ALLEVIATION OF VOLTAGE LIMIT VIOLATION USING LOCAL OPTIMIZATION

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of

MASTER OF ENGINEERING

in

ELECTRICAL ENGINEERING

(With Specialization in Power System Engineering)

By

SANJAY KUMAR

DEPARTMENT OF ELECTRICAL ENGINEERING

UNIVERSITY OF ROORKEE
ROORKEE - 247 667 (INDIA)

21 AUGUST, 1992.

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled "**AALEVIATION OF VOLTAGE LIMIT VIOLATION USING LOCAL OPTIMIZATION**" in partial fulfillment of the **Degree** of **Master of Engineering in Electrical Engineering** with specialization in **POWER SYSTEM ENGINEERING** submitted in the **DEPARTMENT OF ELECTRICAL ENGINEERING, UNIVERISTY OF ROORKEE, ROORKEE**, is an authentic record of my own work carried out for a period of about 10 months, from Aug. 1991 to July 1992 under the supervision of **DR. H.O. GUPTA, READER**, Department of Electrical Engineering and **MR. VINAY PANT, LECTURER**, 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 or Diploma.

PLACE : ROORKEE
DATED : 21 AUGUST 1992.

(SANJAY KUMAR)

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

24/8/92

(VINAY PANT)
LECTURER
DEPARTMENT OF ELECTRICAL ENGG.
UNIVERSITY OF ROORKEE,
ROORKEE - 247 667. (U.P.)

(DR. H.O. GUPTA)
READER
DEPARTMENT OF ELECTRICAL ENGG.
UNIVERSITY OF ROORKEE,
ROORKEE - 247 667. (U.P.)

SYNOPSIS

And God said 'let there be light' and there was light in the dark world.God saw that the light was good and he separated the light from darkness. But only since Thomas Edison mankind is taking care of this heavenly job religiously and a vigor of a stickler.

Any product is marked by its cost(economy),reliability,and of course quality. So is with Power System.One of the main responsibility of power system planner is to design the system with an eye on reliability and economy. Even today operator maintain reliable performance using their past experience and on the spot assessment of network conditions.

But today as the power network are becoming titanic and more involved, the increased number of possible operating [illegible] scenarios can lead to exigencies beyond the ken of the operator.Power system operation become more complex under emergency conditions due to scheduled or random events.These conditions may be of voltage limit violations or overloading of the circuits.

This study is directed towards alleviation of voltage limit violations [illegible] the method developed the technique of 'Local solution' using Gauss Siedel is carried out for few buses in the vicinity of the outage line, and a mathematical model is developed for this selection of buses for local solution.

The solution so obtained is improved by using the Jacobian at the base case and improving the right hand side (RHS) vector for outaged line admittance. This adjustment on the RHS is incorporated by injecting the suitable power sources at the terminal buses to the outaged line, and is called as Source Compensation. An acceleration factor is used to expedite the process of convergence.

In the literature available, many methods have been developed which are normally of the form of optimally load flow, using optimization techniques. All these methods are quite complicated and consume more time from computational point of view, especially for large systems. An emergency condition warrants a quick decision on the part of the operator without caring much for the optimality of the operating point.

Explan

Here a direct and efficient method has been developed for alleviation of voltage limit violation.

In this method the concept of local optimization is extended and a direct method is developed to obtain emergency adjustment to VAR control variables to alleviate the voltage limit violation.

A few buses in the vicinity of the buses suffering with voltage limit violation are processed for the local optimization and 'Conjugate Gradient' technique is used for optimization.

This method [illegible] efficiently, the sparsity of matrices to reduce the computational effort and memory requirement.

Incomplete para

ACKNOWLEDGEMENT

At the onset I'd like to express my gratitude to my Supervisors Dr. H.O. Gupta and Mr. Vinay Pant for the kind help the rendered , precisely at the moment , when it was needed the most. I can never forget the helping hands that were offered to me , particularly at the culminating phase of my dissertation.

I thank Dr. J.D. Sharma for all technical help and troubles hooting he did for me and all other favor I accrued out of him.

I don't claim to be a stickler , but I confess to have learned a bit about truth and particularly trust from Mr. M.K. Vasantha and I wish to express my gratitude to him.

I simply can't put in words my love and thank to Mr. A. D. Pandey , dept. of Earthquake for all I got from his side and I intend to remember it , de facto.

An honest word of thank to Dr. A.K. Shandilya for help from his thesis and to Mr. And Mrs. Bhanot for giving me a nice and meaningful companionship and the 'N' no. of times I had food in their home.

Power of words can't express my gratitude towards Dr. V.K. Tiwari for giving me so much facilities in his computer lab and placing the amount of trust on me .I also put in record my feelings for O.I.D.B. staff particularly Mr. Javed Aktar for treating me in such a nice way , that wins a friend for life. Mr. Rajeev Hooda is also acknowledged for all his helps.

Lastly I positively won't thank my friend and brother Mr. Rakesh Lohani for infinite love and care, because I guess I deserve it and I pray my dear God to keep him happy, always.

Roorkee August 21,1992 Sanjay Kumar

CONTENTS

CHAPTER I

INTRODUCTION

1.1 OVERVIEW

A power system is an interconnected system composed of generation, transmission and distribution systems. The transmission subsystem is a highly meshed network of high - voltage transmission lines which carry electric power from the generators to the distribution substations. The distribution subsystem receives power from a substation and distributes it to the consumers through a radial lower - voltage network. In order to study interconnected systems, the distribution subsystem is treated as an aggregate load demand at the substation. The interconnected generation - transmission system with aggregate load demands is commonly called a bulk power system.

In steady - state operation the power generated by the generators and the load demands of the consumers must be balanced. The system must be operated so that there is no overload on the equipment and no abnormal voltages throughout the systems. In other words, "the operating objective of a power system is to serve the load demand economically and reliably, with all the constraints satisfied".

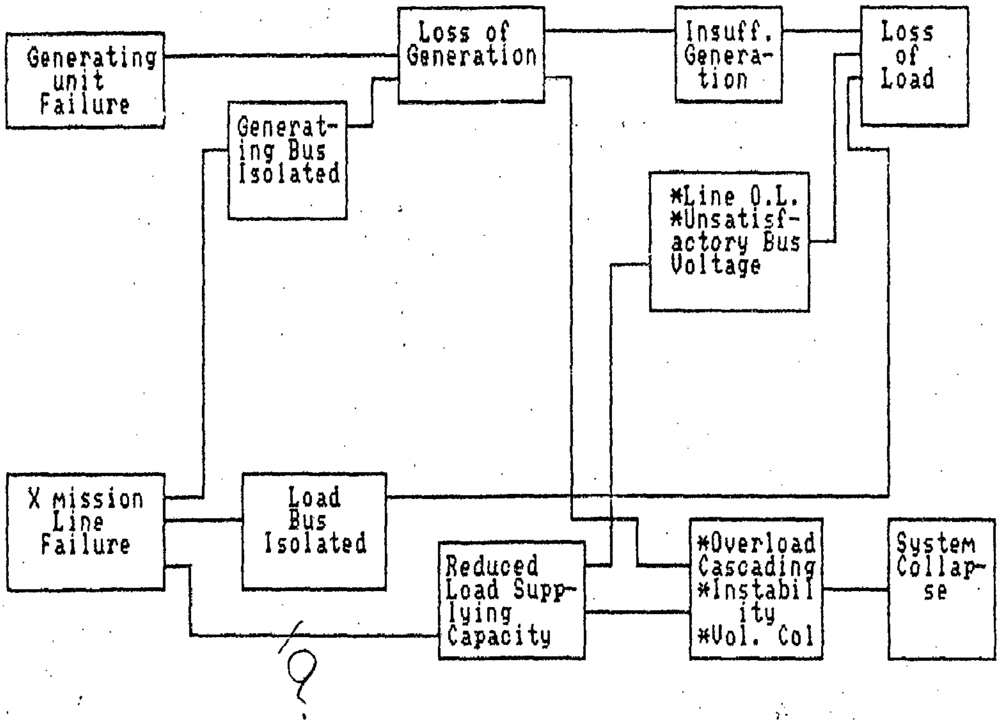
The failure to satisfy the operating constraints may lead to load curtailment (loss of load) or system collapse. Fig. 1.1 shows the major system failure sequences. The initiating events of system failure are the outage of a generator or a transmission line. The system failure events are the loss of load and system collapse.

System failure events can be roughly divided into two cases : one due to violation of steady - state constraints (Fig. 1.2) and the other due to violation of dynamic constraints (Fig. 1.3).

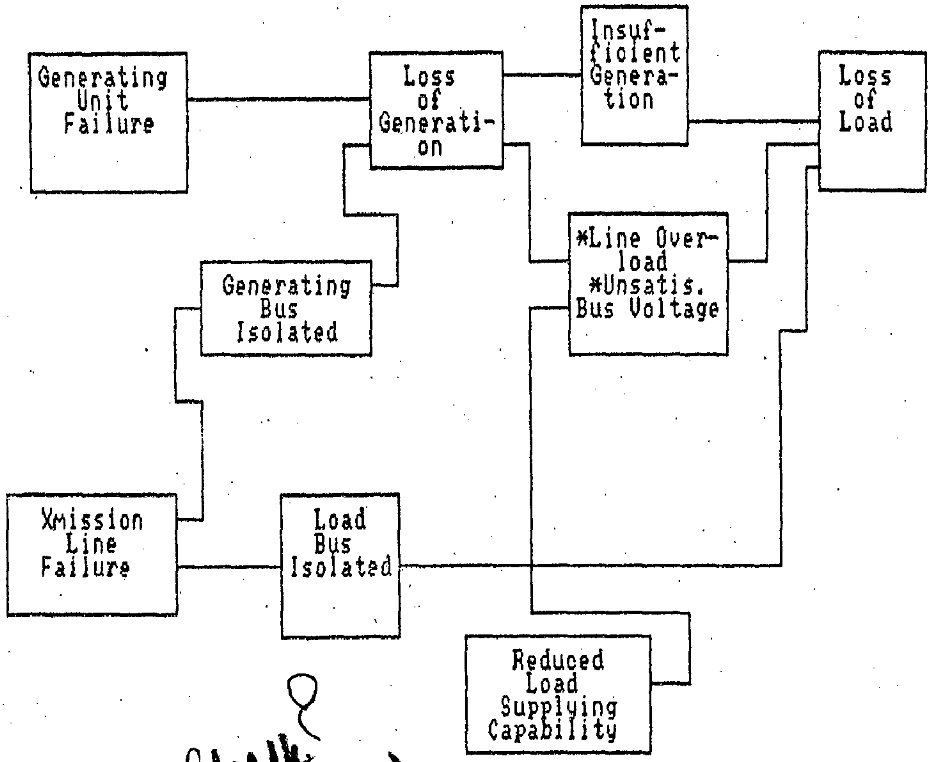
Work reported in this thesis is mainly related to the system failure events due to the violation of steady - state constraints.

1.2 PRESENT STATE - OF - ART

In planning and operation, one is concerned with the ability of the system to serve load demand in the presence of disturbances. In the planning context this is called reliability, and in the operation context this is called security. This double-line of defense is necessary, because for planning, a much longer time period, a large number of possible operating conditions and disturbances have to be considered; whereas for operation only the current situation and imminent disturbances are of concern and more information about them is available. However, the methods for the analysis of the reliability and security are intimately related [18] . In the past operators maintained reliable performance using their experience and on - the - spot assessment of system conditions. As power system networks are now large and more complex, the increased number of possible operating

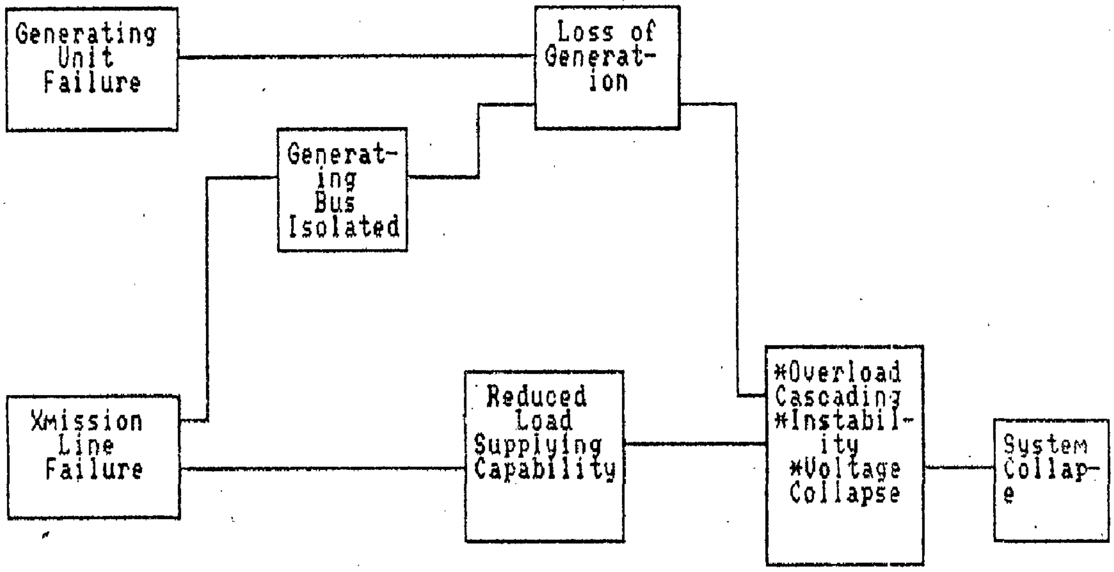


SYSTEM FAILURE EVENTS (Fig 1.1)



Check? from 1.1

SYSTEM FAILURE DUE TO VIOLATION OF STEADY STATE CONSTRAINTS (Fig. 1.2)



SYSTEM FAOLURE DUE TO VIOLATION OF DYNAMIC CONSTRAINTS (Fig. 1.3) scenarios can lead to problems beyond the operator's analytical ability. Power system operation becomes more complex under emergency conditions due to the occurrence of scheduled or random events.

The continuing interconnection of bulk power system, brought about by economic and environment pressures has led to and increasingly complex system that may operate even closer to its limits of stability. Although this work mainly relates to the system failure due to violation of steady state constraints, however it is imperative to add some prefatory about Dynamic criterion.

In their paper Chiang et-al [2] put it this way, one type of system instability which occurs when the system is heavily loaded is voltage collapse. This event is characterized by a slow variation in the system operating point due to increase in loads, in such a way that the voltage magnitude gradually decreases until a sharp accelerated change occurs.

