S.D.NAIK[1], S.S.BHAT[2], M.K.KHEDKAR[3]

S.R.K.N.E.C.Nagpur (1), V.N.I.T.Nagpur (2), Vice Chancellor, S.G.B.A.University Amravati (3)

Static Bifurcation Point and Maximum Loadability in a shunt compensated Multibus Power System

***Abstract**. In heavily loaded systems, voltage stability limit is usually dominant and voltage instability is usually observed following large disturbance. This is typically the case in the deregulated environment as the transmission systems are operating under more stressed condition due to increased transaction level associated with open access. In this paper simple voltage stability analysis is carried out for a multibus power system (26 Bus System).The effect of shunt compensation on critical eigen value of Jacobian matrix, system loadabilty and static voltage stability is established.*

***Streszczenie.** W systemie przeciążonym jednym z najważniejszych parametrów jest stabilność napięcia. W artykule przeprowadzono analizę stabilności napięcia w wieloszynowym systemie (26 szyn). (**Statyczne rozwidlenie i maksimum obciążalności w wieloszynowym systemie z bocznikową kompensacją**)*

Keywords: Loadability, shunt compensation, reactive power, voltage stability
Słowa kluczowe: obciążalność, stabilnosc napięcia

Introduction

The voltage stability is gaining more importance now a days with highly developed networks as a result of heavier loadings. Voltage instability may result in power system collapse. Voltage stability is the ability of power system to maintain steady acceptable voltages at all buses in the system under normal conditions [1].
Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of the power system. When power system is subjected to a sudden increase of reactive power demand following a system contingency, additional demand is met by the reactive power reserves carried by the generators and compensators. If sufficient reserves are there, the system settles to a stable voltage level. However because of a combination of events it is possible that additional reactive demand may lead to voltage collapse.

In deregulated environment the power system usually operates under stressed condition [2].The heavily loaded systems are more prone to the voltage instability and the maximum loadability of the system is greatly affected. In recent years, abnormal voltage instability have occurred in several countries viz.France, Japan,USA.More attention is thus paid to keep voltage profile and hold the voltage stability under control [2,3].

It is common to consider curves which relate voltage to active or reactive power. Such curves are referred to as V-P and Q-V curves. The transmission characteristics of interest are the relationship between the transmitted power, receiving end voltage and reactive power injection [4, 5].

Fig.1 shows the variation of voltage as a function of total active power load at a bus in a power system consisting of many voltage sources and load buses. At the Knee of the curve, the voltage drops rapidly with an increase in load demand. The power flow solution fails to converge beyond this limit, which is indicative of instability [5, 6].

Voltage collapse and loadability computations are discussed in [7, 8]. A new method CPFLOW for tracing power system steady state stationary behavior due to load and generation variations is discussed in [9].

There are two voltage solutions before saddle node bifurcation point SNB for certain loading as shown in Fig.1. The upper voltage solution corresponds to normal behavior of the system and represents stable system. The lower voltage solution represents unstable solution.

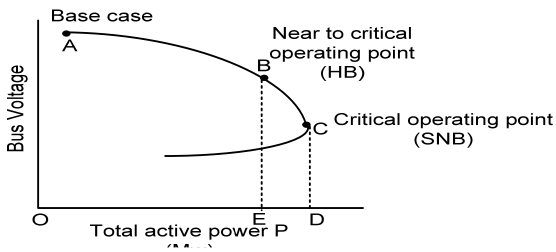

Fig. 1 V-P Curve

At saddle point SNB only one voltage solution occurs. Thus the system can be loaded up to SNB, which is called as critical or maximum loadability point. The critical load for static voltage stability is given by distance OD in Fig.1.The SNB occurs due to slow and gradual increase in loading and may result in static voltage instability At SNB point, the sensitivity ∂V/∂P becomes infinity and Newton Raphson Load Flow Jacobian becomes singular. The minimum singular value of Jacobian indicates the distance between studied operating point and the steady state stability limit. In voltage stability studies, the minimum singular value of the Jacobian becoming zero corresponds to the critical mode of the system [10].There is another possibility of voltage instability due to Hopf bifurcation[11].There are few incidences of voltage collapse due to Hopf bifurcation described in [12,13].With the increase in system loading, the Hopf bifurcation occurs when one pair of complex eign values crosses imaginary axis.Hopf bifurcation may occur before SNB leading to oscillatory instability and voltage collapse. When the loading is further increased the complex pair of eigen values may move away from imaginary axis, either to the right or left side. Consequently stable or unstable limit cycles (Oscillations) may appear or disappear. The horizontal (OE) between base case operating point and HOPF bifurcation point is called oscillatory voltage stability margin or dynamic loading margin.

