VOLTAGE STABILITY IMPROVEMENT IN POWER SYSTEM

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ABSTRACT

This paper presents the study on voltage stability and its improvement in power system. Load flow analysis at various loading conditions will be performed to view the effect of loading condition to voltage instability. Voltage instability will be improved using shunt capacitors and tap changing transformers. This paper will apply the Newton-Raphson algorithm in the load flow analysis. The programs were simulated on the IEEE 30 bus Reliability Test System (RTS). All simulations were done using MATLAB version 7.0 program.

Keywords: Voltage stability, shunt capacitors, tap changing transformer, Newton-Raphson

1.0 INTRODUCTION

Electric utilities of today are facing more problems than ever before with trying to provide economical electric power to their customers and trying to allow an increase in the amount of power that is transferred between interconnected utilities and independent power producers. This increase in power flow leads to transmission networks becoming heavily loaded, causing the thermal capacity of the line to reach their limits. In the event of a contingency in the system, the lines are required to carry an even larger load. With the increased power flow due to heavy loading, the system reactive power loses increase dramatically; this loss of reactive power may eventually lead to voltage instability [1].

The voltage stability problem has become a major concern in operating and planning today's power system as a result of heavier loading conditions, without sufficient transmission and/or generation enhancements. Voltage stability problems normally occur in heavily stressed systems. While the disturbance leading to voltage collapse may be initiated by a variety of causes, the underlying problem is an inherent weakness in the power system. The factors contributing to voltage collapse are the generator reactive power voltage control limits, load characteristics, characteristics of reactive compensation devices, and the action of the voltage control devices such as transformer on - load tap changers (OLTCs) [5].

Two methods to improve the voltage stability on the system network, which will be discussed in this paper, are:

(1) Application of shunt capacitor using reactive compensation.
(2) Transformer tap changing.

These two methods proposed to improve voltage stability are a few from many other different methods such as using static VAR compensator, shunt reactors, thyristor controlled series compensator (TCSC) and Unified Power Flow Controller (UPFC).

The main objective of this project is to improve the voltage profile of the network in a satisfactory range. It is essential to ensure that the power demand is satisfied and the voltage at each load bus is between a specified limit because with the increased loading of existing power transmission systems, the problem of voltage stability has become a major concern in power system planning and operation.

2.0 THEORETICAL BACKGROUND

2.1 Shunt Capacitors

Shunt capacitors are used for lagging power factor circuits created by heavy loads. The effect is to supply the requisite reactive power to maintain the receiving end voltage at a satisfactory level. Capacitors are connected either directly to a bus bar or to the tertiary winding of a main transformer and are disposed along the route to minimize the losses and voltage drops [2].

Series capacitors increase the maximum power limit while shunt capacitors have several effects:

a. Reduce lagging component of circuit current
b. Increase voltage level at the load and power factor of source generators
c. Improve voltage regulation if the capacitor units are properly switched
d. Reduce direct and reactive power loss in the system
e. Decrease kVA loading on source generators and circuits to relieve an over-loaded condition or release capacity for additional load growth [3].

2.2 Tap Changing Transformer

Transformers provide a means of control of the power flow both real and reactive. The main concept of the function of transformer in a power system is to convert one voltage level to another. However, transformers which provide a small change to the voltage magnitude, usually in the range of ±10% are called tap changing transformers [4].

Real and reactive powers can be controlled by use of tap changing transformers and regulating transformers [2]. Static on load tap changing is widely used to control the voltage difference between the sending and receiving end voltages of a transformer i.e maintaining a constant voltage at the receiving end.

The tap-changing transformer gives some control of the power network by changing the voltages and current magnitudes and angles by small amounts.

