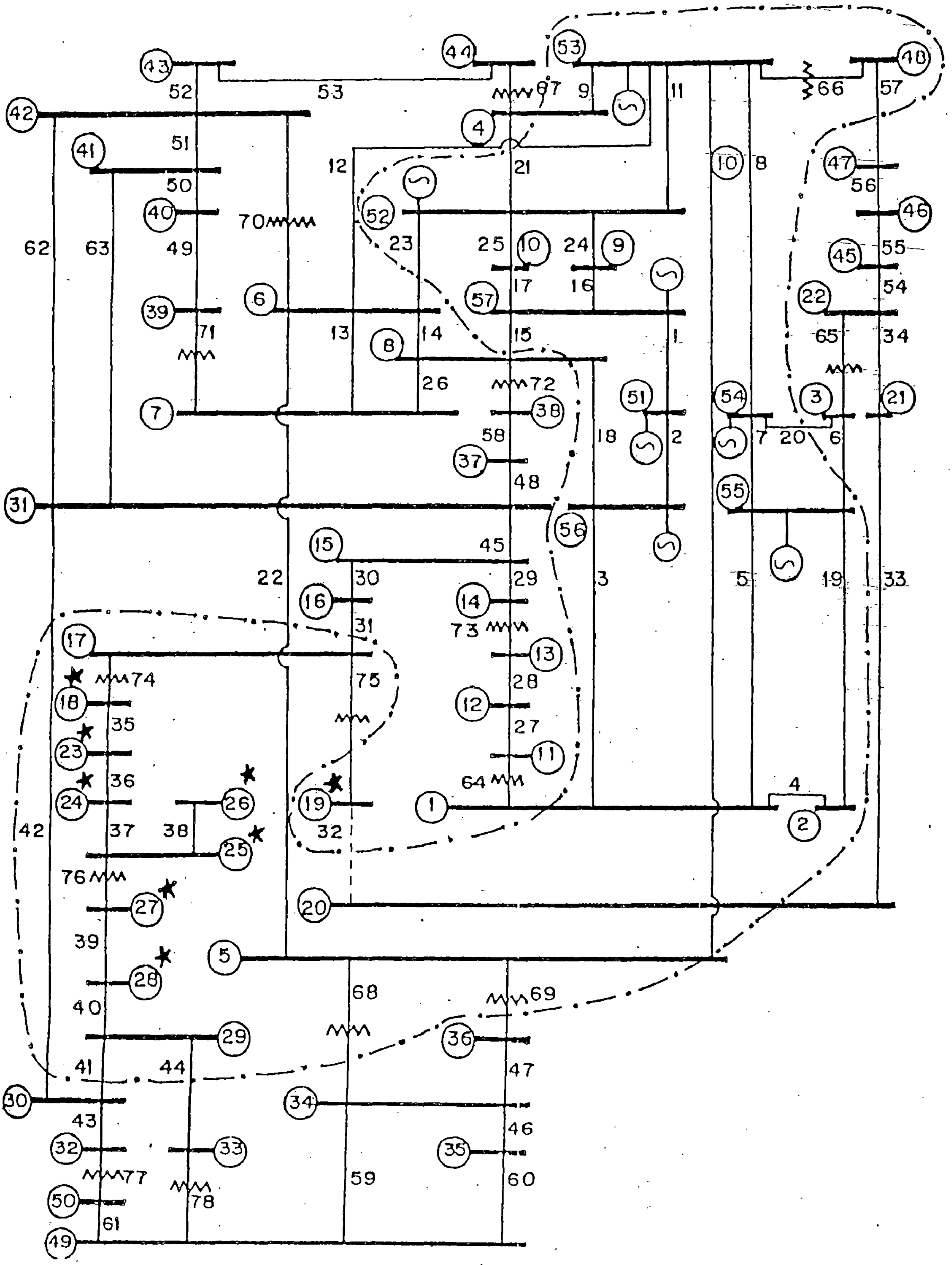


FIG (4.3) 57 - BUS IEEE TEST SYSTEM : Line No. 32 Remoevd

* : Buses At Which Voltage Limits Are Violated

-.-.-. : Area Processed For Local Optimization

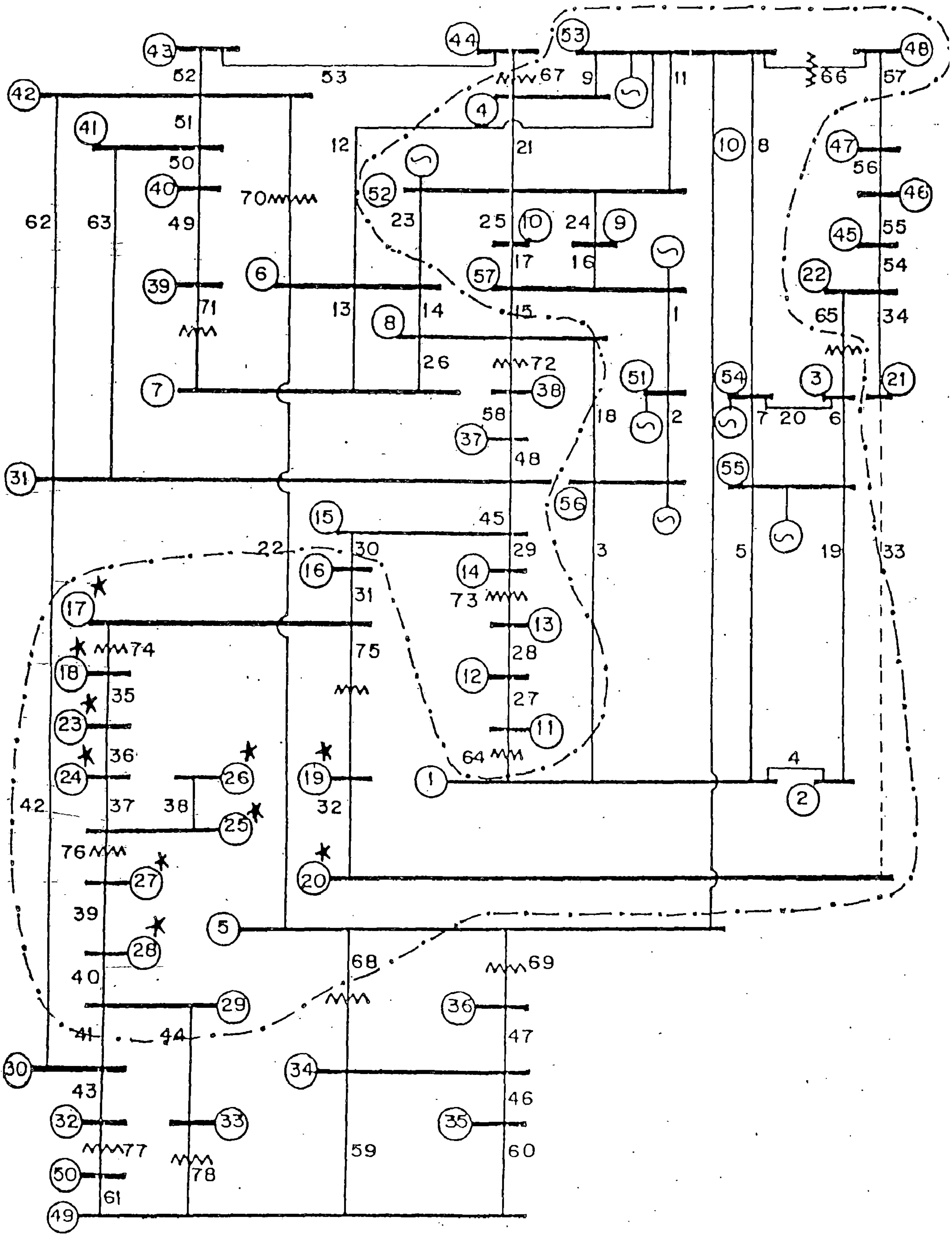


FIG (4.4) 57 - BUS IEEE TEST SYSTEM : Line No. 33 Remoevd

* : Buses At Which Voltage Limits Are Violated

-.-.-. : Area Processed For Local Optimization

TABLE 4.1: TEST RESULTS OBTAINED FOR ALLEVIATION OF VOLTAGE LIMIT VIOLATION FOR 24 BUS IEEE (RTS) SYSTEM LINE NO. 26 REMOVED Fig. 4.1

bus No	Details of buses at which limits are violated			Local optimisation	Controls					
	violated limit	Bus voltage		no. of buses processed	Type	at bus/transformer	Adjustment in U			
		pre. adjusted	post adjusted				initial	final	Limit UL	LL
1.	2	3	4	5	6	7	8	9	10	11
1	0.9	0.8542	0.9908	4	Q at generator buses	22	28.96	-26.083	80.0	-50.00
13	0.9	0.8137	0.9439			23	73.69	-9.528	80.0	-50.00
					at load buses	1	180.0+j37	0.0+j0.0		
						6	175.0+j36	154.81+j3723		

TABLE 4.2: TEST RESULTS OBTAINED FOR ALLEVIATION OF VOLTAGE LIMIT VIOLATION FOR 57 BUS IEEE TEST SYSTEM: CASE - A: LINE NO. 10 REMOVED (Fig. 4.2)

bus No	Details of buses at which limits are violated			Local optimisation	Controls					
	violated limit	Bus voltage		no. of buses processed	Type	at bus/transformer	Adjustment in U			
		pre. adjusted	post adjusted				initial	final	Limit UL	Limit LL
1.	2	3	4	5	6	7	8	9	10	11
24	0.85	0.844	0.9383	23						
27	0.90	0.8927	0.9165							
50	0.90	0.8945	0.9102							
					Q at Generator	51	65.434	48.825	50.0	-17.0
						52	194.525	145.9674	155.00	-50.0
					Q	53	92.414	13.370	9.0	-3.0
						55	104.326	22.788	25.0	-8.0
						1	0.988	1.0944	1.1	0.9
						2	1.007	1.0809	1.1	0.9
					Transformer	3	0.980	1.0761	1.1	0.9
						4	1.005	1.0527	1.1	0.9
						5	1.015	1.0826	1.1	0.9
						7	0.987	1.0807	1.1	0.9
						9	0.993	1.0354	1.1	0.9
						11	1.03	1.1	1.1	0.9
						12	1.004	1.0506	1.1	0.9

Contd... ..