It is interesting to know that prior to the sharp change in voltage magnitude, bus angle and frequency remains fairly constant, a condition observed in several collapses. During a collapse, voltage controlling devices such as tap changing transformer, may not be activated if the voltage magnitude prior to undergoing the sharp change lie in a ' permissible range' and, after the change occurs, the fast rate of change trips under voltage relays, before the transformer can respond to it.

Furthermore, control center operator observes none of the classical advance warning signals since the bus angle, frequency and voltage magnitudes may remain normal until large changes in the system state cause protective equipment to begin dismantle the network.

1.2.1 Bifurcation :

Consider the following system model,

$$\dot{x} = F(x,\lambda) \quad \text{------}(1.1)$$

where x : state vector (δ,ω,v)
λ : parameter vector that includes both real real and reactive power demand at each local bus.

The parameter at (1.1) are subject to variation and as a result changes may occur in the the qualitative structure of solution static eq. associated with (1.1), i.e. $F(x,\lambda) = 0$ for certain values of λ.

Bifurcation theory is concerned with branching of static solution of (1.1), and in particular, it is interested in how solutions $x(\lambda)$ branch as λ varies. These changes, when they occur, are called Bifurcation and the parameter values at which a Bifurcation occurs are called bifurcation values.

The result of changes shown above clearly depict a slowly increasing reacting power demand may cause a voltage collapse. This contrasts with the conjecture that it is protection system that causes the abrupt change in trajectory.

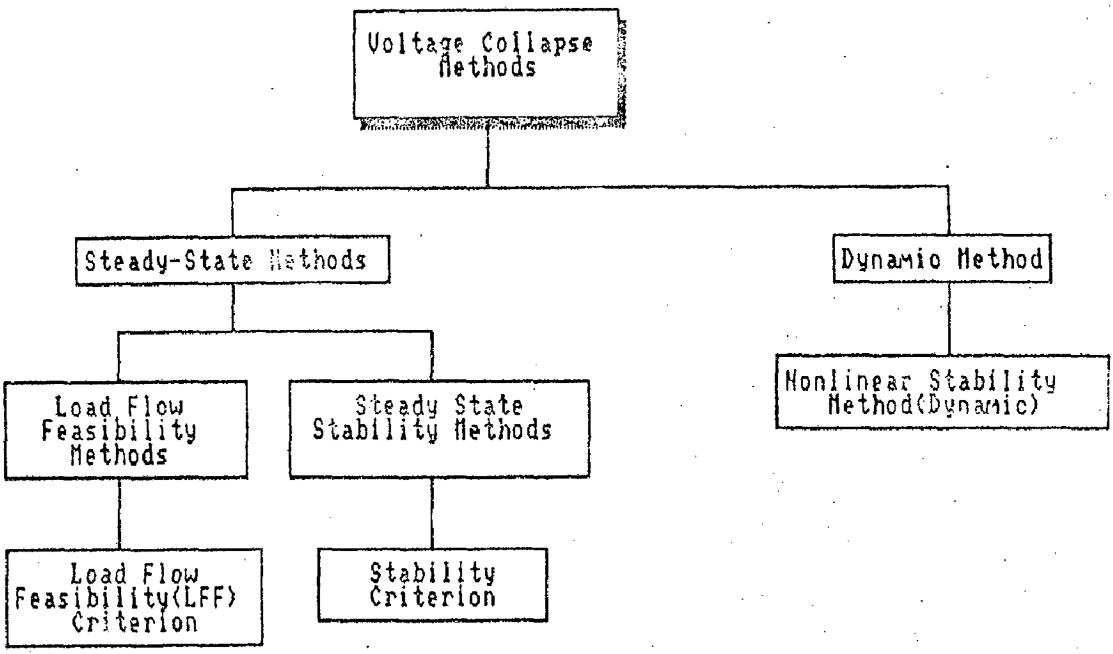

Voltage Collapse Methods
Steady-State Methods
Dynamic Method
Load Flow Feasibility Methods
Steady State Stability Methods
Nonlinear Stability Method(Dynamic)
Load Flow Feasibility(LFF) Criterion
Stability Criterion

Fig. 1.4

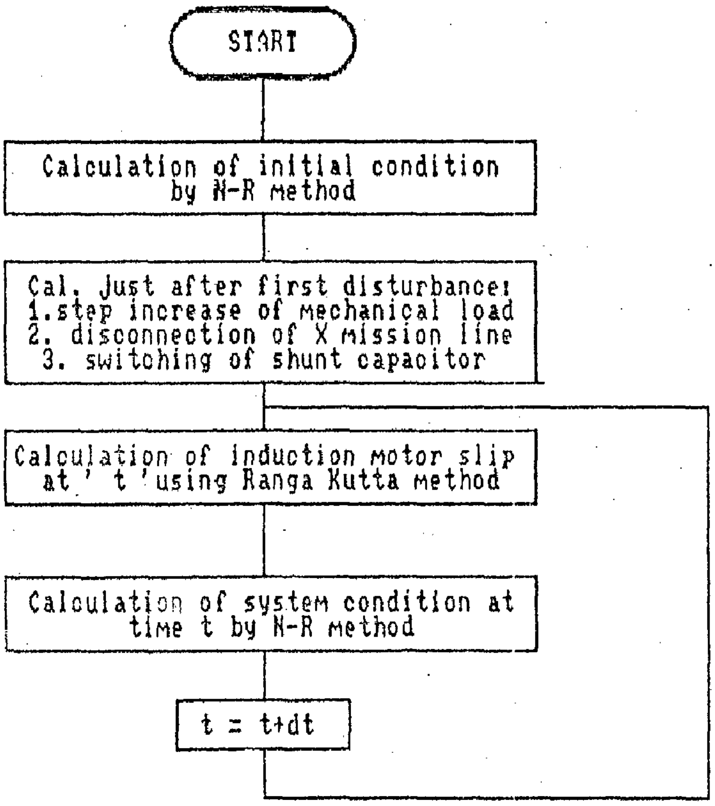

START
Calculation of initial condition by N-R method
Cal. Just after first disturbance:
1.step increase of mechanical load
2. disconnection of X mission line
3. switching of shunt capacitor
Calculation of induction motor slip at ' t 'using Ranga Kutta method
Calculation of system condition at time t by N-R method
t = t+dt

Fig. 1.5

1.2.2 Overview of Voltage Collapse criteria :

As shown in fig.(1.4), the methods can be divided into either steady state (static) or dynamic methods.The steady state method imply that a steady state model (such as power flow model) or a linear dynamic model (about the the steady state operation) has been use, while the dynamic methods imply the use of model characterized by nonlinear differential ~~differential~~ and algebraic equations.

1.2.3 Cascaded Voltage Collapse :-.

In order to minimize the area of blackout caused by the the voltage collapse, it is necessary to halt the process of voltage collapse.

A beautiful paper in this regard is published by 'Yasugi Sekine & Hiroshi Ohtsuki' - [5]. They ignore transient phenomena of generator as they state it to be negligible. Only the transient phenomenon of loads are considered.

The essence of their toil is as follows,

1. Uneven loading of parallel connected induction motor loads (small capacity, more load) weakens the voltage stability.
2. If nodes located far from a power source have a heavier loads, voltage collapse occurs.
3. The dynamic mechanism of voltage collapse starts locally from vulnerable points of power system and voltage collapse spreads

gradually from one node to other. The final area of blackout caused by the voltage collapse is dependent upon the power system.

It is time now we move to steady state area. Much work has been done in it since its inception, to mention a few,

In one good work presented by 'Marija Ilic' & 'William Stobart' of M.I.T. [13] , have presented an algorithm for very effective monitoring and control of system wide control. In addition to its applicability to large outages and independence on power system size, it has a nature of a rule based algorithm. They have defined a vector 'D', which takes the brunt of all changes in the network and its computation requires no inversion. After a fault a shortage in reactive power is recognized thru the 'D' vector and the algorithm makes use of the numerical system data to suggest action.

Chang,Marks and Kenkoto. [1] presented an algorithm for real time application , the algorithm pre assigns priority sequence to the control objective. The priorities are,

1. Voltage limit violation.
2. Minimize those violation that can't be eliminated.
3. Minimize system active transmission losses.

Provisions have been made to allow the selection of control variables and to limit their movement for the following reasons ;

1. To avoid perturbing the power system greatly from the current state.

2. To provide a leeway for corrective rescheduling under contingencies.

3. To achieve the fast solution time required for the real time application.

However it may result in a suboptimal solution, but since the program is executed periodically as a part of real time sequence of programs, over a time the state of system will move towards the optimal point.

Girotti et. al. [17] have developed a program called CAPCON in SCADA mode in which every 15 minutes SCADA provides data to CAPCON which decides whether the Capacitor banks on low side bus of the transformer which was scanned for, should be on or off line, based on VAR and voltage needs. It is a real time practical system and is working in Virginia Power and has resulted in more efficiency and cost saving.

Deeb et. al. [16] In their paper have presented a mathematical framework for optimization problem which is decomposed into several subproblems corresponding to specific areas in power systems. The decomposition is suggested for Reactive power optimization because in most large power system the Reactive power devices are remotely located and they posses localized control characteristics. The Dantzigwolfe decomposition method is used to solve this problem.

1.3 LINE AND TRANSFORMER OUTAGE SIMULATION

In the present practice, after selection of critical contingencies full AC load flow is performed to evaluate the effects of each critical contingency. For the present day large and complex power system, the critical contingencies are very large in number and to perform the full AC load flow for all of them demands large computational burden as network configuration changes with the outage of a transmission line. Although a large number of methods for line outage simulation have been reported in literature; since most of them given the approximate solution a full AC load flow is to be performed for the exact solution. In the following paragraphs a brief account of state - of - art in line outage simulation is given.

Baughman et al [12] used the concept of DC load flow for contingency evaluation. Though, this method is fast and simple but it is inaccurate as only real power flows are considered. Denial et al [3] developed the method for line outage simulation in which they used the real power injections at the terminal buses of the outaged line. This method is also inaccurate as only real powers are injected. Stagg and Phadke modified the Jacobian matrix of power flow equation and used the bus power mismatches to simulate the line outages. But, this method is not computationally efficient as it requires the same computational efforts as the constant Jacobian N-R load flow approach.

Peternoson et al [18] developed an iterative linear AC power flow technique for fast approximate outage studies. In this method line outage is simulated using matrix inverse lemma. It has over all good performance but it requires the processing of the basic state data prior to outage simulation. Each simulation takes time equivalent to about one - half the time for a N - R load flow iteration.

Many compensation methods] have been developed for the line outage simulation. In these methods matrix inverse lemma is used to modify the sensitivity matrix and hence refactorization of Jacob ian is not required. Single element outages are simulated efficiently by these methods, but their accuracy is very poor.

Sachdev and Ibrahim [15] have developed a fast and approximate technique for line and transformer outage. In this paper they developed a novel mathematical model for line outage simulation which restores the system configuration to the preoutaged state by injecting suitable power sources at the terminal buses of the outaged line i.e. source compensation technique. There after large number of methods have been reported for line outage simulation using the source compensation technique of [15] along with different load flow techniques and different methods for estimation of amount of source compensation. In these methods -

* For calculating the amount of source compensation, element of the sensitivity matrix of the columns corresponding to the

terminal buses of the outaged line are used. This does not give the accurate results if the changes due to line outage are large.

* It is assumed that after line outage load and generation remains unchanged. This may not be true in case of isolation of any of the buses due to line outage, which is most likely in case of radial and multiple line outages.

1.4 AUTHOR'S CONTRIBUTION

The objective of this study is to develop efficient and reliable algorithm for identification of system emergency conditions due to violation of steady state voltage constraint, i.e., the voltage limit violations and alleviation of such emergencies in Power System operations.

The author's contribution in this area of work is summarized as follows :

- The concept of Local Solution in the vicinity of the Outaged line has been used[6], buses for Local Solution are selected on the basis of level of disturbance. The constraints over the controls are introduced. Thus the controls suggested for the alleviation of voltage limit violation are more realistic.

- Based on the sensitivity analysis , less sensitive controls are ignored . SO the number of adjustments are reduced.

- Multivariable optimization used for solving local voltage alleviation problem gives the best possible control combination in the vicinity of the voltage problem.

- Base case Jacobian has been used for the simulation of line outages and no refactorization is required and hence the method is efficient.

CHAPTER II

LINE , TRANSFORMER OUTAGE SIMULATION AND LOCAL SOLUTION

2.1 INTRODUCTION

A power system continuously experiences changes in its operating state. these changes can either be due to load demand variations, planned rescheduling of power generation, disconnecting lines and transformers for maintenance or as a consequence of system faults. The effect of these disturbances is investigated both during system planning and operation. Quite often a faulty element is automatically disconnected from the system by the protective devices, therefore, the stem configuration changes. It is required to know whether (or not) the modified system would be stable from steady state considerations. Also, before the lines and repairs, it is essential to ensure that the modified system would be stable. In addition, line outage studies are a desirable part of a comprehensive system security monitoring process.

The effect of load changes and generation rescheduling can be easily evaluated but, the outage simulation of a line or transformer is more complex because these contingencies change the system configuration. One of the obvious solutions is the use of well known load flow techniques. Although high speed computers and fast AC load flow solution techniques are available, the analysis of hundreds or even thousands of system outages has become very tedious and uneconomical. In order to overcome the computational burden involved in contingency analysis, considerable effort has been devoted to develop fast and approximate solution techniques. Normally, a sacrifice in accuracy for speed has become a basic feature of all the developed methods and hence, full AC load flow is required for the exact solution.

Initial approach for the line outage simulation was the use of DC load flow . This is the simplest and fastest method, but the most inaccurate as only real power flows are considered. Same is the case with the method suggested by Denial and Chen [3], which uses the injection of real power at the terminal buses of the outaged line. Stagg and Phadke [3] modified the Jacobian matrix of the Newton - Raphson (N - R) load flow technique and used the bus power mismatches to simulate the line outage. This method requires the same computational effort as the constant Jacobian N - R load flow approach.

In this chapter, an efficient and accurate method is developed for line outage simulation which is free from above deficiencies . In this method first the local solution using Gauss - Seidel technique is carried out for few selected buses in the vicinity of the outaged line. The buses for local solution are selected on the basis of the effect of line outage on the bus voltages. The solution so obtained is improved by performing global solution using the Jacobian at the base and adjusting the right hand side vector for the outaged line admittance. This adjustment in the right hand side vector is incorporated by injecting the suitable power sources at the buses to which the outaged line was connected. The method is very efficient as the Jacobian at the base case has been used for all the outages and no refactorization is carried out for determining the solution for various line outages.