2.3 Newton-Raphson Method

The ubiquitous Newton Raphson iteration method derived from Taylor's series expansion about a point x^k is given by

$$x^{k+1} = x^k - \left[\frac{\partial f}{\partial x}\right]^{-1} f(x^k) \qquad (1)$$

With a few modifications, the derived Newton-Raphson formula above can be extended to systems of nonlinear equations. The system of nonlinear equation with n-dimensional systems can be written as:

$$x^{k+1} = x^k - \left[J(x^k)\right]^{-1} F(x^k) \qquad (2)$$

Where $x = [x1\ x2\ x3 \ldots xn]^T$ and
$F(x^k) = \left[f1(x^k)\ f2(x^k)\ f3(x^k) \ldots fn(x^k)\right]^T$

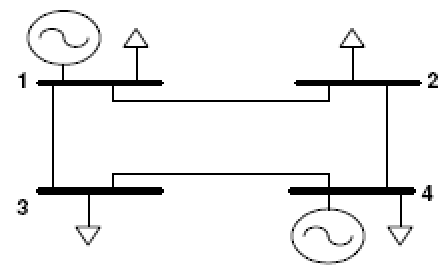

Figure 2.3: One-line diagram of 4-bus system

Typically the inverse of the Jacobian $[J(x^k)]$ is not found directly, but rather through LU factorization by posing the Newton-Raphson method as:

$$\left[J(x^k)\right](x^{k+1} - x^k) = -F(x^k) \qquad (3)$$

Which is now in the form of Ax = b where the Jacobian is the matrix A, the unknowns is x which is a difference vector. The convergence is typically evaluated by considering the norm of the function

$$\|F(x^x)\| < \varepsilon$$

Because the Jacobian matrix and the input function, $F(x^k)$ is a function of x^k, they are updated in every iteration. This makes this method more time consuming.

In a typical 4-bus system shown in Figure 2.3, collecting the mismatch equations into vector matrix yields

$$\begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial V_3} & \frac{\partial P_2}{\partial \delta_3} & \frac{\partial P_2}{\partial V_2} & \frac{\partial P_2}{\partial V_4} \\ \frac{\partial P_3}{\partial \delta_2} & \frac{\partial P_3}{\partial V_3} & \frac{\partial P_3}{\partial \delta_3} & \frac{\partial P_3}{\partial V_2} & \frac{\partial P_3}{\partial V_4} \\ \frac{\partial P_4}{\partial \delta_2} & \frac{\partial P_4}{\partial V_3} & \frac{\partial P_4}{\partial \delta_3} & \frac{\partial P_4}{\partial V_2} & \frac{\partial P_4}{\partial V_4} \\ \frac{\partial Q_2}{\partial \delta_2} & \frac{\partial Q_2}{\partial V_3} & \frac{\partial Q_2}{\partial \delta_3} & \frac{\partial Q_2}{\partial V_2} & \frac{\partial Q_2}{\partial V_4} \\ \frac{\partial Q_3}{\partial \delta_2} & \frac{\partial Q_3}{\partial V_3} & \frac{\partial Q_3}{\partial \delta_3} & \frac{\partial Q_3}{\partial V_2} & \frac{\partial Q_3}{\partial V_4} \end{bmatrix} \begin{bmatrix} \Delta\delta 2 \\ \Delta\delta 3 \\ \Delta\delta 4 \\ \Delta V2 \\ \Delta V3 \end{bmatrix} = \begin{bmatrix} \Delta P2 \\ \Delta P3 \\ \Delta P4 \\ \Delta Q2 \\ \Delta Q3 \end{bmatrix}$$

Bus 1 is the slack bus so its power mismatch cannot be included in the Jacobian matrix as the voltage and angle are known. Also any of the known state variables at a bus will eliminate the power mismatch with respect to it from the matrix also. The relationship between the current and the node voltage in a network of N nodes is given by

$$\overline{I_i} = \sum_{j=1}^{N} \overline{Y_{ij}}\,\overline{V_j} \qquad (4)$$

Where $\overline{Y_{ij}}$ is the element of the admittance matrix and the super bar indicates a complex quantity. The complex power at node i is given by

$$(P_i + jQ_i) = \overline{V_i} \sum_{j=1}^{N} \overline{Y_{ij}}^{*}\,\overline{V_j}^{*} \qquad (5)$$

where *Pi* and *Qi* are respectively, the real and reactive power injection at node i, where the * means a complex conjugate and the j in front of *Qi* is square root of minus one [4].