Table 4.2 Continued

bus No	Details of buses at which limits are violated			Local optimisation	Controls					
	violated limit	Bus voltage					Adjustment in U			
		pre. adjusted	post adjusted	no. of buses processed	Type	at bus/trans former	initial	final	Limit UL	LL
1.	2	3	4	5	6	7	8	9	10	11
						13	1.03	1.0831	1.1	0.9
						14	0.999	1.040	1.1	0.9
						15	0.998	1.0372	1.1	0.9
					at load buses	4	5.0+j2.0	0.0+j0.0		
						2	13.0+j4.0	0.0+j0.0		
						6	18.0+j2.3	0.0+j0.0		
						9	43.0+j3.0	0.0+j0.0		
						10	42.0+j8.0	23.57+j4.48		
						23	3.6+j1.8	3.49+j1.75		
						24	5.8+j2.9	5.04+j2.12		
						25	1.6+j.08	0.0+j0.0		
						28	6.0+j3.0	0.0+j0.0		
						48	6.8+j3.4	0.0+j0.0		
						49	7.6+j2.0	0.0+j0.0		
						50	6.7+j2.0	0.0+j0.0		

TABLE 4.3: TEST RESULTS OBTAINED FOR ALLEVIATION OF VOLTAGE LIMIT VIOLATION FOR 57 BUS IEEE TEST SYSTEM: CASE - B : LINE NO. 32 REMOVED (Fig. 4.4)

bus No	Details of buses at which limits are violated			Local optimisation	Controls					
	violated limit	Bus voltage		no. of buses processed	Type	at bus/transformer	Adjustment in U			
		pre. adjusted	post adjusted				initial	final	Limit UL	Limit LL
1.	2	3	4	5	6	7	8	9	10	11
18	0.85	0.8281	0.8660	25	Q at generator buses	51	65.328	29.03	50.0	-17.0
19	0.90	0.8993	0.9097			52	175.762	106.10	155,00	50.0
23	0.85	0.8126	0.8562			53	135.860	16.379	9.0	-3.0
24	0.85	0.8005	0.8497			55	97.548	25.017	25.0	-8.0
25	0.85	0.8469	0.8730							
26	0.85	0.8443	0.8706		Trans-former	1	0.988	1.100	1.1	0.9
27	0.90	0.8835	0.8901			2	1.007	1.083	1.1	0.9
28	0.90	0.8953	0.8987			3	0.980	1.087	1.1	0.9
						4	1.005	1.047	1.1	0.9
						5	1.015	1.082	1.1	0.9
						6	1.008	1.066	1.1	0.9
						7	0.987	1.091	1.1	0.9
						11	1.03	1.100	1.1	0.9
						12	1.004	1.1042	1.1	0.9
						13	1.03	1.077	1.1	0.9
						14	0.999	1.035	1.1	0.9
						15	0.998	1.032	1.1	0.9

Contd

Table 4.3 Continued.....

bus No	Details of buses at which limits are violated			Local optimisation	Controls					
	violated limit	Bus voltage		no. of buses processed	Type	at bus/trans former	Adjustment in U			
		pre. adjusted	post adjusted				initial	final	Limit UL	LL
1.	2	3	4	5	6	7	8	9	10	11
					at load buses	2	13.0+j4.0	0.0+j0.0		
						4	5.0+j2.0	0.0+j0.0		
						6	18.0+j2.3	0.0+j0.0		
						9	43.0+j3.0	0.0+j0.0		
						10	42.0+j8.0	25.94+j5.21		
						18	6.30+j3.2	5.78+j2.99		
						23	3.6+j1.8	2.54+j1.34		
						24	5.8+j2.9	3.08+j1.63		
						25	1.6+j0.80	1.49+j0.75		
						26	3.8+j1.9	3.76+j1.89		
						28	6.0+j3.0	5.82+j2.92		
						48	6.8+j3.4	0.0+j0.0		

TABLE 4.4: TEST RESULTS OBTAINED FOR ALLEVIATION OF VOLTAGE LIMIT VIOLATION FOR 57 BUS IEEE TEST SYSTEM:
CASE - C : LINE NO. 33 REMOVED (Fig. 4.4)

bus No	Details of buses at which limits are violated			Local optimisation	Controls					
	violated limit	Bus voltage		no. of buses processed	Type	at bus/trans former	Adjustment in U			
		pre. adjusted	post adjusted				initial	final	Limit UL	LL
1.	2	3	4	5	6	7	8	9	10	11
17	0.90	0.8742	0.9205	28	Q at generator buses	51	65.298	36.4423	50.0	-17.0
18	0.85	0.7990	0.8846			52	205.103	117.3790	155.00	-50.0
19	0.90	0.8703	0.9167			53	125.493	10.488	9.0	-3.0
20	0.90	0.8504	0.9120			55	95.716	17.1538	25.0	-8.0
23	0.85	0.7849	0.8776							
24	0.85	0.7770	0.8763		Trans-former	1	0.988	1.100	1.1	0.9
25	0.85	0.8320	0.9054			2	1.007	1.094	1.1	0.9
26	0.85	0.8294	0.9030			3	0.980	1.100	1.1	0.9
27	0.90	0.8759	0.9150			4	1.005	1.050	1.1	0.9
28	0.90	0.8889	0.9222			5	1.015	1.090	1.1	0.9
						7	1.008	1.073	1.1	0.9
						9	0.987	1.100	1.1	0.9
						11	1.03	1.100	1.1	0.9
						12	0.999	1.045	1.1	0.9
						13	1.03	1.079	1.1	0.9
						14	0.999	1.037	1.1	0.9
						15	0.998	1.033	1.1	0.9

Contd...

Table 4.4 Contd.....

bus No	Details of buses at which limits are violated			Local optimisation	Controls					
	violated limit	Bus voltage		no. of buses processed	Type	at bus/trans former	Adjustment in U			
		pre. adjusted	post adjusted				initial	final	Limit UL	LL
1.	2	3	4	5	6	7	8	9	10	11
					at load buses	2	13.0+j4.0	0.0+j0.0		
						4	5.0+j2.0	0.0+j0.0		
						6	18.0+j2.3	0.0+j0.0		
						9	43.0+j3.0	0.0+j0.0		
						10	42.0+j8.0	11.37+j2.52		
						18	6.30+j3.2	5.45+j2.94		
						20	9.3+j0.5	2.34+j1.31		
						23	3.6+j1.8	2.27+j1.30		
						24	5.8+j2.9	2.85+j1.64		
						25	1.6+j.08	0.0+j0.0		
						26	3.80+j1.9	3.71+j1.88		
						28	6.0+j3.0	0.0+j0.0		
						48	6.8+j3.4	0.0+j0.0		
						49	7.6+j2.2	7.55+j1.92		
						50	6.7+j2.0	6.43+j1.92		

reactive power is adjusted at bus number 22 and 23. At last load shedding is done at bus number 1 and 6.

4.1.2 57 Bus IEEE System

Three critical cases of line outage are considered in this case. The results are presented in tables(4.2 to 4.4).

Case A:

Line number 10 is removed. The method successfully corrects the voltage profile at three buses using controls of generator reactive power and transformer tap and at last load shedding is done. Twenty three buses are considered in the local area to obtain the new secure state with minimum deviation from the pre adjusted state as given in table (4.2).

Outage of line number 32 and 33 are taken care of in the same manner under cases B and C depicted in table (4.3) and (4.4) respectively.

4.2 RESULTS FOR ALLEVIATION OF VOLTAGE LIMIT VIOLATION COMBINED WITH MINIMIZATION OF REACTIVE GENERATION AND LOSSES OF THE SYSTEM

The operating state of a power system will undergo changes due to various contingencies and disturbances on the system. The emergency state may occur as result of a sudden increase in system demand, the unexpected outage of a generating unit or a transmission line, or a failure in any of the system components. If the system survives the outage or disturbance, it will operate in a new steady state, in which one or more transmission lines may be overloaded and/or voltage constraints at some buses may be violated.

The main objective of power system operation is to attain security and economy. Since security and economy are normally conflicting requirements,. System security means the availability and quality of supply which is necessary for system operation. The final aim of economy is the security function of the utility-company. The energy management system is to operate the system at minimum losses, with the guaranteed alleviation of emergency conditions.

In the present dissertation work an attempt is made to alleviate voltage violation in the system and operate the system optimally, considering the voltage security of the system. To demonstrate the work the voltage violations are created by considering the contingency in the system. This gives the changed system configuration and voltage limits are violated at some buses which are corrected using local optimization techniques.

The algorithms are tested on two types of system.

(4.2.1) 24 Bus IEEE test system.

(4.2.2)57 bus IEEE test system.

4.2.1 24 Bus IEEE Test System

In the first part reactive generation at the generator buses and the losses in the system are minimized. By doing so value of minimization function decreases from 3.92418to 3.33790. But by optimally operating the system the voltage security of the system is deteriorated, because the value of voltage security index named

Sl. No.	No. of Buses	Optimal Soltuion Before Contingency				Contingency Created			Optimal Solution After Contingency			
		Function Value (min.)		Voltage Security Index		Type of Contingency	Voltage Security Index		Function Value (min.)		Voltage Security Index	
		Pre Optimization	Post Optimization	Pre Optimization	Post Optimization		Pre Optimization	Post Optimization	Pre Optimization	Post Optimization	Pre Optimization	Pre Optimization
1.	24	3.92418	3.33790	925.192	8349.20	Line 26 removed	32359.9	1212.06	4.16741	4.16741	1212.06	1212.06
[illegible].	57					Lime 10 removed	256.773	2.42882	5.52416	5.31277	2.42882	16.9844
3.	57	7.63532	7.58309	397.944	64.9815	Lime 32 removed	4795.73	1217.75	6.29383	5.89094	1217.75	478.168
4.	57					Line 33 removed	1377.89	117.627	5.83064	5.38474	117.627	61.6264

TABLE 4.5: RESULTS FOR ALLEVIATION OF VOLTAGE LIMIT VIOLATION COMBINED WITH MINIMIZATION OF REACTIVE GENERATION AND LOSSES FOR 24 & 57 IEEE BUS SYSTEMS

as diagonal element dependent index increases from 925.192 to 8349.20. The complete results for 24 bus system are shown in table (4.5).

Now for creating voltage violations in the system, contingency is created by outing line 26 from the system. On creating the contingency the value of voltage security index is increased to 32359.9 which indicates the ill conditioning of the network. Due to contingency voltage limits are violated at buses 1 and 13. The results for alleviation of voltage limit violations are shown in table (4.1) and described in section (4.1.1).

After alleviating the voltage limit violations by locally adjusting the independent variable as described in chapter 3, the voltage security of the system also improves.

Because of the contingency the optimal operation of the system may be disturbed. Thus again reactive generation and the losses of the system are minimized. By coincidence, in this particular case we found that at this stage base case load flow solution is the optimal load flow solution.

4.2.2 57 Bus IEEE System

In the case of 57 bus system again to operate the system optimally, reactive generation and losses of the system are minimized. The minimization function decreases from 7.63532 to 7.58309. The optimal solution of the system improves the ill conditioning and voltage security of the system as the value of voltage security index improves from 397.944 to 64.9815. The results for 57 bus IEEE system is given in table (4.5).

Voltage violations are created in the system by outing heavily loaded lines from the system. For this purpose three cases of 57 bus systems are tested in the present dissertation work.

Case A: Line 10 removed from 57 bus system.
Case B: Line 32 removed from 57 bus system.
Case C: Line 33 removed from 57 bus system.

Case A: Line 10 Removed from 57 Bus System

Due to outing line 10 from the system voltage limits are violated at buses no. 24, 27 and 50. Alleviation of these violations are described in section 4.1.2 and results are shown in table (4.2). Due to contingency the value of voltage security index increase from 64.9815 to 256.777.

After alleviating the violations at buses the voltage security index come to a value 2.42882 indicating the secure operation of the system.

Due to contingency optimal performance of the system is deteriorated so again minimizing the reactive generation and losses of the system, the minimization function minimized from 5.52416 to 5.31277. But due to optimal operation the security of the system is deteriorated as voltage security index increases from 2.42882 to 16.9844.

Case B: Line 32 Removed from 57 Bus System

In this case, due to contingency voltage limits are violated at buses 18, 19, 23, 24, 27 and 28. Table (4.13) shows the results for alleviation of voltage limit violations.

Due to contingency, the system goes to highly insecure operation as the value of voltage security index increased to a very high value, from 64.9815 to 4795.73. After alleviating the effect of this contingency the voltage security index decreases to 1217.75. Again optimizing the reactive generation and losses of the system, function value deceases from 6.29383 to 5.8904. In this case optimal solution assures more secure operation of the system, as voltage security index decreases from 1217.75 to 478.168.

Case C: Line 33 Removed from 57 Bus System

In this case contingency creates voltage violations at buses 17, 18, 19, 20, 26, 27 and 28. Results for alleviation of these violations are shown in table (4.4) and discussed in section (4.1.2).

In this case contingency made the voltage security index to rise from 64.9815 to 1377.89, indicating the deterioration of the stability of the system. Alleviating the limit violations, voltage security index improves from 1377.89 to 117.627 indicating that the system's distance from collapse or instability condition is increased. Due to contingency the optimal operation of the system is deteriorated. In this case reactive power generation and losses function is minimized from 5.83064 to 5.38474. In this case optimal solution also improves the voltage profile and stability of the system, as the value of voltage security index is decreased from 117.627 to 61.6264.

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The main concern of electric utilities these days is to run their system as efficiently as possible, keeping in view the maximum possible utilization of the existing setup as well as to maintain the secure operation of the power system. This chapter concludes the work done on few apsects of the alleviation of voltage limit violation in power networks. Main conclusions have been described below.

