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Study of methods to predict voltage collapse

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ABSTRACT

STUDY OF METHODS TO PREDICT VOLTAGE COLLAPSE

by
Niki Patel

One of the problems that must be addressed for a secure power system operation is the voltage collapse problem. The ever increasing size and connectivity of the power grid have lead to making the problem more multifarious. Widespread blackouts, similar to the one that occurred in the northeast in August 2003, could result from failure to address the problem.

This thesis presents an overview of the voltage collapse problem and reviews some existing methods to calculate voltage collapse indicators.

Thevenin and Maximum Power Transfer Theorems are used to provide indicators of the proximity of the system to voltage collapse. The maximum power that could be transferred to a load node is predicted by these theorems and then the load at a load bus is gradually increased to determine the maximum constant power factor load that would result in voltage collapse.

The limitations of the presented method are discussed and a framework for quantifying its effectiveness is presented.

STUDY OF METHODS TO PREDICT VOLTAGE COLLAPSE

by
Niki Patel

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APPROVAL PAGE

STUDY OF METHODS TO PREDICT VOLTAGE COLLAPSE

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श्रीमत्परब्रह्म गुरुं स्मरामि
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श्रीमत्परब्रह्म गुरुं भजामि ॥ ८८ ॥

ब्रह्मानन्दं परमसुखदं केवलं ज्ञानमूर्तिं
द्वन्द्वातीतं गगनसदृशं तत्त्वमस्यादिलक्ष्यम् ।
एकं नित्यं विमलमचलं सर्वधीसाक्षिभूतं
भावातीतं त्रिगुणरहितं सद्गुरुं तं नमामि ॥ ८९ ॥

At the feet of my teachers with love and affection

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LIST OF SYMBOLS

R_L	Load resistance
X_L	Load reactance
Z_L	Load impedance
Z_S	Source impedance
P	Active power
Q	Reactive power
S	Apparent power
P_{load}	Active power delivered to load
Q_{load}	Reactive power delivered to load
S_{load}	Apparent power delivered to load
P_{gen}	Generated active power
Q_{gen}	Generated reactive power
R_t	Time Varying Resistance
P_o	Power Demand
P_{max}	Maximum Active Power
V_m	Magnitude of voltage at bus
V_{th}	Thevenin Voltage
Z_{th}	Thevenin Impedance

R_{th}	Thevenin Resistance
X_{th}	Thevenin Reactance
n	Total number of buses in a system
N	Set of all the buses in a system
N_L	Set of all load buses in a system
n_l	Total number of load buses in a system

All symbols with an over bar indicate complex numbers.

CHAPTER 1

INTRODUCTION

1.1 Objective

The objective of this thesis is to review some methods to predict voltage collapse in the power system, analyze them and address some of the limitations these method projects.

1.2 Background Information

In this era of increasing dependency on electricity, it is very important to have a constant, uninterrupted system. The cost to the society of a major power outage could be in billions of dollars. The present day power supply is more complex than ever before and hence its operation in an economic and secure fashion offers the engineer formidable problems. Among these problems is maintaining a stable voltage profile to avoid loss of stability and voltage collapse.

1.2.1 Voltage Collapse

Voltage collapse can be defined as the rapid and uncontrollable drop of bus voltage due to increase in load at a bus or group of busses, generally characterized by inadequate reactive support in a high-load area. Voltage collapse could be caused also by a sudden change in the system, such as a line outage.

With the rest of the system conditions remaining unchanged, if the load at a particular bus is varied, the voltage at that bus will also vary. Also, the node voltage at other buses varies due to this change in load. Hence, it can be said that, voltage at a load bus is partially dependent on the power delivered to that node. This power can be broken into segments of active and reactive powers and hence the equations can be stated as: $\frac{\partial V}{\partial P}$ and $\frac{\partial V}{\partial Q}$, where P is active power, Q is reactive power and V is the voltage at that node. These last expressions cannot be expressedly evaluated because V cannot be expressed as an analytic function of P and Q.

It is really hard to predict a voltage collapse as it has similar characteristics as that of a voltage drop due to alteration of operating condition. The main symptoms of voltage collapse are low bus voltages, flow of more reactive power, and shortage of reactive support as well as heavy load on the system. Therefore, a proper diagnosis of the underlying factors causing low voltage is very important. The consequences of a voltage collapse is system outage as it often takes a long while to restore the system and a large area remains without supply for some time.

1.2.2 Voltage Stability

Many a times, the term voltage collapse and voltage instability are overlooked as a similar phenomenon. At this point, it is necessary to make a statement clarifying the thin line of difference between the two terms. In a power system, there might be disturbances created leading to a gradual decrease in voltage profile at various buses. This is termed as voltage instability, while voltage collapse is an unfeasible value of voltage whose magnitude is decreasing fast. Voltage instabilities might lead to voltage collapse. In fact it can be said that, during a disturbance caused in the power system, there is a point in time where the voltage becomes uncontrollable. This shows that actual voltage collapse may occur later than occurrence of Voltage instability.

1.2.3 Importance in Present Day Scenario

As mentioned in IEEE committee paper, 'Voltage Collapse Mitigation – Report to IEEE Power System Relaying Committee' [1], the problems associated with voltage control are not new for the power system industry but the problems in the past were primarily associated with the transfer of power from remote generation sites to load centers. These problems were addressed by specific control and / or protection schemes dedicated to the particular transmission system.

From the 1990s, the combined effects of inter-utility power transfers, wholesale wheeling (an arrangement in which electricity is transmitted from a generator to a utility through the transmission facilities of an intervening system) and difficulty in building new transmission facilities have resulted in operating transmission systems closer to their voltage or reactive limits. Interestingly, voltage control problems are now appearing in more tightly meshed transmission systems and over wide areas. Maintaining adequate network voltage with reduced transmission margins has become a major source of vulnerability for many interconnected systems.

Voltage instability is a threat to utility sector in both developed as well as developing countries as it takes several hours to be restored to a normal system imparting a great monetary as well as non-monetary loss.

1.3 Assessment of Voltage Collapse

To assess voltage collapse, there are two main categories: Static and Dynamic. There are different events that affect the speed and probability of voltage collapse. A few of them are equipment outages or faults due to equipment outages, load disturbances, etc.

Load disturbances can either be fast like a sudden outage of a large block of load or slow, gradual random load fluctuation. The slow load fluctuation can be treated as a static phenomenon as the voltage changes in small discrete steps of steady states while the fast load change as well as equipment outage or faults due to it are to be counted in the dynamic phenomenon.

The disturbances that require dynamic analysis are leading causes for transient instability but they may cause voltage instability only if the voltage values after the disturbance are low, the transient voltage dips are too long or the voltage equilibrium attained after the disturbance is unstable and adding any reactive power support that that bus will lower the voltage at that bus.

1.4 Brief Account of Voltage Collapse Indicators

Static simulators are usually used for planning and operating purposes to determine things like reactive support requirements as well as system loading capabilities. Time domain simulations are also used for voltage stability analysis.

Earlier, to investigate voltage unstable conditions, attempts were made to improve the solution of static load flow programs applied to heavily loaded power systems having low voltage profiles. At higher loads and near to the point of voltage collapse there is no real steady state solution to load flow; hence it was difficult to arrive at a solution. Table 1.4 shows two different voltage magnitude and delta results for the same operating conditions with different initial estimates, proving that multiple solutions exists for power flow results. Also, looking at these sets of voltage magnitudes and delta values, it shows that those are just analytical results and does not lie in the voltage stability region for it to have practical possibility of such system. Later, it was observed that the dual solutions in a 2-Bus system (i.e., two voltage profiles for same operating conditions) converge to a single point beyond which it becomes impossible to solve power flow.

Table 1.1 Multiple Solutions of a Load Flow Analysis

Bus	**V_m initial**	**V_m solution**	**V_m initial**	**V_m solution**
1	1.06	1.06	1.06	1.06
2	**-0.562**	-0.0057	1.057	0.9835
3	1.055	1.0198	**-0.098**	0.0104
4	1.019	0.8845	1.019	0.8955
5	1.02	0.8818	1.02	0.8728
6	1.05	0.9854	1.05	0.7295
7	1.062	0.8246	1.062	0.9509
8	1.036	0.7587	1.036	0.7919
9	1.056	0.6475	1.056	0.9199
10	1.051	0.4407	1.051	0.9285
11	1.045	1.045	1.045	1.045
12	1.01	1.01	1.01	1.01
13	1.07	1.07	1.07	1.07
14	1.09	1.09	1.09	1.09

As stated in IEEE committee paper, 'Voltage Collapse Mitigation – Report to IEEE Power System Relaying Committee' [1], certain early indicators used the distance between these two solution points as an indicator of proximity to voltage collapse. The distance decreases as the point of maximum permissible load approaches. This paper used the Voltage – Power (VP) diagram shown in Figure 1.1 to explain the method.

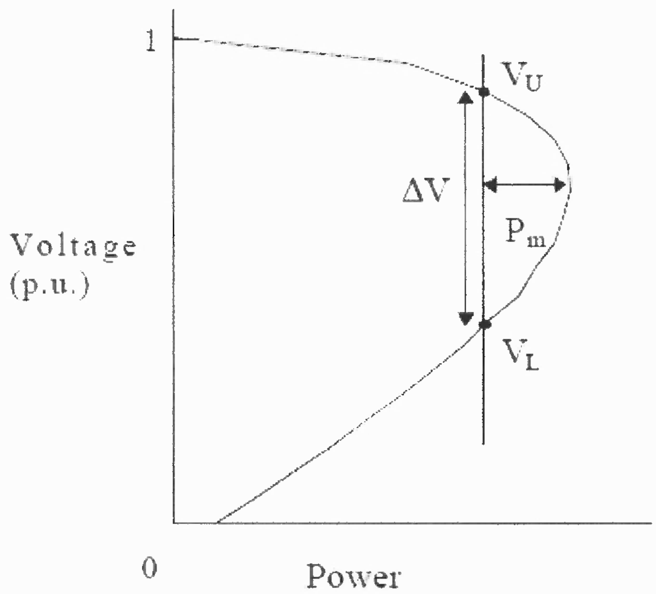

Figure 1.1 Voltage – Power diagram.

The VP curves do not take into consideration the reactive power component of the load. To include the reactive component a third dimension is added as shown in Figure 1.2.

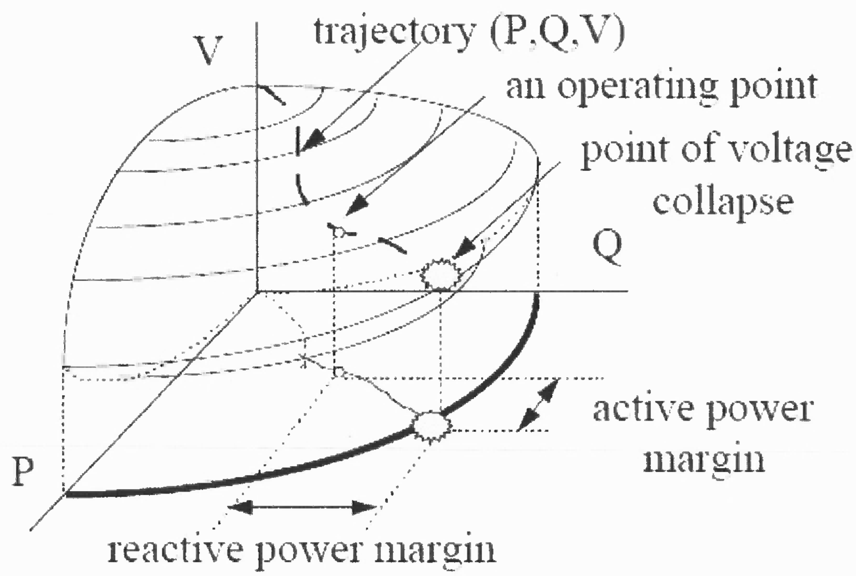

Figure 1.2 Voltage – Power diagram including reactive power.

It was observed that there are many possible trajectories and various points of voltage collapse. Also the active and reactive power margins depend on the initial operating point and the trajectory leading to collapse. Numerous other attempts have been recorded to find more accurate voltage collapse proximity indicators. Most of them are based on measuring a state and deriving certain parameters which indicate the stability or closeness to instability of that system.

Although it is useful to derive parameters based on measurements of system conditions to avoid situation where a voltage collapse might occur, it is difficult to calculate the system condition and derive parameters in real time. The derivation and analysis of these parameters need to be very rapid to initiate corrective actions fast enough to avoid collapse under emergency conditions which arise due to sudden equipment failure or fast load change.

As pointed by IEEE committee paper, 'Voltage Collapse Mitigation – Report to IEEE Power System Relaying Committee' [1], to avoid the above mentioned problem, it is advisable to have a few critical parameters which can be directly measured to quickly indicate proximity to collapse in real time. For example, the sensitivity of the generated reactive powers with respect to the load parameters can be used as an indicator. As the system approaches collapse, small increase in load results in large increase in reactive power absorption which is to be supplied by dynamic sources of reactive power in that region. At the point of collapse, the rate of change of generated reactive power at key sources with respect to load increases at key buses tends to infinity. This sensitivity matrix can be calculated in off-line studies but could be a problem in real time applications because of the need of system wide measurement information. The norm of such a sensitivity matrix represents a useful proximity indicator but it is still relatively difficult to interpret. It is not the generated reactive power, but its derivatives with respect to loading parameters which becomes infinite at the point of imminent collapse.

One of the other directly measuring indicators are power margins themselves – margins of active or reactive power on an individual bus or may be a group of buses when a restricted number of load parameters are allowed to freely change. If the system is stable, any additional reactive power will increase the voltage and any decrease in it will decrease the voltage. The system would be most stable at light loads where there is chance of additional load increase before the reserves of reactive power gets exhausted. For loads with requiring the reactive load equal to the reactive reserve of the system, the voltage is marginally stable. For heavy loads, there is need of additional reactive power to be injected in the system to allow the voltage to be balanced and the system to be stable. Hence, the measure of the reactive reserve available in a system gives an indication of the margin between stability and instability.