2.2 Local Solution :-

Outage of line in any network causes large disturbance in bus voltages and in line flows in the vicinity. As we move away from the terminal buses of the outaged line the disturbances wane away. If a local solution is carried out for all the buses which have a percept able and significant effect due to the line outage, a fairly accurate accurate of final outage steady state operating condition can be accrued.

It is very imperative to decide for the buses to be considered for the local solution. A mathematical model has been developed to determine the length of local area for the local solution.,

Complex power injected into bus 'm' is equal to net power flow in the elements connected to the bus,

$$S_{Gm} - S_{Lm} = V_m \sum_{k\epsilon Am} Y^*_{mk} V^*_k \qquad ....(2.1)$$

assuming $\overline{V}_k$ be constant and equal to (1.0 + j 0.0),

$$\Delta S_m = \Delta \overline{V}_m \sum_{k\epsilon Am} Y^*_{mk} \qquad ....(2.2)$$

$$\Delta \overline{V}_m = \Delta S_m \Big/ \sum_{k\epsilon Am} Y^*_{mk} \qquad ....(2.3)$$

For a change in voltage Vm by ΔVm from (2.3), ΔSm is calculated . This value represents the level of disturbance on this bus due to ΔVm. Particular level of disturbance is used to decide the area for local solution. This is achieved by specifying the value of ΔSm from which ΔVm is calculated and used as terminating criterion for further inclusion of buses for local solution. It is observed that 0.2 is suitable value of |ΔSm| from the point of view of speed and accuracy.

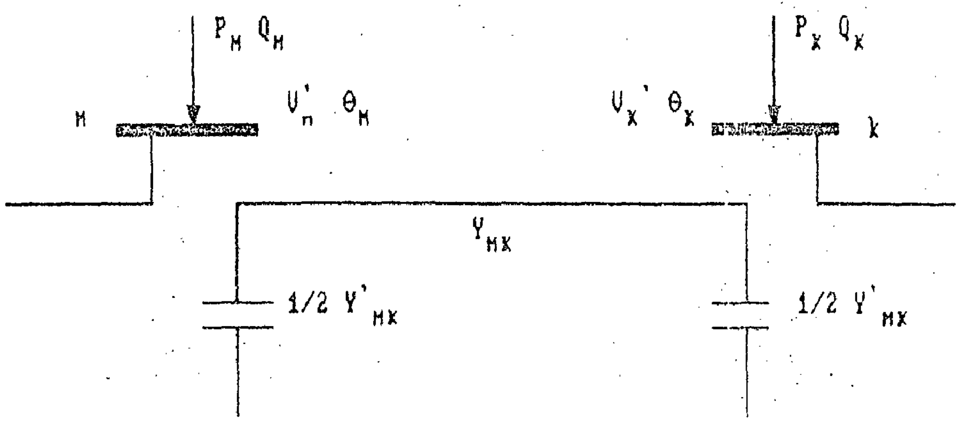
An optimum length of local area is also beyond which buses need not to be considered. It is concluded that enlargement of local area beyond three steps does pay it back.

So the final scheme is like that, it starts with the the terminal buses of the outaged line. In the successive iterations of Gauss-Siedel method for solving local area selected so far, change in the bus voltages from the base case values are compared with the limits are determined above. If the change in bus voltage is greater than the limits, the local area is extended to extended all the buses connected to it, and again the process is repeated till all the buses are included for local solution causing change in bus voltage greater than the limit determined (2.3), with a limit of three step length for enlarging local area. After local solution is completed, the amount of source compensation is calculated at the terminal bus using (2.4) & (2.5),

$$\Delta P_{Ik} + j\,\Delta Q_{Ik} = P_{km} + j\,Q_{km} = V_k\,[(V_k - V_m)^{*}\,Y_{km}^{*} + V_k^{*}\,Y_{km}^{'*}/2] \qquad \text{----(2.4)}$$

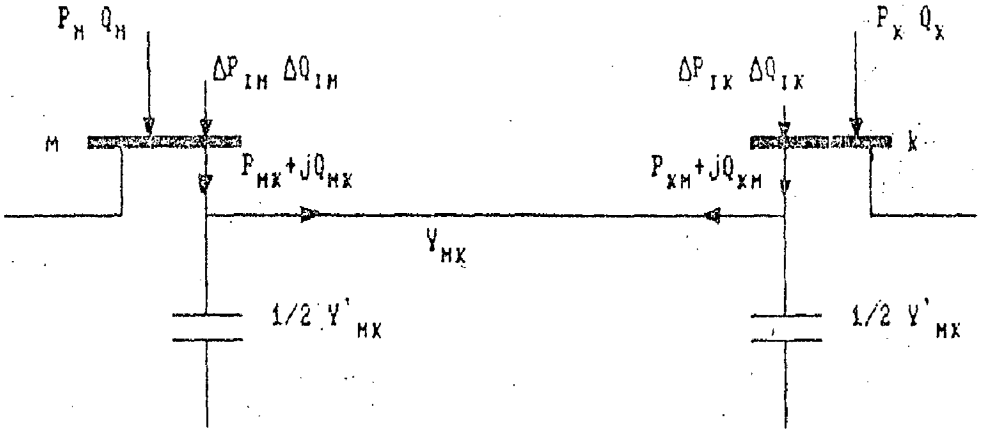
Outaged System State

Fig 2·1



Simulated Outaged System State

Fig 2·2



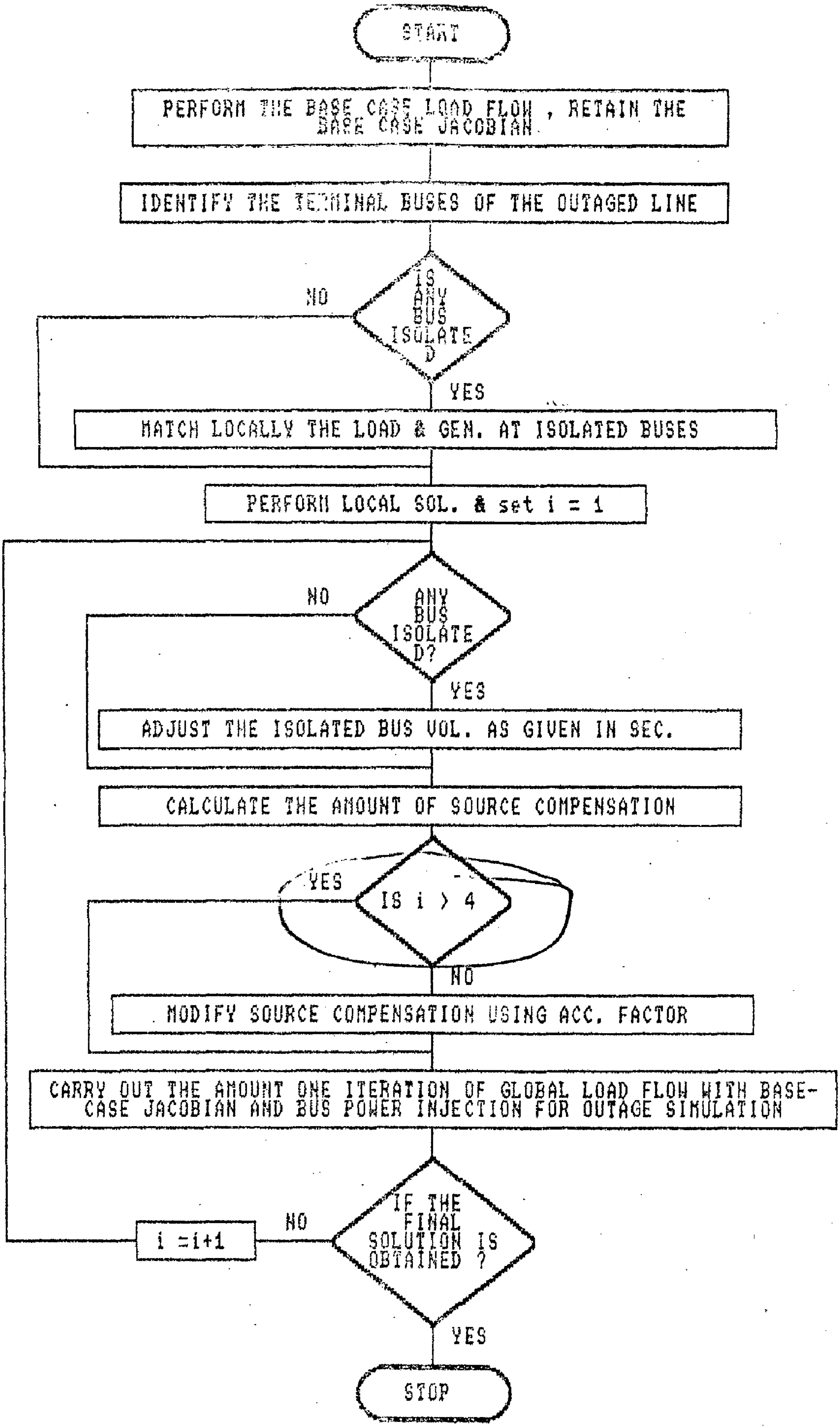

START
PERFORM THE BASE CASE LOAD FLOW , RETAIN THE BASE CASE JACOBIAN
IDENTIFY THE TERMINAL BUSES OF THE OUTAGED LINE
IS ANY BUS ISOLATED
NO
YES
MATCH LOCALLY THE LOAD & GEN. AT ISOLATED BUSES
PERFORM LOCAL SOL. & set i = 1
ANY BUS ISOLATED?
NO
YES
ADJUST THE ISOLATED BUS VOL. AS GIVEN IN SEC.
CALCULATE THE AMOUNT OF SOURCE COMPENSATION
IS i > 4
YES
NO
MODIFY SOURCE COMPENSATION USING ACC. FACTOR
CARRY OUT THE AMOUNT ONE ITERATION OF GLOBAL LOAD FLOW WITH BASE-CASE JACOBIAN AND BUS POWER INJECTION FOR OUTAGE SIMULATION
IF THE FINAL SOLUTION IS OBTAINED ?
NO
i =i+1
YES
STOP

Fig. 2·3

$$\Delta P_{Im} + j\Delta Q_{Im} = P_{Im} + j\, Q_{mk} = V_{mk}\, [(V_m - V_k)^{*}\, Y_{mk}^{*} + V_m^{*}\, Y_{km}^{'\,*}/2] \quad ,\ldots(2.5)$$

Special care has to be taken when simulating radial lines. Outage of radial line isolates one terminal bus and as such local solution doesn't provide correct solution. So the cure is to make the power injection for the isolated bus as zero and to isolated bus voltage equal to other terminal bus voltage of isolated line after local solution is obtained.

2.3 SOLUTION ALGORITHM

The self explanatory flow chart of the method developed is shown as Fig. 2.3. Detailed step wise procedure for line outage simulation is explained as under :

Step 1 Perfrom the load flow solution using specified loads and generations. Retain the base case Jacobian.

Step 2. Identify the terminal buses of the lines to be outaged. Treat isolated buses, if any present due to outaged line.

Step 3. Perfrom the local solution using Gauss-Seidel technique.

Step 4. Adjusted the isolated bus voltages, if any and modify the source compensation amount.

Step 5. Carry out one iteration of global solution with the base case Jacobian, and bus power injections for outage simulation.

Step 6. Check for convergence. If solution is obtained go to Step 7, otherwise set i = i +1, and go to Step 4.

An efficient and accurate method is used for simulation of line outage simulation, introducing local solution concept.Buses for local solution are properly selected based on the level of disturbance. This computational efforts depends on the level of disturbance due to the line outage. Solution of line outage simulation to a prespecified accuracy is obtained by using the base case Jacobian and no refactorization is required. Accuracy of the solution is so high that the need of full AC load flow is eliminated. This method will find extensive application in planning, operational planning, security and reliability calculations.

Chapter III

ALLEVIATION OF VOLTAGE LIMIT VIOLATIONS

3.1 INTRODUCTION AND STATE OF ART

Emergency state may develop . in a power system resulting in loss of line or a transformer, this may cause over-voltages or under-voltages. the system operator must take appropriate actions quickly to alleviate these problems.

Loose coupling exists between the magnitude and angle of the bus voltage and is precisely that was used in the past to develop control methods have been developed for preventive/corrective control computations for active and reactive power constraints. Reactive power flow subproblem has been extensively investigated for voltage and reactive power constraints [4,5,7,8,11,16].

Some papers have been reported in literature where-in algorithms for corrective control computations have been developed for alleviation of voltage limit violations [7,11,16].

Mamndur [11] developed a direct method for emergency adjustments to VAR control variables to alleviate voltage limits (over and under limits) as well as generator VAR limits , that are violated. The method minimizes the overall control actions to be performed by the system operator. The method has made use of Linear Programming to minimise the control variables.Formulation of Jacobian matrix and it's factorization in each iteration is required. Hence, the computation time for large systems will be very large and therefore this method becomes unsuitable for emergency operation of large systems.

Lachs has covered almost every area of reactive power and voltage control in system emergencies. But majority of work reported is in form of preventive controli.e., scheduling of reactive power, generator bus voltages, transformer taps etc. to optimize the system performance However they employ different optimization techniques. these methods are complex and require significant computational efforts to find the required adjustments be made in the control variables. As they attempted to minimize real power losses, the VAR control adjustments determined by these methods are not the easiest to perform during emergency situations.

A Real time corrective process was reported by Zhang et al [12] , they have also developed a direct method for real time corrective power control that attempts to keep within permissible limits the bus voltages and branch reactive power flows. They have used a dual relaxation LP technique to minimize the adjustments to the control variables. They have developed the incremental reactive current models for reactive control devices.

In continuaton with Real time work Chang, Marks and Kenkoto. [1] presented an algorithm for real time application , the algorithm pre assigns priority sequence to the control objective. The priorities are, Voltage limit violation, minimize those violation that can't be eliminated and minimize system active transmission losses.Provisions have been made to allow the selection of control variables and to limit their movement for the following reasons ;

1. To avoid perturbing the power system greatly from the current state.
2. To provide a leeway for corrective rescheduling under contingencies.
3. To achieve the fast solution time required for the real time application.

However it may result in a suboptimal solution, but since the program is executed periodically as a part of real time sequence of programs, over a time the state of system will move towards the optimal point.

Girotti et. al. [17] have developed a program called CAPCON in SCADA mode in which every 15 minutes SCADA provides data to CAPCON which decides whether the Capacitor banks on low side bus of the transformer which was scanned for, should be on or off line, based on VAR and voltage needs.