Reactive generation of generator buses and losses of the system ares minimized to select optimally out of the available generating sources to operate, to meet the expected load and provide a specified margin of operating reserve over a specified period of time. By doing this, it is observed that normally the profile of the system from the view point of voltage security improves. After creating contingency in the system and removing the voltage limit violations at the buses locally, this optimal power flow solution i.e. minimization of reactive generation and losses again provide the solution which has better system voltage security and improves the system voltage profile.

Optimal power flow is recognized as an important tool utilized in power system planning and its optimal operation in closed loop dispatching control mode. In the first part of the dissertation, problem is taken as optimal power flow problem out of the two subproblems of OPF described in section (2.1), only reactive power (Q) optimization subproblem is considered in the present dissertation work. In this problem reactive generation at generation buses and the losses in the system are minimized by taking the reactive generation at generator buses and the transformer tap ratio as independent variables and the bus voltage magnitude as dependent variables. Voltage security index named as diagonal element dependent Index (Id) which is the ratio of maximum diagonal element of power flow Jacobian to the minimum diagonal element of power flow Jacobian is calculated at each iteration of load flow..

24 and 57 bus system are considered to test the algorithm. For the 24 bus system we obtained the optimal power flow solution at the cost of system security. In this case after optimization, value of voltage security index increases which indicates the ill conditioning of the network from the view point of voltage collapse. In the case of 57 bus system optimal power flow solution improves the stability of the system.

In the second part of the dissertation, alleviation of voltage limit violations are corrected by coordinating controls at the local level during any severe disturbance to avoid the disintegration of the power system. By using the optimization method, the objective function given as the weighted sum of squares of the voltage limit violation is minimized. In this method, few buses in the vicinity of the buses having voltage limit violations are processed for local optimization, irrespective of the size of the system under study. In this, voltage security index is also calculated just after creating contingency in the system and after alleviating the limit violations at the buses.

The algorithm gives satisfactory results when tested on 24 bus IEEE (RTS) and 57 bus IEEE systems under severe and extreme loading conditions. The new secure operating points after an outage has occurred is efficiently obtained under steady state conditions. The method may prove to be suitable for on line applications because of its efficiency and reliability.

After obtaining a new secure operating point, after an contingency has occurred the optimal power flow operation of the system may be detoriated. For obtaining OPF solution we again minimized reactive generation at generator buses and losses in the system, and also calculated voltage security index pre and past optimization. After alleviating the violation at buses this OPF solution can be obtained on line or off line, when ever the operator will find the time.

For all the cases tested except one case of 57 bus system the new optimal power flow solution improves the ill conditioning of the network and presents a better system voltage profile.

5.2 RECOMMENDATIONS FOR FUTURE WORK

Suggestions for future work is summarized below;

* Power system networks are large and complex. The complexity and computational difficulty associated with analyzing with a single large network has led to the development of decomposition methods, in which the power network is divided into number of areas. Computation time and memory required is reduced

substantially by decomposing the large network matrices and it gives better flexibility in studying the power networks in parts rather than as whole. The algorithms for alleviation of voltage limit violation may be modified using the concept of network decomposition along with the local optimization technique.

* Voltage collapse analysis involves both static and dynamic factors. From a system operator's view point a stressed (heavily loaded) system has to be carefully monitored and adequate control action taken when the operating point approaches the limit of voltage stability. In the day-to-day operation and control of power systems these divisions require very fast computations in the energy control center. Since conventional optimization techniques for voltage stability improvment are computationally intensive, there is a need for a heuristic approach which can make decisions very fast with a minimum of numerical computation. Expert systems can be used as a decision support system tool for online application in energy control centers.

* In the present work optimal power flow is solved separately as decoupled problem considering only reactive power optimization subproblem. The OPF problem can be solved simultaneously or coupled problems considering both active power and reactive power optimization subproblem.

* The study of voltage instability has become an important area of research in the field of power system engineering. The main thrust of research has been to arrive at a accurate and reliable indicator of the proximity of a system to voltage collapse. Such an index would be useful to utilities in operating their systems with maximum economy and reliability. Artificial neural networks

(ANNs) can be used for securing assessment due to its ability to achieve complicated input output mappings through a learning process, without, explicit programming. Once an ANN has been trained, it can classify new data much faster than would be possible by solving the model analytically.

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APPENDIX-A

POWER SYSTEM REPRESENTATION

Basically power system consists of three principal components- Generating stations, Transmission lines and Distribution systems. The connecting link between the generators and the distribution system are transmission lines. A simple two bus system in Fig A.1 explains the basic features of power system operation. Each bus is being fed from the generators SG_i and SG_j, into the buses i and j respectively. Loads tapped from each bus are SD_i and SD_j. Fig.A.2 shows the equivalent circuit of the two bus system. The transmission line is represented by a pi-equivalent model.

The transformer tap representation and its equivalent circuit is described in Fig. A.3. If the transformer ratio is $(a_{ij} : 1)$ from bus i to bus j, then transformer admittance y_{ij} is replaced by (y_{ij}/a_{ij}), a shunt admittance of $\left[\left[\frac{1}{a_{ij}}\right] \cdot \left[\frac{1}{a_{ij}} - 1\right] \cdot y_{ij} \right]$ is added at bus i and a shunt admittance of $\left[\left[1 - \frac{1}{a_{ij}} \right] \cdot y_{ij} \right]$ is added at bus j.

Switchable capacitor banks are represented in the power system by replacing B_{ii} by $(B_{ii} - b_{ci})$, where i is the bus at which the capacitor bank is connected, and $(b_{ij}/2)$ is replaced by $\left(\frac{b_{ij}}{2} - b_{ci} \right)$, where b_{ci} is the admittance of the capacitor bank at bus i.

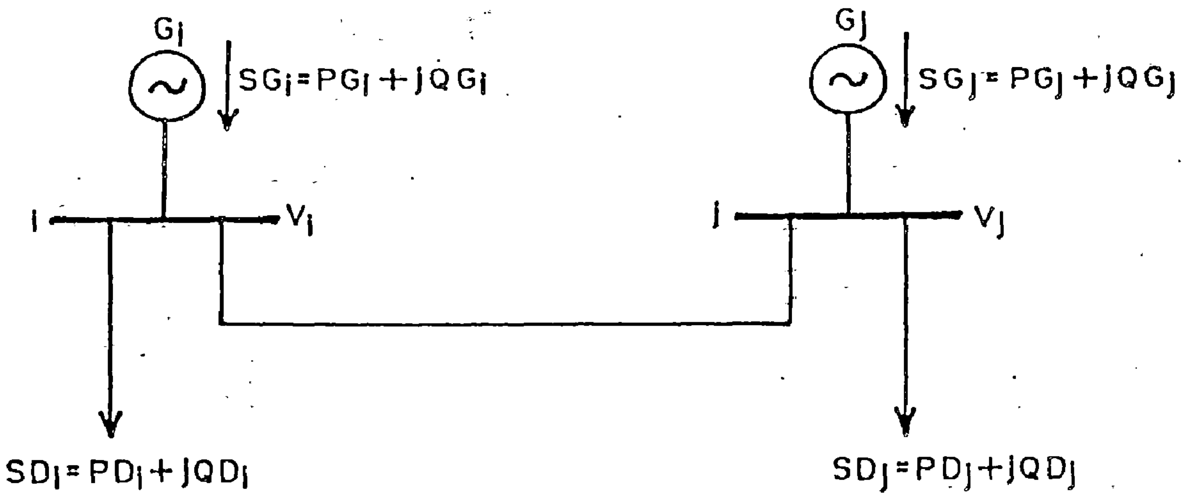

FIG. A.1 TWO BUS SYSTEM

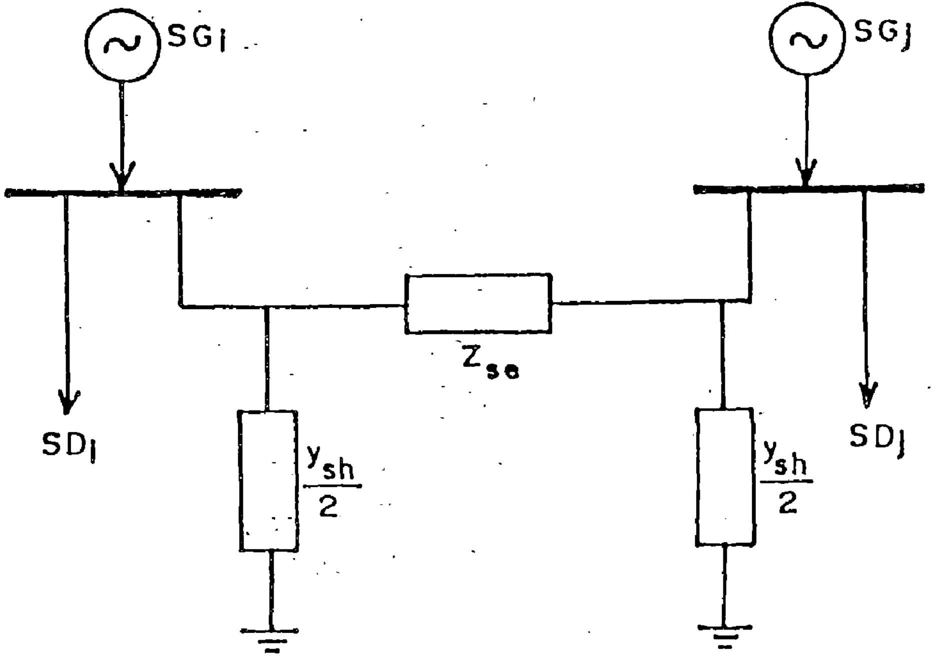

FIG. A.2 EQUIVALENT CIRCUIT

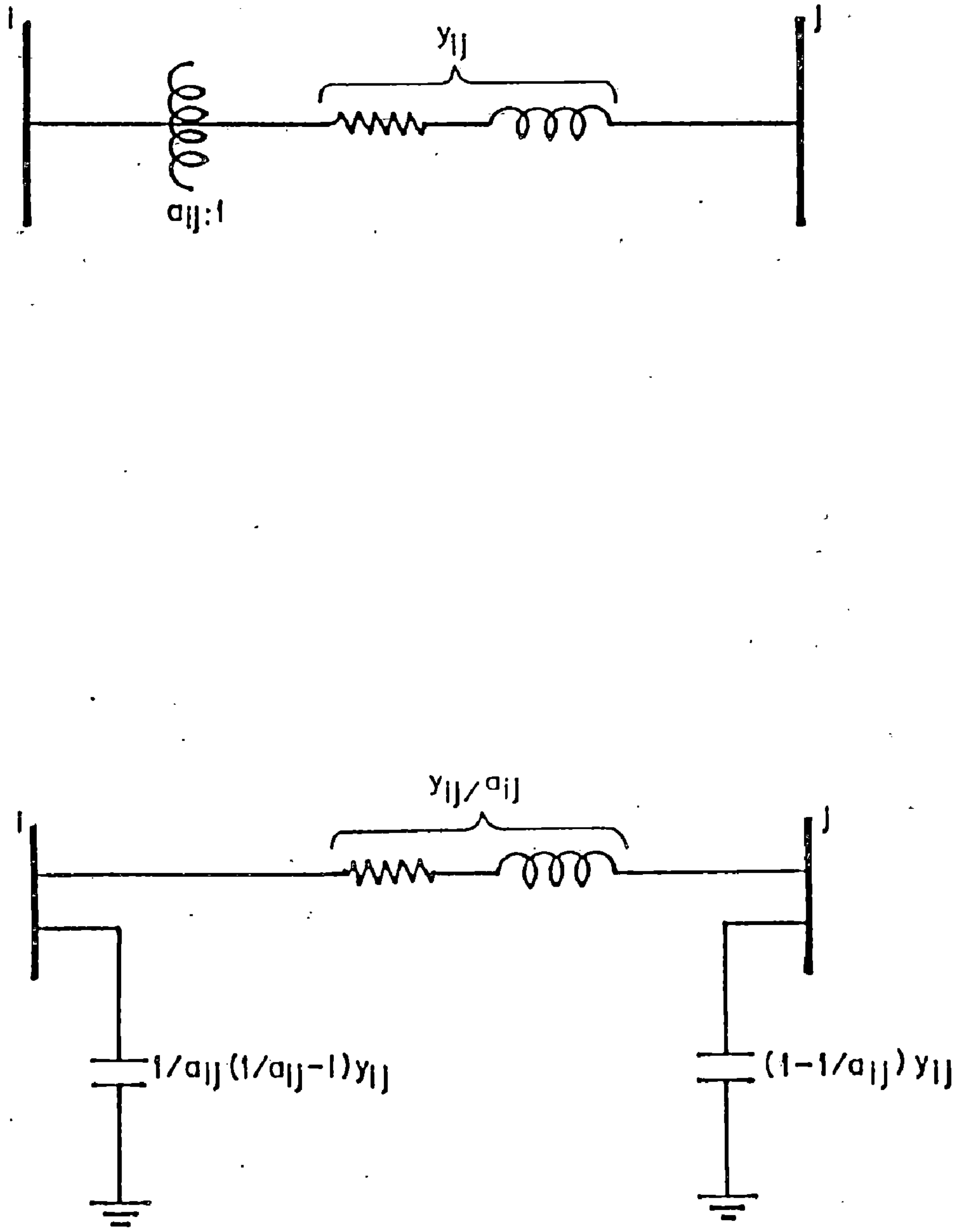

FIG.A.3 TRANSFORMER REPRESENTATION

SAMPLE CALCULATION OF INDICES

A sample calculation of the voltage security index is given below:

Let

$$A = \begin{bmatrix} -1 & 2 & 3 \\ 2 & 0.1 & 1 \\ 4 & -3 & 2 \end{bmatrix}$$

Diagonal Element Dependent Index (I_d), which is the ratio of absolute value of the maximum diagonal element value to the absolute value of the minimum diagonal element value is found as,

$$I_d = \frac{|\,2\,|}{|0.1|} = 20$$

TEST SYSTEM DATA

In this Appendix single line diagrams (Fig. C.1 to C.2) and Test system data (Table C.1 (a,b,c & d) through Table C.2 (a,b,c & d)) for the following system are given.

- 24-Bus IEEE Reliability Test System (RTS)
- 57-Bus IEEE Test System

The data are presented in the following manner.

-Bus data
-Constraints on bus variables
-Line data
-Transformer data

In bus data, bus type 1 indicates a load bus, bus type 2 a generator bus and bus type 3 the reference bus. In the line data, line type 1 indicates an ordinary line, line type 2 a tie line and line type 3 a transformer line.

In the transformer data, transformer type 1 indicates the fixed tap transformer and transformer type 2 indicates the tap changing transformer.

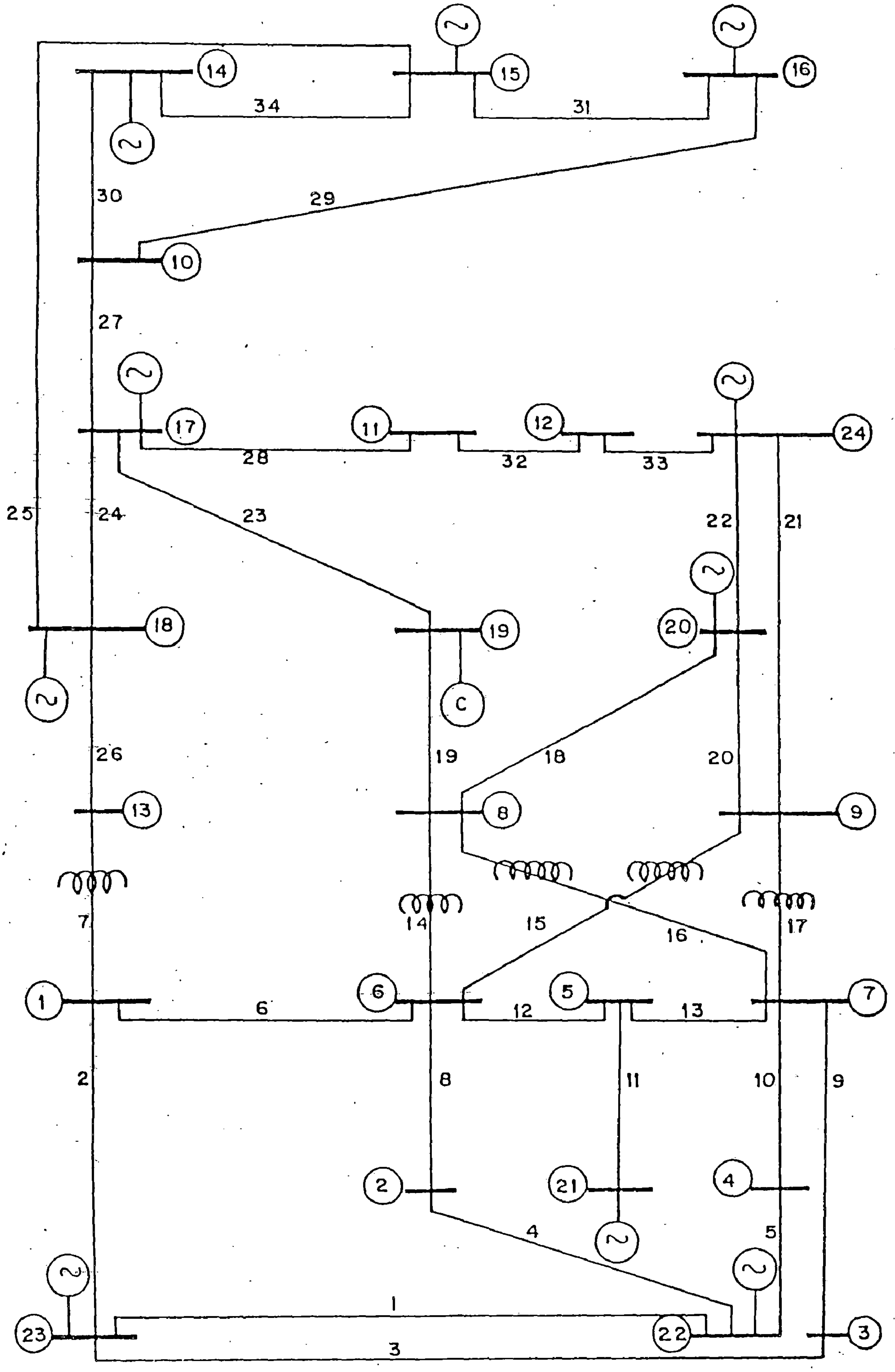

FIG (C.1) 24- BUS IEEE TEST SYSTEM

TABLE - C.1(a)
24 BUS SYSTEM : BUS DATA

BUS No.	BUS Type	BUS VOLTAGE		GENERATION		LOAD		REACTOR/ CAPACITOR SUSCEPT (P.U.)
		Magnitude (P.U.)	Angle Radians	Active (MW)	Reactive (MVAR)	Active (MW)	Reactive (MVAR)	
1	2	3	4	5	6	7	8	9
1	0	0.9696	-0.1622	0.000	0.000	180.000	37.000	0.000
2	0	0.9628	-0.1999	0.000	0.000	74.000	15.000	0.000
3	0	0.9834	-0.1999	0.000	0.000	71.000	14.000	0.000
4	0	0.9786	-0.2494	0.000	0.000	136.000	28.000	-0.958
5	0	0.9613	-0.1789	0.000	0.000	171.000	35.000	0.000
6	0	0.9678	-0.1681	0.000	0.000	175.000	36.000	0.000
7	0	0.9948	-0.1979	0.000	0.000	195.000	40.000	0.000
8	0	0.9884	-0.0799	0.000	0.000	0.000	0.000	0.000
9	0	0.9861	-0.0753	0.000	0.000	0.000	0.000	0.000
10	0	1.0009	0.1521	0.000	0.000	0.000	0.000	0.000
11	0	0.9928	0.0073	0.000	0.000	181.000	37.000	0.000
12	0	0.9982	-0.0067	0.000	0.000	128.000	26.000	0.000
13	0	0.9594	0.0004	0.000	0.000	0.000	0.000	0.000
14	2	1.0240	0.2983	300.000	-60.000	0.000	0.000	0.000
15	2	1.0000	0.1967	400.000	-50.000	0.000	0.000	0.000
16	2	1.0000	0.1803	400.000	117.000	333.000	68.000	0.000
17	2	1.0000	0.0650	155.000	80.000	100.000	20.000	0.000
18	2	1.0000	0.0906	215.000	110.000	317.000	64.000	0.000
19	2	1.0000	-0.0457	0.000	-50.000	194.000	39.000	0.000
20	2	1.0000	-0.0046	591.000	121.600	265.000	54.000	0.000
21	2	1.0000	-0.0713	300.000	39.600	125.000	25.000	0.000
22	2	1.0000	-0.1442	192.000	-0.700	97.000	20.000	0.000
23	2	1.0000	-0.1434	192.000	4.480	108.000	22.000	0.000
24	2	1.0000	0.0000	145.690	-49.338	0.000	0.000	0.000

TABLE C.1(b)

24 BUS SYSTEM : CONSTRAINTS ON BUS VARIABLES

BUS No.	BUS VOLTAGE (P.U.)		ACTIVE GENERATION (MW)		REACTIVE GENERATION (MVAR)	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1	2	3	4	5	6	7
1	0.900	1.050	0.000	0.000	0.000	0.000
2	0.900	1.050	0.000	0.000	0.000	0.000
3	0.900	1.050	0.000	0.000	0.000	0.000
4	0.900	1.050	0.000	0.000	0.000	0.000
5	0.900	1.050	0.000	0.000	0.000	0.000
6	0.900	1.050	0.000	0.000	0.000	0.000
7	0.900	1.050	0.000	0.000	0.000	0.000
8	0.900	1.050	0.000	0.000	0.000	0.000
9	0.900	1.050	0.000	0.000	0.000	0.000
10	0.900	1.050	0.000	0.000	0.000	0.000
11	0.900	1.050	0.000	0.000	0.000	0.000
12	0.900	1.050	0.000	0.000	0.000	0.000
13	0.900	1.050	0.000	0.000	0.000	0.000
14	0.900	1.050	0.000	300.000	-60.000	96.000
15	0.900	1.050	0.000	400.000	-50.000	200.000
16	0.900	1.050	0.000	400.000	-50.000	200.000
17	0.900	1.050	0.000	155.000	-50.000	80.000
18	0.900	1.050	0.000	245.000	-50.000	110.000
19	0.900	1.050	0.000	0.000	-200.000	50.000
20	0.900	1.050	0.000	591.000	0.000	240.000
21	0.900	1.050	0.000	300.000	0.000	180.000
22	0.900	1.050	0.000	192.000	-50.000	80.000
23	0.950	1.050	0.000	192.000	-50.000	80.000
24	0.900	1.050	0.000	151.400	-125.000	310.000