It is impossible to directly measure the reactive reserve in a system, but there are a few methods which can estimate the reserve available. Out of this, one method is to find the dynamic sources of reactive power supply that is playing a significant role in supporting the voltage in a specific area that may be subject to voltage collapse. One may also compute the significance of dynamic sources, measure their unused Var capability and compute the reserve reactive power from it.

Most of the systems do not take into account the operating limits such as reactive power generation limits, loads which are sensitive to voltage, etc.

Short term load forecasting techniques might also be used in order to access the most likely direction of the load changes and corresponding margins.

Other method, commonly used is to monitor low voltage area for a prolonged period. Actions such as tap changing or load shedding are taken under such conditions. Although the limitation of this method is that the low voltage will persist over a complete region, this method is widely used for years and has been reliable. However, it is rare condition to be in danger of imminent voltage collapse and hence, experience under a wide variety of system conditions is not available.

Monitoring the limiters would also give an indication of impeding collapses as when reactive power limiters on generators or synchronous condensers operate to maintain the machines within their capabilities these machines could not do any more to support system voltage. Also, when system studies define the critical reserves and levels, measurement of remaining reserves can give a dependable warning of the approach of voltage instability.

CHAPTER 2

REVIEWING EXISTING METHODS

The first step towards developing a method for predicting a voltage collapse situation is to study the existing methods and the problems associated with those methods.

The paper, presented by T.K. Abdul Rahman and G. B. Jasmon, 'A new technique for voltage stability analysis in power system and improved loadflow algorithm for distribution network' [2], gives an idea of a new technique to determine the static voltage stability of load buses in a power system for a certain operating condition and hence identifies the load buses which are close to voltage collapse.

A voltage stability index with respect to a load bus is formulated from the voltage equation derived from a two bus network and it is computed using Thevenin equivalent circuit of the power system referred to a load bus. This index indicates how far the load buses are from their voltage stability limits and hence identifies the critical buses.

They have listed the following methods for stability analysis:

- Using reduced system model to derive voltage stability for stressed power station.
- Developing line stability factors to identify critical lines.
- Voltage stability index from minimum singular value of the power flow Jacobian matrix.
- Space theory: Identifying the phenomenon of voltage collapse and bifurcation points from singularity of the power flow Jacobian matrix.
- Using the Thevenin equivalent circuit with respect to the load bus concerned and applying the concept of maximum power transfer theorem, a voltage collapse proximity indicator is derived from the ratio between the load impedance and the Thevenin impedance in the equivalent circuit.

The voltage stability factor is derived from the voltage equation for a two bus network which is computed by applying it to a Thevenin equivalent circuit looking across each load bus.

Buses with values of voltage stability factors close to 1.0 are identified as the critical buses.

For deriving the mathematical formulation for the voltage stability index, the voltage equation derived from improved distflow loadflow technique is used. Disflow is a technique which uses set of recursive equations for estimating the power loss reduction due to branch exchange in a radial network. It does not require admittance matrix calculation & also takes less iteration to converge. For deriving this equation, a two bus model is used and then it is extended to a generalized form. This voltage equation is as follows:

$$V_{i+1} = \left[\frac{2(P_{i+1} r_i + Q_{i+1} X_i) - V_i^2}{2}\right] + \sqrt{\frac{\left[2(P_{i+1} r_i + Q_{i+1} X_i) - V_i^2\right]^2 - 4(P_{i+1}^2 + Q_{i+1}^2)(r_i^2 + X_i^2)}{2}} \tag{1.1}$$

From the above voltage equation as well as using the basic power flow equations, the load flow index L is derived. Its equation is as follows:

$$L = 4[V_i V_{i+1} \cos(\theta_i - \theta_{i+1}) - V_{i+1}^2 \cos(\theta_i - \theta_{i+1})^2] / V_i^2 \tag{1.2}$$

L must be kept less than 1.0 to maintain voltage stability. If L exceeds 1.0, the voltage at the referred bus becomes imaginary which indicates that voltage collapse has occurred in the system.

Also, from the maximum power transfer theorem, it can be derived that to maintain a secure system at load bus i, the ratio $Zs / Z_L \leq 1.0$.

In the paper, Can voltage security indices predict voltage collapse problems in large-scale power networks?, the writer R. Fischl and F. Mercede [3], points out that there are number of methods like evaluating steady state instability; load flow infeasibility; static bifurcation of equilibria; dynamic bifurcation of the stability region; and multiple load flow solutions. These methods use some type of Voltage Collapse Indicator which can be generalized as a function of measureable variables, reference values and their weights.

The paper gives the necessary conditions for a voltage collapse indicator to indicate the collapse effectively. The steady state operating point as well as the dynamic operating point both should be taken into consideration.

They conclude that Voltage collapse indicator cannot predict the voltage collapse correctly because in order to correctly identify the voltage collapse phenomenon, it is necessary that the non-linear dynamic model should include pertinent generator and load component models, such as models for generator flux decay effects and voltage regulator dynamics, automatic tap changing under load (TCUL) transformers and any other relevant load dynamics.

The type of voltage collapse phenomenon the indicator predicts depends on whether the steady state operating point or the dynamic operating point is considered.

In the paper, "Voltage Collapse Proximity Indicator: Behavior and Implications" the authors, A.M. Chebbo, M.R. Irving and M.J.H. Sterling [4], considers the problem of voltage stability and investigates a proposed voltage collapse proximity indicator applicable to the load points of a power system. The indicator is based on optimal impedance solution of 2-Bbus system.

The indicator so proposed is generalized and applied to an actual system. Finally, the performance of this new indicator is investigated over both the stable and the unstable regions, as the load at a particular node or the system load increases.

The paper shows a study of various methods proposed like use of convergence in Newton Raphson Load flow calculations to estimate voltage stability limit, using indices to estimate how far a given operating condition is from the voltage stability limit, load voltage stability margin, reactive power margins, voltage to load sensitivity, generation to load sensitivity, minimum singular value of the Jacobian matrix of the power flow equations as a global voltage stability index as well as generalized eigen value approach.

Some limitations of all these methods were also studied. Based on the computational procedures, the methods suffer from the following drawbacks:

- Some methods use the quantitative results of the two bus theory, which is not always true for multiple generators model
- Few methods do not take into account the reactive power generation limits
- Repeated load flow calculations is time consuming as well as it might be inadequate due to the potentially unreliable behavior of load flow algorithms in the vicinity of voltage collapse. It is linked to the singularity of the Jacobian matrix; a fact related to the existence of close multiple load flow solutions.

Next, the paper presents the problem formulation for two bus system. The evaluation is limited to study of the phenomenon of voltage collapse associated with operation at a limit of the maximum power to be transmitted.

The maximum power transferred to the load is obtained when $\frac{\partial Pi}{\partial Zi} = 0$, which corresponds to $\frac{Zl}{Zs} = 1$.

This approach is generalized to an actual network with the aid of Thevenin's theorem. A general conclusion about the conditions for maximum power transfer is drawn. Any network of linear elements and energy sources (and, approximately, any real generator and its associated circuitry) can be represented by a series combination of an ideal voltage *V* and an impedance *Z*. In the simplest case, these are the open circuit generator voltage *V*, and the Thevenin's equivalent impedance of the network *Z*,. For a network with *n* buses, the Thevenin's equivalent impedance looking into the port between bus *i* and the ground is $Zii\ angle\ \beta i$ .Therefore, at load bus *i*, the Thevenin's equivalent impedance is $Zii\ angle\ \beta i$ and therefore for permissible power transfer to the load at bus *i* it must have

$$\frac{Z_{ii}}{Z_i} \leqslant 1 \tag{2.1}$$

The collapse of the system at load bus *i* occurs when the impedance of the load is equal to the equivalent impedance looking into the port between bus *i* and the ground. Basically, for a secure system the condition is as shown in Equation 2.1.

Z_{ii} / Z_i was therefore taken as the measure of voltage stability at node *i*.

The method use to investigate the proposed indicator was:

1. Compute a load-flow solution at the operating point to obtain the system power and voltage profile;

2. Linearise the system load and generator active and reactive powers, by representing them as shunt elements with appropriate signs;

3. Evaluate the admittance matrix [Y] and invert it to obtain the impedance matrix [Z];

4. Determine the Thevenin impedance seen at node *i* (Z_{it});

5. Determine the voltage collapse proximity indicator (Z_{ii} / Z_i);

6. Evaluate the predicted critical power and critical voltage;

7. Increase system loading, run the load-flow program; if divergence occurs, then stop; otherwise go to step (2).

The testing was conducted under the following conditions:

- Without limitations on the reactive-power output of the generators

- With limitations on the reactive-power output of the generators

- With limitations on the reactive power output of the generators, and with artificially increased line charging and reactive-power sources.

The conclusion drawn from the tests were:

- At light loads the voltage collapse proximity indicator behaves nearly linear with the load; as the load increases, non-linearity starts to appear.
- The actual voltage curve and critical voltage curve intercept each other, or tend to interception at the predicted critical point.
- The value of indicator does not indicate the amount of voltage level to collapse, but the value of predicted critical power and critical voltage at that point can give a true indication of how far is it from collapse.
- The critical power prediction is acceptable and very accurate for single-load change and is an approximation for system – load change.

For single – load change the accuracy of predicted critical power improves as the load increases and the prediction is very accurate in the vicinity of the critical power. Also, additional reactive resources lead to a higher critical power and critical voltage and the indicator provides increasingly accurate predictions as reactive resources become exhausted.

For system – load change the voltage collapse indicator gives more accurate prediction for unlimited case. The more reactive power that can be injected into the system to overcome reactive power of the load, the better the prediction becomes. The critical power predicted is less accurate than for the single – load change, and the voltage collapse proximity indicator is more sensitive over the operating region.

In the IEEE Transaction paper 'Use of Local Measurements to Estimate Voltage - Stability Margin' by Khoi Vu, Miroslav M. Begovic, Damir Novosel and Murari Mohan Saha, it has been shown that for a given power transfer at the most two voltage solutions exists as the phasor equation is quadratic.

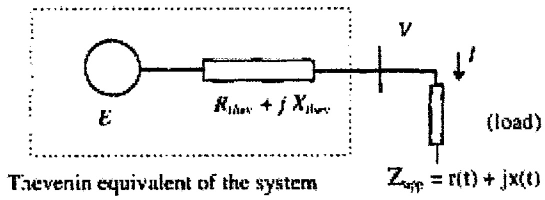

Figure 2.1 Local bus and the rest of the system treated as a Thevenin equivalent, source [7].

It was shown that if one of the solutions is $\bar{V}$ then the other solution will be the conjugate of $(\bar{E} - \bar{V})$. At Maximum Power Transfer, the two solutions become equal and from that came the equation,

$$\overline{Z_{app}}\,\bar{I} = (\overline{Z_{th}}\,\bar{I})^* \qquad (2.2)$$

A further increase in power demand would yield no solution. From Equation 2.2 it is clear that,

$$|Z_{app}| = |Z_{th}| \qquad (2.3)$$

Equation 2.3 is one of the essential conditions for Equation 2.2 to be true, but it is not the only condition for Equation 2.2. to be valid. In short, Equation 2.3 occurs when the power is maximum, but Equation 2.3 alone might not always deliver maximum power.

Z_{app}, the apparent impedance, is the ratio between voltage and current phasors measured at that bus. Equation 2.3 holds true regardless of the load characteristics. $|Z_{th}|$ is plotted as a circle and the second part of the equation Z_{app} separates the load plane into two regions. As the load varies, Z_{app} traces a path in the plane. When the Z_{app} point crosses thevenin circle, voltage instability occurs. Therefore, they proved that to know the closeness to a voltage collapse point, one has to calculate the distance of Z_{app} (of present time) to the Thevenin circle.

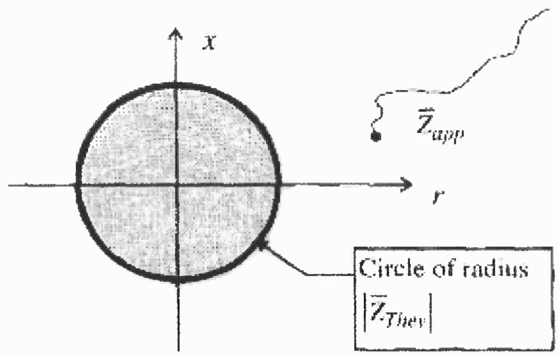

Figure 2.2 Maximum power is reached when the apparent impedance of the load bus hits the Thevenin Circle, Source [7].

They also point out that although this theme has its own merit and is unique as it is tailored for relay application and involves only local measurements, but it requires all network information and so can be only implemented at control center with communication link to sub-stations. Also, in an actual dynamic power-system, voltage collapse can occur before the maximum power transfer static limit has been arrived at.

CHAPTER 3

LOAD FLOW ANALYSIS

3.1 MULTIPLE SOLUTION OF LOAD FLOW PROBLEM

Although, voltage collapse is a dynamic phenomenon, it can be treated as static problem if the parameters of the system change slowly. Hence load flow calculations have been one of the most used methods to determine proximity to voltage collapse.

Normally, if Newton - Raphson method is used, the iterative solution is arrived at in a few iterations and hence a limit on the maximum number of iterations is defined to be somewhere around 20. For a real power system, with large number of unknowns, the iterations do not converge in the defined number of iterations to be tried and a solution is not achieved. This does not always mean that the system failed or is out of stability. In the power flow program used, if maximum number of iteration was reached for a certain operating condition, it was then tried to get a solution with higher number of iterations. When the number of iterations was increased, solution was achieved, although not always acceptable.

The non-linear load flow equations can provide multiple solutions. Usually, only one of the solutions corresponds to stable operating point in the system and others corresponds to unstable operating points of equilibrium which are analytically possible but practically they are not feasible in real power system operation.

In intention to prove the above mentioned fact, the loads at certain buses were increased gradually. The maximum number of allowable iterations was also kept much higher. The results were monitored. Each load increase would provide an analytically possible solution. Although the voltages obtained so were of values not feasible in a real power system.

3.1.1 Example with 14-Bus System to Show Multiple Solutions

Load at Bus 4 in the 14-Bus system was increased gradually and the voltage magnitude as well as angle delta were plot against the multiplier (the amount of load increase). The result is as shown in Figure 3.1. The procedure was repeated with another set of initial values and the result thus obtained is shown is Figure 3.2 showing a new set of solution at high load values.