Kirschen et al [7] modified the LP based optimal power flow, which allows the rescheduling of active power controls to correct the voltage magnitude constraints violations.

In this chapter, a direct method is developed for alleviation of voltage limit violations. The vothage profiles are corrected locally and the accent is on efficient controls ,rather that overall optimal operation .concept of local optimization has been used to develop the method for alleviation of voltage limit violations [6]. The objective function to be minimized is formed as a square of limit violations. Conjugate gradient technique have been used for local optimization. In order to limit the corrective actions.The controls which are less sensitive with respect to current contingency are ignored and this reduces the overall control adjustments. A limit is also set on control variables. To minimise the computational time base case Jacobian is used for global solution. To power sources without modifying base case Jacobian, source compensation technique have been employed to model them as equivalent reactive power injections at corresponding buses.

3.2 TAP CHANGING TRANSFORMER AND SWITCHABLE REACTIVE SOURCE MODELLING

3.2.1 TAP CHANGING TRANSFORMER

Most commonly used control device for controlling voltage profile is the tap changing transformers. Change in tap position modifies the transformers ratio and hence corresponding elements of Jacobian are to be modified. Modification of elements of Jacobian requires large computational burden. In this section a simple model is developed for tap changing transformer, based on the concept of source compensation. It provides the proper adjustments in right hand side vector to incorporate the changes in transformer admittance.

Role of AVR is not motivated

In local optimization procedure very small step size is assumed for transformer taps, so that continuous variation in transformer ratio is allowed. In global solution, tap position is adjusted to the next available discrete value.

In global solution, the change in tap position (transformer ratio), for the transformer between the buses i & j, is simulated by way of source compensation, so that base case Jacobian can be used. Fig. 3.1 illustrates the same. Reactive power flows through the transformer, corresponding to the base case tap position (T^{o}_{ij}) and the new tap position as calculated after local optimization (T_{ij}) are calculated using equation (3.1) through (3.4).

$$Q^{o}_{ij} = -[G_{ij} V_i V_j T^{o}_{ij} \mathrm{Sin}\theta_{ij} + B_{ij}(V^{2}_{i} {T^{o}_{ij}}^{2} - V_i V_j T^{o}_{ij} \mathrm{Cos}\theta_{ij})] \quad \ldots\ldots (3.1)$$

$$Q^{o}_{ji} = -[G_{ij} V_j V_i T^{o}_{ij} \mathrm{Sin}\theta_{ij} - B_{ij}(V^{2}_{j} - V_j V_i T^{i}_{ij} \mathrm{Cos}\theta_{ij})] \quad \ldots\ldots (3.2)$$

$$Q_{ji} = -[G_{ij} V_i V_j T_{ij} \mathrm{Sin}\theta_{ij} + B_{ij}(V^{2}_{i} T^{2}_{ij} - V_i V_j T_{ij} \mathrm{Cos}\theta_{ij})] \quad \ldots\ldots (3.3)$$

$$Q_{ji} = [G_{ij} V_j V_i T_{ij} \mathrm{Sin}\theta_{ij} - B_{ij}(V^{2}_{j} - V_j V_i T_{ij} \mathrm{Cos}\theta_{ij})] \quad \ldots\ldots (3.4)$$

Amount of source compensation ΔQ_{Ii} and ΔQ_{Ij} is calculated using equation (3.5) and (3.6)

$$\Delta Q_{Ii} = Q_{ij} - Q_{ij}^{o} \qquad .....(3.5)$$

$$\Delta Q_{Ij} = Q_{ji} - Q_{ji} \qquad .....(3.6)$$

3.2.2 SWITCHABLE REACTIVE POWER SOURCE

Switchable reactors and capacitors are normally used to absorb the excessive reactive power or supply the reactive power to maintain the system voltage profile. They are modelled as reactive power sources at the buses, where they are connected.

In local optimization procedure, switchable reactive sources are assumed as varying continuously. In global solution, the reactive power sources is rounded off to the nearest permissible discrete value.

Since the voltage profiles are controlled locally, efficient control are important than overall optimal operation during emergencies, hence concept of local optimization is used to develop an algorithm to alleviate voltage limit violation. The objective function is taken to be minimized, hence selected as square of limit violation. Conjugate gradient technique is used for locally optimizing.

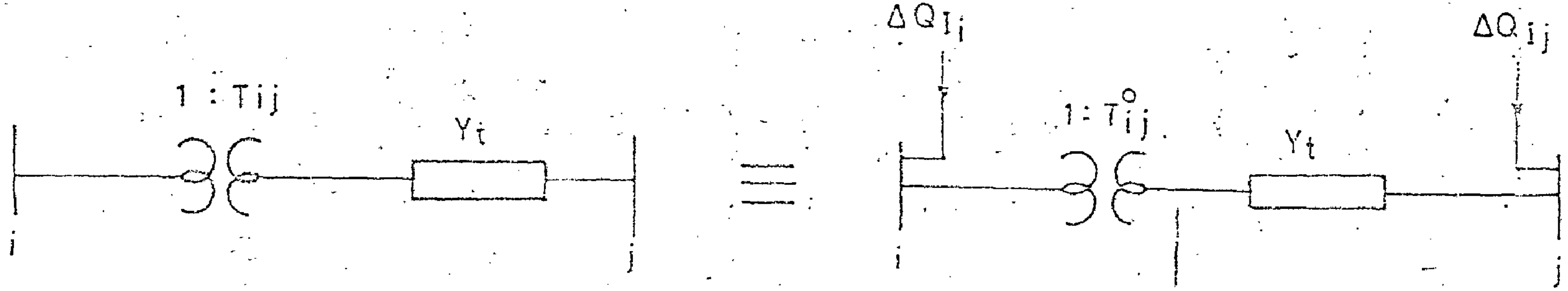


FIG.3.1 REPRESENTATION OF TAP CHANGING TRANSFORMER AS A SOURCE COMPENSATION MODEL

Amount of source compensation ΔQ_{Ii} and ΔQ_{Ij} is calculated using equation (3.5) and (3.6)

3.2.2 SWITCHABLE REACTIVE-POWER SOURCE

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Since the voltage profiles are controlled locally, efficient control are important than overall optimal operation during emergencies, hence concept of local optimization is used to develop an algorithm to alleviate voltage limit violation. The objective function is taken to be minimized, hence selected as square of limit violation. Conjugate gradient technique is used for locally optimizing.

In order to limit the corrective actions, less sensitive controls are neglected. To improve the computational efficiency the base case Jacobian is used for global solution. To incorporate the changes in transformer and switchable reactive power sources without modifying the base case jacobian the source compensation technique is employed to model them as equivalent reactive power injections at corresponding buses.

3.3 Problem formulation :

The objective is taken as an optimizing problem. The objective function is the sum of square of voltage limit violations, of course to take care of both the upper and the lower limit violations,

$$\text{minimize,} \quad f(X,U) = \sum_{i \in Lv} (\Delta V_i)^2 \qquad \text{----(3.8)}$$

$$\text{where} \quad \Delta V_i = \begin{cases} V_i - V_i^{max} & ; \text{ if } V_i > V_i^{max} \\ V_i - V_i^{min} & ; \text{ if } V_i < V_i^{min} \end{cases} \qquad \text{----(3.9)}$$

$$\text{subject to} \quad g(X,U) = 0 \qquad \text{----(3.10)}$$

$$X^{min} \leq X \leq X^{max} \qquad \text{----(3.11)}$$

$$U^{min} \leq U \leq U^{max} \qquad \text{-----(3.12)}$$

where, X : state vector (dependent variable), consisting of,

a) Bus voltage for load (P-Q) buses,

b) Reactive power generation for generator buses

V : vector of control (independent) variables available to the operator, or the control system and consisting of,

a) Bus voltage of generator bus

b) Reactive power generation of switchable reactor /capacitor banks

c) Transformer ratio of tap changing transformers.

3.4 Solution Method :

Reactive power balance at bus 'i' is expressed as ,

$$g_i = (B_i - \sum_{j \epsilon Ai} B_{ij}) V_i^2 + [\sum_{j \epsilon Ai} (G_{ij} \sin(\theta_i - \theta_j) + B_{ij} \cos(\theta_i - \theta_j)) V_j] V_i + (Q_{Gi} - Q_{Li}) = 0 \quad ---(3.13)$$

$$i = 1 \ldots NLO$$

or,

$$g_i = AA . V_i^2 + BB . V_i + CC = 0 \quad ----(3.14)$$

$$\text{where} \quad AA = B_i - \sum_{j \in Ai} B_{ij} \quad ----(3.15)$$

$$BB = \sum (G_{ij} \sin(\theta_i - \theta_j) + B_{ij} \cos(\theta_i - \theta_j)) \quad -----(3.16)$$

$$CC = (Q_{Gi} - Q_{Li}) \quad -----(3.17)$$

for which,

$$V_i = (-BB - (BB^2 - 4\, AA.CC)^{1/2})/(2.AA) \quad ----(3.18)$$

This equation (3.18) is used to derive the objective function for local optimization.

expanding 'g', i.e., eq. (3.10) for small variation in ΔX at point (U^0, X^0),

$$\partial g/\partial X|_{X^0} \Delta X + \partial g/\partial U|_{U^0} = 0 \quad ----(3.19)$$

$$\Delta X = - [(\partial g/\partial x)^{-1} . \partial g/\partial U] \Delta U \quad ----(3.20)$$

the quantity inside the bracket is known as the Sensitivity Matrix.

The Lagrangian function of the optimization problem, considering only equality constraints is,

$$L(X,U,\lambda) = f(X,U) + \lambda^t g(X,U) \quad -----(3.21)$$

where λ is selected such that,

$$\partial f/\partial X^0 + \lambda^t \, \partial g/\partial X^0 = 0 \qquad \text{-----(3.22)}$$

$$\text{i.e. } \lambda^t = -\, \partial f/\partial X^0 \, [\partial g/\partial X^0]^{-1} \qquad \text{-----(3.23)}$$

expanding Lagrangian function, eq.(3.21) for small variation ΔU and ΔX at point (U^0, X^0),

$$\Delta L_{Ui} = (\partial f/\partial U^0 + \lambda^t \, \partial g/\partial U^0)\, \Delta U + (\partial f/\partial X^0 + \lambda^t + \partial g/\partial X^0]\, \Delta X \quad \text{--(3.24)}$$

substituting the value of λ^t from (3.23) into (3.24),

$$\Delta L_{Ui} = \partial L/\partial U = \partial f/\partial U^0 - \partial f/\partial X^0 \, [(\partial g/\partial X\,)^{-1} \, \partial g/\partial U] \quad \text{---(3.25)}$$

3.5 STEPWISE ALGORITHM

Flow chart for the solution method for the solution method of alleviation of voltage limit violations is given in fig. 3.2. The complete stepwise solution procedure is explained as under :

Step 1 : Perform the base case load flow.

Step 2 : Check for voltage limit violations. If at no bus voltage limit is violated or $P_s > P_s^{max}$ stop.

Step 3 : Determine the number of buses to be processed for local optimization, depending on the prespecified step length and identify the set of control buses /variable available in the control area.

Step 4 : Calculate the objective function using present operating point values of variables and equations (3.14) and (3.15). Set iteration count $i = 1$.

Step 5 : Calculate λ using equation (3.22) and calculate $\partial g/\partial U$ using equations (B-25), (B-27) and (B-28).

Step 6 : Calculate the sensitivity matrix Calculate the ΔL_U using equation (3.24). Ignore the less sensitive controls.

Step 7 : Calculate the conjugate search direction $S = -\Delta L_U$.

Step 8 : Calculate the projection of the gradient on the bounds of independent variables such that

Step 9 : Calculate maximum step length t^{max} such that

$$s_j = \begin{cases} 0 \left[\begin{array}{l} \text{if } U_j^{max} - U_j = 0 \text{ and } s_j > 0 \\ \text{if } U_j - U_j^{min} = 0 \text{ and } s_j < 0 \end{array} \right. \\ s_j, \text{ other wise} \end{cases}$$

Step 10 : Calculate maximum step length $t \le t^{max}$ such that

$$t^{max} = \min_j \left[\min_{s_j^i > 0} \left[\frac{U_j^{max} - U_j}{s_j^i} \right] \min_{s_j^i < 0} \left[\frac{U_j^{min} - U_j^i}{s_j^i} \right] \right]$$

Where $X^{i+1} = X^i + \Delta X$ and ΔX is calculated, such that constraints are satisfied and $U = tS^i$ and $U^{i+1} = U^i + \Delta U$. Elements of ΔU which are less then prespecified values make them equal to zero. Constraints over control variables are exercised.

