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VOLTAGE STABILITY ASSESSMENT IN ELECTRICAL GRIDS

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Abstract*— *Power system voltage stability analysis is a crucial aspect of electrical engineering that focuses on ensuring the steady and reliable operation of a power network under various operating conditions. Voltage stability is a key factor in maintaining the desired electrical supply within acceptable limits. It refers to the ability of a power system to maintain steady voltage levels at all points within the network, even when subjected to disturbances or changes in operating conditions. In a power system, voltage stability is influenced by factors such as load variations, generator output changes, and the network's overall impedance characteristics. When these factors approach critical levels, the power system may experience voltage instability, leading to undesirable consequences like voltage collapse or voltage collapse-induced cascading failures. The analysis of power system voltage stability involves mathematical modeling, simulations, and analytical methods to assess the system's ability to maintain voltage levels within acceptable limits. Engineers use tools such as load flow analysis, transient stability analysis, and eigenvalue analysis to evaluate the dynamic behavior of the power system under different scenarios. Additionally, advanced techniques like continuation methods and voltage stability indices are employed to predict and mitigate potential voltage instability issues. Understanding power system voltage stability is essential for power system planners, operators, and researchers to ensure the reliable and secure operation of electrical grids. By identifying potential voltage stability issues and implementing appropriate control strategies, engineers can enhance the resilience of power systems, minimize the risk of voltage collapse, and contribute to the overall stability of the electric grid. To further enhance power system voltage stability, engineers often employ control strategies and technologies such as automatic voltage regulators (AVRs), flexible AC transmission systems (FACTS), and power system stabilizers (PSS). These devices and control systems help regulate voltage levels, improve transient stability, and mitigate the impact of disturbances on the power network. Additionally, the integration of renewable energy sources and the increasing complexity of modern power systems pose new challenges to voltage stability

***Keywords* — *P-V and Q-V curve* , Load Tap Changers**

I. INTRODUCTION

The analysis of voltage stability can be done using different methods. One of the mostly used method is finding the maximum loading point using the P-V curve or the Q-V curve with the help of power flow calculations. In this method, the distance between operating point and maximum loading point is taken as the stability criterion. Voltage stability analysis also can be done by using bifurcation as the stability criterion. Minimum singular value or minimum eigen value helps to find the critical operating point. Modal analysis in which system is represented by using eigenvectors is also used. At the voltage collapse point, solution of power flow equations experiences convergence problem. So to avoid this convergence problem, voltage stability indices are proposed based on power flow equations. These indices gives information such as critical buses and critical branches. In this chapter, MATLAB simulation is performed on IEEE standard 6 bus and 14 bus system.

II. REAL POWER MARGIN COMPUTATION USING THE P- V CURVE

In voltage stability analysis, relation between power transfer to the load and voltage of the load bus is not weak.

Variation in power transfer from one bus to another bus effects the bus voltages. This can be studied using P-V curve. For a network, load buses (PQ buses) are identified to plot the P-V curves. The load model is taken as constant real power which is represented by Equation .1.

$$P = P0(1 + \lambda KL) \qquad (1)$$

Where P0 is the base case load real power,
λ is loading factor
KL is the load increment factor.
The power-flow solution of the system is taken as a base case.

Steps in P-V curve analysis:
Select a load bus, vary the load real power using loading factor λ and load increment factor KL. Keep the power factor as constant. Compute the power flow solution for the present load condition and record thevoltage of the load bus. Increase the loading factor by small amount and repeat step 2 until power flow does not have convergence. P-V curve is plotted using the calculated load bus voltages for increased load values. Real power margin is computed by subtracting the base load value from maximum load value at which voltage collapse occurs.

In P-V curve shown in Figure 1, there are three regions related to real power load P. In the first region up to loadability limit, power flow equation has two solutions for each P of which one is stable voltage and other is unstable voltage. If load is increased , two solutions will coalesce and P is maximum. If load is further increased, power flow equation doesn't have a solution. Voltage corresponding to "maximum loading point" is called as critical voltage.