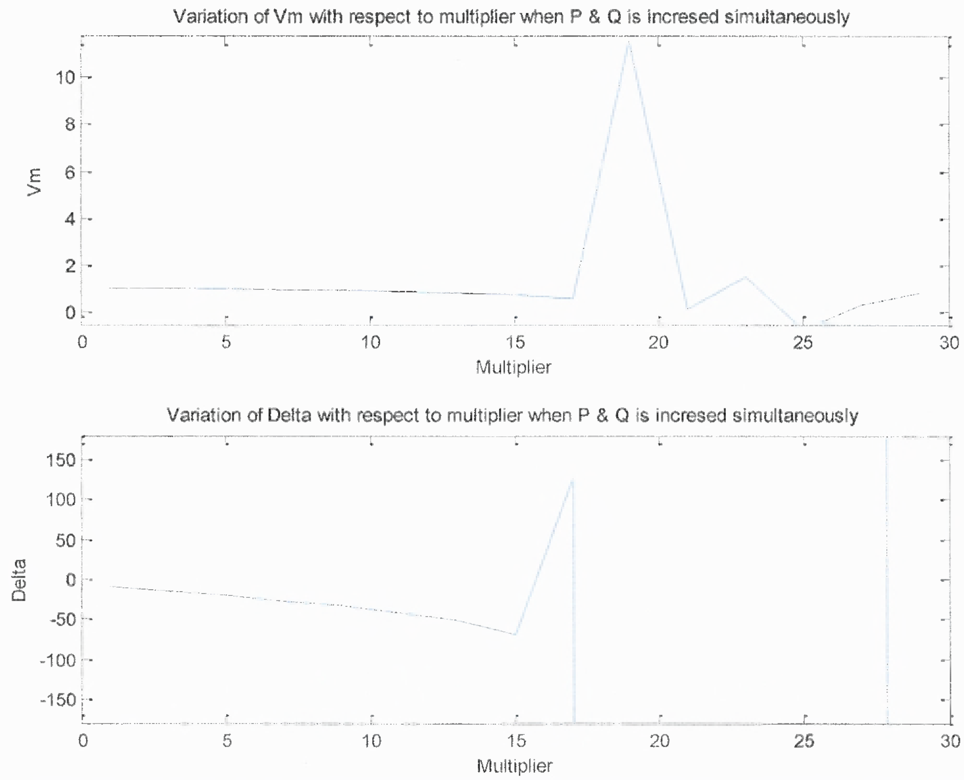

Figure 3.1 Depicting divergence of Load Flow solutions at large load at Bus 4 in a 14-Bus system.

Figure 3.1 also shows how the solutions diverge from the set of solutions obtained at lower loads. It proves the fact that at large loads the voltages go out of range of the stability. After the point of maximum load, that Bus 4 is able to withstand without the voltage going out of the practically possible range of values, the next solution obtained by load flow is an unreasonable value of voltage. It shows that at unreasonable loads, the solution of load flow also becomes unreasonable.

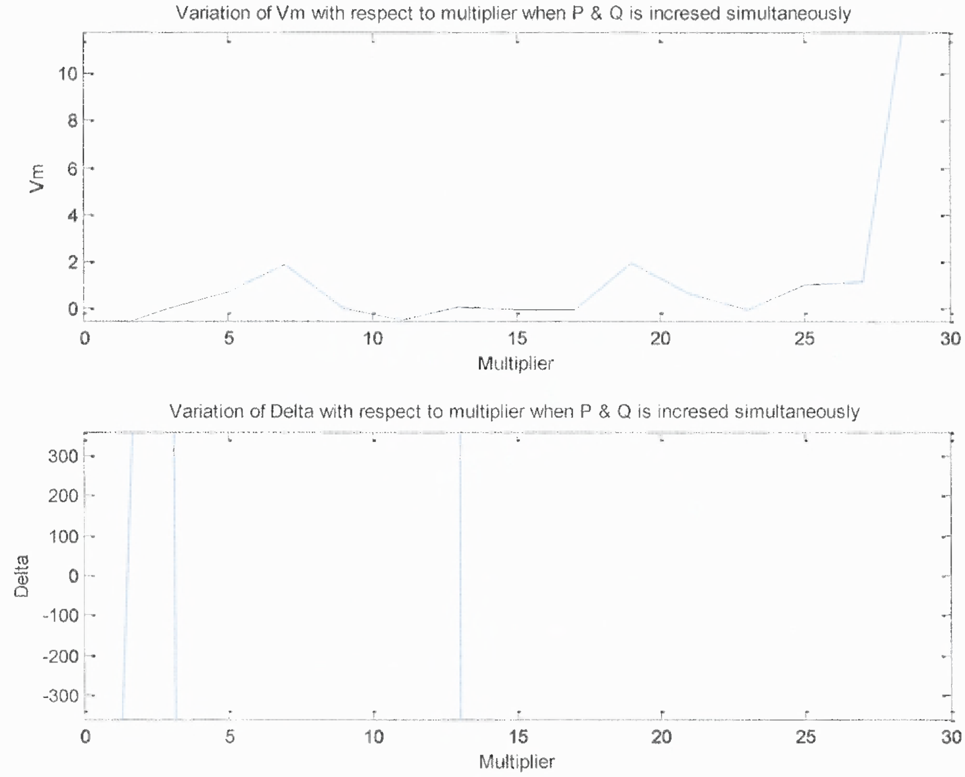

Figure 3.2 Depicting existences of multiple unreasonable solutions with unreasonable starting values for Load Flow.

3.1.2 Example with 14-Bus System to Impractical Solutions for Unreasonable Initial Values

Figure 3.1 and Figure 3.2 also show that, if the initial estimated values of bus voltages are changed to unreasonable values, the result obtained with same loads (operating condition) are different, proving the fact that load flow has multiple solutions in multi-dimensional model.

Table 3.1 Unreasonable Solution of Load Flow Analysis for Unreasonable Initial Values

V_m-Initial values	V_m-LF Solution	V_m- Initial values	V_m-LF Solution
1.06	1.06	1.06	1.06
1	13.2389	0.67	-225.6458
0.992	-0.5517	1	49.5939
-0.78	-1.1987	-0.35	-13.8823
-0.95	2.5983	1	-19.8699
1	-0.0049	-1	21.3069
0.578	1.1491	0.98	-19.5107
1	0.1406	-0.743	-9.3394
-0.87	-1.7833	1	-60.0208
1	-6.2082	1	-100.2786
1.045	1.045	1.045	1.045
1.01	1.01	1.01	1.01
1.07	1.07	1.07	1.07
1.09	1.09	1.09	1.09

The fact can also be proven using Table 3.1. The load was made 10,000 times the initial value and so the number of iterations that took to attain the following results were also very high. The first two columns show a certain initial estimates (unreasonable values) and the solution obtained thereafter. The 3rd and the 4th column show another set of unreasonable initial estimates for the same operating conditions and its corresponding load flow solution (at about 10,000 times the initial load). Both the solutions obtained are unreasonable, but proves the fact that there are multiple solutions of a load flow analysis.

3.2 Finding Maximum Limit for Load that a Bus Can Deliver

Both P and Q were increased by a factor on each bus. The attempts lead to the conclusion that, the voltage at the bus, whose load was increased, decreased the most. The voltage values at other buses are affected negligibly. The decrease was more dramatic as the voltage stability margins were reached. The delta values increased too with the increase in load. A few of the results for certain buses are shown in the Table 3.2 through Table 3.7 as well as the graphs are shown in Figures 3.3 to 3.5. The base case load at Bus 4, Bus 6 and Bus 10 are multiplied by the multiplying factor shown one by one in each case.

Table 3.2 The Solution Voltage Vector V_m in p.u. for Increase in Load at Bus 4 in 14-Bus System

Multiplying factor	**1**	**2**	**5**	**10**	**14**	**15**	**16**
Bus							
1	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600
2	1.0453	1.0438	1.0383	1.0245	1.0027	0.9897	0.0025
3	1.0531	1.0529	1.0521	1.0499	1.0463	1.0441	0.0110
4	**1.0282**	**1.0214**	**0.9960**	**0.9299**	**0.8215**	**0.7550**	**-0.0986**
5	1.0351	1.0297	1.0083	0.9475	0.8416	0.7751	-1.3059
6	1.0464	1.0458	1.0438	1.0389	1.0312	1.0266	0.5891
7	1.0458	1.0425	1.0307	1.0002	0.9507	0.9206	0.5585
8	1.0180	1.0158	1.0078	0.9875	0.9553	0.9359	0.3977
9	1.0285	1.0251	1.0128	0.9816	0.9320	0.9021	-0.3320
10	1.0283	1.0254	1.0150	0.9888	0.9472	0.9221	0.0293
11	1.0450	1.0450	1.0450	1.0450	1.0450	1.0450	1.0450
12	1.0100	1.0100	1.0100	1.0100	1.0100	1.0100	1.0100
13	1.0700	1.0700	1.0700	1.0700	1.0700	1.0700	1.0700
14	1.0900	1.0900	1.0900	1.0900	1.0900	1.0900	1.0900

Table 3.3 The Solution Delta Vector in Degrees for Increase in Load at Bus 4 in 14-Bus System

Multiplying factor	**1**	**2**	**5**	**10**	**14**	**15**	**16**
Bus							
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	-15.22	-17.68	-25.54	-41.33	-61.22	-71.64	-41944.61
3	-15.72	-18.12	-25.76	-41.21	-60.82	-71.17	-49488.48
4	**-10.39**	**-13.11**	**-21.77**	**-39.10**	**-60.72**	**-71.92**	**-40557.82**
5	-8.98	-11.10	-17.84	-31.22	-47.54	-55.70	-2786.34
6	-15.74	-18.15	-25.83	-41.33	-60.96	-71.30	-48371.28
7	-13.47	-16.10	-24.50	-41.31	-62.31	-73.19	-61133.06
8	-16.40	-18.92	-26.92	-43.01	-63.23	-73.79	-37022.34
9	-15.09	-17.67	-25.91	-42.42	-63.04	-73.75	-98768.27
10	-15.33	-17.88	-26.00	-42.29	-62.68	-73.29	-85819.08
11	-4.95	-6.14	-9.97	-17.67	-27.09	-31.69	-4366.43
12	-12.61	-14.68	-21.32	-34.75	-51.48	-59.96	15391.17
13	-14.88	-17.26	-24.85	-40.21	-59.71	-70.01	-50164.97
14	-13.47	-16.10	-24.50	-41.31	-62.31	-73.19	-61133.06

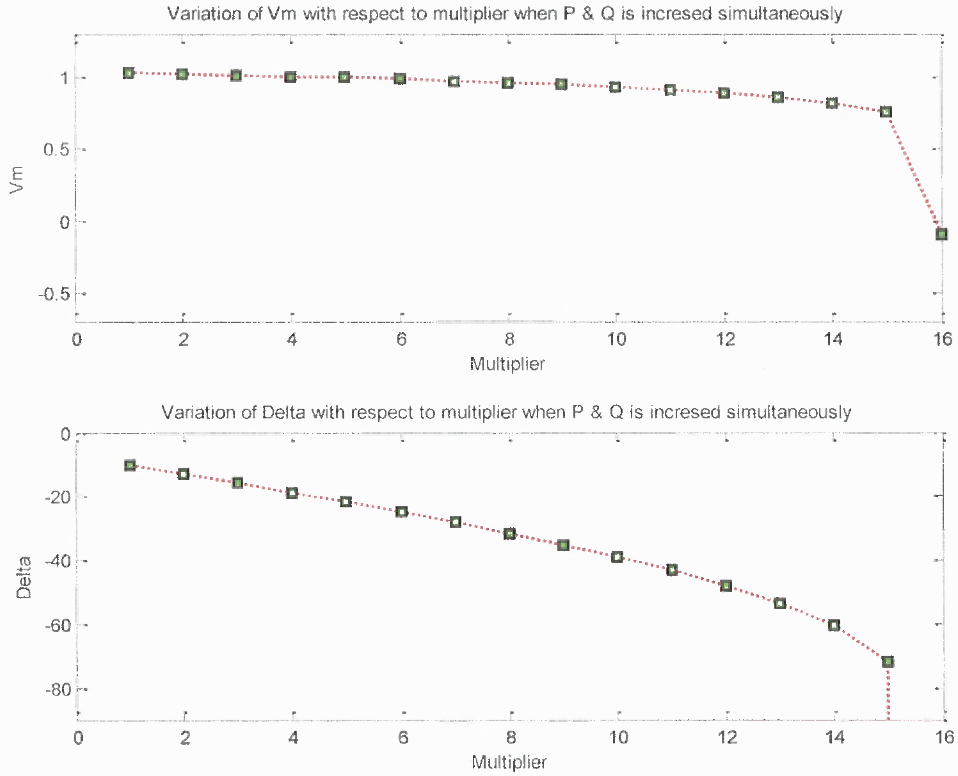

Figure 3.3 Variation of V_m and Delta with increase in P & Q simultaneously at Bus 4 for 14-Bus system.