TABLE - C.1(c)
24 BUS SYSTEM : LINE DATA

LINE No.	LINE Type	FROM BUS	TO BUS	LINE IMPEDANCE		HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
				RESISTANCE (P.U.)	REACTANCE (P.U.)		
1	2	3	4	5	6	7	8
1	1	23	22	0.0026	0.0139	0.2306	173.7000
2	1	23	1	0.0546	0.2112	0.0286	180.0000
3	1	23	3	0.0218	0.0845	0.0114	187.2000
4	1	22	2	0.0328	0.1267	0.0171	187.2000
5	1	22	4	0.0497	0.1920	0.0260	187.2000
6	1	1	6	0.0497	0.1920	0.0260	187.2000
7	1	1	13	0.0023	0.0839	0.0000	459.0000
8	1	2	6	0.0268	0.1037	0.0141	187.2000
9	1	3	7	0.0228	0.0883	0.0119	187.2000
10	1	4	7	0.0139	0.0605	1.2295	173.7000
11	1	21	5	0.0159	0.0614	0.0083	187.2000
12	1	5	6	0.0427	0.1651	0.0220	187.2000
13	1	5	7	0.0427	0.1651	0.0220	187.2000
14	3	6	8	0.0023	0.0839	0.0000	459.0000
15	3	6	9	0.0023	0.0839	0.0000	459.0000
16	3	7	8	0.0023	0.0839	0.0000	459.0000
17	3	7	9	0.0023	0.0839	0.0000	459.0000
18	1	8	20	0.0061	0.0476	0.0499	540.0000
19	1	8	19	0.0054	0.0418	0.0439	540.0000
20	1	9	20	0.00661	0.0406	0.0499	540.0000
21	1	9	24	0.0124	0.0966	0.1015	540.0000
22	1	20	24	0.0111	0.0865	0.0909	540.0000
23	1	19	17	0.0050	0.0389	0.0409	540.0000
24	1	18	17	0.0022	0.0173	0.0182	540.0000
25	1	18	15	0.0032	0.0245	0.1030	1080.0000
26	1	18	15	0.0067	0.0519	0.0546	540.0000

TABLE - C.1(d)
24 BUS SYSTEM : TRANSFORMER DATA

TRANSFORMER								
No.	Type	TTAP	TIMP	TLTPTR	TRATIO	TMAXR	TMINR	TSTEP
1	2	3	4	5	6	7	8	9
1	2	1	13	7	1.05000	1.10000	0.85000	0.01250
2	2	6	8	14	1.00000	1.10000	0.85000	0.01250
3	2	6	9	15	1.00000	1.10000	0.85000	0.01250
4	2	7	8	16	1.00000	1.10000	0.85000	0.01250
5	2	7	9	17	1.00000	1.10000	0.85000	0.01250

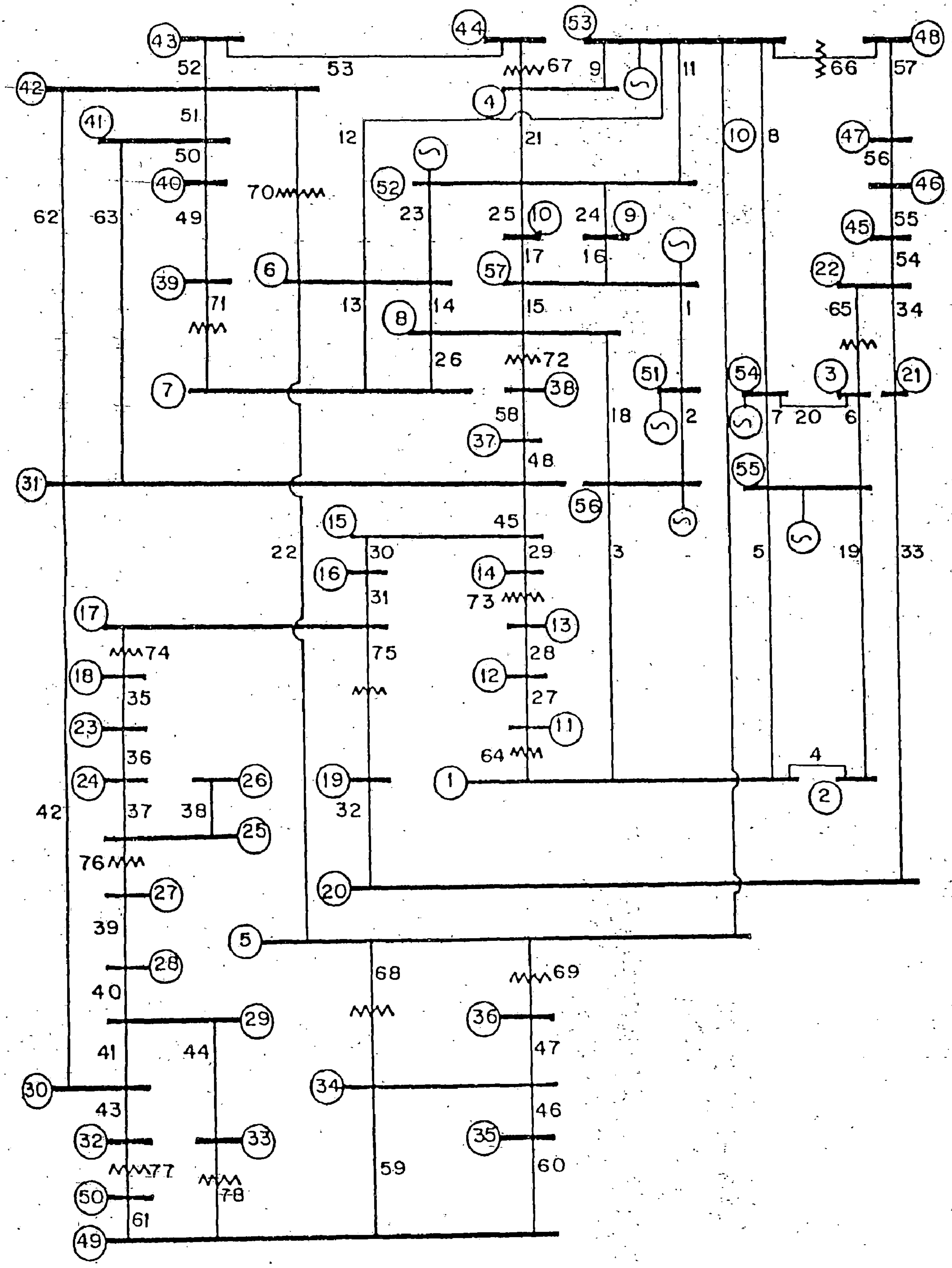

FIG (C.2) 57- BUS IEEE TEST SYSTEM

TABLE - C.2(a)
57 BUS SYSTEM : BUS DATA

BUS No.	BUS Type	BUS VOLTAGE		GENERATION		LOAD		REACTOR/ CAPACITOR SUSCEPT. (P.U.)
		MAGNITUDE (P.U.)	ANGLE (Radian)	ACTIVE (MW)	REACTIVE (MVAR)	ACTIVE (MW)	REACTIVE (MVAR)	
1	2	3	4	5	6	7	8	9
1	0	0.9799	-0.1261	0.000	0.000	0.000	0.000	0.000
2	0	0.9762	-0.1474	0.000	0.000	13.000	4.000	0.000
3	0	0.9853	-6.1307	0.000	0.000	0.000	0.000	0.000
4	0	0.9825	-0.2031	0.000	0.000	5.000	2.000	0.000
[illegible]	0	0.9719	-0.1799	0.000	0.000	0.000	0.000	0.000
6	0	0.9800	-0.1729	0.000	0.000	18.000	2.300	0.000
7	0	0.9708	-0.1646	0.000	0.000	10.500	5.300	0.000
8	0	0.9854	-0.1263	0.000	0.000	22.000	5.000	0.000
9	0	1.0133	-0.1559	0.000	0.000	43.000	3.000	0.000
10	0	1.0174	-0.0949	0.000	0.000	42.000	8.000	0.000
11	0	0.9301	-0.3035	0.000	0.000	27.200	9.800	0.100
12	0	0.9106	-0.3048	0.000	0.000	3.300	0.600	0.000
13	0	0.9116	-0.2907	0.000	0.000	2.300	1.000	0.000
14	0	0.9000	-0.2494	0.000	0.000	0.000	0.000	0.000
15	0	0.9036	-0.2433	0.000	0.000	0.000	0.000	0.000
16	0	0.9012	-0.2442	0.000	0.000	6.300	2.100	0.000
17	0	0.8770	-0.2431	0.000	0.000	0.000	0.000	0.000
18	0	0.7794	-0.4448	0.000	0.000	6.300	3.200	0.059
19	0	0.8733	-0.2379	0.000	0.000	0.000	0.000	0.000
20	0	0.8899	-0.2094	0.000	0.000	9.300	0.500	0.000
21	0	0.9034	-0.1885	0.000	0.000	4.600	2.300	0.000
22	0	0.9164	-0.1740	0.000	0.000	17.000	2.600	0.000
23	0	0.7603	-0.4538	0.000	0.000	3.600	1.800	0.000
24	0	0.7409	-0.4571	0.000	0.000	5.800	2.900	0.000
25	0	0.7807	-0.4134	0.000	0.000	1.600	0.800	0.000
26	0	0.7779	-0.4144	0.000	0.000	3.800	1.900	0.000

Table C.2(a) Contd.

BUS No.	BUS Type	BUS VOLTAGE		GENERATION		LOAD		REACTOR/ CAPACITOR SUSCEPT. (P.U.)
		MAGNITUDE (P.U.)	ANGLE (Radian)	ACTIVE (MW)	REACTIVE (MVAR)	ACTIVE (MW)	REACTIVE (MVAR)	
1	2	3	4	5	6	7	8	9
27	0	0.8461	-0.2783	0.000	0.000	0.000	0.000	0.000
28	0	0.8574	-0.2714	0.000	0.000	6.000	3.000	0.000
29	0	0.8708	-0.2645	0.000	0.000	0.000	0.000	0.000
30	0	0.8808	-0.2590	0.000	0.000	0.000	0.000	0.000
31	0	0.9093	-0.2401	0.000	0.000	14.000	7.000	0.000
32	0	0.8793	-0.2600	0.000	0.000	0.000	0.000	0.000
33	0	0.8698	-0.2658	0.000	0.000	0.000	0.000	0.000
34	0	0.9200	-0.2657	0.000	0.000	6.300	3.000	0.000
35	0	0.8769	-0.2938	0.000	0.000	7.100	4.000	0.000
36	0	0.9504	-0.2049	0.000	0.000	2.000	1.000	0.000
37	0	0.9239	-0.2229	0.000	0.000	12.000	1.800	0.000
38	0	0.9670	-0.1729	0.000	0.000	0.000	0.000	0.000
39	0	0.9521	-0.2016	0.000	0.000	0.000	0.000	0.000
40	0	0.9263	-0.2319	0.000	0.000	29.700	11.600	0.000
41	0	0.9212	-0.2348	0.000	0.000	0.000	0.000	0.000
42	0	0.9279	-0.2378	0.000	0.000	18.000	8.500	0.000
43	0	0.9208	-0.2474	0.000	0.000	21.000	10.500	0.000
44	0	0.9656	-0.2277	0.000	0.000	18.000	5.300	0.000
45	0	0.8859	-0.2091	0.000	0.000	4.900	2.200	0.000
46	0	0.8768	-0.2244	0.000	0.000	20.300	10.500	0.063
47	0	0.9111	-0.2137	0.000	0.000	4.100	1.400	0.000
48	0	0.9551	-0.1953	0.000	0.000	6.800	3.400	0.000
49	0	0.8668	-0.3017	0.000	0.000	7.600	2.200	0.000
50	0	0.8573	-0.3130	0.000	0.000	6.700	2.000	0.000
51	2	1.0100	-0.0207	0.000	0.000	3.000	88.000	0.000
52	2	1.0150	-0.1845	310.000	128.500	377.000	24.000	0.000
53	2	0.9800	-0.1689	0.000	2.200	121.000	26.000	0.000
54	2	1.0050	-0.0780	450.000	62.100	150.000	22.000	0.000
55	2	0.9800	-0.1497	0.000	0.800	75.000	2.000	0.000
56	2	0.9850	-0.1042	40.000	-1.000	41.000	21.000	0.000
57	2	1.0400	0.0000	480.931	131.722	55.000	17.000	0.000

TABLE - C.2(b)
57 BUS SYSTEM : CONSTRAINTS ON BUS VARIABLES

BUS No.	BUS VOLTAGE (P.U.)		ACTIVE GENERATION (MW)		REACTIVE GENERATION (MVAR)	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1	2	3	4	5	6	7
1	0.900	1.100	0.000	0.000	0.000	0.000
2	0.900	1.100	0.000	0.000	0.000	0.000
3	0.900	1.100	0.000	0.000	0.000	0.000
4	0.900	1.100	0.000	0.000	0.000	0.000
5	0.900	1.100	0.000	0.000	0.000	9.000
6	0.900	1.100	0.000	0.000	0.000	0.000
7	0.900	1.100	0.000	0.000	0.000	0.000
8	0.900	1.100	0.000	0.000	0.000	0.000
9	0.900	1.100	0.000	0.000	0.000	0.000
10	0.900	1.100	0.000	0.000	0.000	0.000
11	0.900	1.100	0.000	0.000	0.000	0.000
12	0.900	1.100	0.000	0.000	0.000	0.000
13	0.900	1.100	0.000	0.000	0.000	0.000
14	0.900	1.100	0.000	0.000	0.000	0.000
15	0.900	1.100	0.000	0.000	0.000	0.000
16	0.900	1.100	0.000	0.000	0.000	0.000
17	0.900	1.100	0.000	0.000	0.000	0.000
18	0.900	1.100	0.000	0.000	0.000	0.000
19	0.900	1.100	0.000	0.000	0.000	0.000
20	0.900	1.100	0.000	0.000	0.000	0.000
21	0.900	1.100	0.000	0.000	0.000	0.000
22	0.900	1.100	0.000	0.000	0.000	0.000
23	0.900	1.100	0.000	0.000	0.000	0.000
24	0.900	1.100	0.000	0.000	0.000	0.000
25	0.900	1.100	0.000	0.000	0.000	0.000
26	0.900	1.100	0.000	0.000	0.000	0.000

TABLE C.2.(b) CONTD....