Q-V Modal Analysis

The NR power flow equations are of form

$$\begin{bmatrix} \Delta P \\ \Delta \theta \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{1}$$

where: Δ P = Incremental change in bus real power, Δ Q = Incremental change in bus reactive power, Δ θ = Incremental change in bus voltage angle, ΔV = Incremental change in bus voltage magnitude, The reduced Jacobian matrix of the system is given by

(2) $J_R = [J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}]$

Voltage stability characteristic of the system can be identified by computing eigen values and eigen vectors of reduced Jacobian matrix J_R given by equation

(3) $J_R = \xi \Lambda \eta$

Where ξ = Right eigenvector matrix of J_R
η = Left eigen vector matrix of J_R
Λ = Diagonal eigen value matrix of J_R

From equation

(4) $J_R^{-1} = \xi \Lambda^{-1} \eta$, we get

(5) $\Delta V = \xi \Lambda^{-1} \eta \Delta Q$ or

(6) $$\Delta V = \sum \frac{\xi_i \eta_i}{\lambda_i} \Delta Q$$

Where: ξ_i = i th column right eigen vector, η_i = i th row left eigen vector

Each eigen value λ_i and corresponding right and left eigen vectors define the i th mode of Q-V response.

Since $\xi^{-1} = \eta$, equation (5) will be written as
$\Delta V = (\eta^{-1} \Lambda^{-1} \eta) \Delta Q$ and $\eta \Delta V = (\Lambda^{-1} \eta) \Delta Q$

(7) $v = \Lambda^{-1} q$

Where: v =Vector of modal voltage variations, q = Vector of modal reactive power variations, Λ^{-1} = A diagonal matrix of inverse of eigen values

Therefore

(8) $v_i = q_i / \lambda_i$

If q increases and v increases or vice versa then $\lambda_i > 0$, which means that i th modal voltage variation and i th modal Q variation are along same direction indicating voltage stability.

If q increases and v decreases or vice versa then $\lambda_i < 0$, which means that i th modal voltage variation and i th modal Q variation are in opposite direction indicating voltage instability.

When the system reaches the voltage stability critical point, modal analysis is helpful in finding voltage critical areas and the elements which participates in this mode.

Bus Participation Factor:

It gives the information on how effective reactive power compensation at a bus is required to increase the modal voltage at that bus. It is given by,

(9) $P_{ki} = \xi_{ki} \eta_{ik}$

Thus P_{ki} determines the contribution of λi of mode i to V-Q sensitivity at bus k. A bus with high participation factor indicates that it has large contribution to this mode.

The size of bus participation in a given mode indicates effectiveness of remedial action applied at that bus

Local Modes: Buses with high participation factor needs high reactive power compensation.

Non Local Modes: It indicates that the large number of buses with small participation factor needs Small reactive compensation.

Since the transmission of reactive power is difficult at heavy loads, local reactive support may be more effective in enhancing voltage stability margin. Placement of shunt capacitors at critical buses may provide local reactive support to maintain bus voltages. The most inexpensive way of providing reactive power and voltage support is the use of shunt capacitors. They can be up to a certain point to enhance the voltage stability margin. They can also be used to free up spinning reactive support in generators and thereby prevent voltage collapse. The compensation provided at the buses with highest participation factor can definitely extend the SNB further improving the system loadability

Methodology

1. Read the system data (Base Data).
2. Perform Load Flow Analysis.
3. Check for the divergence of load flow
4. Increase the load on selected buses in proportion to their original loading.
5. Distribute the increased load on the generators in proportion to their original generation.
6. Repeat step 2 above.
7. Identify the critical load when load flow diverges. Print the values of bus voltages, total critical load etc.
8. Find bus participation factors at critical load, in least stable mode. (Least stable mode corresponds to minimum eigen value of reduced Jacobian matrix).
9. Plot the nose curves (V-P curves) for selected buses.
10. Identify the buses with low voltages at critical Load.
11. Insert the shunt compensation at low voltage buses and repeat step (2) above.
12. Find the minimum eigen value, critical Load, highest bus participation factor for each shunt compensation installed.
13. Plot minimum eigen value vs. total load for each shunt compensation installed.

Fig.2 shows the flow chart of the methodology of analysis. The strategy outlined above is applied to a 26 bus large power system shown in Fig.3 and voltage stability analysis is carried out by increasing the load on selected buses.