Table 3.4 The Solution Voltage Vector V_m in p.u. for Increase in Load at Bus 10 in 14- Bus System

Multiplying factor	**1**	**2**	**5**	**10**	**17**	**18**	**19**
Bus							
1	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600
2	1.0453	1.0387	1.0173	0.9738	0.8683	0.8300	-0.9323
3	1.0531	1.0526	1.0509	1.0472	1.0379	1.0343	-0.0168
4	1.0282	1.0256	1.0168	0.9989	0.9567	0.9425	-0.0007
5	1.0351	1.0329	1.0255	1.0103	0.9739	0.9616	1.0478
6	1.0464	1.0452	1.0415	1.0337	1.0141	1.0069	-0.0190
7	1.0458	1.0415	1.0275	0.9980	0.9232	0.8957	0.0000
8	1.0180	1.0133	0.9976	0.9650	0.8824	0.8516	-0.0139
9	1.0285	1.0212	0.9969	0.9465	0.8191	0.7715	0.0676
10	**1.0283**	**1.0157**	**0.9748**	**0.8924**	**0.6943**	**0.6227**	**-0.1300**
11	1.0450	1.0450	1.0450	1.0450	1.0450	1.0450	1.0450
12	1.0100	1.0100	1.0100	1.0100	1.0100	1.0100	1.0100
13	1.0700	1.0700	1.0700	1.0700	1.0700	1.0700	1.0700
14	1.0900	1.0900	1.0900	1.0900	1.0900	1.0900	1.0900

Table 3.5 The Solution Delta Vector in Degrees for Increase in Load at Bus 10 for 14-Bus System

Multiplying factor	**1**	**2**	**5**	**10**	**17**	**18**	**19**
Bus							
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	-15.22	-16.34	-19.82	-26.32	-39.21	-42.94	57619.62
3	-15.72	-16.66	-19.60	-25.12	-36.26	-39.59	28066.66
4	-10.39	-10.84	-12.24	-14.76	-19.23	-20.33	18326.96
5	-8.98	-9.39	-10.67	-12.99	-17.24	-18.34	-805.36
6	-15.74	-16.69	-19.65	-25.18	-36.30	-39.59	29396.93
7	-13.47	-14.34	-17.04	-21.98	-31.23	-33.66	825109.52
8	-16.40	-17.44	-20.69	-26.74	-38.78	-42.28	173815.24
9	-15.09	-16.18	-19.61	-25.98	-38.57	-42.18	150859.31
10	**-15.33**	**-16.65**	**-20.82**	**-28.73**	**-45.40**	**-50.70**	**371940.57**
11	-4.95	-5.17	-5.85	-7.09	-9.36	-9.94	7151.68
12	-12.61	-12.99	-14.15	-16.27	-20.19	-21.21	30798.58
13	-14.88	-15.80	-18.69	-24.11	-35.07	-38.35	28295.59
14	-13.47	-14.34	-17.04	-21.98	-31.23	-33.66	825109.52

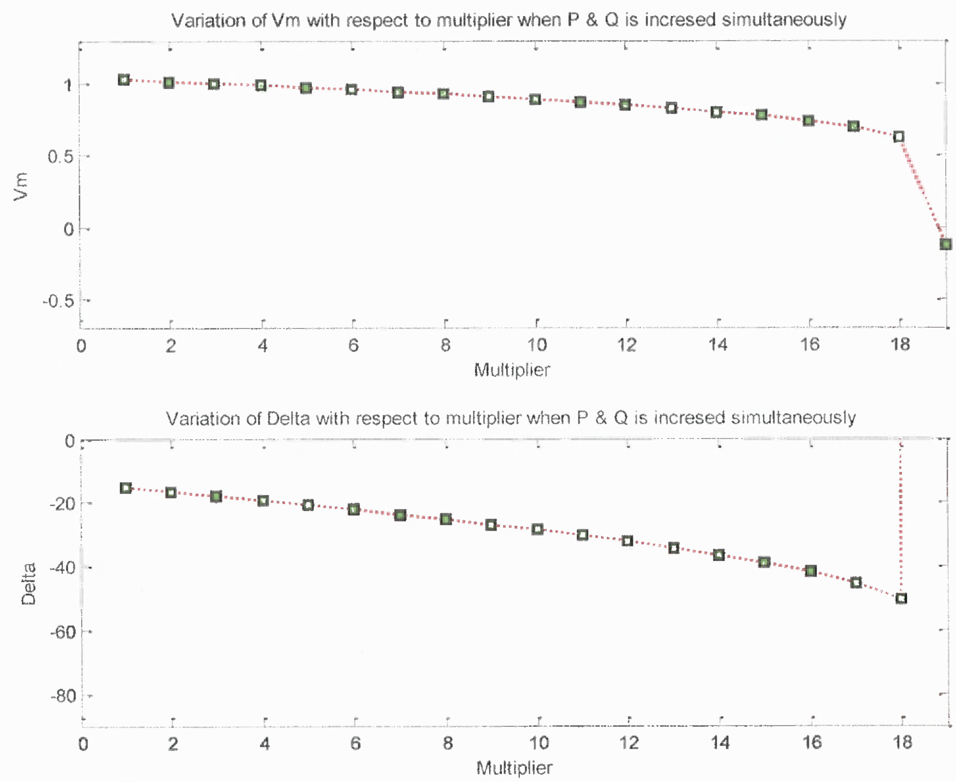

Figure 3.4 Variation of V_m and Delta with increase in P & Q simultaneously at Bus 10 in 14-Bus system.

Table 3.6 The Solution Voltage Vector V_m in p.u. for Increase in Load at Bus 6 in 14-Bus System

Multiplying factor	**1**	**2**	**5**	**10**	**18**	**19**	**20**
Bus							
1	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600	1.0600
2	1.0453	1.0451	1.0435	1.0374	1.0036	0.9890	-0.1476
3	1.0531	1.0481	1.0321	0.9996	0.9113	0.8872	-0.0095
4	1.0282	1.0260	1.0181	0.9998	0.9336	0.9096	-61.9248
5	1.0351	1.0325	1.0233	1.0017	0.9222	0.8929	-33.9306
6	**1.0464**	**1.0349**	**0.9980**	**0.9253**	**0.7350**	**0.6846**	**-4.8436**
7	1.0458	1.0446	1.0401	1.0278	0.9757	0.9557	0.0101
8	1.0180	1.0123	0.9929	0.9497	0.8097	0.7652	-10.9814
9	1.0285	1.0275	1.0232	1.0096	0.9457	0.9205	21.6309
10	1.0283	1.0276	1.0241	1.0127	0.9556	0.9322	12.5122
11	1.0450	1.0450	1.0450	1.0450	1.0450	1.0450	1.0450
12	1.0100	1.0100	1.0100	1.0100	1.0100	1.0100	1.0100
13	1.0700	1.0700	1.0700	1.0700	1.0700	1.0700	1.0700
14	1.0900	1.0900	1.0900	1.0900	1.0900	1.0900	1.0900

Table 3.7 The Solution Delta Vector in Degrees for Increase in Load at Bus 6 in 14-Bus System

Multiplying factor	**1**	**2**	**5**	**10**	**18**	**19**	**20**
Bus							
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	-15.22	-16.81	-21.84	-31.52	-57.16	-64.84	-126215.49
3	-15.72	-17.81	-24.43	-37.11	-70.19	-79.86	-144347.83
4	-10.39	-11.06	-13.16	-17.15	-26.89	-29.46	-65969.61
5	-8.98	-9.63	-11.71	-15.63	-25.17	-27.65	-185672.40
6	**-15.74**	**-17.98**	**-25.06**	**-38.64**	**-74.12**	**-84.44**	**-119249.11**
7	-13.47	-14.51	-17.80	-24.07	-39.95	-44.41	-208241.13
8	-16.40	-18.09	-23.39	-33.41	-58.59	-65.67	-769173.24
9	-15.09	-16.32	-20.23	-27.67	-46.69	-52.12	-146365.15
10	-15.33	-16.68	-20.93	-29.06	-50.20	-56.37	-52881.33
11	-4.95	-5.28	-6.30	-8.26	-13.10	-14.38	-8861.96
12	-12.61	-13.14	-14.83	-18.06	-26.20	-28.42	9241.08
13	-14.88	-16.72	-22.55	-33.76	-63.56	-72.49	-121049.89
14	-13.47	-14.51	-17.80	-24.07	-39.95	-44.41	-208241.13

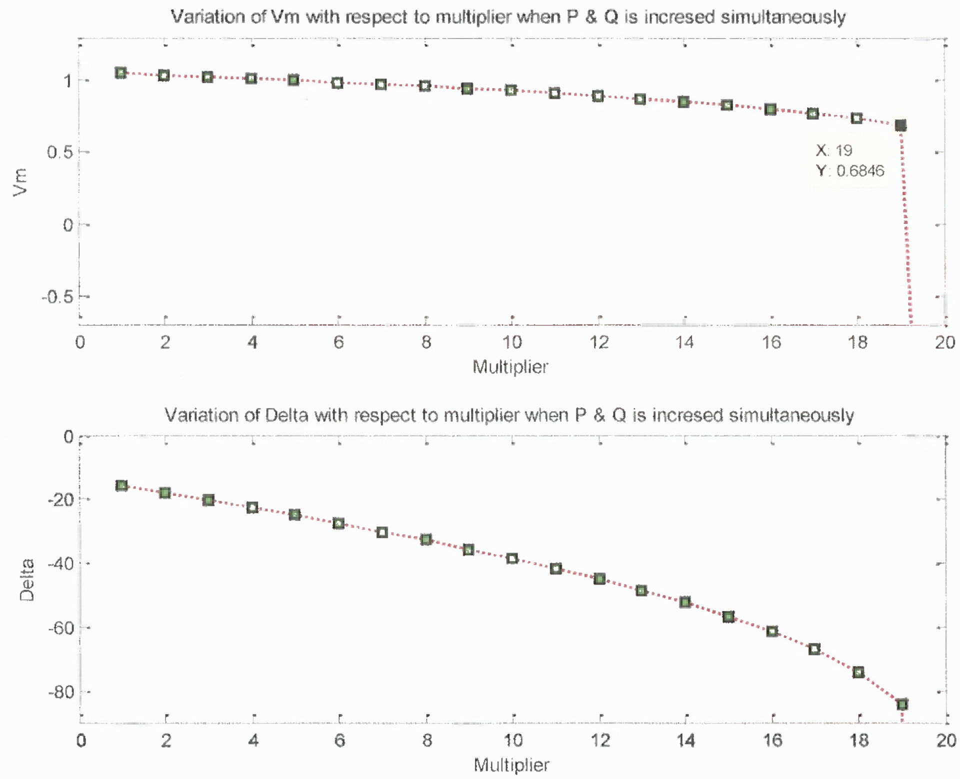

Figure 3.5 Variation of V_m and Delta with increase in P & Q simultaneously at Bus 6 in 14-Bus system.

3.3 Restricting the Load Flow Solutions in the Range of Voltage Stability

When the load flow was conducted keeping the same operating conditions with high load values and different initial voltage values, the results showed that the load flow calculations led to a new set of voltage values each time. All these values were unacceptable for an actual power system.

These unstable solutions included certain lower voltage solution usually showing voltage instability as well as few higher voltage solutions with angles shifted by 180 degrees related to angle instability.

It should also be noted that the point where the voltage goes below stability limit arises before the point where the power flow solutions diverge from their normal trajectory. Also at this point, even though the solution converges, it takes a large number of iterations to give the solution. This also proves the need of having a check on the voltage limits in the power flow program to ensure voltage stability and to give results which are practically possible.

It is now important to alter the load flow program by a criterion which would lead to solutions which are acceptable and practically feasible. Therefore, limits of +/- 20% change on the voltage values were imparted on the iterative solutions. Using this program, attempt was made to find out the load limits at every bus, by manually increasing the load at a bus each time until the point of divergence or voltage instability was reached. The Matlab program for the power flow with voltage limits is shown in Appendix D.

3.4 Dependency of Voltage Solutions on P_{load} and Q_{load}

An attempt was made to check the dependency of voltage values on active and reactive loads individually. Hence using the same program as in Appendix D, only active load values and then only reactive load values were modified. These were increased until the point voltage stability limits were reached. The results were again as expected. Voltage fell out of the stability limit of 0.8 p.u. and 1.2 p.u. as loads were increased or it could be said that as power delivered by the bus increased beyond the capacity, the voltage fell below stability limits.

The limit where individually only active power delivered was increased, was much higher than when just reactive power delivered was increased. It is because of the fact that voltage values are majorly governed by reactive power than by active power. AC systems are dominated by reactance and there is a close connection between voltage control and reactive power, but active and reactive powers both share the leading role in the effect on the voltage values.

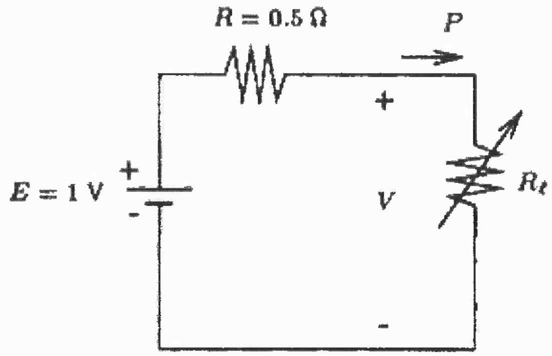

Figure 3.6 DC System, source [5].

For normal operating conditions, the coupling between active power and phase angles as well as reactive power and voltage magnitudes holds perfectly true. However, it is not completely extendable to extreme loading conditions such as voltage instability scenarios. A wonderful example is given in the book, 'Voltage stability of electric power systems' by Thierry Van Custem, Costas Vournas [5], to illustrate there is no "cause and effect" relationship between reactive power and voltage instability. They considered a system as shown in figure 4.1 made up of a DC voltage source E feeding through a line resistance R and a variable load resistanceR_t. It was assumed that R_t varies automatically with the help of a control device, so as to achieve a power consumption setpoint P_o . From the well known theorem of Maximum power transfer, the maximum power that could be transferred to the load corresponds to the condition $R_t = R$ and is given by $P_{max} = \frac{E^2}{4R}$

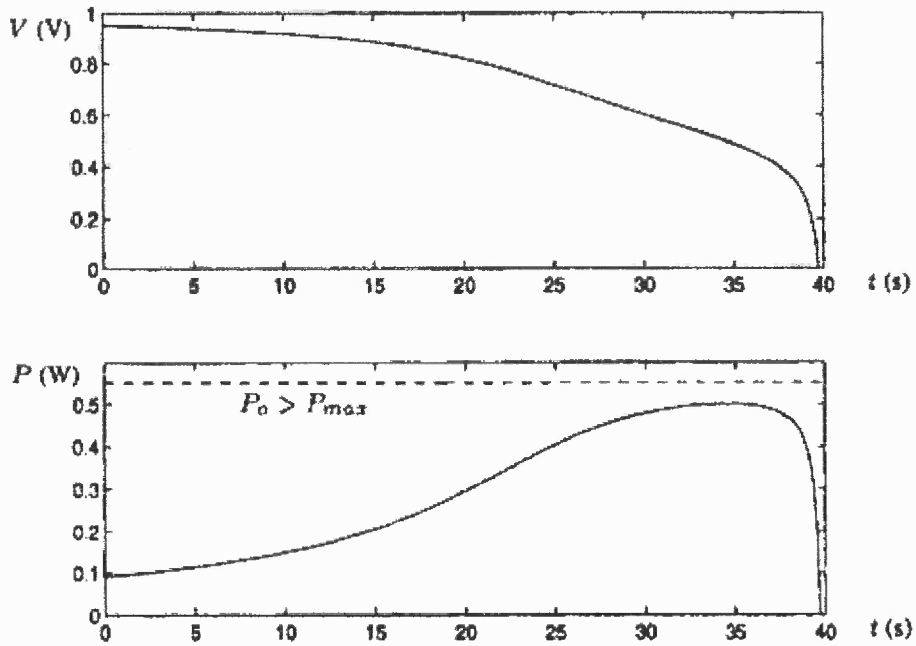

Figure 3.7 Voltage instability in a DC system, source [5].