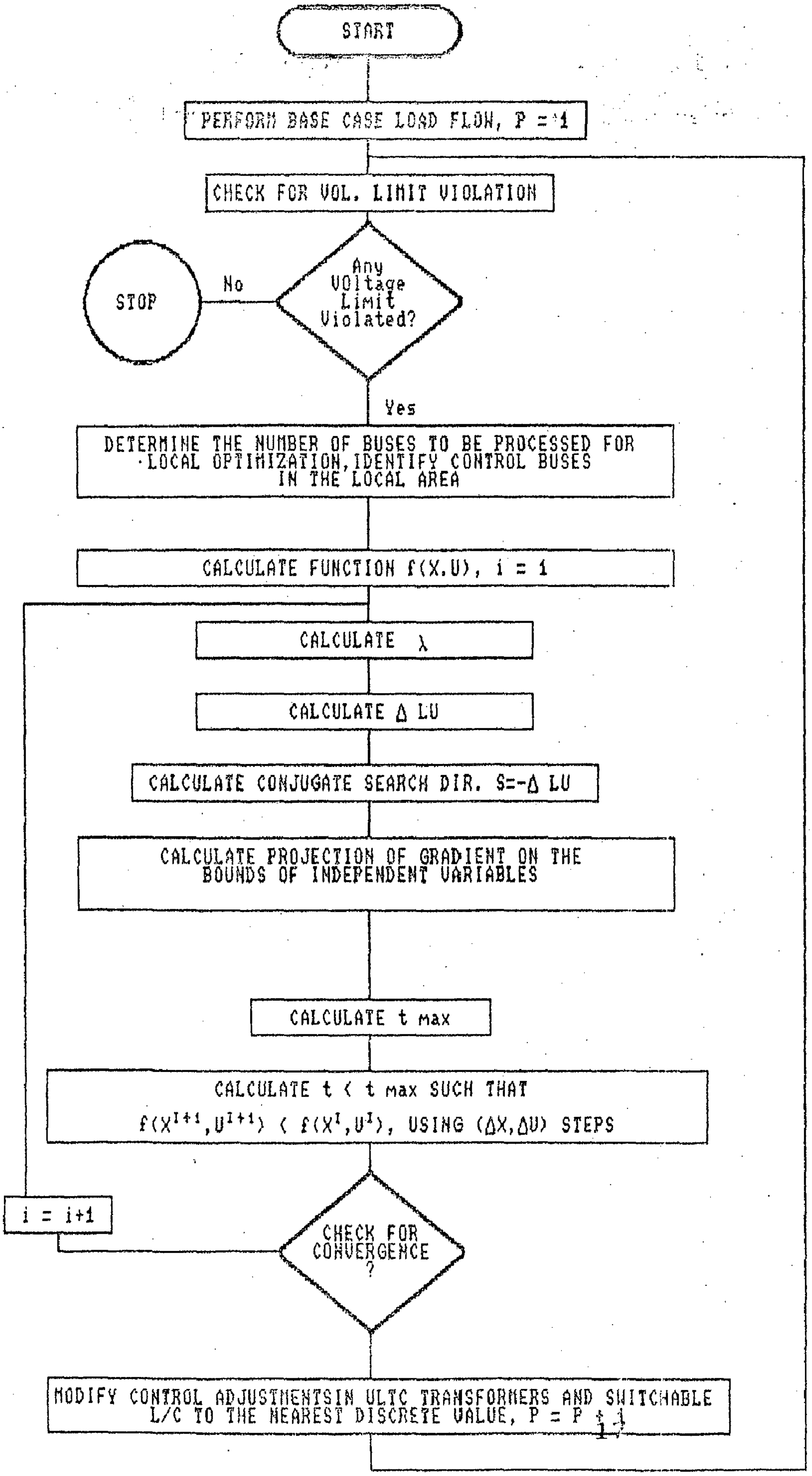
Step 11 : Check for convergence. If $(f(X^{i+1}, U^{i+1}) \le Tol$ or $[f(X^{i+1}, U^{i+1}) - f(X^i, U^i)] \le Tol$,og to step 16. Otherwise $i \longleftarrow i + 1$ and goto step 7.

Step 12 : Modify the discrete variables to nearest permissible values. perform the load flow for the complete system.

$P_s = P_s + 1$ go to step 2

Execution of Step 7 through Step 14 constitutes one iteration of local optimization, and execution of Steps 2 through Step 16 constitutes one pass of alleviation of voltage limit violations.

Flow Chart of the Alleviation Technique : FIG 3.2



CHAPTER IV

RESULTS AND CONCLUSION

4.1 RESULTS

Voltage limit violation resulting due to contingencies (line outage/transformeroutage) in the 14 bus, 24 bus, 26 bus, 57 bus, model are studied and successfully alleviated, and a new secure point is obtained. The system data is referred to [6].

For global solution a step size of 10 MVAR (0.1 pu) for switchable capacitor/reactor is assumed.

From the study of table [5.1] it is observed that the for all cases of voltage limit violation, the new and secure operating point is obtained in one pass only. For most of the cases the solution is obtained in within three iteration of local optimization. an explaination of the results presented in the table [5.1] is givem below.

CASE STUDY

1. Line 3 outaged in the 24 bus system :

- Reactive source installed and their respective capacities,

1. 0.444 3. 0.124 5. 0.8972 7. 0.4321
9. 0.0099 14. -0.134 16. 0.284

- Load Flow - no limit violation detected

- Local Solution - Iteration

Iteration	Bus no.	
1	23,3	terminal buses
2	23,3,22,7	
3	23,3,22,7,4,2,9,8,5	
4	23,3,22,7,4,2,9,8,5,6,24, 20,19	

The of the Local Area from the terminal buses and with an accent on the level of disturbance is demostrated in the figure (4.1) iteration of the local solution.

- Voltage violation after local solution

3	1.1041
7	1.1302
4	1.1626

- Outage Simulation : Total iteration = 2

Power in Reconnected line 3 after local solution with 14 bus is (188.77034, -154.0252), (-175.985, 198.497)

- Alleviation of Voltage limit Violation - Tolerance limit on voltage mismatch = 0.001

Control Area :

1. Bus 3 : 3,7,9,8,5,4
2. Bus 4 : 4,7,22,9,8,5,3,2,23
3. Bus 7 : 7,9,8,5,4,3,24,20,6,19,21,22

Total control buses : (3,7,9,8,5,22,20,21)

The control area for voltage violation in buses 3,4,7 is demostrated in figure (4.2).

Full iteration of optimization program = 2

Control MVA (ΔU)

1.	10.000	2.	10.000	3.	10.000	4.	10.000
5.	89.720	6.	10.000	7.	10.000	8.	34.250
9.	0.987	10.	10.000	11.	10.000	12.	10.000
13.	10.000	14.	-13.400	15.	16.680	16.	28.400

From the result removal of 3rd line in 24 bus system, resulted in voltage limit violation at three buses, viz. 3,4,7. The same has been corrected by 3 iteration of Local optimization for which eight buses were considered, using a two step limit from the affected bus formula. For the post adjustment local flow few iteration were required and less sensitive controls is for capacitor/inductor less than 0.01 pu are neglected. This resulted in minimum controls without damaging the efficiency. The controls at bus no. 5 th being most sensitive and with the highest sensitivity of 0.5879 tributed 89.7 MVA which is well within the supplying limits set ,and bus 8 is next most sensitive and it contributed 34.25 M.V.A. .

3. Line 5 outaged in the 24 bus system :

Similar results are reported on outage of line 5 th , 24 bus system where an area of 15 buses was selected for local solution which resulted in a violation at 4th and 7th bus. The control buses for the violated buses were 7 in number and the solution was obtained in one iteration of local optimization.

- Reactive source installed and their respective capacities,

1. 0.444 8. 0.3425 5. 0.8972 7. 0.4321

9. 0.0099 14. -0.134 16. 0.284 15. 0.168

- Local Flow - no limit violation detected

- Local Solution - Iteration

Iteration	Bus no.	
1	24.4	terminal buses
2	24,4,2,23,7	
3	24,4,,7,4,2,9,8,5	
4	22,4,23,7,9,8,5,24,20,6,19,21	

- Voltage violation after local solution

7	1.2082
4	1.1199

- Outage Simulation : Total iteration = 2

Power in Reconnected line 5 after local solution with 12 buses (74.48 ,-123.901), (-64.734,148.778)

- Alleviation of Voltage limit Violation - Tolerance limit on voltage mismatch = 0.001

Control Area :

1. Bus 4 : 4,7,9,8,5,3
3. Bus 7 : 7,9,8,5,4,3,24,20,6,19,21,23

Total control buses : (4,7,9,8,5,20,23)

Full iteration of optimization program = 2

Control MVA (ΔU)

5.	60.000	6.	10.000	7.	43.21	8.	30.000
9.	0.987	8.	10.000				

From the result removal of 5th line in 24 bus system, resulted in voltage limit violation at two buses, viz. 4,7. The same has been corrected by 2 iteration of Local optimization for which seven buses were considered, using a two step limit from the affected bus formula. For the post adjustment local flow few iteration were required and less sensitive controls is for capacitor/inductor less than 0.01 pu are neglected. This resulted in minimum controls without damaging the efficiency. The controls at bus no. 5 th being most sensitive and with the highest sensitivity of 0.6929 tributed 60.0 MVA which is well within the supplying limits set ,and bus 7 is next most sensitive and it contributed 43.21 M.V.A. .

3. Line 17 outaged in the 24 bus system :

- Reactive source installed and their respective capacities,

1.	0.444	3.	0.124	5.	0.8972	7.	0.4321
12.	-0.231	14.	-0.134	9.	0.0098		

- Local Flow - no limit violation detected

- Local Solution - Iteration / Bus no.

Iteration	Bus no.	
1	7,9	terminal buses
2	7,9,8,5,4,3,24,20,6	
3	7,9,8,5,4,3,20,6,19,21,22,23,2	

- Voltage violation after local solution

7	1.1358
4	1.1677

- Outage Simulation : Total iteration = 2

Power in Reconnected line 5 after local solution with 14 buses (312.325, -121.61) and (-309.8, 213.74)

- Alleviation of Voltage limit Violation - Tolerance limit on voltage mismatch = 0.001

Control Area :

1. Bus 7 : 7,8,5,4,3,19,20,6,23

Total control buses : (4,7,9,8,5,20,23)

Full iteration of optimization program = 1

Control MVA (ΔU)

7. 10.000   8. 10.000   4. 20.00   5. 10.000

9. 0.987   20. 12.330

resulted in voltage limit violation at one buse, i.e. 7 after local solution and one iteration of global load flow. The same has been corrected by 1 iteration of Local optimization for which seven buses were considered, using a two step limit from the affected bus formula.

4. Line 3 outaged in the 26 bus system :

Results are reported on outage of line 3 rd , 26 bus system where an area of 15 buses was selected for local solution which resulted in a violation at 4th and 7th bus. The control buses for the violated buses were 7 in number and the solution was obtained in one iteration of local optimization.

- Reactive source installed and their respective capacities,

13. 0.112 10. -0.129 9. 0.00987 14 -0.134
12 - 0.231 11. 0.234 16. 0.284 15. 0.168
1 0.434

- Local Flow - no limit violation detected

- Local Solution - Iteration

Iteration	Bus no.	
1	13,26	terminal buses
2	23,2	
3	13,2,25,10	
4	13,2,10,9	

- Outage Simulation : Total iteration = 2

Power in Reconnected line 3 after local solution
is (8.912 ,31.85), (-8.92, -23.62)

- Alleviation of Voltage limit Violation - Tolerance limit on voltage mismatch = 0.001

Voltage violated after Global Solution :

2. 1.2319 9. 1.1187 10. 1.2072 13. 1.361

Control Area :

1. Bus 2 : 2,25,13,10,9
2. Bus 9 : 9,14,12,10,11,26,2
3. Bus10: 10,9,2,14,12,25,13
4. Bus13: 13,2,25,10

Total control buses : (9,11,12,13,10,14,25)

Full iteration of optimization program = 1

Control MVA (ΔU)

10. 10.000 11. 10.000 12. 10.000 13. 10.000
9. 0.987

From the result removal of 3 rd line in 26 bus system, resulted in voltage limit violation at 4 buses, viz. 2,9,10,13 The same has been corrected by 1 iteration of Local optimization for which seven buses were considered, using a two step limit from the affected bus formula. For the post adjustment local flow few iteration were required and less sensitive controls is for capacitor/inductor less than 0.01 pu are neglected.

5. Line 5 outaged in the 24 bus system :

At 57 bus system the contingency is created in the system data itself by deleting the line 3rd from the system data , as a result the voltage contingency at bus number 24 is detected which is alleviated by the alleviation program.

- Reactive source installed and their respective capacities,

1. 0.444 8. 0.3425 5. 0.8972 7. 0.4321
9. 0.0099 14. -0.134 16. 0.284 15. 0.168

- Local Flow - violation detected

Voltage violated at :

24. 0.850

- Alleviation of Voltage limit Violation - Tolerance limit on voltage mismatch = 0.001

Control Area :

1. Bus 24 : 24,25,23,27,26,18

Full iteration of optimization program = 2

Control MVA (ΔU)

24 30.000 25. 23.4 27. 30.0 26. 23.1
18. 12.37

4.3 CONCLUSION

The problem of Voltage Limit Violation in Power System Emergencies has been investigated .A concept of Local Optimization has been introduced and direct method is introduc~~ed~~ to alleviate system emergencies due to Voltage Limit Violation. The method is quite efficient and the results are analysed in 24 bus system , 26 bus system and also in 57 bus system .

As clear from the table (4.1) the results are obtained in one or two iteration and very few buses need to be analysed for the local optimization. A maximum and minimum limit has been assigned to the controls and the new operating point is obtained by minimum controls as less sensitive controls are neglected . An extra adjustments has been put in the program to take care any violation that can be put by system data , in this case the line outage simulation and local simulation part is bypassed and straight away the voltage violatin is treated for.

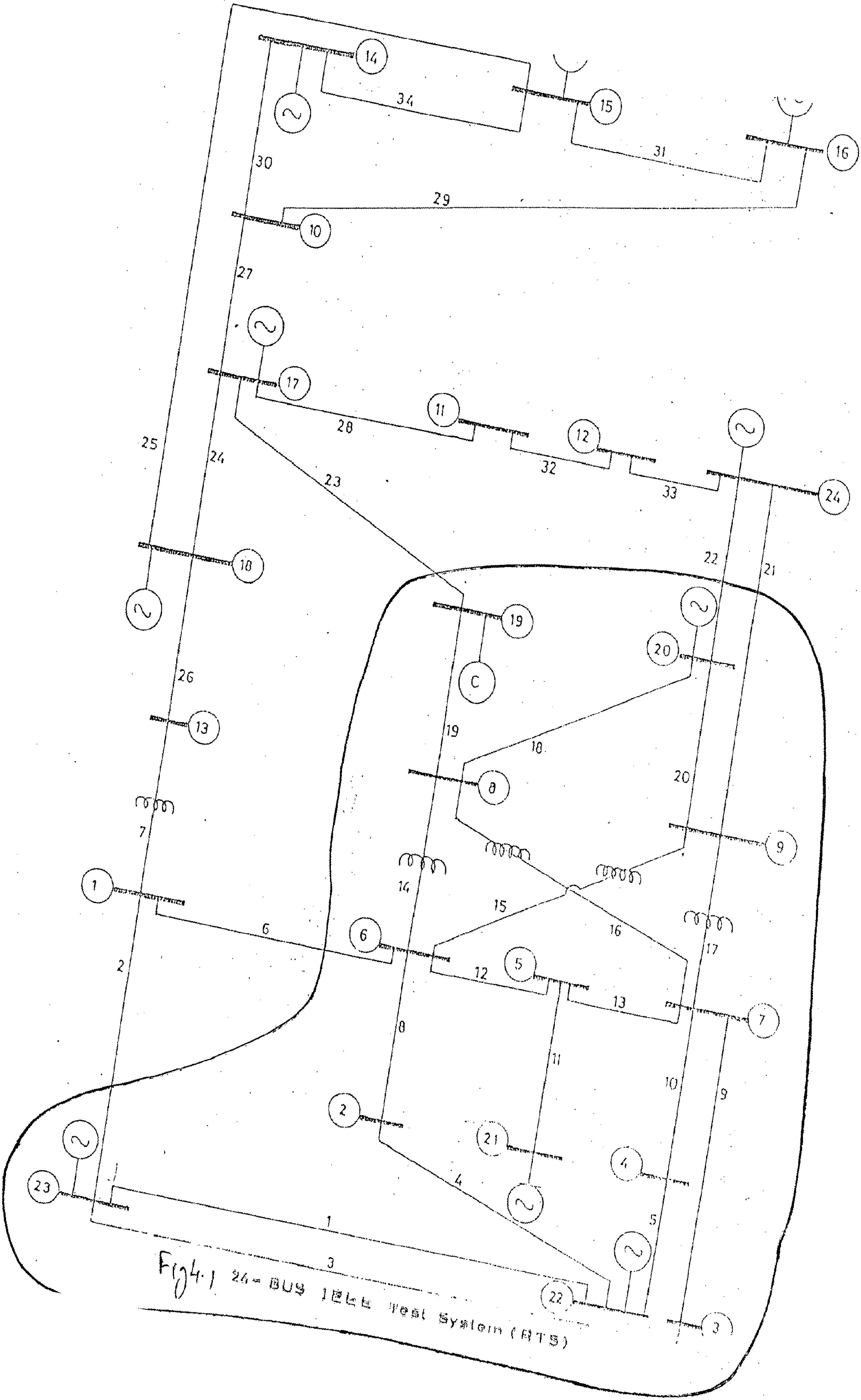


Fig4.1 24-BUS IEEE Test System (RTS)