3.0 METHODOLOGY

3.1 Improvement of voltage stability using shunt capacitors

The following steps are implemented:

1. Increase the reactive load, Ql_{oad} at particular bus.
2. Run load flow program using Newton-Raphson method.
3. The value of voltage magnitude that is relative to the increased Q_{load} is recorded.
4. Insert the maximum reactive power loading at particular bus
5. Inject shunt capacitor value and steadily increased the value until the voltage magnitude equal to 1 p.u.
6. The value of shunt capacitor which gives the voltage magnitude equal to 1 p.u is recorded.

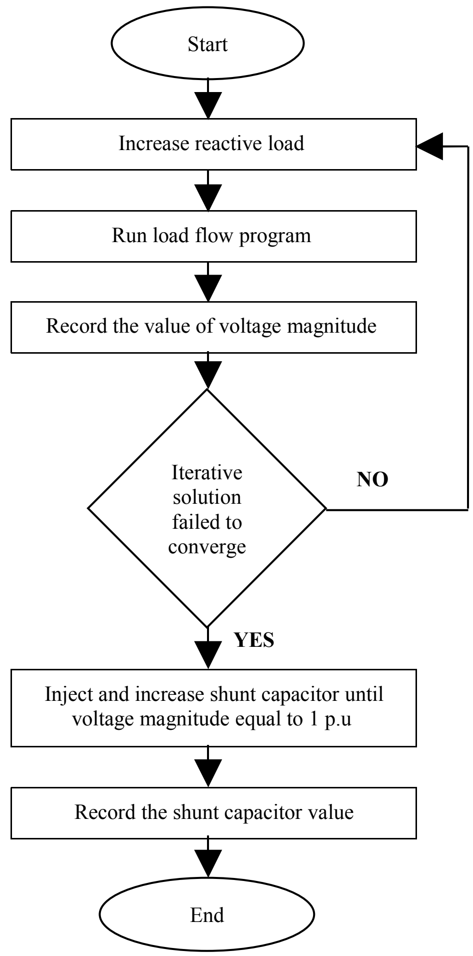

Figure 3.1: Flowchart of improvement of voltage stability using shunt capacitor

3.2 Improvement of voltage stability using tap changing transformer

1. Increase the reactive load, Q_{load} at particular bus
2. Run load flow program using Newton-Raphson method.
3. The value of voltage magnitude that is relative to the increased Q_{load} is recorded.
4. Insert the maximum reactive power loading at particular bus
5. Change the transformer tap setting until the magnitude of voltage is improved within limit ($0.95 \le V \le 1.05$).
6. The value of tap changing transformer that brings the value of voltage magnitude within limit is recorded.