If the demand P_o is made larger than P_{max} the load resistance will decrease below R and voltage instability will result after crossing the maximum power point. A typical simulation for this case was also shown as in Figure 4.2

The simple exemplar has the major characteristic of voltage instability, although it does not involve reactive power. Hence as concluded in [5], in the actual AC power system, reactive power makes the picture much more complicated but it is certainly not the only source of problem.

Also, for a bus (Bus 4 for the 14-Bus system in appendix A) since reactive power was injected i.e., negative value of reactive power load, the voltage increased instead of decreasing when the reactive power injection was increased. A further increase in the reactive power injection led the voltage at that bus to rise above voltage limit (1.2 p.u.). The results showing the effects as discussed are formulated in the following graphs.

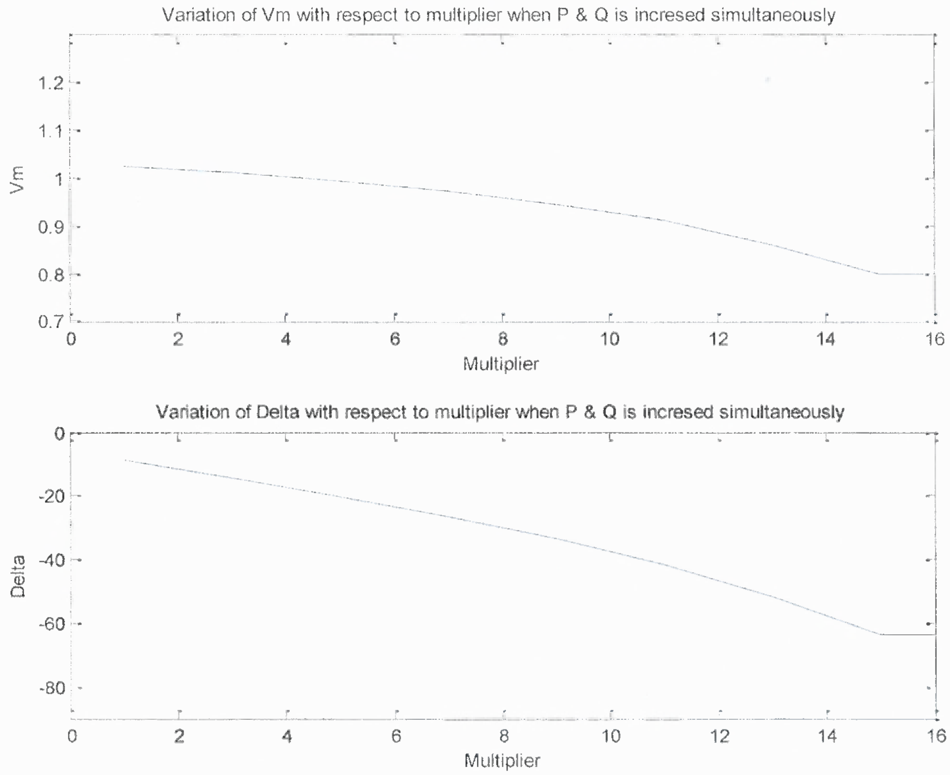

Figure 3.8 Effect of increasing active and reactive power both simultaneously on voltage magnitudes and delta at Bus 4 with voltage limits applied.

When active and reactive power both are increased by a common multiplying factor simultaneously, the maximum power that could be delivered to the load before the voltage goes beyond stability limits is 669.2 – j54.6 MVA.

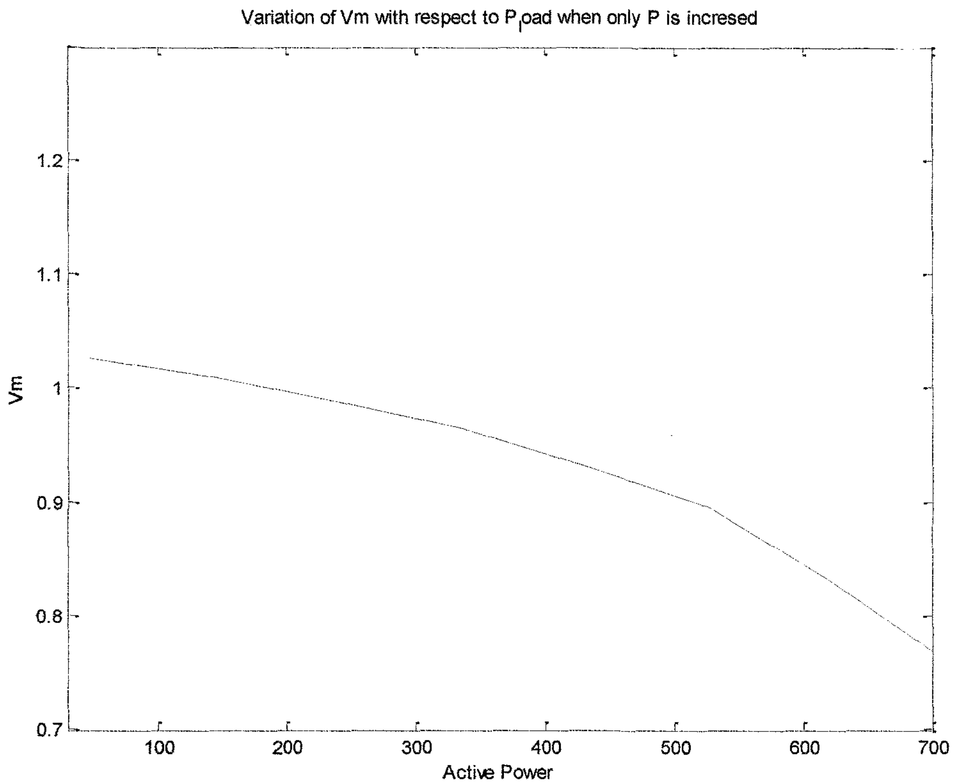

Figure 3.9 Effect of increasing only active power on the voltage magnitudes at Bus 4 with voltage limits applied.

When only active power was increased, with a constant reactive power of - 3.9 Mvar, the maximum active power that could be delivered to load in the voltage stability region was 621.4 MW.

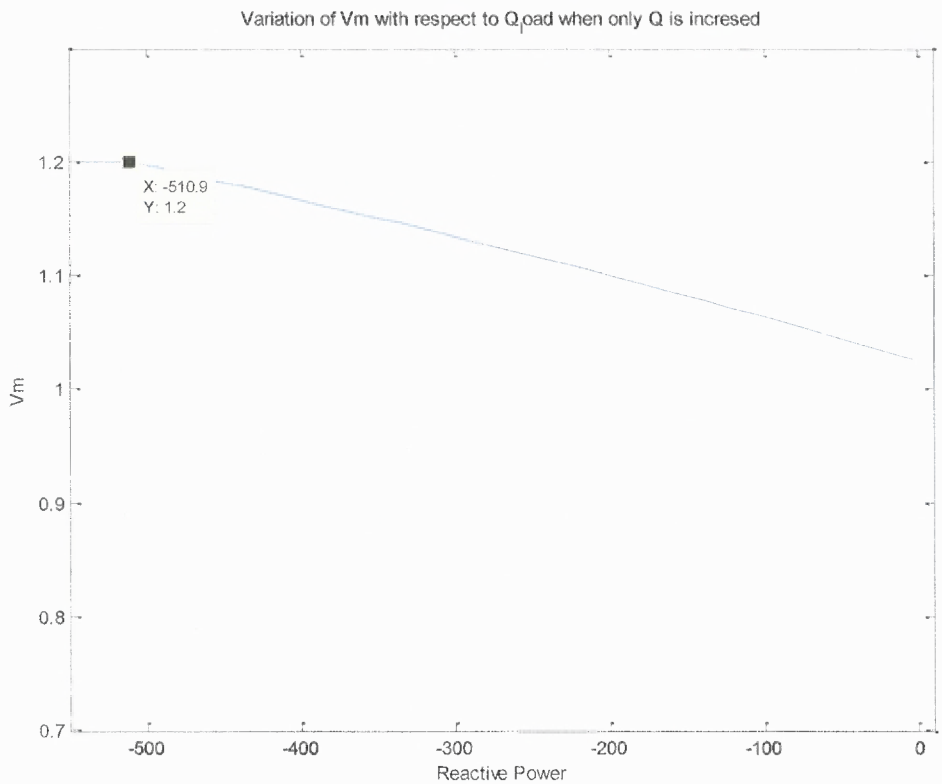

Figure 3.10 Effect of increasing only reactive power on voltage magnitude at Bus 4 with voltage limits applied.

Similarly, the maximum reactive power that could be injected at the bus without disturbing the voltage stability and delivering a constant active power of 47.8 MW is -491.4 Mvar. Note that the negative sign is because reactive power was injected at this bus.

3.5 Results for Increasing Both P and Q for All Buses Simultaneously

In practical systems, loads do not vary on a single bus at a time, but there will be random increase or decrease at various buses of the system. The worst case will be increase of load at all buses simultaneously. To see the effect of such an increase, the load (Both P and Q) was increased simultaneously on all buses gradually. The figure below shows the variation of V_m at all load buses for the 14-Bus system with respect to the multiplier – the factor by which the load is increased.

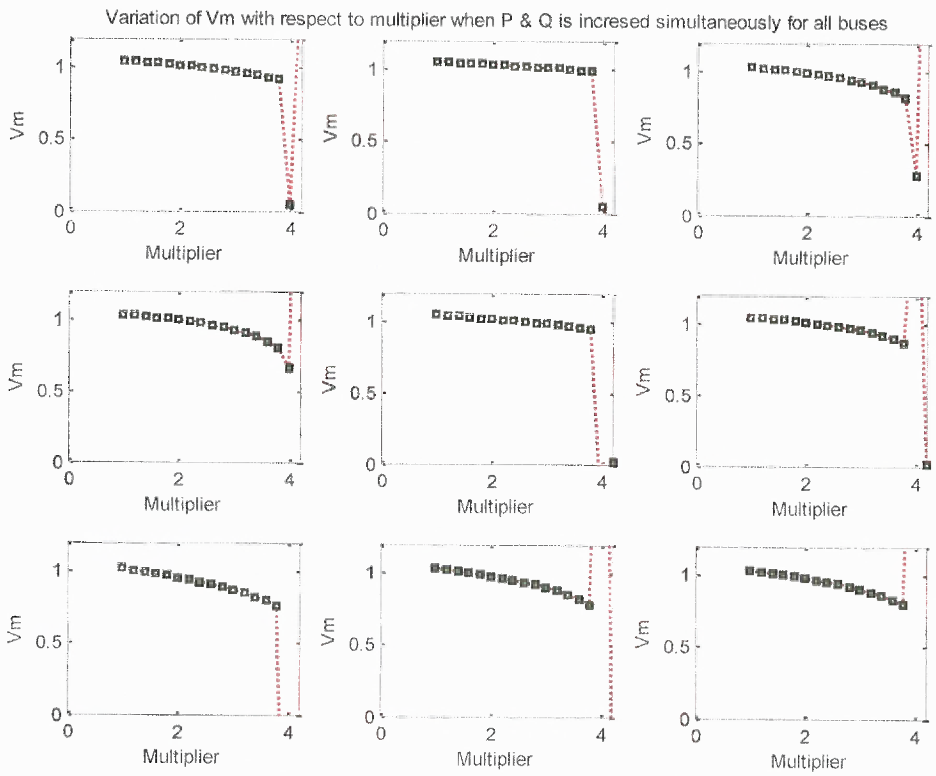

Figure 3.11 Variation of V_m with respect to the multiplier when P and Q both are increased simultaneously for all load buses in a 14-Bus system.

The results show that the curve diverges at very slight increase in load. When load was varied on a single bus at a time, the load limits achieved at those buses were in range of 9 to 61 times the initial system load given in the data, while in this case with simultaneous increase, the system collapses just with an increase of about 3 to 4 times the actual load of the system. This can be summarized with the Table 4.7

Table 3.8 Comparison Between the Breakdown Point with Increase in Load at Single Bus and at All Buses Simultaneously

Bus K	**Multiplier when the system collapses with load increase on Bus K**	**Multiplier when the system collapses with load increase on all bus simultaneously**
2	61	4
3	30	4
4	16	4
5	81	4
6	20	4
8	9	4
9	9	4
10	19	4

The Bus 7 has been omitted in the table as it has zero ‘0’ load in the system data and hence when load was increased in multiples of system data load, the load on Bus 7 was still '0'. The bus voltage at Bus 7 drops because of the loads on other buses showing dependency of all variables on each other.

It is evident from the above discussion that, in practical system, the case may vary from increase in just a single bus at a time to all bus at a time. Hence the maximum load that a bus can deliver varies between 4 times to about 60 times.

CHAPTER 4

Z-THEVENIN APPROACH

One of the methods to calculate an index for knowing voltage collapse point is using Maximum power transfer theorem.

The maximum power transfer theorem states that, to obtain maximum external power from a source with a finite internal resistance, the resistance of the load must be made the same as that of the source.