BUS No.	BUS VOLTAGE (P.U.)		ACTIVE GENERATION (MW)		REACTIVE GENERATION (MVAR)	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1	2	3	4	5	6	7
27	0.900	1.100	0.000	0.000	0.000	0.000
28	0.900	1.100	0.000	0.000	0.000	0.000
29	0.900	1.100	0.000	0.000	0.000	0.000
30	0.900	1.100	0.000	0.000	0.000	0.000
31	0.900	1.100	0.000	0.000	0.000	9.000
32	0.900	1.100	0.000	0.000	0.000	0.000
33	0.900	1.100	0.000	0.000	0.000	0.000
34	0.900	1.100	0.000	0.000	0.000	0.000
35	0.900	1.100	0.000	0.000	0.000	0.000
36	0.900	1.100	0.000	0.000	0.000	0.000
37	0.900	1.100	0.000	0.000	0.000	0.000
38	0.900	1.100	0.000	0.000	0.000	0.000
39	0.900	1.100	0.000	0.000	0.000	0.000
40	0.900	1.100	0.000	0.000	0.000	0.000
41	0.900	1.100	0.000	0.000	0.000	0.000
42	0.900	1.100	0.000	0.000	0.000	0.000
43	0.900	1.100	0.000	0.000	0.000	0.000
44	0.900	1.100	0.000	0.000	0.000	0.000
45	0.900	1.100	0.000	0.000	0.000	0.000
46	0.900	1.100	0.000	0.000	0.000	0.000
47	0.900	1.100	0.000	0.000	0.000	0.000
48	0.900	1.100	0.000	0.000	0.000	0.000
49	0.900	1.100	0.000	0.000	0.000	0.000
50	0.900	1.100	0.000	0.000	0.000	0.000
51	0.900	1.100	0.000	0.000	-17.000	50.000
52	0.900	1.100	0.000	387.500	-50.000	155.000
53	0.900	1.100	0.000	0.000	-3.000	9.000
54	0.900	1.100	0.000	562.500	-140.000	200.000
55	0.900	1.100	0.000	0.000	-8.000	25.000
56	0.900	1.100	0.000	50.000	-10.000	60.000
57	0.900	1.100	0.000	600.000	-500.000	500.000

TABLE - C.2 (c)

57-BUS SYSTEM : LINE DATA

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE		HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
				RESISTANCE (P.U.)	REACTANCE (P.U.)		
1	2	3	4	5	6	7	8
1	1	57	51	0.0083	0.0280	0.0645	150.0000
2	1	51	56	0.0298	0.0850	0.0409	130.0000
3	1	56	1	0.0112	0.0366	0.0190	75.0000
4	1	1	2	0.0625	0.1320	0.0129	25.0000
5	1	1	55	0.0430	0.1480	0.0174	25.0000
6	1	55	3	0.0200	0.1020	0.0138	25.0000
7	1	55	54	0.0339	0.1730	0.0235	50.0000
8	1	54	53	0.0099	0.0505	0.0274	230.0000
9	1	53	4	0.0369	0.1679	0.0220	25.0000
10	1	53	5	0.0258	0.0848	0.0109	25.0000
11	1	53	52	0.0648	0.2950	0.0386	25.0000
12	1	53	6	0.0481	0.1580	0.0203	25.0000
13	1	6	7	0.0132	0.0434	0.0055	25.0000
14	1	6	8	0.0269	0.0869	0.0115	62.5000
15	1	57	8	0.0178	0.0910	0.0494	200.0000
16	1	57	9	0.0454	0.2060	0.0273	100.0000
17	1	57	10	0.0238	0.1080	0.0143	125.0000
18	1	56	8	0.0162	0.0530	0.0272	50.0000
19	1	2	55	0.0302	0.0641	0.0062	25.0000
20	1	3	54	0.0139	0.0712	0.0097	100.0000
21	1	4	52	0.0277	0.1262	0.0164	25.0000
22	1	5	6	0.0223	0.0732	0.0094	25.0000
23	1	52	6	0.0178	0.0580	0.0302	25.0000
24	1	52	9	0.0180	0.0813	0.0108	50.0000
25	1	52	10	0.0397	0.1700	0.0238	62.5000
26	1	7	8	0.0171	0.0547	0.0074	100.0000

Table - C.2 (c) contd ...

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE		HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
				RESISTANCE (P.U.)	REACTANCE (P.U.)		
1	2	3	4	5	6	7	8
27	1	11	12	0.4610	0.6850	0.0000	25.0000
28	1	12	13	0.2830	0.4340	0.0000	25.0000
29	1	14	15	0.0736	0.1170	0.0000	25.0000
30	1	15	16	0.0099	0.0152	0.0000	25.0000
31	1	16	17	0.1660	0.2560	0.0042	25.0000
32	1	19	20	0.1650	0.2540	0.0000	25.0000
33	1	20	21	0.0618	0.0954	0.0000	25.0000
34	1	21	22	0.0418	0.0587	0.0000	25.0000
35	1	18	23	0.1350	0.2020	0.0000	25.0000
36	1	23	24	0.3260	0.4970	0.0000	25.0000
37	1	24	25	0.5070	0.7550	0.0000	25.0000
38	1	25	26	0.0392	0.0360	0.0000	25.0000
39	1	27	28	0.0520	0.0780	0.0016	25.0000
40	1	28	29	0.0430	0.0537	0.0008	25.0000
41	1	29	30	0.0290	0.0366	0.0000	25.0000
42	1	30	31	0.0651	0.1009	0.0010	30.0000
43	1	30	32	0.0239	0.0379	0.0000	25.0000
44	1	29	33	0.0300	0.0466	0.0000	25.0000
45	1	15	31	0.0192	0.0295	0.0000	25.0000
46	1	34	35	0.2070	0.3520	0.0000	25.0000
47	1	34	36	0.0000	0.4120	0.0000	25.0000
48	1	31	37	0.0289	0.0585	0.0010	50.0000
49	1	39	40	0.0230	0.0680	0.0016	62.5000
50	1	40	41	0.0182	0.0233	0.0000	25.0000
51	1	41	42	0.0834	0.1290	0.0024	25.0000
52	1	42	43	0.0801	0.1280	0.0000	25.0000
53	1	43	44	0.1386	0.2200	0.0000	25.0000
54	1	22	45	0.1442	0.1870	0.0000	25.0000
55	1	45	46	0.0762	0.0984	0.0000	25.0000
56	1	46	47	0.1878	0.2320	0.0000	25.0000
57	1	47	48	0.1732	0.2265	0.0000	25.0000
58	1	37	38	0.0624	0.1242	0.0020	62.5000
59	1	49	34	0.5530	0.5400	0.0000	25.0000

TABLE - C.2(d)
57 BUS SYSTEM : TRANSFORMER DATA

TRANSFORMER								
No.	Type	TTAP	TIMP	TLTPTR	TRATIO	TMAXR	TMINR	TSTEP
1	2	3	4	5	6	7	8	9
1	2	1	11	64	1.01800	1.10000	0.90000	0.01000
2	2	3	22	65	1.06700	1.10000	0.90000	0.01000
3	2	53	48	66	1.01000	1.10000	0.90000	0.01000
4	2	4	44	67	1.00500	1.10000	0.90000	0.01000
5	2	5	34	68	1.01500	1.10000	0.90000	0.01000
6	2	5	36	69	1.00800	1.10000	0.90000	0.10000
7	2	6	42	70	1.01000	1.10000	0.90000	0.01000
8	2	7	39	71	1.00200	1.10000	0.90000	0.01000
9	2	8	38	72	1.00350	1.10000	0.90000	0.01000
10	2	13	14	73	1.01300	1.10000	0.90000	0.01000
11	2	17	18	74	1.03000	1.10000	0.90000	0.01000
12	2	17	19	75	1.00430	1.10000	0.90000	0.01000
13	2	25	27	76	0.99500	1.10000	0.90000	0.01000
14	2	32	50	77	0.99900	1.10000	0.90000	0.01000
15	2	33	49	78	0.99800	1.10000	0.90000	0.01000

APPENDIX-D

CALCULATION OF PARTIAL DERIVATIVES

D.1 CALCULATION OF PARTIAL DERIVATIVES FOR PROBLEM OF REACTIVE GEHNERATION AND LOSSES MINIMIZATION

The partial derivative of the objective function as given by equation (2.4.1) w.r.t. the dependent variable i.e bus voltage magnitude is :

$$\frac{\partial G}{\partial V_i} = 0 + 2.\ W_s \cdot \left[QG_s - QL_s - Q_s(V,\theta) \right]$$

$$\cdot \left[(-1) \sum_{j=i+1}^{NB} V_j \,.(g_{sj} \,.\mathrm{Sin}\theta_{sj} - b_{sj} \,.\mathrm{Cos}\theta_{sj}) \right]$$

$$+ W_r \sum_{i=1}^{NB} \left[\sum_{j=i+1}^{NB} -g_{ij} \cdot \left[2.\ (V_i - V_j) + V_j \,.(\theta_i - \theta_j)^2 \right] \right] \Big]$$

$$+ W_x \sum_{i=1}^{NB} \left[\sum_{j=i+1}^{NB} \left[b_{ij} . \left[2.\ (V_i - V_j) + V_j .(\theta_i - \theta_j)^2 \right] \right] \right]$$

$$+ W_x \sum_{i=}^{N} \left[\sum_{j=i+1}^{NB} \left[2.\frac{1\ .V_j}{T_{ij}}.\mathrm{Cos}\theta_{ij} - \left[\frac{1}{T_{ij}} - 1\right].\left[\frac{2.V_i}{T_{ij}} - V_j^2\right] \right].b_{ij} \right] \quad \ldots(D.1)$$

The partial derivatives of the objective function as given by equation (2.4.1) w.r.t the independent variables i.e the generator reactive generation and the off nominal transformer tap ratio are :

$$\frac{\partial G}{\partial QG_i} = 2\ .W_{gi}.QG_i + W_s.2.\left[QG_s - QL_s - Q_s(V,\theta) \right] \quad \ldots(D.2)$$

$$\frac{\partial G}{\partial T_{ij}} = W_x \sum_{i=1}^{NB} \left[\sum_{j=i+1}^{NB} \left[-2.\left(\frac{V_i.V_j}{T_{ij}^2} \right.\ .\mathrm{Cos}\theta_{ij} - \frac{V_i^2}{T_{ij}^3} \right].b_{ij} \right]\Bigg] \quad \ldots(D.3)$$

The partial derivative of the equality constraint as given by equation (2.4.3) w.r.t. the independent variables i.e., generator reactive generation and the transformer ratio are,

$$\frac{\partial g_q}{\partial QG_i} = \begin{cases} 1 & \text{for generator buses} \\ 0 & \text{for load buses} \end{cases} \quad \ldots(D.4)$$

For line having transformer,

$$NB \; \frac{\partial g_q}{\partial V_i} = \sum_{\substack{j=1 \\ j \neq i}} \left[g_{ij} \cdot \frac{V_j}{T_{ij}} . \mathrm{Sin}\theta_{ij} + b_{ij} \cdot \left\{ 2 . \frac{V_i}{T_{ij}^2} - \frac{V_j}{T_{ij}} . \mathrm{Cos}\theta_{ij} \right\} \right]$$

for i = Tap side bus

...(D.7)

$$\frac{\partial g_q}{\partial V_i} = \sum_{\substack{j=1 \\ j \neq i}}^{NB} \left[g_{ij} \cdot \frac{V_j}{T_{ij}} . \mathrm{Sin}\theta_{ij} + b_{ij} \cdot \left[\frac{V_j}{T_{ij}} . \mathrm{Cos}\theta_{ij} + V^2_j \left(1 - \frac{1}{T_{ij}}\right) \right] \right]$$

for i = Impedance side bus

...(D.7a)

D.2 CALCULATION OF PARTIAL DERIVATIVES FOR THE PROBLEM OF ALLEVIATION OF VOLTAGE LIMIT VIOLATION

Equations for calculating the partial derivatives of the objective function and equality constraint as given by equations (3.2.1) and (3.2.3) with respect to the independent (U) and dependent (X) variables respectively in local optimization procedure are given below.