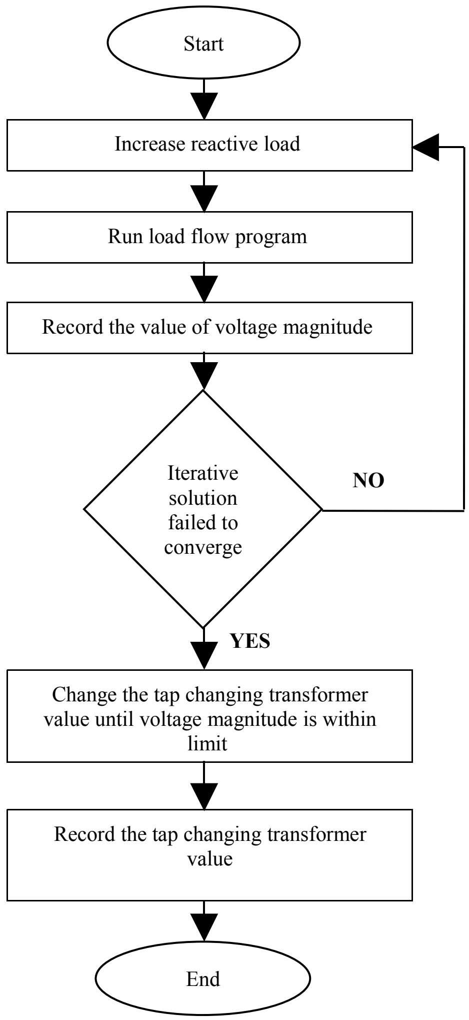

Figure 3.2: Flowchart of improvement of voltage stability using tap changing transformer

4.0 RESULTS AND DISCUSSION

The proposed technique was tested on the IEEE 30 bus System. The study focused on the location and the size of shunt capacitor and the transformer tap changing with a test load of 100MVar at each chosen bus. The voltage magnitudes of each condition before and after the improvement were recorded.

4.1 IEEE 30 Bus System

The IEEE 30 bus system is shown as in appendix 1(a). The network consists of 41 branches, 6 generator buses and 21 load buses. Six generator buses are selected as PV buses and a slack bus; PV buses: Bus 2, 5, 8, 11 and 13; Slack Bus: Bus 1. The others are PQ buses and all the following quantities are in per unit values.

4.2 Results and discussion of voltage stability without shunt capacitor and tap changing transformer

Table 4.2(a), 4.2(b) and 4.2(c) showed the result of voltage magnitude at Bus 3, Bus 4 and Bus 9 respectively in 30-Bus IEEE system with the maximum injected reactive load was 300MVar for Bus 3 and Bus 9 and 620MVar for Bus 4 before the iterative solution failed to converge.

Bus no.	Load, Q (MVAR)	Voltage (p.u)
3	100	0.943
3	150	0.902
3	200	0.860
3	250	0.816
3	300	0.764

Table 4.2(a): Result of voltage magnitude without shunt capacitor and tap changing transformer at Bus 3

Bus no.	Load, Q (MVAR)	Voltage (p.u)
4	100	0.948
4	200	0.896
4	300	0.845
4	400	0.789
4	500	0.719
4	600	0.608
4	610	0.589
4	620	0.564

Table 4.2(b): Result of voltage magnitude without shunt capacitor and tap changing transformer at Bus 4

Bus no.	Load, Q (MVAR)	Voltage (p.u)
9	100	0.944
9	150	0.886
9	200	0.820
9	250	0.742
9	300	0.612

Table 4.2(c): Result of voltage magnitude without shunt capacitor and tap changing transformer at Bus 9

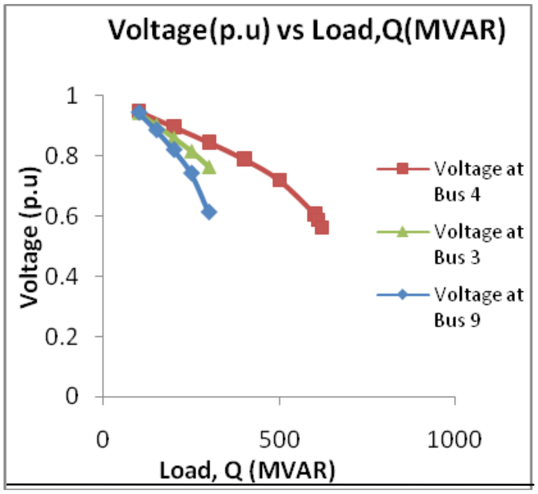

Figure 4.1: Voltage magnitude reduced with increased load at Bus 3, Bus 4 and Bus 9

Referring to Table 4.2(a), Table 4.2(b) and Table 4.2(c), the graphs plotted in Figure 1 showed the magnitude of Voltage (p.u) versus Load (Q) without shunt capacitor and tap changing transformer at Bus 3, Bus 4 and Bus 9. Bus 3, Bus 4 and Bus 9 in the IEEE 30-Bus Reliability Test System are the PQ type buses. It can be observed that as the reactive power increased, the voltage profile reduced accordingly. The load was increased until it reached a point where the load flow failed to converge. The maximum value of reactive power loading was 300MVAR for Bus 3 and Bus 9 and 620MVar for Bus 4. The reduced value of voltage magnitude was 0.764(p.u) at Bus 3, 0.564(p.u) at Bus 4 and 0.612(p.u) at Bus 9. At this particular point, instability condition is possible to occur, leading to a voltage collapse to the whole system.