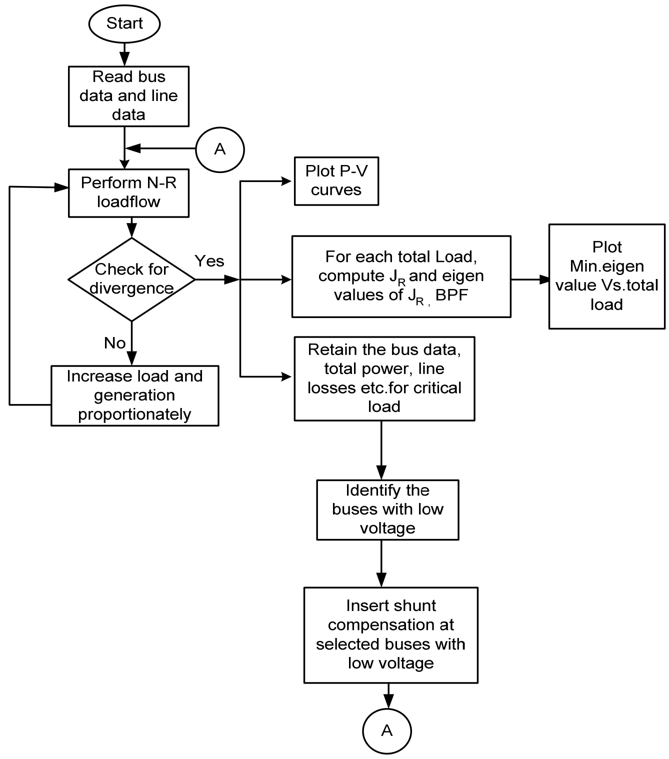

Fig.2 Flow Chart of Applied Strategy

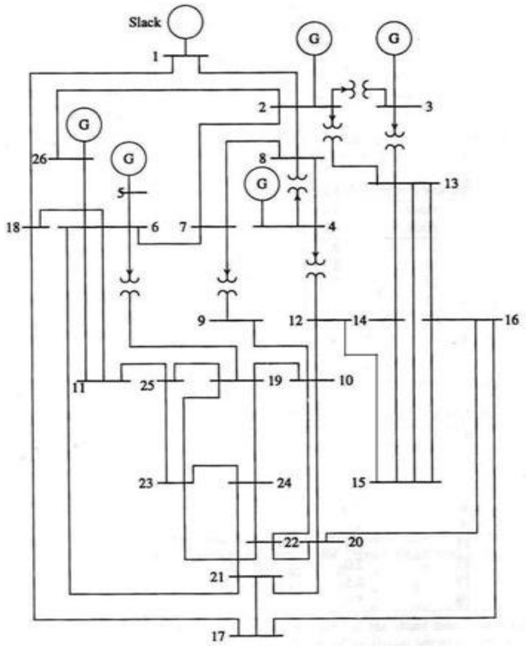

Fig.3 26 Bus Power System

Results and Discussion

Following cases are studied and analyzed.

1. Base case with original data for the system
2. Load variation on selected buses(bus 17 and 21) till the critical load without additional shunt compensation
3. Load variation on selected buses till the critical load with variable shunt compensation provided at the bus with minimum voltage and high bus participation factor.

The results of above cases are tabulated in Table 1, Table 2 and Table 3.

Table 1. Base Case

Total Load	Minimum eigen value
1263 MW	6.1217

Table 2 With load increment on buses 17 and 21 without compensation

TotalLoad	Min.Eigen value	Highest BPF	Min Bus Voltage
1969 Mw	0.9723	Bus 17:0.774	V17=0.53 pu

Table 3 With load increment on buses 17 and 21 with shunt compensation of 10 MVAR at Bus 17

Total Load	Min.Eigen value	Min.Bus voltage
2024 MW	3.2	V17=0.611

Fig.4 shows the bus voltages for base case. All the bus voltages are near to 1.0 pu.Fig.5 shows bus participation factors after the load increment on buses 17 and 21 till the maximum loadability point. It is found that BPF for bus 17 is highest.Fig.6 shows the bus voltages when the system reaches maximum loadability point. It is clear that the voltage of bus 17 is greatly reduced. Fig.7 shows the variation of minimum eigen value corresponding to critical mode with respect to total load. At maximum loadability point the value of minimum eigen value is near to zero.Fig.8 shows the P-V curves of selected buses without shunt compensation.Fig.9 shows the variation of minimum eigen value with respect to the total load with shunt compensation of 10 MVAR provided at bus 17.Minimum eigen value at maximum loadability point rises to 3.2 with shunt compensation.Fig.10 shows the P-V curves of selected buses with shunt compensation. It can be seen that the maximum loadability point is extended to 2024 Mw and voltage of bus 17 has increased.