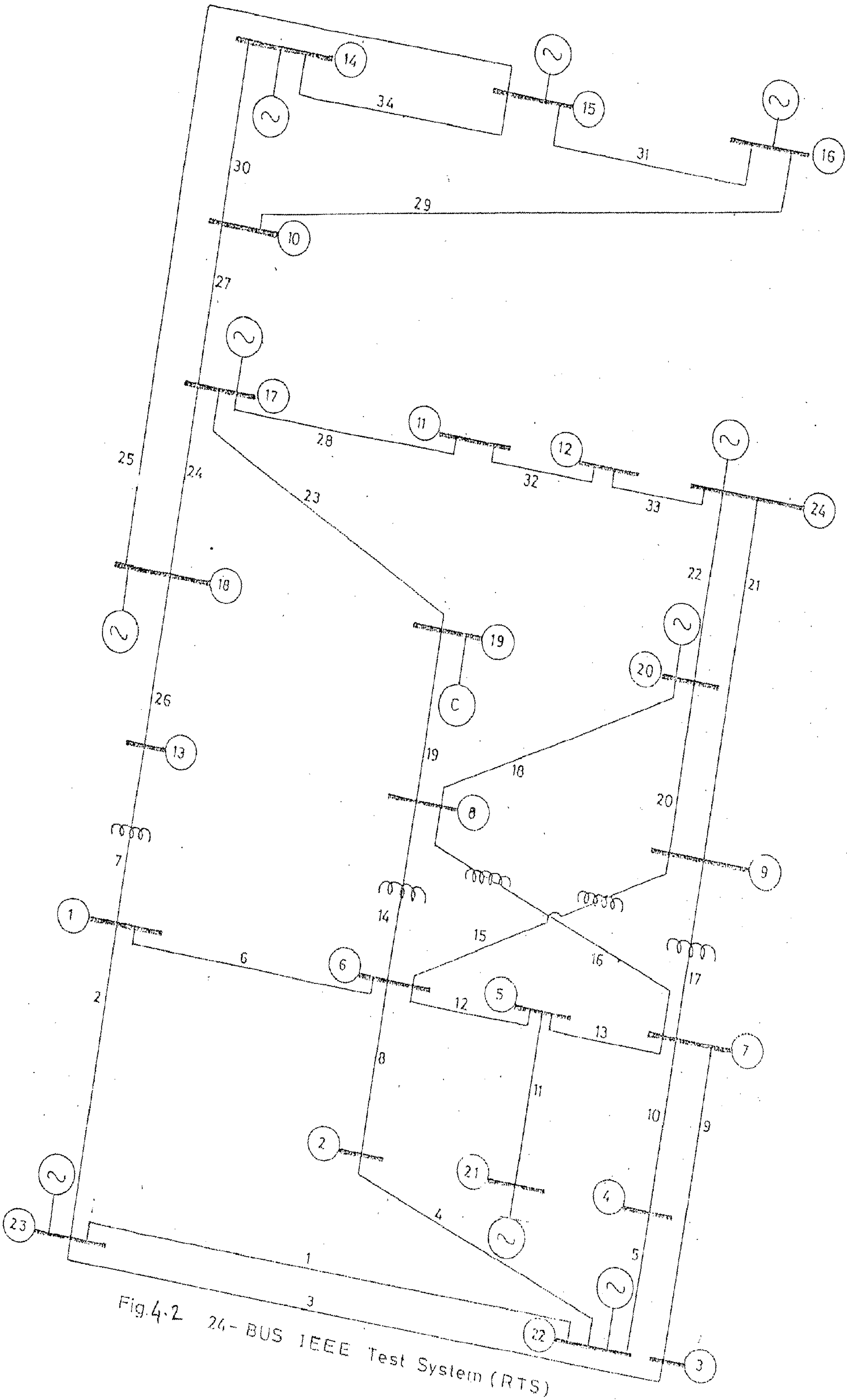


Fig.4.2 24-BUS IEEE Test System (RTS)

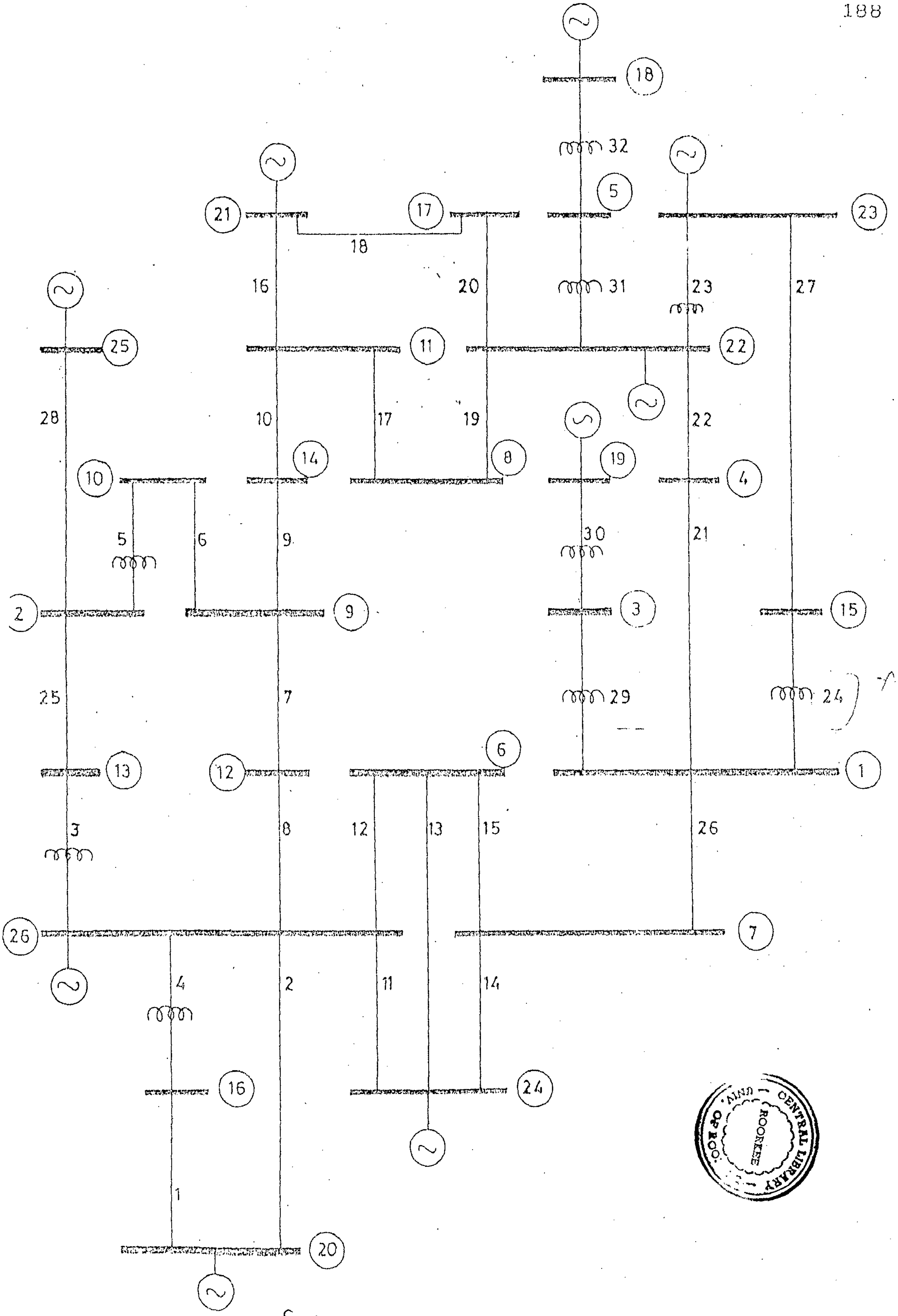


Fig 4.3 26-BUS (SPC) System

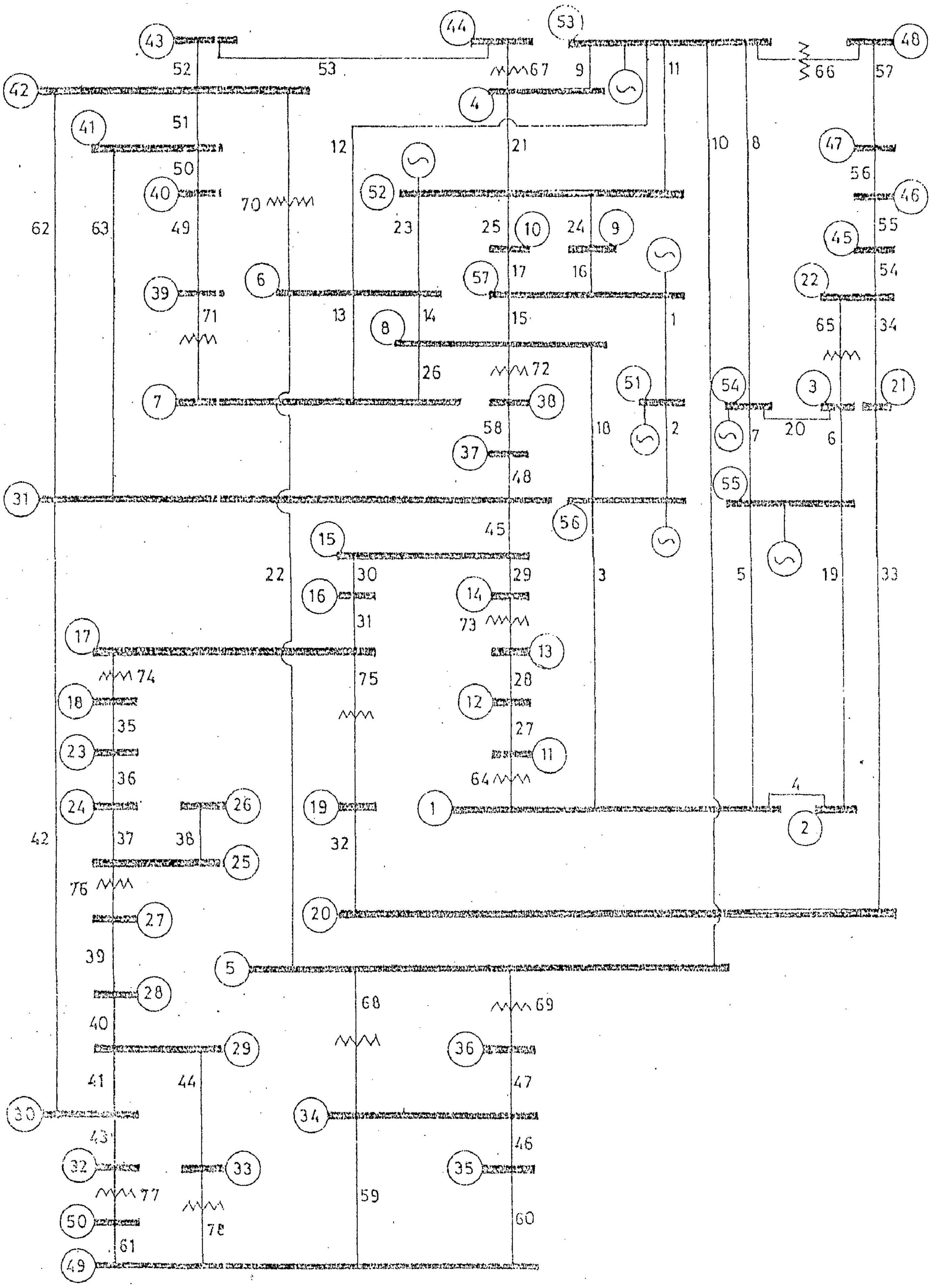


Fig. 4.7 57-BUS IEEE Test System

TABLE 4.1

ALLEVIATION OF BUS VOLTAGE LIMIT VIOLATIONS BY LOCAL OPTIMIZATION

Sr. No.	Particulars of test systems	Pass	Details of the buses at which limit violated				Local Optimization		Controls		
			Bus No.	Violated limit	Bus voltage		No. of Busses Proce.	No. of iteration	Type	At Bus	Adjustments U
					Pre-Adjustment	Post-Adjustment					
1	2	3	4	5	6	7	8	9	10	11	12
1.	24/3	1	3	1.100	1.1041	1.0853	8	3	L/C	3	10.0
			4	1.100	1.1302	1.0591				7	10.0
			7	1.100	1.1626	1.0986				9	0.987
										8	34.25
									xer	5	89.72
										16	0.01
										14	13.9
2.	24/17	1	4	1.100	1.208	1.10139	7	1	L/C	5	60.0
			7	1.100	1.1199	1.0959				6	10.0
										7	43.21
										8	30.0
										9	0.987
										14	13.40
										15	16.80
										16	28.4
									xer	17	0.02
										23	0.10
3.	24/17	1	7	1.100	1.1080	1.10	6	2	L/C	7	10.00
										8	10.00
										5	16.80
										14	-13.4
										9	0.987
4.	26/3	1	2	1.100	1.232	1.104	7	3	L/C	1	10.0
			9		1.119	1.031				2	10.0
			10		1.207	1.109				3	10.0
			13		1.361	1.003				4	10.0
										9	0.997
										13	13.4
5.	57	1	24	0.9	0.8499	0.895	6	2	L/C	24	30.00
										25	23.40
										26	23.10
										29	30.00
										18	12.30
										12	-23.10

CHAPTER V

CONCLUSION AND SUGGESTION FOR FURTHER WORK

The problem of alleviation of voltage limit violation in the power network has been studied. The method presented is based on local optimization which adjusts the power system parameters in the vicinity of voltage limit violation. It may possible that the alleviation of voltage limit violation at one may cause the volatage violation elsewhere in an interconnected large system. Voltage problem is solved in the iterative mannar however the system studied in thesis, such phenomena is not observed.