4.3 Results and discussion on improvement of voltage stability using shunt capacitor

Bus no.	Load MVar	Injected MVar	Voltage (p.u)
3	100	72	1.000
9	100	49	1.000

Table 4.3(a): Result of injected shunt capacitor that obtained voltage magnitude of 1 p.u

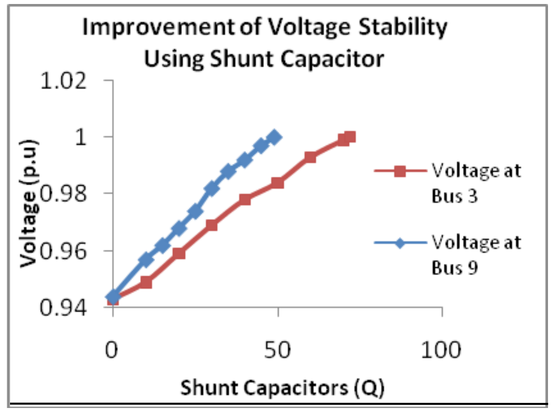

Figure 4.3: Improvement of voltage by injection of shunt capacitor at Bus 3 and Bus 9

Figure 4.3 showed that the voltages at Bus 3 and Bus 9 were increased to 1 p.u at injected MVar of 72MVar and 49MVar at Bus 3 and Bus 9 respectively (refer table 4.3(a)). The value of injected MVar was tested on fixed reactive power loading of 100MVar at both buses. The values of injected MVars were gradually increased until the voltage magnitude is equal to 1 p.u (Refer Appendix 2(a) and Appendix 2(b)). From the curves, it can be observed that the voltage magnitude is proportional to the value of injected MVar at both buses.

4.4 Results and discussion on improvement of voltage stability using tap changing transformer

Load MVar	Location / Tap Changing Value	Bus 4 / Voltage (p.u)
100	0.8	0.927
	0.85	0.935
	0.9	0.946
	0.95	0.949
	1.0	0.957
	1.05	0.960
	1.1	0.967
	1.15	0.970
	1.2	**0.972**

Table 4.4(a): Result of tap changing transformer that improved the voltage to near 1 p.u with fixed reactive power loading of 100MVar at Bus 4

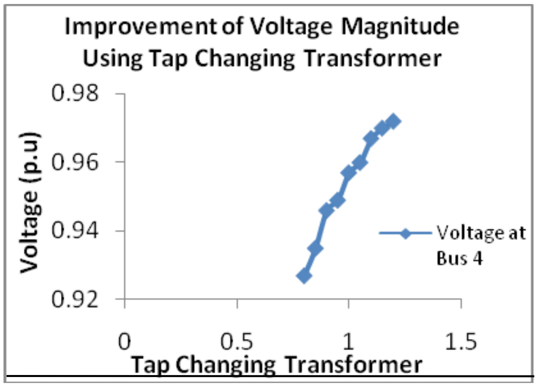

Figure 4.4: Improvement of voltage by tap changing transformer at Bus 4

Figure 4.4 showed the improvement of voltage using tap changing transformer. From table 4.4(a), it can be observed that as the tap changing transformer values were increased, the values of voltage magnitude at Bus 4 were also increased. The main cause of the proportionality was because Bus 4 is the sending bus in IEEE 30-Bus line flow. The tap changing transformer ability to improve voltage was tested at Bus 4 with a fixed reactive power loading of 100MVar. The voltage magnitude of Bus 4 started to be within limit (0.95p.u<V<1.05p.u) at transformer tap changing value of 1.0 onward. From table 4.4(a), the value of tap changing transformer that brought voltage magnitude near to 1 (p.u) was 1.2.