The maximum power transfer theorem can be extended to AC circuits with reactance. The condition achieved for that is Z-load = Z-thevenin*.

$$\overline{Z_{load}} = (\overline{Z_{thevenin}})^* \tag{4.1}$$

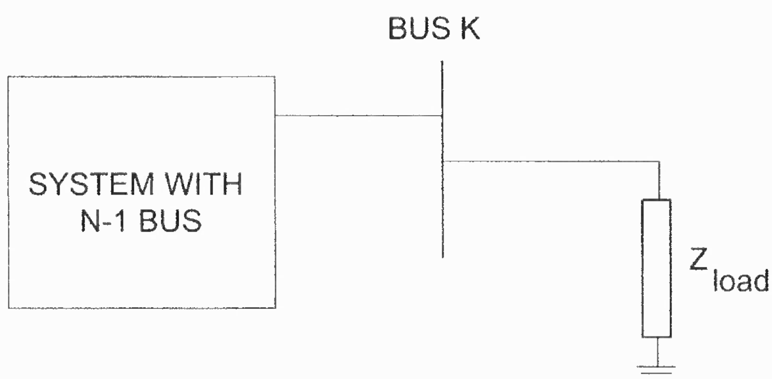

Figure 4.1 System for Calculating Z-thevenin at Bus K.

4.1 Algorithm for Calculating Z-Thevenin of the System with respect to a Load Bus

1. Assume the load at the bus being considered, Bus K = 0;

2. Get Y-bus, V_m and delta using load flow analysis with linedata and the modified busdata of step 1;

3. Get S_{load} (KVA) in rectangular form;

4. Represent the load at every load bus except Bus K by an admittance
$Y_{load} = S / V_m^2$;

5. Modify Y_{ii}, $i \in N_l$, $i \neq K$, such that $Y_{ii} = Y_{ii} + Y_{load(i)}$;

6. Delete the axes corresponding to all generator buses including the slack bus;

7. Invert to get Z-bus with load.

8. Z-thevenin for Bus K is Z_{KK}.

9. Repeat steps 1 to 8 for all buses in the set N_l.

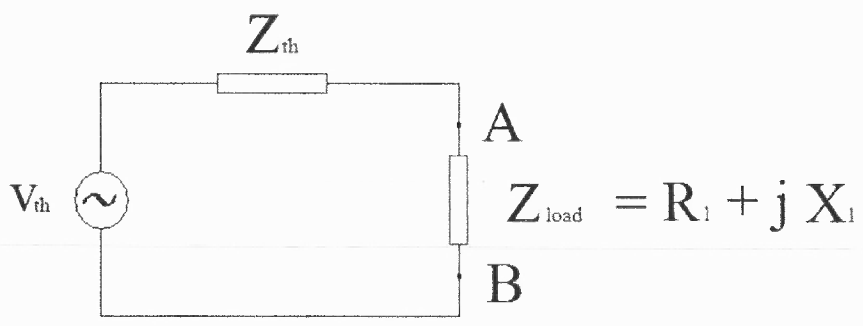

Figure 4.2 Thevenin Equivalent Circuit for System in Figure 4.1.

A study verifying the above algorithm was carried out with 14-Bus system and the results are as shown in Table 4.1. The Matlab program used to find Z-thevenin is provided in Appendix G.

Table 4.1 Z-thevenin Values for Load Buses of 14-Bus System

Load Bus No	**Z-thevenin**
2	0.0578 + 0.1345i
3	0.0913 + 0.1443i
4	0.0112 + 0.0419i
5	0.0105 + 0.0433i
6	0.0487 + 0.0895i
7	0.0077 + 0.0806i
8	0.0922 + 0.2110i
9	0.0198 + 0.1087i
10	0.0443 + 0.1426i

4.2 Applying Maximum Power Transfer Theorem

According to the Maximum Power Transfer Theorem, the conjugate of the Z-thevenin values obtained in Table 4.1 was used as load at that particular bus to calculate the power. The apparent power S-load is the power between nodes A and B in figure 4.2.

For the condition in Equation 4.1, the equation for S_{load} can be written as,

$$S_{load} = P_{load} + jQ_{load} = \frac{{V_{th}}^2 {Z_{th}}^*}{(Z_{th} + {Z_{th}}^*)^2} \tag{4.2}$$

Also, power factor for the same could be found out as,

$$p.f. = \frac{P_{load}}{S_{load}} = \frac{R_{th}}{|Z_{th}|} \tag{4.3}$$

The results obtained are shown in Table 4.2. The Matlab commands are presented as part of Z-thevenin program in Appendix G.

Table 4.2 P_{load} and Q_{load} Values Obtained for Load Z-thevenin*

Load Bus No	P_{load}	Q_{load}	Power Factor
2	4.7719	-11.1119	0.3946
3	3.1030	-4.9050	0.5346
4	23.6042	-88.1150	0.2588
5	25.2650	-103.8902	0.2363
6	5.7380	-10.5397	0.4782
7	35.6348	-374.7277	0.0947
8	2.9592	-6.7701	0.4005
9	14.0370	-77.0992	0.1791
10	6.1138	-19.6588	0.2970

CHAPTER 5

CONSTANT POWER FACTOR CONCEPT

5.1 Extending Maximum Power Transfer Theorem to Constant Power Factor Concept

The Maximum Power Transfer concept gives maximum P_{load} values possible for the system to supply at a particular bus. What about Q_{load}? The power factor values so obtained are also not possible for a practical system. To take into account the above matters, the load that can be delivered by a bus was found by considering constant load power factor. The condition for maximum power transfer under constant power factor is derived below.

For,

$$cos\emptyset = constant \tag{4.4}$$

$$Z_{Load} = R_l + jX_l = R_l(1 + tan\emptyset) \tag{4.5}$$

$$I^2 = \frac{V_{th}{}^2}{(R_{th} + R_l)^2 + (X_{th} + R_l tan\emptyset)^2} \tag{4.6}$$

$$P_{load} = I^2 R_l \tag{4.7}$$

$$P_{load} = \frac{{V_{th}}^2 R_l}{(R_{th} + R_l)^2 + (X_{th} + R_l tan\emptyset)^2} \tag{4.8}$$

For P_{load} to be maximum,

$$\frac{\partial P_{load}}{\partial R_l} = 0 \tag{4.9}$$

$$\Rightarrow \frac{{V_{th}}^2[(R_{th} + R_l)^2 + (X_{th} + R_l tan\emptyset)^2] - {V_{th}}^2 R_l[\,2(R_{th} + R_l) + 2(X_{th} + R_l tan\emptyset)tan\emptyset}{[(R_{th} + R_l)^2 + (X_{th} + R_l tan\emptyset)^2]^2} = 0 \tag{4.10}$$

$$\Rightarrow {R_{th}}^2 + {X_{th}}^2 = {R_l}^2 + {R_l}^2 tan\emptyset^2 \tag{4.11}$$

$$\Rightarrow R_l = |Z_{th}| cos\emptyset \tag{4.12}$$

$$P_{load} = I^2 |Z_{th}| cos\emptyset \tag{4.13}$$

$$Q_{load} = P_{load} . tan\emptyset \tag{4.14}$$

The results obtained from the equations are in Table 5.1

Table 5.1 Maximum Load Values for Constant Power Factor

Load Bus No	Power Factor	P_{load} from Equation 4.13	Q_{load} from Equation 4.14
2	0.8893	1.8909	0.9724
3	0.9673	1.8534	0.4861
4	0.9967	9.11	0.7433
5	0.9785	8.1628	1.7185
6	0.963	3.1137	0.8713
8	0.948	1.3446	0.4512
9	0.8715	2.6745	1.505
10	0.8406	1.7275	1.1133

5.2 Comparison with Maximum Load Limits Obtained from Manual Load Increase

From the various methods that were verified and examined in this paper, Table 5.2, Table 5.3 and Table 5.4 summarizes the results for the maximum limit of load that a bus can deliver.

The columns 3 and 4 of Table 5.2 are the maximum power value in p.u. obtained by manually increasing the load at each bus & verifying using load flow and the one obtained from Equation 4.13 under the condition for constant power factor.

The columns 3 and 4 of Table 5.3 are Q_{load} values in p.u. corresponding to the maximum power value obtained by manually increasing the load at each bus & verifying using load flow and the one obtained from Equation 4.14 under the condition for constant power factor.

Table 5.2 Comparison of Maximum Power Values

Bus No	Load Power Factor	Maximum Power in p.u. with Voltage beyond limit - manual increase	P_{load} from const pf derivation
2	0.8893	1.7850	1.8909
3	0.9673	1.7690	1.8534
4	0.9967 lead	7.1700	9.11
5	0.9785	5.7760	8.1628
6	0.963	2.5650	3.1137
7	NaN	2.1600	NaN
8	0.948	1.1920	1.3446
9	0.8715	2.3600	2.6745
10	0.8406	1.6200	1.7275

Table 5.3 Comparison of Q_{load} for Maximum Power Results

Bus No	Load Power Factor	Q_{load} in p.u. with voltage beyond limit - manual increase	Q_{load} from P_{load}*tan(phi)
2	0.8893	0.9180	0.9711
3	0.9673	0.4640	0.4841
4	0.9967 lead	-0.5850	0.7462
5	0.9785	1.2160	1.7273
6	0.963	1.1020	1.2128
7	NaN	2.1600	NaN
8	0.948	0.4000	0.4497
9	0.8715	1.3280	1.5012
10	0.8406	1.0440	1.1111

The columns 3 and 4 of Table 5.4are bus voltage when maximum power value is obtained by manually increasing the load at each bus & Thevenin voltage used while verifying using load flow in p.u.

Table 5.4 Comparison of Voltage Values for Maximum Power Results

Bus No	Load Power Factor	V_m for the maximum load in column 3 & 4	V-thevenin calculated
2	0.8893	0.6486	1.0501
3	0.9673	0.6574	1.0644
4	0.9967 lead	0.7550	1.0299
5	0.9785	0.7414	1.0316
6	0.963	0.6846	1.0573
7	NaN	0.6182	1.0450
8	0.948	0.7291	1.0448
9	0.8715	0.6956	1.0541
10	0.8406	0.6227	1.0414

Next the values obtained for maximum power by manually increasing the load only upto the point where the bus voltage falls in +/- 20% stability region were compared with the ones in columns 4 of Table 5.2. The corresponding reactive load values and voltage values were also observed. The results are shown in Table 5.5

The limit for manual increase in load was obtained at the breakdown point. A breakdown point can be defined as the point from which the solutions diverged than the actual curve the solutions formed. At this point the load flow takes large number of iterations to converge. It is worth noting that the voltage values at the bus obtained for maximum attainable power is below the voltage stability limit. This shows that there is a possibility of voltage collapse to occur before system attains maximum power.

Table 5.5 Comparison of Power and Voltage Values for Maximum Power Results within Voltage Stability Limit

Bus No	Load Power Factor	Maximum Power in p.u. with Voltage in stability limit - manual increase	Bus Voltage for maximum power	P_{load} from const pf derivation	V-thevenin calculated
2	0.8893	1.4350	0.8018	1.8909	1.0501
3	0.9673	1.4030	0.8162	1.8534	1.0644
4	0.9967 lead	6.6920	0.8215	9.11	1.0299
5	0.9785	5.0160	0.8272	8.1628	1.0316
6	0.963	2.1600	0.8011	3.1137	1.0573
7	NaN	1.7600	0.8008	NaN	1.0450
8	0.948	1.0430	0.8006	1.3446	1.0448
9	0.8715	1.7700	0.8519	2.6745	1.0541
10	0.8406	1.2600	0.8024	1.7275	1.0414

The difference in the value of maximum Power is due to two reasons. The calculations made in both methods had different load values at the bus as well as the voltage values are different. Since the load at the bus whose Z-thevenin is calculated is removed during the calculation for V-thevenin, the actual system voltage is about 20%

lower than V-thevenin. Also, Z-load values governed by Equations 4.5 and 4.12, is affected by the change in Z-thevenin if the load was considered in the system like in the manual increase case. The decrease in Z-thevenin would be around 2 - 4%. This will affect the total impedance in the Thevenin circuit as well as the load impedance since both these impedances are based on Z-thevenin values. The power is directly proportional to square of Voltage, inversely proportional to the square of current as well as directly proportional to the load impedance. Considering all the decrements, the decrease in the value of power delivered to the load from the one that is calculated using Equation 4.13 is of about 25-30%. Let the percentage decrease be called factor X.

Table 5.6 Comparison of Power Values for Maximum Power Results Considering Factor X of 25%

Bus No	Load Power Factor	Maximum Power in pu with Voltage in stability limit - manual increase	P_{load} from const pf derivation considering factor X = 25%
2	0.8893	1.4350	1.4182
3	0.9673	1.4030	1.3901
4	0.9967 lead	6.6920	6.8325
5	0.9785	5.0160	6.1221
6	0.963	2.1600	2.3353
7	NaN	1.7600	NaN
8	0.948	1.0430	1.0085
9	0.8715	1.7700	2.0059
10	0.8406	1.2600	1.2956

The Table 5.6 shows the comparison between the maximum power values obtained by manual increase of load limited to the solutions which are in voltage stability region and considering factor X to be 25% for the maximum power obtained by constant power factor method. This values are quite close approximation to the ones in column 3, but yet not exactly same.

5.3 Conclusive Remarks

The following points can be summarized from the work in this thesis:

Non - Convergence of Newton – Raphson Load Flow Analysis is not a reliable indicator about occurrence of Voltage Collapse. At heavy loads Load Flow may converge and give impractical solutions.

New criterion has been developed in the thesis for maximum power transfer at constant power factor. This criterion takes into account the reactive power load during maximum power transfer & hence has closer approximation to the practical maximum power a bus can deliver in an actual system. It could be a base for further research on how does contingencies affect Z-thevenin & the maximum power limit for the load buses in that case.

APPENDIX A

DATA FILES USED FOR ANALYSIS

Tables A.1 to A.4 are the data tables used during the study. The bus type '1' means slack bus, '0' means load bus and '2' means generator bus.Figure A.1 is the diagram for the 14-Bus system used during the study.