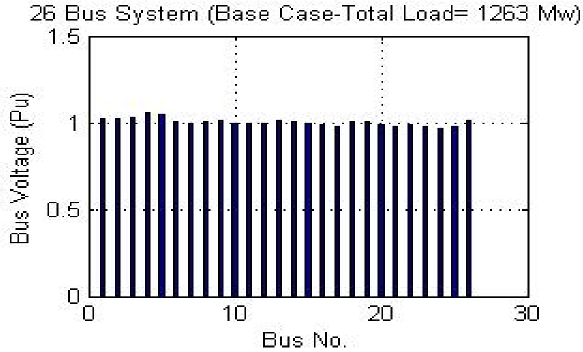

Fig.4 Bus Voltages for Base Case

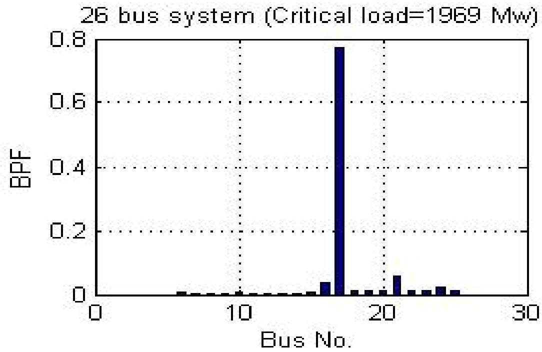

Fig.5 Bus Participation Factors for Critical Load

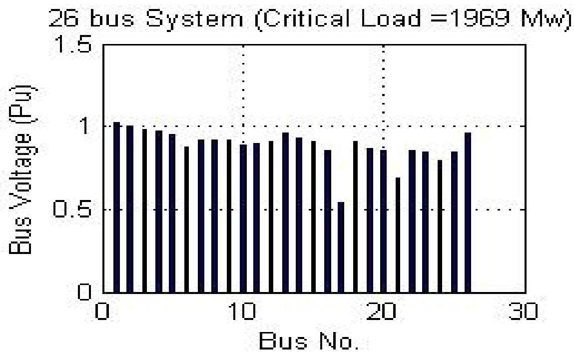

Fig.6 Bus Voltages for Critical Load

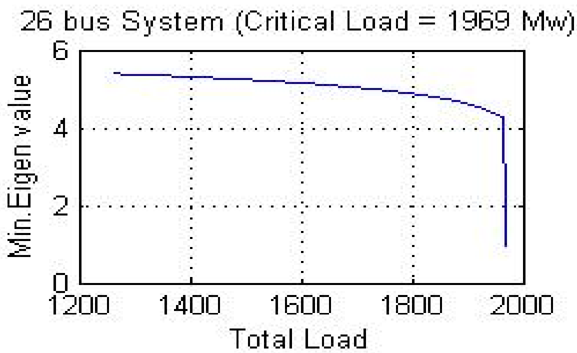

Fig.7 Variation of Minimum Eigen Value with Total Load (Without Shunt Compensation)

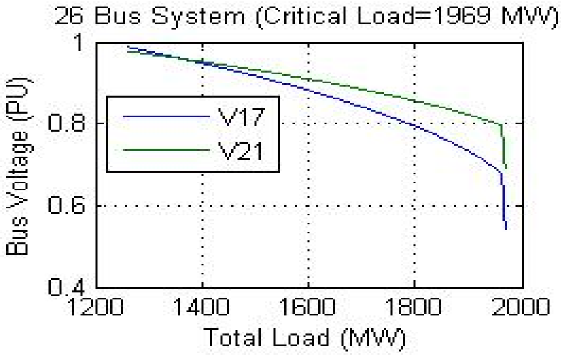

Fig.8 P-V Curves Without Shunt Compensation

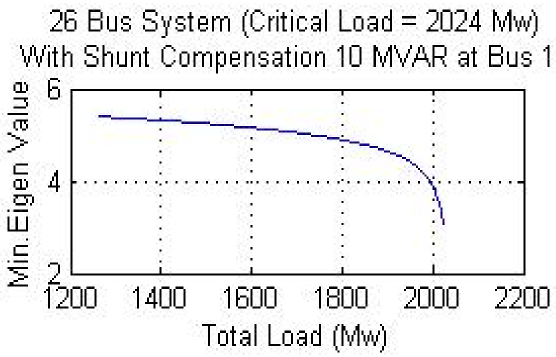

Fig.9 Variation of Minimum Eigen Value with Total Load (With Shunt Compensation)