4.5 Results and discussion on improvement of voltage stability using combination of shunt capacitor and tap changing transformer

Load MVar	Injected MVar	Location Tap Changing Value	Bus 9 Voltage (p.u)
100	30	0.80	1.050
		0.85	1.029
		0.90	1.007
		0.91	1.006
		0.92	**1.001**
		0.93	0.997
		0.94	0.993
		0.95	0.991
		0.96	0.987
		0.97	0.982
		0.98	0.981
		0.99	0.978
		1.00	0.974
		1.10	0.944
		1.20	0.913

Table 4.5(a): Result of voltage magnitude with combination of shunt capacitor and tap changing transformer

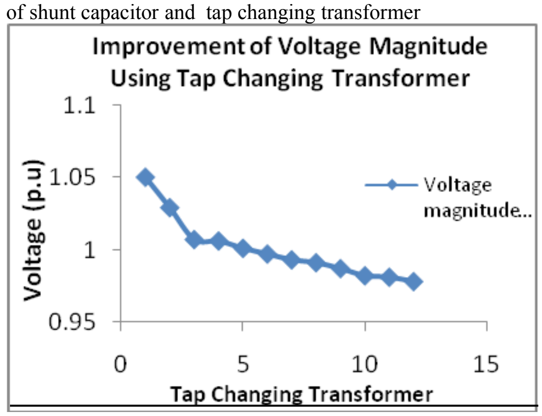

Figure 4.5: Improvement of voltage by combination of shunt capacitor and tap changing transformer at Bus 9

It can be observed that from table 4.5(a), the value of tap changing transformer that gave the nearest voltage magnitude value to 1 (p.u) was 0.92. The voltage magnitude was inversely proportional to the value of tap changing transformer was because Bus 9 is the receiving bus in IEEE 30-Bus line flow.

5.0 CONCLUSION

This project demonstrates the location and size of shunt capacitor and tap changing transformer to improve voltage stability in power system. In the IEEE 30-Bus system, the locations and size of shunt capacitors are 72MVar at Bus 3 and 49MVar at Bus 9 system with a fixed reactive power loading of 100MVar. The tap changing transformer value that improved the voltage magnitude near to 1 (p.u) is 1.2 at Bus 4 with fixed load of 100MVar. When shunt capacitor and tap changing transformer are combined, the value of injected shunt capacitor and tap changing transformer value that bring the voltage magnitude close to 1 (p.u) are 30MVar and 0.92 respectively.

6.0 RECOMMENDATION

For future development, Static Var Compensator (SVC) can be used to improve the voltage stability. Static VAR devices are used to address two common problems encountered in practical power systems:

i. Load compensation, where there is a need to reduce or cancel the reactive power demand of large and fluctuating industrial loads.

ii. Balancing the real power drawn from the ac supply lines. This type of compensation is related to the voltage support of transmission lines at a given terminal in response to disturbances of both the load and the supply. This voltage support is achieved by rapid control of the SVC reactance and, thus, its reactive power output.