Table A.1 Busdata for 14-Bus System

Bus	Bus Type	Voltage in p.u.	Delta in degrees	P_{load} in MW	Q_{load} in Mvar	P_{gen} in MW	Q_{gen} in Mvar
1	1	1.06	0	0	0	232.4	-16.9
2	0	1.057	-14.79	3.5	1.8	0	0
3	0	1.055	-15.07	6.1	1.6	0	0
4	0	1.019	-10.33	47.8	-3.9	0	0
5	0	1.02	-8.78	7.6	1.6	0	0
6	0	1.05	-15.16	13.5	5.8	0	0
7	0	1.062	-13.37	0	0	0	0
8	0	1.036	-16.04	14.9	5	0	0
9	0	1.056	-14.94	29.5	16.6	0	0
10	0	1.051	-15.1	9	5.8	0	0
11	2	1.045	-4.98	21.7	12.7	40	42.4
12	2	1.01	-12.72	94.2	19	0	23.4
13	2	1.07	-14.22	11.2	7.5	0	12.2
14	2	1.09	-13.36	0	0	0	17.4

Table A.2 Linedata for 14-Bus System

Bus from	Bus to	Resistance	Reactance	Susceptance
1	11	0.01938	0.05917	0.0528
1	5	0.05403	0.22304	0.0492
11	12	0.04699	0.19797	0.0438
11	4	0.05811	0.17632	0.034
11	5	0.05695	0.17388	0.0346
12	4	0.06701	0.17103	0.0128
4	5	0.01335	0.04211	0
4	7	0	0.20912	0
4	9	0	0.55618	0
5	13	0	0.25202	0
13	2	0.09498	0.1989	0
13	3	0.12291	0.25581	0
13	6	0.06615	0.13027	0
7	14	0	0.17615	0
7	9	0	0.11001	0
9	10	0.03183	0.0845	0
9	8	0.12711	0.27038	0
10	2	0.08205	0.19207	0
3	6	0.22092	0.19988	0
6	8	0.17093	0.34802	0

Table A.3 Busdata for 30-Bus System

Bus	Bus Type	Voltage in p.u.	Angle in degrees	P_{load} in MW	Q_{load} in Mvar	P_{gen} in MW	Q_{gen} in Mvar
1	1	1.06	0	0	0	260.2	-16.1
2	2	1.043	-5.48	21.7	12.7	40	50
3	0	1.021	-7.96	2.4	1.2	0	0
4	0	1.012	-9.62	7.6	1.6	0	0
5	2	1.01	-14.37	94.2	19	0	37
6	0	1.01	-11.34	0	0	0	0
7	0	1.002	-13.12	22.8	10.9	0	0
8	2	1.01	-12.1	30	30	0	37.3
9	0	1.051	-14.38	0	0	0	0
10	0	1.045	-15.97	5.8	2	0	0
11	2	1.082	-14.39	0	0	0	16.2
12	0	1.057	-15.24	11.2	7.5	0	0
13	2	1.071	-15.24	0	0	0	10.6
14	0	1.042	-16.13	6.2	1.6	0	0
15	0	1.038	-16.22	8.2	2.5	0	0

Table A.3 Busdata for 30-Bus System (Continued)

Bus	**Bus type**	**Voltage in p.u.**	**Angle in degrees**	**P_{load} in MW**	**Q_{load} in Mvar**	**P_{gen} in MW**	**Q_{gen} in Mvar**
16	0	1.045	-15.83	3.5	1.8	0	0
17	0	1.04	-16.14	9	5.8	0	0
18	0	1.028	-16.82	3.2	0.9	0	0
19	0	1.026	-17	9.5	3.4	0	0
20	0	1.03	-16.8	2.2	0.7	0	0
21	0	1.033	-16.42	17.5	11.2	0	0
22	0	1.033	-16.41	0	0	0	0
23	0	1.027	-16.61	3.2	1.6	0	0
24	0	1.021	-16.78	8.7	6.7	0	0
25	0	1.017	-16.35	0	0	0	0
26	0	1	-16.77	3.5	2.3	0	0
27	0	1.023	-15.82	0	0	0	0
28	0	1.007	-11.97	0	0	0	0
29	0	1.003	-17.06	2.4	0.9	0	0
30	0	0.992	-17.94	10.6	1.9	0	0

Table A.4 Linedata for 30-Bus System

Bus from	Bus to	Resistance	Reactance	Susceptance
1	2	0.0192	0.0575	0.0528
1	3	0.0452	0.1652	0.0408
2	4	0.057	0.1737	0.0368
3	4	0.0132	0.0379	0.0084
2	5	0.0472	0.1983	0.0418
2	6	0.0581	0.1763	0.0374
4	6	0.0119	0.0414	0.009
5	7	0.046	0.116	0.0204
6	7	0.0267	0.082	0.017
6	8	0.012	0.042	0.009
6	9	0	0.208	0
6	10	0	0.556	0
9	11	0	0.208	0
9	10	0	0.11	0
4	12	0	0.256	0
12	13	0	0.14	0
12	14	0.1231	0.2559	0
12	15	0.0662	0.1304	0
12	16	0.0945	0.1987	0
14	15	0.221	0.1997	0

Table A.4 Linedata for 30-Bus System (Continued)

Bus from	Bus to	Resistance	Reactance	Susceptance
16	17	0.0524	0.1923	0
15	18	0.1073	0.2185	0
18	19	0.0639	0.1292	0
19	20	0.034	0.068	0
10	20	0.0936	0.209	0
10	17	0.0324	0.0845	0
10	21	0.0348	0.0749	0
10	22	0.0727	0.1499	0
21	22	0.0116	0.0236	0
15	23	0.1	0.202	0
22	24	0.115	0.179	0
23	24	0.132	0.27	0
24	25	0.1885	0.3292	0
25	26	0.2544	0.38	0
25	27	0.1093	0.2087	0
28	27	0	0.396	0
27	29	0.2198	0.4153	0
27	30	0.3202	0.6027	0
29	30	0.2399	0.4533	0
8	28	0.0636	0.2	0.0428
6	28	0.0169	0.0599	0.013

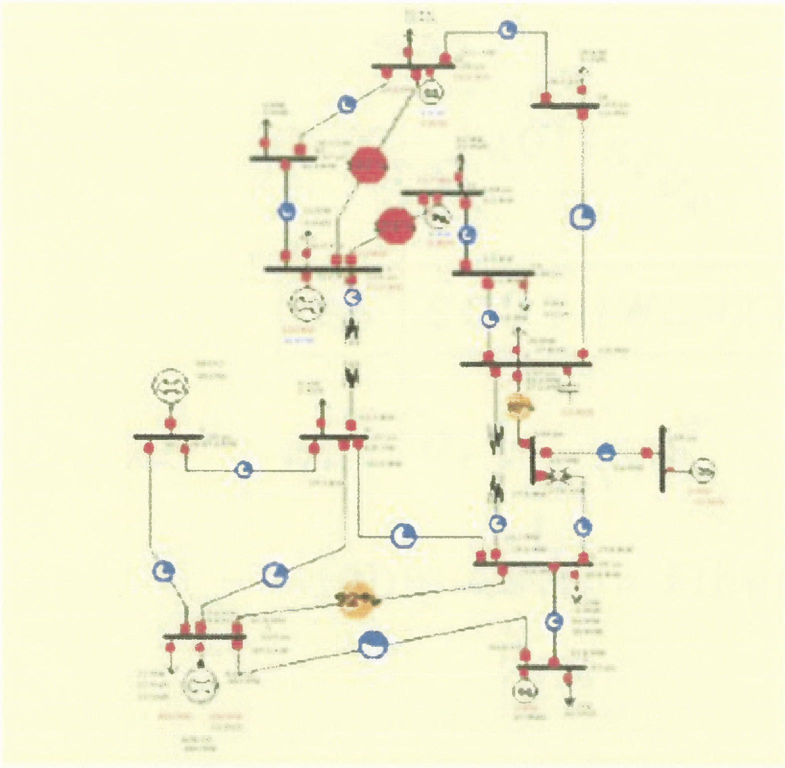

Figure A.1. 14-Bus Diagram.

APPENDIX B

POWER FLOW AND ITS VERIFICATION

One of the important parts of the thesis was to have a proper power flow analysis tool to verify all the methods and try all possibilities of improvisation.

Starting with all the basic Matlab programs provided by Dr. Walid Hubbi, a final load flow program was developed and verified. This program would take line data as well as bus data (the one used are specified in Appendix A) as the input and by using Newton Raphson method of power flow analysis would give a final solution of Voltage V_m and angle delta.

The convergence criterion could also be specified and the solutions will be calculated accordingly maintaining accuracy up to certain specified decimal points. All the work presented in this thesis was calculated on the accuracy of the order of 10^{-5}.

The maximum number of iterations could also be specified in the power flow program. A normal range of number of iterations for getting reasonable solutions is about 10 iterations at the max. It should be brought to notice of the reader at this point, that in this thesis, the verifications including non - reasonable solutions had no limit to maximum number of iterations. Certain unreasonable solutions were obtained at more than a thousand iterations, but by looking at the results it could easily be told that for any iterative load flow analysis, taking more than 20 iterations, was certainly giving unreasonable solutions.

The basic verification of this program was done using data from the book, Power System Analysis by John J. Grainger and William D. Stevenson, Jr. Example 9.5 with input line data is given in table 9.2 on page 337 and input bus data is given in table 9.3 on page 338. (Same listed below in the format of data input in the power flow program developed in Matlab)

Table B.1 Linedata from Example 9.5

Bus to	Bus from	Resistance	Reactance	Susceptance
1	2	0.01008	0.0504	0.05125
1	3	0.00744	0.0372	0.03875
2	4	0.00744	0.0372	0.03875
3	4	0.01272	0.0636	0.06375

Table B.2 Busdata from Example 9.5

Bus	Bus Type	Voltage in p.u.	Angle in degrees	P_{load} in MW	Q_{load} in Mvar	P_{gen} in MW	Q_{gen} in Mvar
1	1	1	0	50	30.99	0	0
2	0	1	0	170	105.35	0	0
3	0	1	0	200	123.94	0	0
4	2	1.02	0	80	49.58	318	0

The convergence criteria was set to 0.00001 and maximum number of iterations to 20.

The solutions converged after 4 iterations. The result obtained for V_m and Delta was same as that in the book in Figure 9.4 on page 358.

Table B.3 Result from Power Flow Program for Example 9.5

V_m in p.u.	Delta in degrees
1	0
0.9824	-0.9761
0.969	-1.8722
1.02	1.5231

Also to be noted here is that the initial estimates of voltage and delta should be reasonable values. It could be either some real time data available for the operating condition or a flat start of V_m = 1 p.u. and delta = 0 degrees.

APPENDIX C

MATLAB PROGRAM FOR BASIC LOAD FLOW ANALYSIS

The main program for power flow analysis is put up in this Appendix. The sub – routines are also included as part of this Appendix. This whole program, including the sub – routines is used as a sub – routine for the programs presented in the following Appendices.

```
function[Vm,delta]=pflow3(busdata,linedata,convergence_criterion, max_num_of_iteration)

load busdata;
load linedata;
load convergence_criterion;
load max_num_of_iteration;

crit= convergence_criterion;
max_iter= max_num_of_iteration;
nbus = length(busdata(:,1));
d=busdata(:,2)==2;        %Finding out how many generator buses
ngen=sum(d);          % ngen = # of generator busses, type 2


bus_kind=busdata(:,2);
Vm=busdata(:,3);        % Vm is the vector of the voltage magnitudes, it contains specified voltages, initial
estimate or best available estimate.

delta=busdata(:, 4);
P_load=busdata(:,5);  % Data has values in MW
Q_load=busdata(:,6);  % Data has values in Mvar
P_generated=busdata(:,7);  % Data has values in MW
Q_generated = busdata(:,8);  % Data has values in Mvar
delta = pi/180*delta;   % Data has delta in degrees & hence converted to radians

basemva=100;
P_net_pu=(P_generated-P_load)/basemva; % Converting values in pu
Q_net_pu=(Q_generated-Q_load)/basemva; % Converting values in pu
S_net_pu = P_net_pu + j*Q_net_pu;


[Y]= ybus(linedata);   % Finding the Y-bus
maxerror = 1;
iter = 0;
```

```
% Start of iterations
while maxerror >= crit & iter <= max_iter    % Test for max. power mismatch

[pcal,qcal] = pqcal(Y,Vm,delta)

[Jacobian, DIM] = jacobian2(Y, Vm, delta, qcal, pcal, nbus,ngen);

[mismatch]=DPDQ(P_net_pu,Q_net_pu,pcal,qcal,nbus,ngen);

correction=Jacobian\mismatch;

[Vm,delta]=update(Vm, delta, correction, nbus, ngen);

maxerror=max(mismatch);

iter = iter+1;
end

if iter >= max_iter & maxerror > crit
  fprintf('\nWARNING: Iterative solution did not converge after ')
  fprintf('%g', iter), fprintf(' iterations.\n\n')
elseif  maxerror <=crit
  fprintf('\nIterative solution converged after ')
  fprintf('%g', iter), fprintf(' iterations.\n\n')
   else
end
delta=delta*180/pi;
```

The following are the sub-routines called in the power flow:

Y-bus – Sub-routine to calculate Y-bus of the system.

```
function [Y] = ybus14(line) %declaring function[Y] that takes as input linedata and outputs Y-matrix.

nl = line (:,1); % extracting column 1 from the linedata file. nl is line from bus

nr = line (:,2); % extracting column 2 from the linedata file. nl is line to bus

R = line (:,3) %extracting the resistance in column 3 from the linedata file.

X = line (:,4) %extracting the line reactance from column 4

B = line (:,5);  %extracting half of the total line susceptance from column 8 OF line FILE

nline = length (line (:,1)) %declaring the total # of lines

nbus = max (max (nl), max (nr)); %defining the toal no of nodes
```

```
Z = R + j*X % declaring the impedance
y = ones (nline,1)./Z ;
Y= zeros (nbus,nbus);

for n = 1:nbus   %defining a for loop to find the diagonal elements of Y-matrix.

   for k = 1:nline
      if nl (k) == n || nr (k) == n
         Y (n,n) = Y (n,n) + y(k) + (j*B(k));
      else end
   end
end


for k = 1:nline  %defining a loop to find the off-diagonal elements of Y-matrix.

   Y (nl(k), nr(k))=Y(nl(k),nr(k))-y(k);
   Y(nr(k),nl(k))=Y(nl(k),nr(k));
end
```

The sub-routine to calculate active and reactive power is as follows:

```
function[pcal,qcal] = pqcal(Y,v,delta)

vcom = v.*cos(delta) + j*v.*sin(delta)
current = Y*vcom;
iconj = conj(current);
s = vcom.*iconj;
pcal = real(s);
qcal = imag(s);
return
```