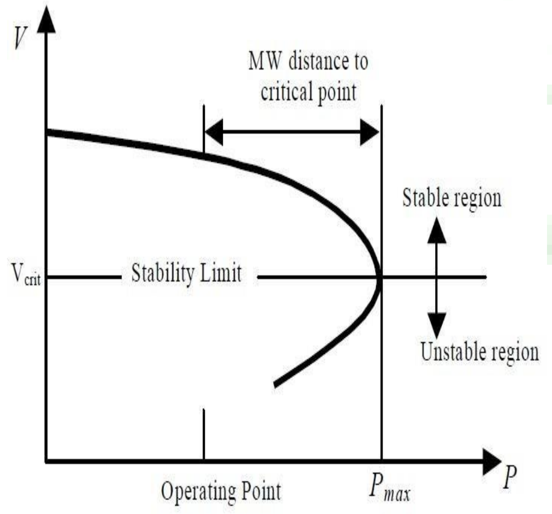


Figure 1: Typical P-V curve.

is related to the "ability of a power system to maintain acceptable voltages at all buses under normal conditions and after being subjected to a disturbance". Voltage instability is a periodic, dynamic phenomenon. As most of the loads are voltage dependent and during disturbances, voltages decrease at a load bus will cause a decrease in the power consumption. However loads tend to restore their initial power consumption with the help of Distribution Voltage Regulators, Load Tap Changers (LTC) and thermostats. These control devices try to adjust the load side voltage to their reference voltage. The increase in voltage will be accompanied by an increase in the power demand which will further weaken the power system stability. Under these conditions voltages undergo a continuous decrease, which is small at starting and leads to voltage collapse.

When a single machine is connected to a load bus then there will be pure voltage instability. When a single machine is connected to infinite bus then there will be pure angle instability. When synchronous machines, infinite bus and loads are connected then there will be both angle and voltage instability but their influence on one another can be separated [2]. The dynamics involved in voltage instability are restricted to load buses with LTC, restorative loads etc.,. These load voltage control devices are operated for few minutes to several minutes. So, generator dynamics can be substituted by appropriate equilibrium conditions. Under stressed conditions, coupling between voltage and active power is not weak [3]. So, insufficient active power in the system also leads to voltage instability problems [11].

III. REACTIVE POWER MARGIN COMPUTATION USING THE Q-V CURVE

The V-Q curves, gives reactive power margin. It shows the reactive power injection or absorption for various scheduled voltages. If reactive power load is scheduled instead of voltages Q-V curves are produced. Q-V curves are a more general method of assessing voltage stability. Many utilities uses Q-V curves to determine the proximity to voltage collapse and to establish system design criteria based on Q and V margins. Q-V curves can be used to check whether the voltage stability of the system can be maintained or not and to take suitable control actions. A typical V-Q curve is shown in Figure 2

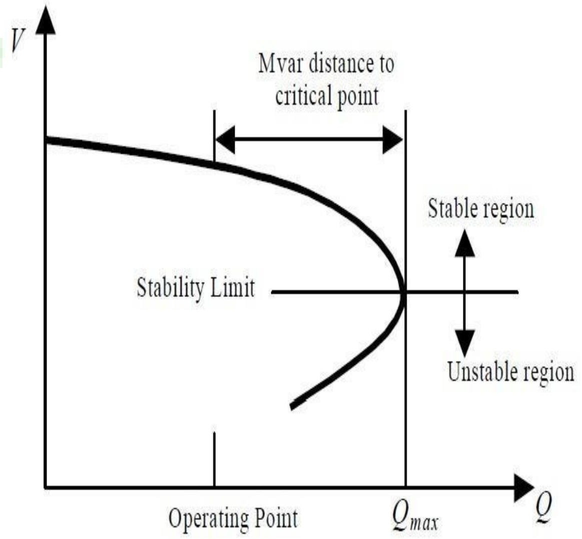


Figure 2: Typical Q-V curve

Near the collapse point of Q-V curve, sensitivities get very large and then reverse sign. Also, it can be seen that the curve shows two possible values of voltage for same value of power. The power system operated at lower voltage value would require very high current to produce the power. That is why the bottom portion of the curve is classified as an unstable region and system can't be operated in this region. Constant reactive power load model is selected and represented by the following Equation 2.

$$Q = Q0(1 + \lambda KL) \qquad (2)$$

Where

$Q0$ is the base case load reactive power,

λ is loading factor

KL is the load increment factor.