7.0 ACKNOWLEDGEMENTS

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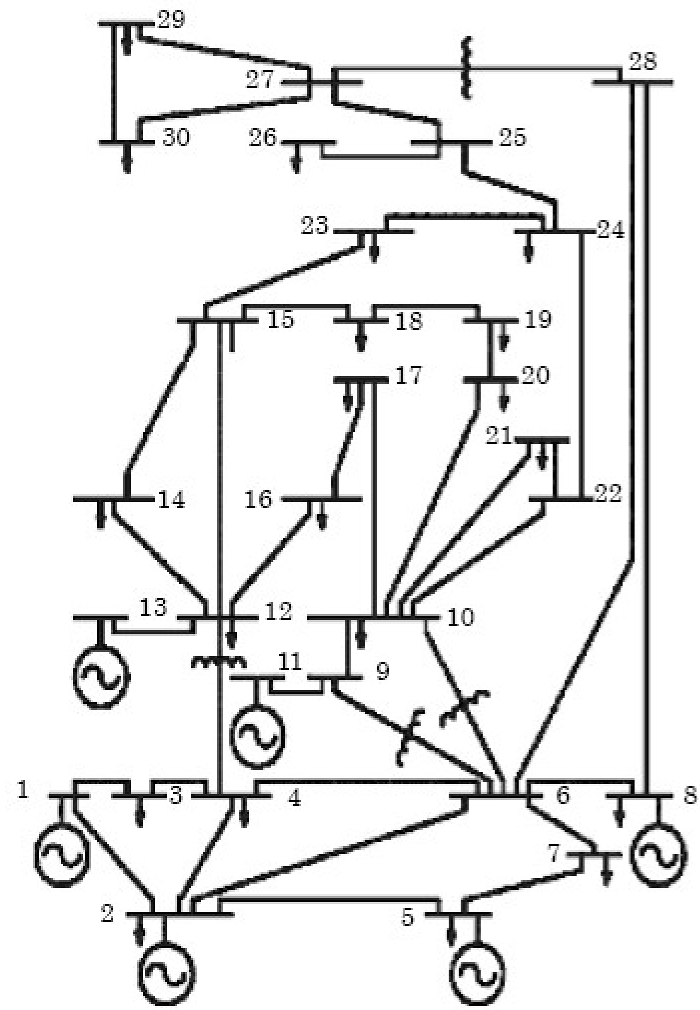
APPENDIX

Appendix 1(a): IEEE 30-bus system



Appendix 1(b): IEEE 30-bus data

Bus Number	Bus Code	Voltage, magnitude	Angle, degree	Load		Generator		Injected MVAR		Static MVAR Qc
				MW	MVAR	MW	MVAR	Qmin	Qmax	
1	1	1.060	0.0	0.0	0.0	0.0	0.0	0	0	0.0
2	2	1.043	0.0	21.7	12.7	40.0	0.0	–40	50	0.0
3	0	1.000	0.0	2.4	1.2	0.0	0.0	0	0	0.0
4	0	1.060	0.0	7.6	1.6	0.0	0.0	0	0	0.0
5	2	1.010	0.0	94.2	19.0	0.0	0.0	–40	40	0.0
6	0	1.000	0.0	0.0	0.0	0.0	0.0	0	0	0.0
7	0	1.000	0.0	22.8	10.9	0.0	0.0	0	0	0.0
8	2	1.010	0.0	30.0	30.0	0.0	0.0	–30	40	0.0
9	0	1.000	0.0	0.0	0.0	0.0	0.0	0	0	0.0
10	0	1.000	0.0	5.8	2.0	0.0	0.0	–6	24	19.0
11	2	1.082	0.0	0.0	0.0	0.0	0.0	0	0	0.0
12	0	1.000	0.0	11.2	7.5	0.0	0.0	0	0	0.0
13	2	1.071	0.0	0.0	0.0	0.0	0.0	–6	24	0.0
14	0	1.000	0.0	6.2	1.6	0.0	0.0	0	0	0.0
15	0	1.000	0.0	8.2	2.5	0.0	0.0	0	0	0.0
16	0	1.000	0.0	3.5	1.8	0.0	0.0	0	0	0.0
17	0	1.000	0.0	9.0	5.8	0.0	0.0	0	0	0.0
18	0	1.000	0.0	3.2	0.9	0.0	0.0	0	0	0.0
19	0	1.000	0.0	9.5	3.4	0.0	0.0	0	0	0.0
20	0	1.000	0.0	2.2	0.7	0.0	0.0	0	0	0.0
21	0	1.000	0.0	17.5	11.2	0.0	0.0	0	0	0.0
22	0	1.000	0.0	0	0.0	0.0	0.0	0	0	0.0
23	0	1.000	0.0	3.2	1.6	0.0	0.0	0	0	0.0
24	0	1.000	0.0	8.7	6.7	0.0	0.0	0	0	4.3
25	0	1.000	0.0	0	0.0	0.0	0.0	0	0	0.0
26	0	1.000	0.0	3.5	2.3	0.0	0.0	0	0	0.0
27	0	1.000	0.0	0	0.0	0.0	0.0	0	0	0.0
28	0	1.000	0.0	0	0.0	0.0	0.0	0	0	0.0
29	0	1.000	0.0	2.4	0.9	0.0	0.0	0	0	0.0
30	0	1.000	0.0	10.6	1.9	0.0	0.0	0	0	0.0