The sub-routine to calculate Jacobian matrix is as follows:

```
function[Jacobian, DIM] = jacobian2(Ycomp, Vm, delta, qcal, pcal, nbus,ngen)
theta=angle(Ycomp);
g=real(Ycomp);
b=imag(Ycomp);
Y=abs(Ycomp);

for i=1:nbus
   for jj=1:nbus
      A11(i,jj)=0.0;
      A12(i,jj)=0.0;
      A21(i,jj)=0.0;
      A22(i,jj)=0.0;
   end
end
%
%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
%now calculate off-diagnal elements
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
for i=1:nbus
  for jj=1:nbus
    A11(i,jj)=-(Vm(i)*Vm(jj)*Y(i,jj))*sin(theta(i,jj)+delta(jj)-delta(i));
    A12(i,jj)=(Vm(jj)*(Vm(i)*Y(i,jj)))*cos(theta(i,jj)+delta(jj)-delta(i));
    A21(i,jj)=-(Vm(i)*Vm(jj)*Y(i,jj))*cos(theta(i,jj)+delta(jj)-delta(i));
    A22(i,jj)=-Vm(jj)*(Vm(i)*Y(i,jj))*sin(theta(i,jj)+delta(jj)-delta(i));
  end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
%now calculate all diagnal elements
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
  for i=1:nbus
    A11(i,i)=-qcal(i)-(Vm(i))^2*b(i,i);
    A12(i,i)=pcal(i)+(Vm(i))^2*g(i,i);
    A21(i,i)=pcal(i)-(Vm(i)^2)*g(i,i);
    A22(i,i)=qcal(i)-(Vm(i)^2)*b(i,i);
  end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
%Deleting the rows and columns corresponding to the slack bus
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
for i=1:nbus-1
  for jj=1:nbus-1
    jk11(i,jj)=A11(i+1,jj+1);
    jk12(i,jj)=A12(i+1,jj+1);
    jk21(i,jj)=A21(i+1,jj+1);
    jk22(i,jj)=A22(i+1,jj+1);
  end
end

DIM = 2*nbus -2 -ngen;        %Determine the size of the Jacobian Matrix.
A_temp = [jk11 jk12; jk21 jk22];
for ii = 1 : DIM              % Grab the proper number of rows for the Jacobian Matrix.

  for jj = 1 : DIM            % Grab the proper number of Columns for the Jacobian Matrix.

    Jacobian(ii,jj)= A_temp(ii,jj);
  end
end
```

The sub- routine to calculate mismatch vector whose dimension is same as the number of unknowns is as follows:

```
function [mismatch]=DPDQ(p_net,q_net,pcal,qcal,nbus,ngen)

DIM=2*nbus-2-ngen;
delta_p = p_net - pcal;
delta_q = q_net - qcal;

for ii=1:nbus-1
  mismatch(ii)=delta_p(ii+1);
end

for ii=nbus:DIM
  mismatch(ii)=delta_q(ii-nbus+2);
end

mismatch=mismatch'
```

The last sub-routine to update the values of V_m and delta is as follows:

```
function [Vm,delta]=update(Vm, delta, correction, nbus, ngen);

n_load_nodes = nbus-1-ngen;

for i=2:nbus
  delta(i) =delta(i) + correction(i-1);
end

for i=2:n_load_nodes+1
  Vm(i)=Vm(i)*(correction(nbus+i-2)) + Vm(i);
end
```

APPENDIX D

MATLAB PROGRAM FOR POWER FLOW WITH VOLTAGE MAGNITUDE STABILITY LIMITS

The Matlab program for power flow with a 20% limit on voltage magnitude value is as under. The only difference is in the main program, the sub-routines are same as in APPENDIX C.

```
function[Vm, delta, pcal, qcal, iter] = pflow3 (busdata_new, linedata, convergence_criterion,
max_num_of_iteration)

load busdata_new;
load linedata;
load convergence_criterion;
load max_num_of_iteration;

crit= convergence_criterion;
max_iter= max_num_of_iteration;
nbus = length(busdata_new(:,1));
d=busdata_new(:,2)==2;        %Finding out how many generator buses
ngen=sum(d);          % ngen = # of generator busses, type 2

bus_kind=busdata_new(:,2);
Vm=busdata_new(:,3);
delta=busdata_new(:,4);
% Vm is the vector of the voltage magnitudes, it contains specified voltages, initial estimate or best
available estimate.

P_load=busdata_new(:,5);
Q_load=busdata_new(:,6);
P_generated=busdata_new(:,7);
Q_generated = busdata_new(:,8);

delta = pi/180*delta;
basemva=100;
P_net_pu=(P_generated-P_load)/basemva;
Q_net_pu=(Q_generated-Q_load)/basemva;
S_net_pu = P_net_pu + j*Q_net_pu;


[Y]= ybus(linedata)
maxerror = 1;
iter = 0;
```

```
limit1 = 1.2; %Maximum permissible limit of voltage magnitude
limit2 = 0.8; %Minimum permissible limit of voltage magnitude

% Start of iterations

while maxerror >= crit && iter <= max_iter && max(Vm) < limit1 && min(Vm) > limit2 % Test for max.
power mismatch
% the delta vector must be in radians.

[pcal,qcal] = pqcal(Y,Vm,delta);

[Jacobian, DIM] = jacobian2(Y, Vm, delta, qcal, pcal, nbus,ngen);

[mismatch]=DPDQ(P_net_pu,Q_net_pu,pcal,qcal,nbus,ngen);

correction=Jacobian\mismatch;

[Vm,delta]=update(Vm, delta, correction, nbus, ngen);

maxerror=max(mismatch);
iter = iter+1;
end

if iter >= max_iter & maxerror > crit & max(Vm) < limit1 & min(Vm) > limit2
    fprintf('\nWARNING: Iterative solution did not converge after ')
    fprintf('%g', iter), fprintf(' iterations.\n\n')

        elseif maxerror <=crit
      fprintf('\nIterative solution converged after ')
      fprintf('%g', iter), fprintf(' iterations.\n\n')

        elseif max(Vm) > limit1
     fprintf('\nWARNING: bus voltage above stability limit after ' )
     fprintf('%g', iter), fprintf(' iterations.\n\n')

        elseif min(Vm) < limit2
     fprintf('\nWARNING: bus voltage below stability limit after ' )
     fprintf('%g', iter), fprintf(' iterations.\n\n')

        else
end

delta=delta*180/pi
```

APPENDIX E

MATLAB PROGRAM FOR PLOTTING VARIATION WITH RESPECT TO LOAD CHANGE AT A SINGLE BUS AT A TIME

The following Matlab program will plot the variation of voltage magnitude as well as angle with respect to multiplier by which the load is increased as well as show the relation with the P_{load} and Q_{load}. The graph is useful to track a point from where the solution diverges from the normal flow of reasonable values. Also note that the increase in load here means simultaneous increase in both P_{load} as well as Q_{load}. Same program might be used to increase only P_{load} or only Q_{load} by omitting certain commands.

```
% to plot Vm, Pcal, Qcal & delta versus multiplier on same graph for 1 bus at a time

load busdata
load linedata
load convergence_criterion
load max_num_of_iteration
busdata_new = busdata;


xxx = 0;
 bb = 9; % Bus number – change it for the graphs at desired bus
 mul = 9; % Can gradually increase this mumber to find out a point of maximum load

for multiplier = 1:1:mul;
   xxx = xxx + 1;
   P_load=busdata(:,5); Q_load=busdata(:,6);
   Q_load_new(bb,1) = Q_load(bb,1) * multiplier;
   P_load_new(bb,1) = P_load(bb,1) * multiplier;

% for a load node with '0' initial load add multiplier instead of '*'

   busdata_new(bb,5) = P_load_new(bb,1);
   busdata_new(bb,6) = Q_load_new(bb,1);
   save busdata_new;

% Run load flow routine to find Vm & delta for the particular load
  saved in busdata_new

  [Vm, delta, pcal, qcal, iter] = pflow3 (busdata_new, linedata, convergence_criterion,
max_num_of_iteration);
```

```
% Adding a column to the respective tables of Vm, Delta, P_load as well as Q_load for each increament in load

   P_load_increments(xxx,1) = P_load_new(bb,1);
   Q_load_increments(xxx,1) = Q_load_new(bb,1);
   table1(:, xxx) = Vm;
   table2(:,xxx) = delta;
   multipliertable(xxx,1) = multiplier;
   pcal_table(:,xxx)= pcal;
   qcal_table(:,xxx) = qcal;
   iter_tabel(xxx,1) = iter;

end
% Using the tables made in the previous step to generate the graph

plot(multipliertable(:,1),table1(bb,:),multipliertable(:,1),
pcal_table(bb,:),multipliertable(:,1),qcal_table(bb,:),
multipliertable(:,1),table2(bb,:))

axis([0 mul -2.0 1.3])

title ('Variations with respect to multiplier when P & Q is incresed simultaneously at bus 9') % change bus number according to the bus

xlabel('Multiplier')
ylabel('Vm, Pcal, Qcal in p.u. and delta in radians')
```

APPENDIX F

MATLAB PROGRAM TO SIMULATANEOUSLY INCREASE LOAD AT ALL BUSES OF THE SYSTEM

The following program is used to gather data when the load (both P_{load} and Q_{load}) at all buses in the system is increased by a multiplier simultaneously.

```
load busdata
load linedata
load convergence_criterion
load max_num_of_iteration

busdata_new = busdata;

xxx = 0;
mul = 4.2;

for multiplier = 1:0.2:mul;
   xxx = xxx + 1;
   P_load=busdata(:,5);
   Q_load=busdata(:,6);

   Q_load_new(:,1) = Q_load(:,1) * multiplier;
   P_load_new(:,1) = P_load(:,1) * multiplier;

   busdata_new(:,5) = P_load_new(:,1);
   busdata_new(:,6) = Q_load_new(:,1);

   save busdata_new;

  [Vm, delta, pcal, qcal, iter] = pflow3 (busdata_new, linedata, convergence_criterion,
max_num_of_iteration);

   P_load_increments(:,xxx) = P_load_new(:,1);
   Q_load_increments(:,xxx) = Q_load_new(:,1);

   table1(:, xxx) = Vm;
   table2(:,xxx) = delta;

   multipliertable(xxx,1) = multiplier;

   pcal_table(:,xxx)= pcal;
   qcal_table(:,xxx) = qcal;

   iter_tabel(xxx,1) = iter;

end
```

```
for bb = 2:10   % bb = load buses 2 to 10

   subplot(2,5,bb-1);
   plot (multipliertable(:,1),table1(bb,:),': rs','LineWidth',2,...
          'MarkerEdgeColor','k',...
          'MarkerFaceColor','g',...
          'MarkerSize',3)
   axis([0 mul 0 1.2])
   xlabel('Multiplier')
   ylabel('Vm')

end

title ('Variation of Vm and delta with respect to multiplier when P & Q is incresed simultaneously for all buses')
```

APPENDIX G

MATLAB PROGRAM FOR CALCULATING Z-THEVENIN AND EXTENSION TO MAXIMUM POWER TRANSFER AND CONSTANT POWER FACTOR CONCEPT

The Matlab routine to calculate Z-thevenin for a system is given in this appendix. The load at the bus whose Z-thevenin is to be found should not be included in the equivalent circuit.

```
for bb = 1:9   % for all load buses

% Run load flow to get Vm & Delta and Y-bus for the given system

load busdata
load linedata
load convergence_criterion
load max_num_of_iteration

busdata(bb+1,5) = 0;    % for excluding the load at the bus whoose Z-thevenin is calculated

busdata(bb+1,6) = 0;    % for excluding the load at the bus whoose Z-thevenin is calculated

[Vm, delta, Y] = pflow4(busdata,linedata,convergence_criterion, max_num_of_iteration);

  Table_Vm(:,bb) = Vm % to store solution at all bus
  Vth(bb,1) = Vm(bb+1,1)  % V-thevenin for the bus for whihc find Z-thevenin is found


% Calculate Y_load

delta = (pi/180)*delta;

Vm_real = (Vm .* cos(delta));
Vm_img = (Vm .* sin(delta));
Vm_rect = complex(Vm_real, Vm_img);

P_load= busdata(:,5);
Q_load= busdata(:,6);

S = complex(P_load, Q_load); % Load Power
S = S./100;
Y_load = conj(S)./(Vm_rect .* Vm_rect);
```

```
% Calculating Y_bus & Z-thevenin

Y_load = diag([Y_load]);
Y_bus = Y + Y_load;
Y_reduced = Y_bus(2:10, 2:10);
Z_bus_reduced = inv(Y_reduced);   % 9 X 9 matrix only for load bus
Z_th_reduced(bb,1) = Z_bus_reduced(bb,bb)
end


% Power factor for actual load

load busdata;

P_load= busdata(:,5);
Q_load= busdata(:,6);

S_actual = complex(P_load, Q_load);
S_real = real(S_actual);
S_img = imag(S_actual);
S_mag = sqrt((S_real.*S_real)+(S_img.*S_img));

pf_actual = P_load./S_mag
%pf_actual(7,1) = 1.0
phi_actual = acos(pf_actual)



% New Load power and its power factor by making load equal to conj of Z-thevenin

temp = (Vth./(conj(Z_th_reduced)+ Z_th_reduced))
S_new = ((temp.*temp).*conj(Z_th_reduced(1:9,1)))

S_new_real = real(S_new);

S_new_img = imag(S_new)

S_new_mag = sqrt((S_new_real.*S_new_real)+(S_new_img.*S_new_img))

pf_new = S_new_real./S_new_mag
```

```
% New Load Power using the derivation for constant power factor

R_th = real(Z_th_reduced)
X_th = imag(Z_th_reduced)
Z_th_mag = sqrt((R_th.*R_th)+(X_th.*X_th))

Rl = Z_th_mag .* pf_actual(2:10,1)
Xl= Rl .* tan(phi_actual(2:10,1))
I2 = ((Vth .* Vth)./((R_th + Rl).*(R_th + Rl) + (X_th + Xl).*(X_th + Xl)))

P_load_constpf = I2 .* Rl
Q_load_constpf = P_load_constpf .* tan(phi_actual(2:10,1))
```

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