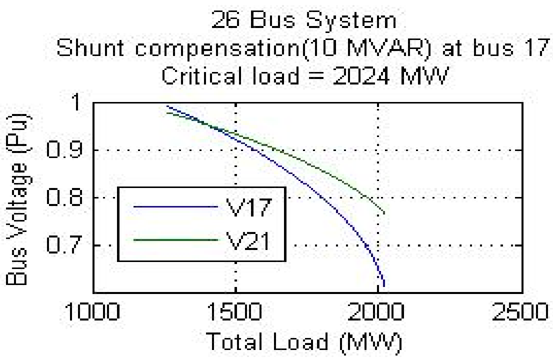

Fig.10 P-V Curves With Shunt Compensation

Conclusion

The driving force for voltage instability is usually loads. In response to the disturbance, power consumed by loads tends to be restored by combined action of distribution voltage regulators, tap changing transformers and thermostats. Restored load increase the stress on high voltage network by increasing the reactive power consumption and causing further voltage reduction. Voltage stability is threatened when a disturbance increases the reactive power demand beyond the sustainable capacity of the available reactive power resources. The magnitude of eigen values can provide the relative measure of proximity to instability and current operating point. It also indicates the requirement of shunt compensation at the buses. The advantage of modal analysis is that it clearly identifies groups of buses which participate in the instability. The application of modal analysis helps in determining how stable the system is and how much extra load or power transfer level should be added. It can also be concluded that providing local shunt compensation at weaker buses not only extends the maximum loadability point further thereby increasing maximum loadability of the system but also helps in improving the bus voltage.

REFERENCES

[1] Ajjarapu V, Christy C. "The continuation power flow: A tool to study steady state voltage stability" *IEEE Trans. On power systems,Vol.7,No.1,pp.416-423 Feb.1992*

[2] G.Hamoud,"Assesment of ATC of transmission system" *IEEE Trans. Power Systems*, vol. 15, No.1 pp. 27-32, Feb. 2000.

[3] Therry Van Cutsem "Voltage instability: Phenomena, Countermeasures and Analysis methods," Proceedings of *IEEE, Vol.88, No.2, pp.208-227, Feb.2000.*

[4] Prabha Kundur "*Power system stability and control*" TATA McGraw-Hill Edition, Power System Engineering Series

[5] Chowdhury B.H., Taylor C.W. "Voltage stability analysis: V-Q power flow simulation versus dynamic simulation" *IEEE Trans. On power systems, Vol.15, No.4, pp.1354-1359, Nov.2000.*

[6] Taylor C.W. "*Power System Voltage Stability*" McGraw-HILL International Editions, Electrical Engineering series J. Jones. (1991, May 10). *Networks*. (2nd ed.) [Online]. Available: http://www.atm.com

[7] Greene S.,Dobson I., Alvarado F.L. "Contingency ranking for voltage collapse via sensitivities from a single nose curve",IEEE Trans on Power Systems,Vol.14,No.1,Feb.1999,pp.2232-40

[8] Taylor,C.,"Indices predicting voltage collapse including dynamic phenomena",CIGRE Task Force 38.02.11,1994

[9] Canizares C.A."Voltage stability assessment: Concepts Practices and Tools,IEEE PES Power System Stability Subcommittee Special Publication, SP101PSS,2003

[10] *V.Ajjarapu "Computational techniques for voltage stability assessment and control* "Springer International Edition, Power Electronics and Power System Series.

[11] Cladio A.Canizares., "On bifurcations, voltage collapse and load modeling", IEEE trans. on power systems,Vol.10,No.1,Feb.1995,pp.512-522

[12] N.Mithulananthan,S.C.Srivastava., "Investigation of a voltage collapse incident in Sri Lanka's power system network" Proc.of EMTD'98,Singapore,IEEE catalogue No.98EX137,March 3,1998,pp.47-52

[13] C.Alsberg."WSCC issues preliminary report on August power outage: press release". Technical report, WSCC, available on www.wscc.com,Sept.1996

Authors:

1. S.D.Naik,Associate Professor,Shri R.K.N.Engineering College,Nagpur,India.Email:sdnaik_ngp@yahoo.co.in
2. S.S.Bhat,Associate professor,V.N.I.T.Nagpur,India Email:ssb2009@yahoo.com
3. M.K.Khedkar, Vice Chancellor, S.G.B.A.University, Amravati,India.Email:mohankhedkar@rediffmail.com