The power-flow solution of the system is taken as a base case.

Steps in Q-V curve analysis:

- Select a load bus, vary the load reactive power using load demand factor λ and load increment factor KL. Keep the real power of load as constant.
- The reactive power output of each generator should be allowed to adjust.
- Compute the power flow solution for the present load condition and record the voltage of the load bus.
- Increase the load demand factor λ by small amount and repeat step 3 until power flow does not have convergence.
- Q-V curve is plotted using the calculated load bus voltages for increased load values.
- Reactive power margin is computed by subtracting the base load value from maximum load value at which voltage collapse occurs.

Disadvantage of P-V Curves and Q-V Curves

Though both methods are widely used as index to find the proximity to voltage collapse, but they have few disadvantages.

- In both methods, at a time only one bus is considered for load variation. As there is no information about critical buses, power flow studies are to be done for many buses which takes so much time.
- As the loading on the system approaches critical point, convergence problem occurs in solving the power flow equation.

IV. MINIMUM SINGULAR VALUE METHOD

Minimum singular value method is proposed as an index to find the proximity to voltage collapse point by Thomas and Lof [9]. This method is based on Jacobian matrix JR of the power system. In this method, determinant of JR is calculated until it reaches a minimum value by increasing the load on the system.

This will give only proximity to voltage collapse but not provides specific causes of voltage instability such as critical lines and generators reaching reactive limits. As the system exhibits non linear behaviour from stable operating point to bifurcation limit, it can't give a linear or absolute measure to voltage collapse point.

V. SIMULATION RESULTS AND DISCUSSIONS

Voltage stability analysis is carried out for determining load ability limits for IEEE standard 6-bus and 14-bus power systems. Newton-Raphson method is used for solving the power flow equations. MATLAB code is written for the used methods.

A. Results For IEEE Standards 6-Bus System

The IEEE standard 6-Bus system consists of two synchronous generators and three loads. Real power margin is calculated from P-V curve. P-V curves are drawn for constant power and constant current load models for all load buses. P-V curve results for constant power load model are shown in the Table 1 and Figure 3.

Table 1: Real power margin of load buses for constant power load model of IEEE 6-bus system

The P-V curves are plotted in Figure 4.4. From the Table 1 and Figure 3, it is observed

Bus No	Critical loading factor λ_{cr}	Real power margin (P_{margin} in p.u)	Critical voltage (V_{cr} in p.u)
3	0.9310	3.2258	0.6340
5	0.8120	0.6340	0.5362
6	0.9080	2.2632	0.6083

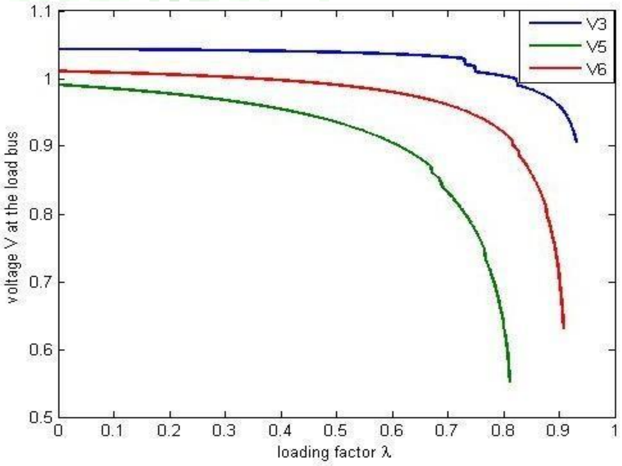


Figure 3: The P-V curves of load buses for constant power load of IEEE 6-bus power system.

that bus number 5 is having least real power margin when constant power load model is used in the analysis.

The P-V curve results for constant current load model are shown in the Table 2 and Figure 4.

Table 2: Real power margin of load buses for constant current load model of IEEE 6-bus system.