Equality constraints as given by equation (3.2.3) are written here for i^{th} bus as equation (D.8).

$$g_i(X,U) \quad = \quad 0 \qquad \ldots(D.8)$$

The partial derivatives of equality constraints with respect to the independent variables are,

$$\frac{\partial g_i}{\partial QG_i} \quad = \quad 1.0 \qquad \ldots(D.9)$$

$$\frac{\partial g_i}{\partial QL_i} \quad = \quad 1.0 \qquad \ldots(D.10)$$

$$\frac{\partial g_i}{\partial TR_k} = \left[\begin{array}{l} -\ 2.\dfrac{b_{ij}}{TR_k^3}.\ V_i^2 \ - \dfrac{1}{TR_k^2}\left[\left\{ g_{ij}.\mathrm{Sin}(\theta_i-\theta_j) - b_{ij}.\ \mathrm{Cos}(\theta_i-\theta_j)\right\} V_j\right] V_i \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{for } i = TTAP_k \\ -\ \dfrac{1}{TR_k^2}\left[\left\{ g_{ij}.\mathrm{Sin}(\theta_i-\theta_j) - b_{ij}.\mathrm{Cos}(\theta_i-\theta_j).\right\} V_j.\right] V_i. \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{for } i = TIMP_k \end{array} \right.$$

$$k = 1,\ldots NTR \qquad \ldots(D.11)$$

$$\frac{\partial g_i}{\partial QR_i} \quad = \quad 1.0 \qquad \ldots(D.12)$$

The partial derivatives of objective function with respect to the independent variables are,

$$\frac{\partial f}{\partial U_k} = \left\{ \begin{array}{ll} 2.\ (\Delta V_i)\ .\left[\dfrac{\partial V_i}{\partial U_k}\right] & , \text{ if } U_k = QG_i \text{ and } V_i > V_i^{max} \\ 2.\ (\Delta V_i).\ \left[(-)\ \dfrac{\partial V_i}{\partial U_k}\right] & , \text{ if } U_k = QG_i \text{ and } V_i < V_i^{min} \end{array} \right. \qquad \ldots(D.13)$$

$$\frac{\partial f}{\partial U_k} = \begin{cases} 2.\Delta V_i.\dfrac{1}{\sqrt{BB^2 - 4.AA.CC}}, & \text{if } U_k = QG_i \text{ and } V_i > V_i^{max} \\ -2.\Delta V_i.\dfrac{1}{\sqrt{BB^2 - 4.AA.CC}}, & \text{if } U_k = QG_i \text{ and } V_i < V_i^{min} \end{cases}$$

$k = 1, \ldots, NC$ and $i \in LV$

...(D.14)

$$\frac{\partial f}{\partial U_k} = \begin{cases} 2.(\Delta V_i).\left[\dfrac{\partial V_i}{\partial TR_k}\right], & \text{if } U_k = TR_k \text{ and } V_i > V_i^{max} \\ 2.(\Delta V_i).\left[-\dfrac{\partial V_i}{\partial TR_k}\right], & \text{if } U_k = TR_k \text{ and } V_i < V_i^{min} \end{cases}$$

...(D.15)

$k = 1, \ldots, NTR$ and i is the terminal bus of k^{th} transformer.

Where $\dfrac{\partial V_i}{\partial TR_k}$ is obtained by differentiating equation (3.2.11)

$$\frac{\partial V_i}{\partial TR_k} = (-)\left[\frac{\partial}{\partial TR_k}\left[\frac{BB}{2.AA}\right] + \frac{\partial}{\partial TR_k}\left[\frac{\sqrt{BB^2 - 4.AA.CC}}{2.AA}\right]\right]$$

...(D.16)

$$\frac{\partial}{\partial TR_k}\left[\frac{BB}{2.AA}\right] = \frac{1}{2}.\left[\frac{AA.\dfrac{\partial BB}{\partial TR_k} - BB.\dfrac{\partial AA}{\partial TR_k}}{AA^2}\right] \qquad \ldots(D.17)$$

$$\frac{\partial}{\partial TR_k}\left[\frac{\sqrt{BB^2 - 4.AA.CC}}{2.AA}\right] =$$

$$\frac{1}{2}.\left[\frac{AA.\dfrac{\partial}{\partial TR_k}\left[\sqrt{BB^2 - 4.AA.CC}\right] - \left[\sqrt{BB^2 - 4.AA.CC}\right].\dfrac{\partial AA}{\partial TR_k}}{AA^2}\right]$$

...(D.18)

Where

$$\frac{\partial}{\partial TR_k}\left[\sqrt{BB^2 - 4.AA.CC}\right] = \frac{1}{\sqrt{BB^2 - 4.AA.CC}}\left[BB.\frac{\partial BB}{\partial TR_k} - 2.CC.\frac{\partial AA}{\partial TR_k}\right] \quad ...(D.19)$$

$$\frac{\partial BB}{\partial TR_k} = -\frac{1}{TR_k^2}\left[g_{ij}.Sin(\theta_i-\theta_j) - b_{ij}.Cos(\theta_i-\theta_j)\right].V_j \quad ...(D.20)$$

$$\frac{\partial AA}{\partial TR_k} = \begin{cases} -2.\frac{b_{ij}}{TR_k^2} & \text{, if i is tap side bus} \\ 0 & \text{, if i is impedance side bus} \end{cases} \quad ...(D.21)$$

$$\frac{\partial f}{\partial QL_i} = 2.\Delta V_i.\frac{\partial V_i}{\partial QL_i} \quad ...(D.22)$$

$$\frac{\partial f}{\partial QR_i} = 2.\Delta V_i.\frac{\partial V_i}{\partial QR_i} \quad ...(D.23)$$

The partial derivatives of equality constraints with respect to the dependent variables are,

If $X_i = V_i$,

$$\frac{\partial g_i}{\partial X_i} = 2.\left(B_i+\sum_{j\in A(i)} b_{ij}\right).V_i + \left[\sum_{j\in A(i)}\left(g_{ij}.Sin(\theta_i-\theta_j) - b_{ij}.Cos(\theta_i-\theta_j)\right).V_i\right], \quad ...(D.24)$$

$i = 1,...,NLO$

If $X_j = V_j$

$$\frac{\partial g_i}{\partial X_j} = \left[g_{ij}\ .\mathrm{Sin}(\theta_i - \theta_j) - b_{ij}\ .\mathrm{Cos}(\theta_i - \theta_j)\right].\ V_i\ , \qquad \begin{matrix} i=1,\dots,NLO \\ i \neq j \end{matrix} \qquad \dots(D.25)$$

In the desired final solution, it may be assumed that,

$$V_i \approx V_j = 1.0$$

$$\mathrm{Cos}(\theta_i - \theta_j) \approx 1.0 \quad \text{and}$$

$$g_{ij}\ .\mathrm{Sin}(\theta_i - \theta_j) \leq b_{ij}$$

The equation (D.24)and (D.25) are reduced to (D.26) and (D.27) respectively.

If $X_i = V_i$

$$\frac{\partial g_i}{\partial X_i} = 2.\left[B_i + \sum_{j \in A(i)} b_{ij}\right] , \qquad i = 1,\dots,NLO \qquad \dots(D.26)$$

If $X_j = V_j$

$$\frac{\partial g_i}{\partial X_j} = -\ b_{ij}\ , \quad i = 1,\dots,NLO\ ;\ j = 1,\dots,NLO,\ i \neq j \qquad \dots(D.27)$$

If line i-j is the transformer line of k^{th} transformer ~~with~~ off nominal tap ratio TR_k and the buses i and j are tap side and impedance side buses respectively, the variable TR_k appears in the equality constraint equation (D.8). The contribution of

TR_k in constants BB and AA is given by equations (D.27) and (D.28) given below.

$$BB = BB^o + \left[\left[g_{ij} \, . \, \mathrm{Sin}(\theta_i - \theta_j)/TR_k\right] - \left[b_{ij} \, . \, \mathrm{Cos}(\theta_i - \theta_j)/TR_k\right]\right] . V_j \qquad \ldots (D.28)$$

$$AA = \begin{cases} AA^o + \dfrac{b_{ij}}{TR_k^2} & \text{, if i is the tap side bus} \\ AA^o + b_{ij} & \text{, if i is the impedance side bus} \end{cases} \qquad \ldots (D.29)$$

Where AA^o and BB^o are the contribution of all the elements except transformer.

The partial derivatives of objective function with respect to the dependent variables are,

If $X_i = V_i$

$$\frac{\partial f}{\partial X_i} = 2.(\Delta V_i) \qquad \ldots (D.30)$$

$$\frac{\partial f}{\partial X_j} = \begin{cases} 2.(\Delta V_i).\left[\dfrac{\partial V_i}{\partial X_j}\right] & \text{, if } X_j = V_j \text{ and } V_j > V_j^{max} \\ -2.(\Delta V_i).\left[\dfrac{\partial V_i}{\partial X_j}\right] & \text{, if } X_j = V_j \text{ and } V_j < V_j^{min} \end{cases}$$

$$j = 1, \ldots, NLO \; ; \; j \neq i \qquad \ldots (D.31)$$

$$\frac{\partial V_i}{\partial X_j} = (-) \frac{1}{2.AA} \left[\frac{\partial BB}{\partial X_j} + \frac{1}{2} \left(\sqrt{BB^2 - 4.AA.CC}\right)^{-1} . \; 2.BB.\frac{\partial BB}{\partial X_j} \right.$$

...(D.32)

Where

$$\frac{\partial BB}{\partial X_j} = g_{ij} \,.\, \mathrm{Sin}(\theta_i - \theta_j) - b_{ij} \,.\, \mathrm{Cos}(\theta_i - \theta_j) \qquad \ldots(D.33)$$

$$\frac{\partial f}{\partial X_j} = \begin{cases} \displaystyle\sum_{\substack{j \in A(i) \\ j \neq i}} \Bigg[- \bigg(\frac{\Delta V_i}{AA} \bigg] \,.\, \bigg(g_{ij} \,.\mathrm{Sin}(\theta_i - \theta_j) - b_{ij} . \mathrm{Cos}(\theta_i - \theta_j) \bigg] .PP & \text{if } X_j = V_j \text{ and } V_j > V_j^{max} \\ \displaystyle\sum_{\substack{j \in A(i) \\ j \neq i}} \Bigg[\bigg(\frac{\Delta V_i}{AA} \bigg] . \bigg(g_{ij} \,.\mathrm{Sin}(\theta_i - \theta_j) - b_j \,.\mathrm{os}(\theta_i - \theta_j) \,.PP & \text{if } X_j = V_j \text{ and } V_j < V_j^{min} \end{cases}$$

...(D.34)

and $PP = 1 + BB. \left\{ \sqrt{BB^2 - 4.AA.CC} \right\}^{-1}$

SOFTWARE DESCRIPTION

G.1 MINIMIZE

The overall organization of the software package is depicted in Fig. G.1. Brief description of the different abbreviated programs is given below.