The method take care of practical constraints over the values of capcitors, rectors and tap changing transformer. Method is tested under the severe conditions by creating line and transformer contingencies which causes voltage limit violation. Thus the robustness of the method is established. In order to minimise the control actions the less sensitive adjustments are neglected.

The source compensation is used to model the various changes in the network cofiguration and parameters from the base case values. Since the Jacobian is not changed hence the the refactorization of Jacobian is avoided which makes the method efficient.

It is expected that the investigation in this thesis will find its application in power system operation and in plant.

The work in the thesis may be extended for Real Time application of power system.

APPENDIX - A

SOFT-WARE DESCRIPTION IN BRIEF

The Software package called "OUT11" written in FORTRAN IV and tested on a 486 based machine, UNIX System 5 Release IV at Roorkee University, O.I.D.B. Lab, Department of Metallurgical Engineering and Department of Electrical Engineering, for all the methods developed in Chapters II - IV is described in brief in this appendix. By assigning the proper value to the variable ISTUDY as given below, desired analysis is performed,

ISTUDY = 1 : Load flow solution
= 2 : Line outage simulation
= 3 : Alleviation of voltage limit violations

For each case analysis starts with the base case load flow. This analysis may be from line No. NLFF to Line No. NLFT or for total NLFTTL lines, line Nos. of which are specified in an array NLFSEL.

The software is developed to solve for large size networks, exploiting the Sparsity of the network. Fig. A-1, with the arrows emanating rom calling program and leading to called subroutines, highlights the overall organization of the program. Brief description of different abbreviated program names are given below.

MASTER PROGRAM

OUT11 : This is the main program. It calls various subroutines listed below, and performs the desired analysis using selected technique and prints the results.

SUBROUTINES CALLED

LFIN : READS and if desired PRINTS input data of the system.

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

NETINJ : Models the buses and determine the net power injections.

YBUS : Models transmission lines, the lines, transformers and phase shifters and determines and stores elements of Y-matrix.

ISSLE : Prepares the data as required by SSLERN

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

SORDRN : Simulates and orders coefficient matrix for Gauss - elimination.

REDURN : Performs the reduction of the 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.

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

MISMAT : Calculates the power mismatches at buses.

UPDBVA : Updates voltage angles of buses.

UPDBVM : Updates voltage magnitudes of buses.

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

LINFLW : Calculates the line flow.

REACTV : Calculates reactive power generation at P-V buses.

SLACK : Calculates slack bus power.

REDIAL : Identifies the radial line and radial end bus No.

LOCAL : Identifies the buses to be processed for local optimization.

SELECT : Compares the change in bus voltage and selects the buses to be included in local area for step by step enlargement of local area for local solution.

LOCSOL : Performs load flow solution for local area using Gauss - Seidel technique.

AVQOPT : Calculates increments in control variables for alleviation of voltage limit violations, using local optimization technique.

MATIN : Calculates matrix inverse.

MATMUL	:	Performs matrix multiplication.
POWER	:	For outage studies the specified power is locally matched.
DEVOLT	:	Voltage limit checking subroutine.

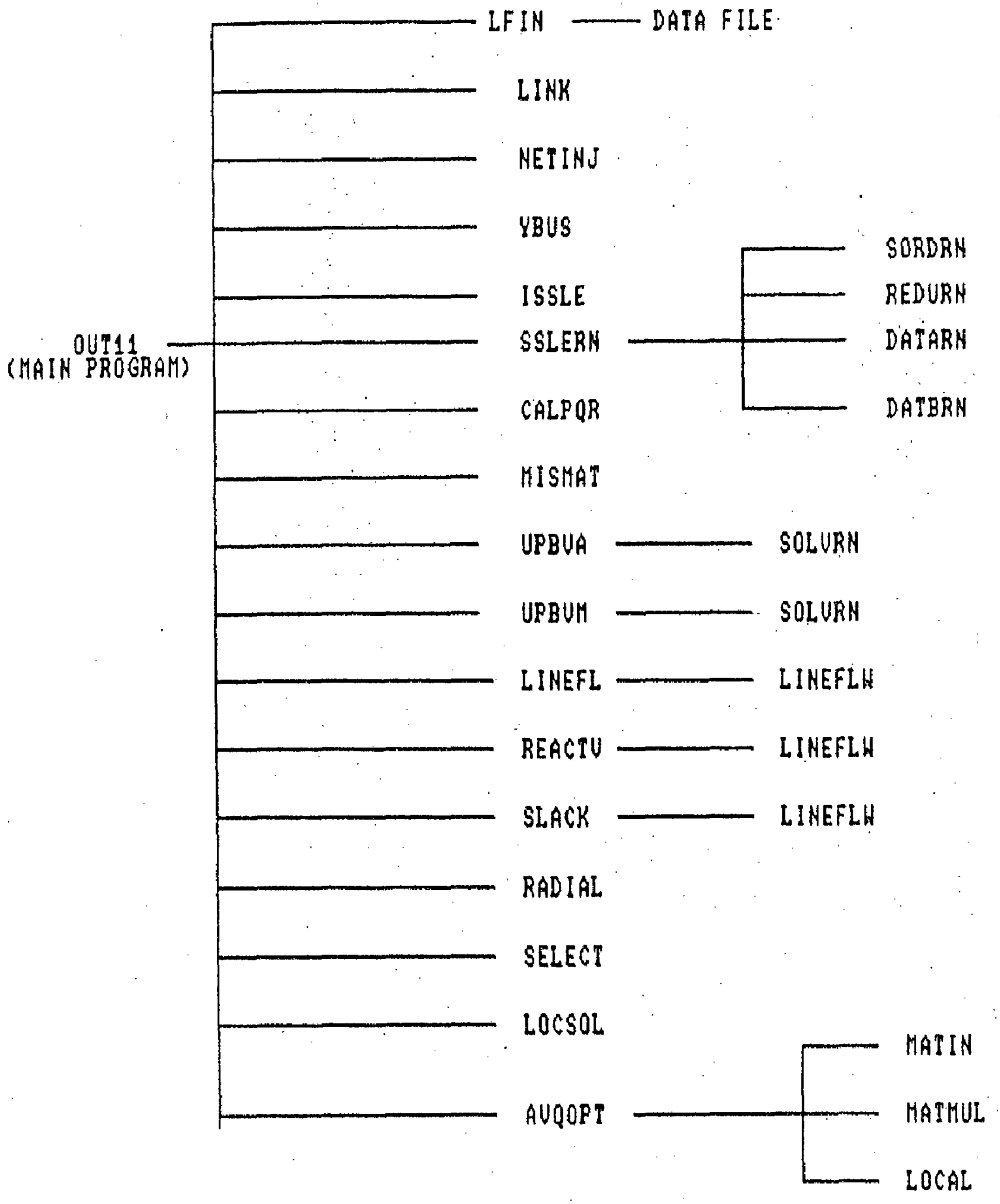


Fig A-1   Overall Organization of the Package

APPENDIX - B

Equation for calculation of elements $\partial g/\partial X$, $\partial g/\partial U$, $\partial f/\partial X$ and $\partial f/\partial U$ in local optimization procedure for alleviation of voltage limit violations are derived in this appendix.

B.1 Equility constraints are given by equation [3.13] and the same is reproduced as equation (B-1) below :

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

Independent (control)variables [U] and dependent variables [X] are defined as :

Independent (Control Variables : [U]

1) For Generator buses : V_i

2) For switchable reactive power source buses : Q_{Gi}

3) For top changing transformers : TR_k

Dependent Variables : [X]

1) For all P-Q buses : V_i

2) For Generator buses : Q_{Gi}

B.1.1 Differentiating equation (B-1) w.r.t X, we obtain the following (B-2) and (B-3) experssions,

$$\frac{\partial g_i}{\partial x_i} = \left[\begin{array}{ll} 2.0(B_i - \sum_{j\in A(i)} B_{ij})V_i + [\sum_{j\in A(i)} (G_{ij}\mathrm{Sin}(\theta_i-\theta_j) + B_{ij}\mathrm{Cos}(\theta_i-\theta_j)V_j] & ,\text{if } X_i = V_i \\ 1.0 \quad \text{if } X = Q_{Gi} & \\ i = 1,\ldots\ldots,NLO & \end{array} \right. \qquad ....(B-2)$$

$$\frac{\partial g_i}{\partial x_i} = \left[\begin{array}{ll} (G_{ij}\mathrm{Sin}(\theta_i-\theta_j) + B_{ij}\mathrm{Cos}(\theta_i-\theta_j))V_i \quad , \text{if } X_j = V_j & \\ 1.0 \qquad \text{if } X = Q_{Gi} & \\ i = 1,\ldots\ldots,NLO \quad j = 1,\ldots\ldots,NLO \quad i = j & \end{array} \right. \qquad ....(B-3)$$

In the desired final solution, it may be assumed that

$$V_i \approx V_j = 1.0$$

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

and $G_{ij}\mathrm{Sin}(\theta_i-\theta_j) \leq B_{ij}$

and the equation (B-2) and (B-3) are reduced to (B-4) and (B-5) respectively.

$$\frac{\partial g_i}{\partial x_i} = \left[\begin{array}{l} 2.0B_i - \sum_{j\in A(i)} B_{ij} \quad , \text{if } X_i = V_i \\ 1.0 \quad , \text{if } X_i = Q_{Gi} \end{array} \right.$$

$$i = 1,\ldots\ldots,NLO \qquad ....(B-4)$$

$$\frac{\partial g_i}{\partial x_i} = \left[\begin{array}{l} B_{ij} \qquad \text{if } X_j = V_j \\ 0 \quad , \text{if } X_j = Q_{Gj} \end{array} \right.$$

$$i = 1,\ldots\ldots,NLO; \; j = 1,\ldots\ldots NLO, \quad 1=j \qquad ....(B-5)$$

Equations (B-4) and (B-5) are used to calculate $\frac{\partial g}{\partial X}$

B.1.2 Differentiating equation (B-1) w.r.t. U, we obtain the following expressions, (B-6), (B-7) and (B-10)

$$\frac{\partial g_i}{\partial x_i} = \begin{bmatrix} 2.0(B_i - \sum\limits_{j\in A(i)} B_{ij})V_i + [\sum\limits_{j\in A(i)} G_{ij}Sin(\theta_i-\theta_j) + B_{ij}Cos(\theta_i-\theta_j)V_j] & ,if\ U_k = V_i \\ 1.0 \qquad\qquad if\ U_k = Q_{Gi} & \\ i = 1,\ldots.,NLO;\ k=1,\ldots,NC & \end{bmatrix} \qquad \ldots.(B-6)$$

$$\frac{\partial g_i}{\partial x_i} = \begin{bmatrix} (G_{ij}Sin(\theta_i-\theta_j) + B_{ij}Cos(\theta_i-\theta_j))V_i & ,if\ U_j = V_j \\ 1.0 & if\ U_k = Q_{Gi} \end{bmatrix}$$

$$i = 1,\ldots.,NLO;\quad k = 1,\ldots.,NLO;\ j\in A(i) \qquad \ldots.(B-7)$$

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 equation (B-1). For simplicity, abbreviated terms AA and BB as defined in equations [3.15] and [3.16] are used for derivation of expressions w.r.t. TR_k. The contribution of TR_k in BB and AA is given by equations (B-8) and (B-9).

$$BB = BB^o + [G_{ij}Sin(\theta_i-\theta_j)/Tr_k + B_{ij}Cos(\theta_i-\theta_j)/TR_k]V_j \qquad \ldots.(B-8)$$

$$AA = \begin{bmatrix} AA^o + \dfrac{B_{ij}}{TR_k^2} & ,if\ i\ is\ the\ tap\ side\ bus \\ \\ AA^o + \left[\dfrac{TR_k - 2}{TR_k}\right. B_{ij} & ,if\ i\ is\ the\ impedance\ side\ bus \end{bmatrix} \qquad \ldots.(B-9)$$

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

Now, differentiating equation (B-1) w.r.t. tap ratio for tap changing transformers in local area, equation (B-10) is obtained as under:

$$\frac{\partial g_i}{\partial U_{NC+K}} = \begin{cases} -\dfrac{B_{ij}}{TR_k^3} V_i^2 - \dfrac{1}{TR_k^2} [G_{ij} \mathrm{Sin}(\Theta_i - \Theta_j) + B_{ij} \mathrm{Cos}(\Theta_i - \Theta_j)] V_i V_j, & \text{if } i = TTAP_k \\ -\dfrac{2B_{ij}}{TR_k^2} V_i^2 - \dfrac{}{TR_k^2} [G_{ij} \mathrm{Sin}(\Theta_i - \Theta_j) + B_{ij} \mathrm{Cos}(\Theta_i - \Theta_j)] V_i V_j, & \text{if } i = TTMP_k \\ K = 1, \ldots.NTR & \end{cases} \quad \text{.....(B-10)}$$

Equation (B-6), (B-7) and (B-10) are used to calculate $\partial g/\partial U$.