Bus No	Critical loading factor λ_{cr}	Real power margin (P_{margin} in p.u)	Critical voltage (V_{cr} in p.u)
3	1.09	3.7056	0.9093
5	1.67	1.3036	0.5373
6	1.65	0.5373	0.5782

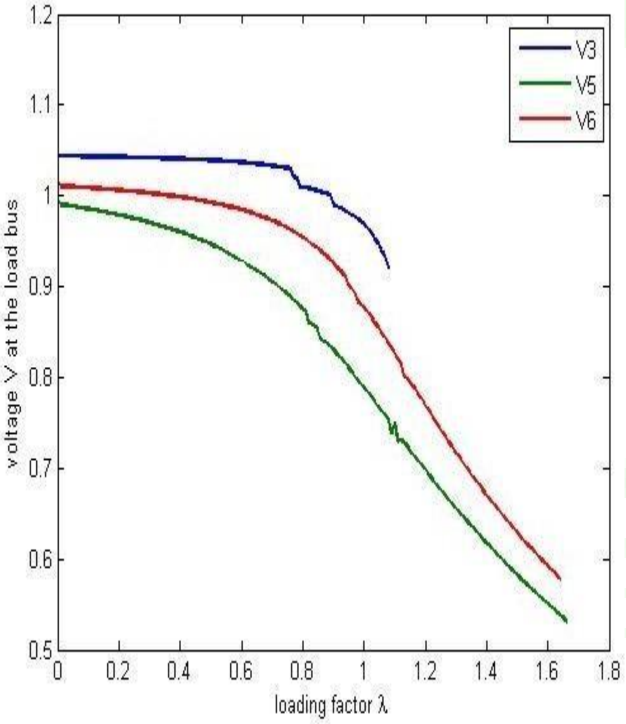


Figure 4: The P-V curves of load buses for constant current load of IEEE 6-bus power system.

From the above results, it is observed that real power margin of bus 6 is small and it is the critical bus. The Q-V curves for constant power load model are shown in Figure 4.6. Reactive power margin of load buses are given in Table 4.3. Results of the Q-V curves shows that bus 5is having least reactive power margin and it is the critical bus.

Table 3: Reactive power margin of load buses of IEEE 6-bus system

use number active power margin (in u)	7244	3973	7978

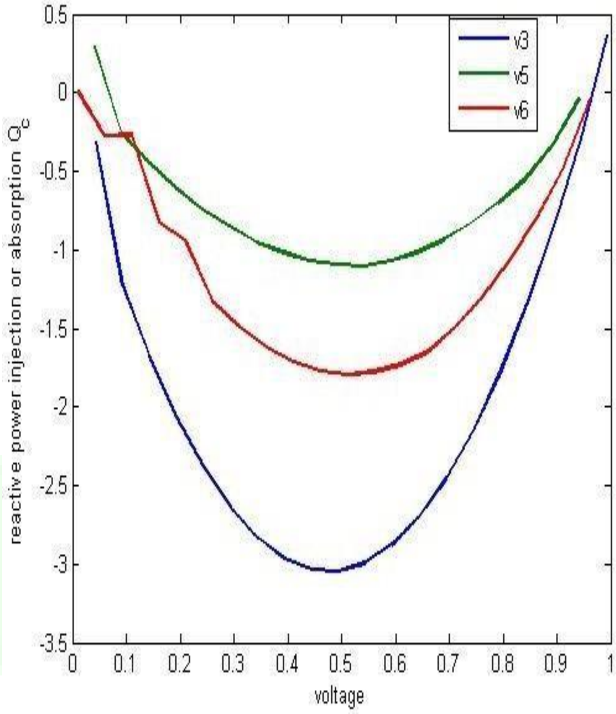
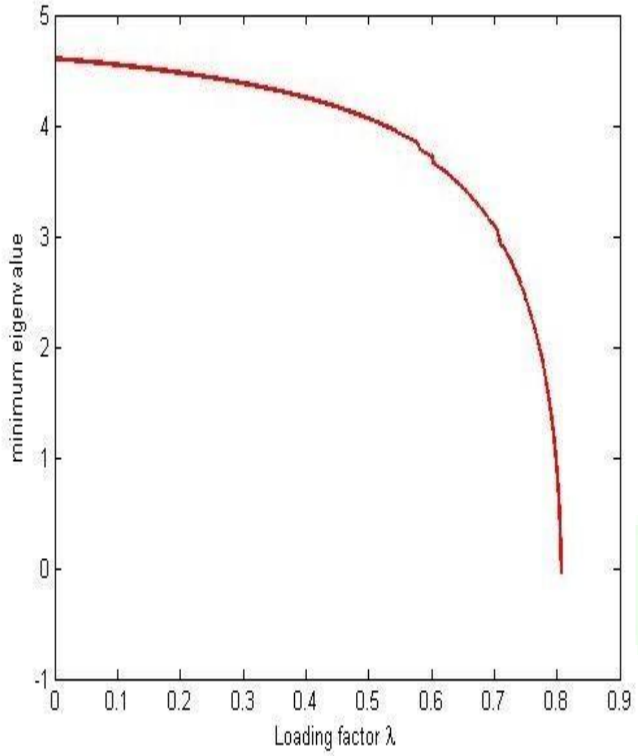