DATA : Reads the data of the system.

LINK : Scans the network and stores the information about network topology.

YBUS : Determines and stores the elements of Y-matrix.

NETINJ : Determines net power injections.

ISSLE : Prepares the data as required by SSLERN.

SSLERN : Solves a system of sparse linear equations based on Zollenkopfs algorithm. It calls SQRDN, REDURN, DATARN and DATBRN.

SQRDN : Simulates and orders coefficient matrix for Gauss elimination.

REDURN : Performs the reduction of coefficient matrix.

DATARN : Calculates elements of arrays to be used in LU decomposition.

DATBRN : Reorders elements of each column if necessary, and calculates elements row-wise.

SOLVRN : Solves linear equations by a sequence of matrix multiplications.

CALPQR : Calculates real and reactive power at a given bus.

MISMAT : Calculates the power mismatches at buses.

UPDBVA : Update voltage angles of buses.

UPDBVM : Update voltage magnitudes of buses.

LINFLW : Calculates the line flow.

LINFEL : Calculates the power distributions (MW, MVAR, MVA) from each bus to the buses connected to it, using subroutine LINFLW.

REACTV : Calculates reactive power generation.

SLACK : Calculates slack bus power.

BQGOPT : Minimizes the objectivbe function consisting of reactive generation and losses.

INDEX : Calculates the voltage security index.

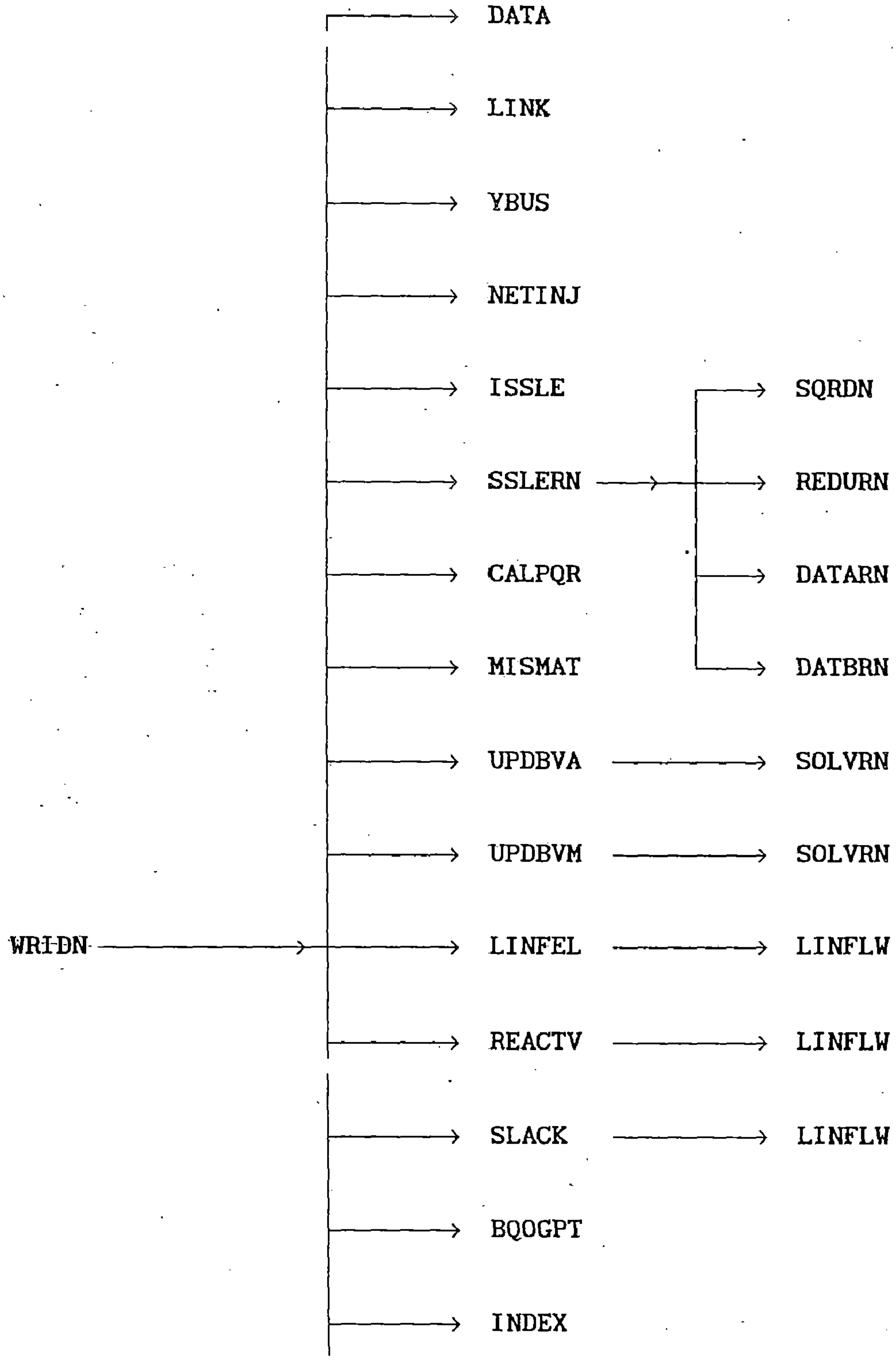

Fig. E.1 Overall Organization of the Software Package MINIMIZE.

G.2 ALLEVIATION

This software package called 'ALLEVIATION' implements the local optimization technique for alleviating the weak regions. The overall organization of the software package is depicted in Fig. G.2. Brief description of the different abbreviated programs is given below.

DATA : Reads the data of the system.

LINK : Scans the network and stores the information about network topology.

YBUS : Determines and stores the elements of Y-matrix.

CALBZI : Modifies the Y-bus diagonal elements for inductors/ capacitors.

NETINJ : Determines net power injections.

RXRTIO : Determines the ratio of line resistance to reactance.

ISSLE : Prepares the data as required by SSLERN.

SSLERN : Solves a system of sparse linear equations based on Zollenkopfs algorithm. It calls SQRDN, REDURN, DATARN and DATBRN.

SQRDN : Simulates and orders coefficient matrix for Gauss elimination.

REDURN : Performs the reduction of coefficient matrix.

DATARN : Calculates elements of arrays to be used in LU decomposition.

DATBRN : Reorders elements of each column if necessary, and calculates elements row-wise.

SOLVRN : Solves linear equations by a sequence of matrix multiplications.

CALPQR : Calculates real and reactive power at a given bus.

MISMAT : Calculates the power mismatches at buses.

UPDBVA : Update voltage angles of buses.

UPDBVM : Update voltage magnitudes of buses.

BVCAL : Calculates bus voltages.

LINFLW : Calculates the line flow.

LINFEL : Calculates the power distributions (MW, MVAR, MVA) from each bus to the buses connected to it, using subroutine LINFLW.

DEVOLT : Checks the voltage limit violation.

SLACK : Calculates slack bus power.

REACTV : Calculates reactive power generation.

VQGMIN : Minimizes the objective function consisting of voltage limit violations.

VQFUN : Calculates the function value.

LOCAV : Identifies the voltage limit violating buses in local area.

DGDXS : Calculates the derivative of equality constraint w.r.t dependent variables.

MATIN : Calculates the matrix inverse.

DFDXS : Calculates the derivatives of objective function w.r.t dependent variables.

DFDUS : Calculates the derivatives of objective function w.r.t. independent variables.

DGDUS : Calculates the derivatives of equality constraint w.r.t independent variables.

MATMUL : Performs matrix multiplication.

DETTRA : Determines the transformer tap limit violation.

INDEX : Calculates the voltage security index.

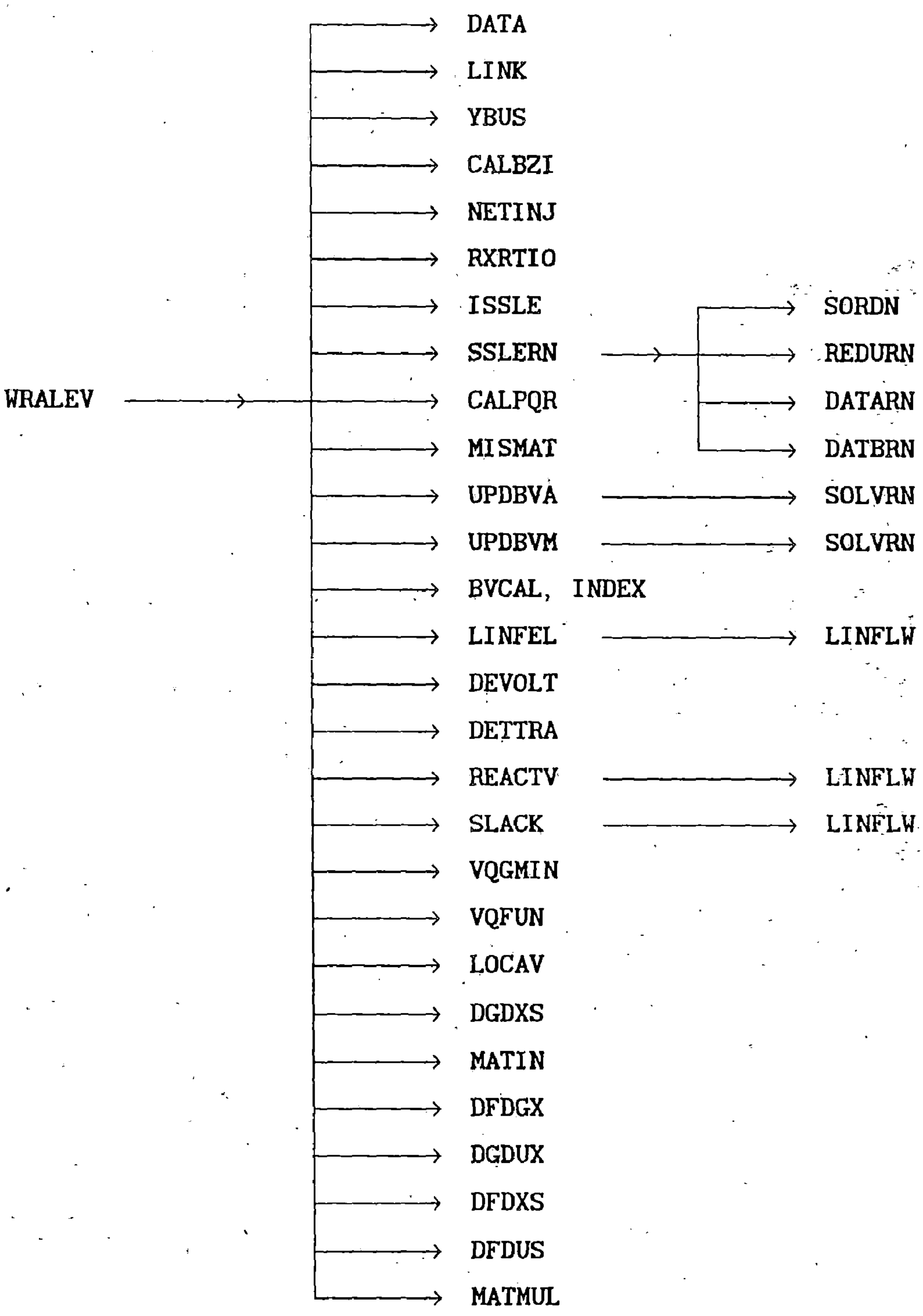

Fig. E.2 Overall Organization of the Software Package 'ALLEVIATION'.