B.2 Theobjective function f(X,U), is expressed as equations through [3.8], [3.9] and [3.18]. Same is reproduced as equation (B-11) through (B-13).

$$f(X,U) = \sum_{i \in LV} (\Delta V_i)^2 \quad \text{.....(B-11)}$$

$$\text{Where } \Delta V = \begin{cases} (V_i^{min} - V_i) & \text{if } V_i < V_i^{min} \\ (V_i - V_i^{max}) & \text{if } V_i > V_i^{max} \end{cases} \quad \text{.....(B-12)}$$

$$V_i = \frac{-BB - (BB^2 - 4AA.CC)^{1/2}}{4\ AA} \qquad \ldots.(B\text{-}13)$$

Variables AA, BB and CC are defined in equations [3.15] through [3,17] and are reproduced as equation (B-14) through (B-16)

$$AA = B_i + \sum_{j \in A(i)} B_{ij} \qquad \ldots.(B\text{-}14)$$

$$BB = \sum_{j \in A(i)} (G_{ij} \operatorname{Sin}(\theta_i - \theta_j) + B_{ij} \operatorname{Cos}(\theta_i - \theta_j)) V_j \qquad \ldots.(B\text{-}15)$$

$$CC = Q_{Gi} - Q_{Li} \qquad \ldots.(B\text{-}16)$$

B.2.1 DERIVATIVES OF OBJECTIVE FUNCTION w.r.t. X

On differentiating equation (B-11) w.r.t. X and using equation (B-12) through (B-16),

$$\frac{\partial f}{\partial X_i} = \left[\begin{array}{lll} 2.0(\Delta V_i) & ,\text{if } X_i = V_i & \\ 2.0(\Delta V_i)(\frac{\partial V_i}{\partial X_i}) & ,\text{if } X_i = Q_{Gi} & \text{and } V_i > V_i^{max} \\ 2.0(\Delta V)(\frac{\partial V_i}{\partial X_i}) & ,\text{if } X_i = Q_{Gi} & \text{and } V_i > V_i^{max} \end{array} \right.$$

$$\ldots i \in LV \qquad \ldots.(B\text{-}17)$$

Where, $\partial V_i / \partial X_i$ is obtained as equation (B-17) on differentiating equation w.r.t. $X_i = Q_{Gi}$ and using equation (B-14) through (B-16)

$$\frac{\partial V_i}{\partial X_i} = \frac{1}{2}(BB^2 - 4AA.CC)^{1/2}, \quad \text{if } X_i = Q_{Gi} \qquad \ldots.(B\text{-}18)$$

Using equation (B-18) in (B-17), equation (B-19) as

$$\frac{\partial f}{\partial X_i} = \begin{cases} 2.0(\Delta V_i) & ,\text{if } X_i = V_i \\ \dfrac{\Delta V_i}{(BB^2 - 4AA.CC)^{1/2}}, & \text{if } X_i = Q_{Gi} \text{ and } V_i > V_i^{max} \\ \dfrac{-(\Delta V_i)}{(BB^2 - 4AA.CC)^{1/2}}, & \text{if } X_i = Q_{Gi} \text{ and } V_i < V_i^{max} \end{cases}$$

$$i \in LV \qquad \ldots.(B\text{-}19)$$

Similarly

$$\frac{\partial f}{\partial X_j} = \begin{cases} \displaystyle\sum_{\substack{i \in A\,(j) \\ j = i}} 2.0\ (\Delta V_i)\ (\frac{\delta V_i}{\delta X_j}), & \text{if } X_j = V_j \text{ and } V_i > V_i^{max} \\ \displaystyle\sum_{\substack{i \in A\,(j) \\ j = i}} 2.0\ (\Delta V_i)\ (-\frac{\delta V_i}{\delta X_j}), & \text{if } X_j = V_j \text{ and } V_i > V_i^{min} \\ 0.0 & \text{if } X_j = Q_{Gi} \end{cases}$$

$$j = 1,\ldots,NLO$$

Where, $\partial V_i/\partial X_j$ is obtained on diferentiating equation (B-13) w.r.t. $X_j = V_j$ and using equations (B-14) through (B-16) as follows,

$$\frac{\partial V_i}{\partial X_j} = -\frac{1}{4AA}\left[\frac{\partial BB}{\partial X_j} + (BB^2 - 4AA.CC)^{1/2}.BB.\frac{\partial BB}{\partial X_j}\right] \qquad \ldots.(B\text{-}21)$$

Where,

$$\frac{\partial BB}{\partial X_j} = G_{ij}\text{Sin}(\theta_i - \theta_j) + B_{ij}\text{Cos}(\theta_i - \theta_j) \qquad \ldots.(B\text{-}22)$$

$$V_i = \frac{-BB - (BB^2 - 4AA.CC)^{1/2}}{4\ AA} \qquad \ldots..(B\text{-}13)$$

Variables AA, BB and CC are defined in equations [3.15] through [3.17] and are reproduced as equation (B-14) through (B-16)

$$AA = B_i + \sum_{j \in A(i)} B_{ij} \qquad \ldots.(B\text{-}14)$$

$$BB = \sum_{j \in A(i)} (G_{ij} \mathrm{Sin}(\theta_i - \theta_j) + B_{ij} \mathrm{Cos}(\theta_i - \theta_j)) V_j \qquad \ldots.(B\text{-}15)$$

$$CC = Q_{Gi} - Q_{Li} \qquad \ldots.(B\text{-}16)$$

B.2.1 DERIVATIVES OF OBJECTIVE FUNCTION w.r.t. X

On differentiating equation (B-11) w.r.t. X and using equation (B-12) through (B-16),

$$\frac{\partial f}{\partial X_i} = \left[\begin{array}{lll} 2.0(\Delta V_i) & ,\text{if } X_i = V_i & \\ 2.0(\Delta V_i)(\frac{\partial V_i}{\partial X_i}) & ,\text{if } X_i = Q_{Gi} & \text{and } V_i > V_i^{max} \\ 2.0(\Delta V\ )(\frac{\partial V_i}{\partial X_i}) & ,\text{if } X_i = Q_{Gi} & \text{and } V_i > V_i^{max} \end{array} \right.$$

$$\ldots\ i \in LV \qquad \ldots.(B\text{-}17)$$

Where, $\partial V_i / \partial X_i$ is obtained as equation (B-17) on differentiating equation w.r.t. $X_i = Q_{Gi}$ and using equation (B-14) through (B-16)

$$\frac{\partial V_i}{\partial X_i} = \frac{1}{2} (BB^2 - 4AA.CC)^{1/2}, \quad \text{if } X_i = Q_{Gi} \qquad \ldots.(B\text{-}18)$$

Using equation (B-18) in (B-17), equation (B-19) is obtained as

$$\frac{\partial f}{\partial X_i} = \begin{cases} 2.0(\Delta V_i) & ,\text{if } X_i = V_i \\ \dfrac{\Delta V_i}{(BB^2 - 4AA.CC)^{1/2}}, & \text{if } X_i = Q_{Gi} \text{ and } V_i > V_i^{max} \\ \dfrac{-(\Delta V_i)}{(BB^2 - 4AA.CC)^{1/2}}, & \text{if } X_i = Q_{Gi} \text{ and } V_i < V_i^{max} \end{cases}$$

$$i \in LV \qquad \text{....(B-19)}$$

Similarly

$$\frac{\partial f}{\partial X_j} = \begin{cases} \sum\limits_{\substack{i \in A(j) \\ j = i}} 2.0\ (\Delta V_i)\ (\dfrac{\delta V_i}{\delta X_j}), & \text{if } X_j = V_j \text{ and } V_i > V_i^{max} \\ \sum\limits_{\substack{i \in A(j) \\ j = i}} 2.0\ (\Delta V_i)\ (-\dfrac{\delta V_i}{\delta X_j}), & \text{if } X_j = V_j \text{ and } V_i > V_i^{min} \\ 0.0 & \text{if } X_j = Q_{Gi} \end{cases}$$

$$j = 1, \ldots, NLO$$

Where, $\partial V_i/\partial X_j$ is obtained on diferentiating equation (B-13) w.r.t. $X_j = V_j$ and using equations (B-14) through (B-16) as follows,

$$\frac{\partial V_i}{\partial X_j} = -\frac{1}{4AA}\left[\frac{\partial BB}{\partial X_j} + (BB^2 - 4AA.CC)^{1/2}.BB.\frac{\partial BB}{\partial X_j}\right] \qquad \text{....(B-21)}$$

Where,

$$\frac{\partial BB}{\partial X_j} = G_{ij}\text{Sin}(\theta_i - \theta_j) + B_{ij}\text{Cos}(\theta_i - \theta_j) \qquad \text{....(B-22)}$$

Using equation (B-21) and (B-22) in (B-20), equation (B-23) is obtained as,

$$\frac{\partial f}{\partial X_j} = \left[\begin{array}{ll} \sum\limits_{\substack{i \in A(j) \\ j = 1}} [-\Delta V_i/2AA)(G_{ij}.\mathrm{Sin}(\theta_i-\theta_j)+B_{ij}\mathrm{Cos}(\theta_i-\theta_j)) & \\ \quad (1+(BB^2 - 4AA.CC).BB)], & \text{if } X_j = V_j \text{ and } V_i > V_i^{max} \\ & \\ \sum\limits_{\substack{i \in A(j) \\ j = 1}} [\ \Delta V_i/2AA)(G_{ij}.\mathrm{Sin}(\theta_i-\theta_i)+B_{ij}\mathrm{Cos}(\theta_i-\theta_j)) & \\ \quad (1+(BB^2 - 4AA.CC).BB)], & \text{if } X_j = V_j \text{ and } V_i < V_i^{min} \\ & \\ 0.0 & \text{if } X_j = Q_{Gi} \end{array} \right.$$

$$j = 1,\ldots,NLO \qquad \ldots\ldots(B\text{-}23)$$

Equations (B-19) and (B-23) are used to calculate the derivatiatives of objective function w.r.t. X.

APPENDIX - C

C.1 POWER SYSTEM REPRESENTATION :

An electric power system consists of three principal components - the generating stations, the transmission lines, and the distribution systems. The transmission lines are the connecting link between all the generating stations and the distribution systems. The essential features of power system operation can be explained by means of a simple two - bus system shown in Fig. C.1.1. Each bus is being fed from generation units SG1 & SG2. Fig. C.1.1 shows the equivalent circuit of two bus system. The transmission line is represented by a π circuit.

An off-nominal transformer representation is described in Fig. C.1.3 and its equivalent circuit in Fig. C.1.4 . Note that, if the transformer ratio is a:1from bus p to q then transformer admittance Y_t is replaced by Y_t/a, a shunt admittance of $[\frac{(1-a)}{2} Y_t]$ is added at bus p and, a shunt admittance of $[\frac{(a-1)}{a} Y_t]$ is added at bus q.

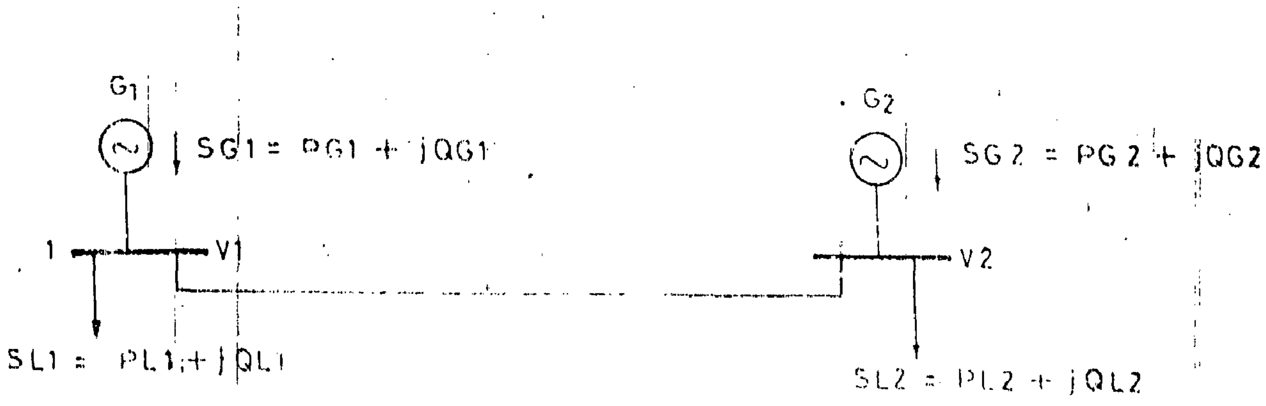


FIG. D.1.1 TWO BUS SAMPLE SYSTEM

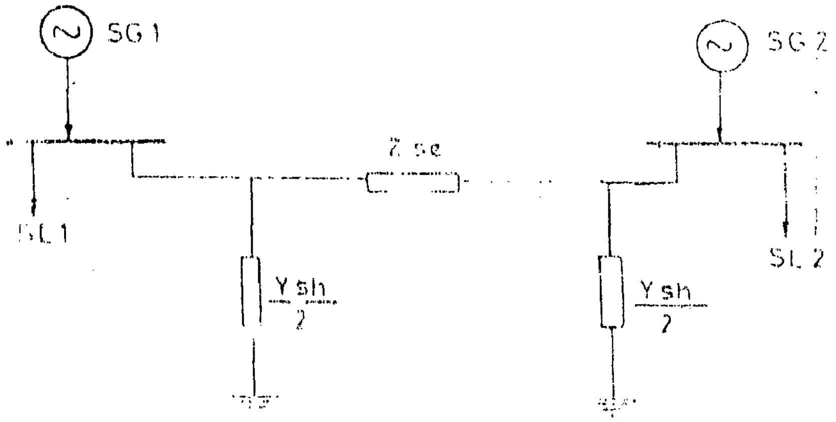


FIG D.1.2 EQUIVALENT CIRCUIT

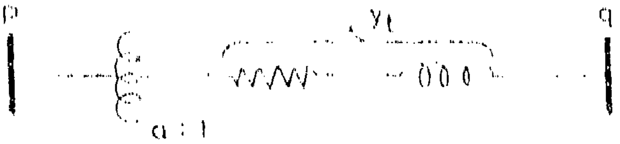


FIG. D.1.3 OFF NOMINAL TRANSFORMER REPRESENTATION

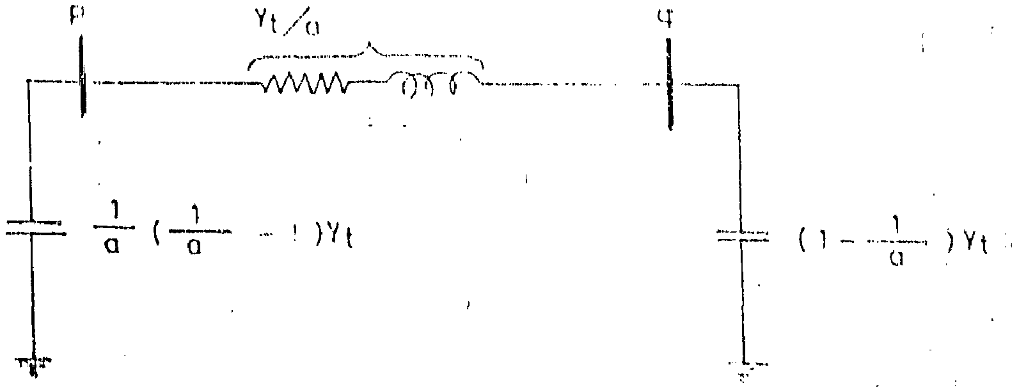


FIG. D.1.4 EQUIVALENT CIRCUIT OF OFF NOMINAL TRANSFORMER full refne

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