Figure 5: The Q-V curves of load buses of IEEE 6-bus power system.

Continuation power flow method is applied to calculate the real power loading margin. It gives a operating point and voltages with respect to loading factor λ are shown in Figure 4.7. Voltage curve of bus 5 is showing sharp decrease in the slope and its voltages reaching low values at the critical point. The critical loading factor λ critical = 0.85, is obtained using Continuation power flow method. Where as in P-V curves, the obtained least loading factor is λ critical = 0.812 which is for bus 5. These two values are nearer to each other. Bus 5 is identified as a critical bus.

Modal analysis is performed by varying only load reactive power. The minimum eigen values of JR represents critical modes of operation. Corresponding to this mode of operation bus participation and branch participation factors are calculated. Variation of minimum eigen value with loading is shown in Figure 4.8. The bus participation factors of load buses are shown in Figure 6. It is observed that bus 5 is having largest participation factor and it is sensitive to voltage instability. The Branch participation factors of branches are shown in Figure 4.10. Branch 4 has largest participation factor and it is consuming most of the reactive power that is available in the network.



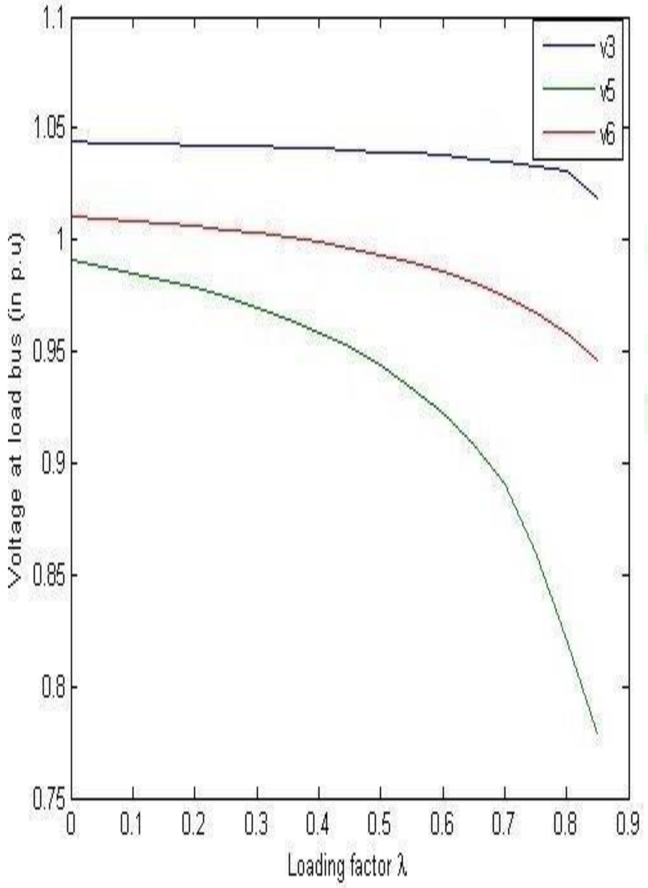


Figure 6: Critical loading factor using Continuation power flow method.