Appendix 1(c): IEEE 30-bus line data

Bus, n l	Bus, n r	R , pu	X , pu	1/2 B pu	=1 for Lines >1or<1 Transformer Tap at Bus nl
1	2	0.0192	0.0575	0.02640	1
1	3	0.0452	0.1852	0.02040	1
2	4	0.0570	0.1737	0.01840	1
3	4	0.0132	0.0379	0.00420	1
2	5	0.0472	0.1983	0.02090	1
2	6	0.0581	0.1763	0.01870	1
4	6	0.0119	0.0414	0.00450	1
5	7	0.0460	0.1160	0.01020	1
6	7	0.0267	0.0820	0.00850	1
6	8	0.0120	0.0420	0.00450	1
6	9	0.0000	0.2080	0.00000	0.978
6	10	0.0000	0.5560	0.00000	0.969
9	11	0.0000	0.2080	0.00000	1
9	10	0.0000	0.1100	0.00000	1
4	12	0.0000	0.2560	0.00000	0.932
12	13	0.0000	0.1400	0.00000	1
12	14	0.1231	0.2559	0.00000	1
12	15	0.0662	0.1304	0.00000	1
12	16	0.0945	0.1987	0.00000	1
14	15	0.2210	0.1997	0.00000	1
16	17	0.0824	0.1923	0.00000	1
15	18	0.1073	0.2185	0.00000	1
18	19	0.0639	0.1292	0.00000	1
19	20	0.0340	0.0680	0.00000	1
10	20	0.0936	0.2090	0.00000	1
10	17	0.0324	0.0845	0.00000	1
10	21	0.0348	0.0749	0.00000	1
10	22	0.0727	0.1499	0.00000	1
21	22	0.0116	0.0236	0.00000	1
15	23	0.1000	0.2020	0.00000	1
22	24	0.1150	0.1790	0.00000	1
23	24	0.1320	0.2700	0.00000	1
24	25	0.1885	0.3292	0.00000	1
25	26	0.2544	0.3800	0.00000	1
25	27	0.1093	0.2087	0.00000	1
28	27	0.0000	0.3960	0.00000	0.968
27	29	0.2198	0.4153	0.00000	1
27	30	0.3202	0.6027	0.00000	1
29	30	0.2399	0.4533	0.00000	1
8	28	0.0636	0.2000	0.02140	1
6	28	0.0169	0.0599	0.06500	1

Appendix 2(a): Value of shunt capacitor was increased until it obtained voltage magnitude of 1 p.u at Bus 3 with fixed load of 100MVar

Bus no.	Injected MVar	Voltage (p.u)
3	0	0.943
3	10	0.949
3	20	0.959
3	30	0.969
3	40	0.978
3	50	0.984
3	60	0.993
3	70	0.999
3	**72**	**1.000**

Appendix 2(b): Value of shunt capacitor was increased until it obtained voltage magnitude of 1 p.u at Bus 9 with fixed load of 100MVar

Bus no.	Injected MVar	Voltage (p.u)
9	0	0.944
9	10	0.957
9	15	0.962
9	20	0.968
9	25	0.974
9	30	0.982
9	35	0.988
9	40	0.992
9	45	0.997
9	**49**	**1.000**