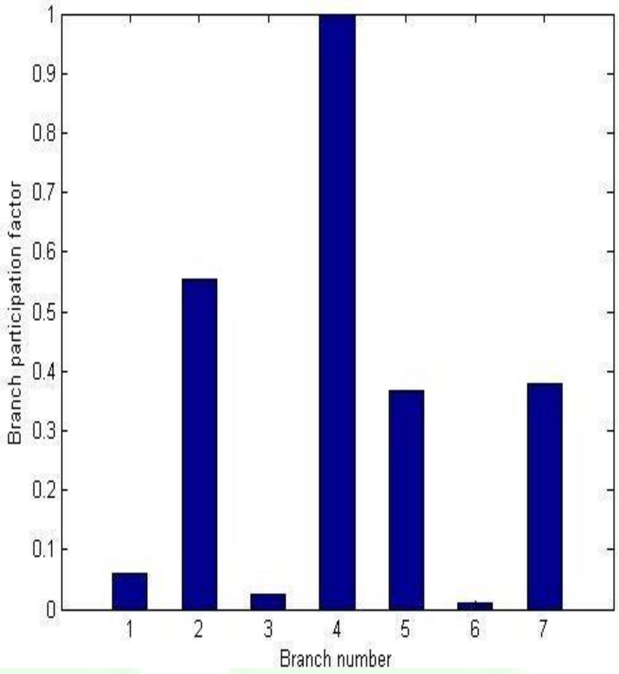


Figure 4.8: Path of minimum Eigen value with increase of loading.

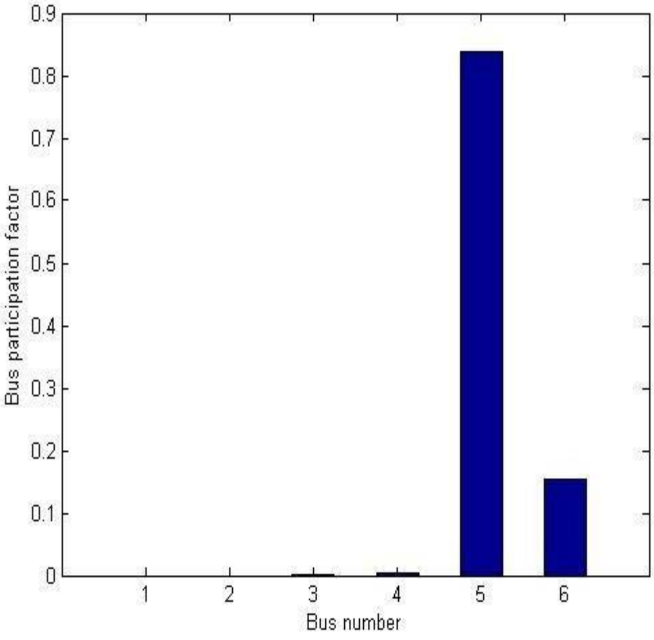


Figure 4.9: Bus Participation factors for most critical modes for the IEEE 6-bus system.

VI. CONCLUSION

In this work, voltage stability problem is analyzed in view of maximum loadability limit. Simulations are carried out on IEEE standard 6 bus and 14 bus systems. Load modeling is an important aspect in voltage stability analysis and various load models are therefore considered. P-V curves and Q-V curves are drawn for various load buses with different load models. From these curves, maximum loadability limit is computed.

The maximum loadability limit is calculated using continuation power flow method in which the power-flow solutions are traced. Critical loading factor is calculated and it is nearly equal to that of from P-V curves. Modal analysis is used and the maximum loadability is identified at the smallest minimum eigen value of the reduced system Jacobian matrix *JR*.

This method gives bus participation factors and branch participation factors that are used to identify the critical buses and critical branches To crosscheck the modal analysis results, Q-V curves are drawn for critical buses and results are matched. These results are helpful for determining the amount of reactive power compensation. Critical buses are provided with reactive power compensation for improving the voltage stability .Voltage stability indices are calculated and voltage instability is observed for various loading scenarios. When the system is voltage stable, these indices are close to zero and move towards to 1 as system is gradually moving towards critical point. Different voltage stability indices are calculated and compared for single and multiple load change scenarios. Using these indices, Critical buses and branches are identified and these results are matching with that of Modal analysis.

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