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Voltage Stability Study using Sensitivity Analysis

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ABSTRACT

Voltage stability problems have been one of the major concerns for electric utilities as a result of system heavy loading. In this paper investigation of sensitivity analysis for voltage stability assessment has been discussed. At a normal operating state, sensitivity analysis provides information about how different parameters influence stability. There has been works reported in the literature on the use of analytical methods to monitor voltage stability of a power system on a real time basis. Some techniques are reported in this paper.

***Keywords:* Voltage stability, Voltage Collapse, Voltage Stability Assessment, Voltage stability Index.**

I INTRODUCTION

In recent years, modern power systems have experienced many technical challenges due to increasing complexities in operation and structure of the interconnected power grid. Voltage stability is recognized as one of the major problems in many power systems throughout the world. The transmission networks need to be utilized ever more efficiently. The transfer capacity of an existing transmission network needs to be increased without major investments but also without compromising the security of the power system. The more efficient use of transmission network has already led to a situation in which many power systems are operated more often and longer close to voltage stability limits. A power system stressed by heavy loading has a substantially different response to disturbances from that of a non-stressed system. The potential size and effect of disturbances has also increased. When a power system is operated closer to a stability limit, a relatively small disturbance may cause a system upset. In addition, larger areas of the interconnected system may be affected by a disturbance [1-5].

Voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all buses under normal conditions and being subjected to a disturbance. The assessment of voltage stability has also become more complicated due to strengthening of power system. For example, voltages do not indicate the proximity to voltage collapse point in heavy loading conditions. Whereas, Voltage instability is mainly associated with the inability of the power system to maintain acceptable voltages at all buses in the system under normal conditions and being subjected to disturbances such as gradual load increase or outages of critical lines or generating units. The general characteristic of voltage instability is that the voltage level at different locations slightly changes after the disturbance but abruptly declines near to the collapse point. Therefore, the voltage level itself is not a good indicator [6]. The system operator needs performance indices either in on-line or off-line modes to determine how close the system is to the collapse and what the control actions should be carried out in that event. In off-line planning activities, computational speed is generally not a problem. However, for on-line analysis, real-time or faster than real-time tools are of the key interest for monitoring and enhancing stability of the power system. The research of the power system voltage stability during the last 10 years has dealt with modeling of voltage stability, computation of voltage collapse point and enhancement of power system stability. The research has mainly been based on analytical methods such as dynamic simulations and load flow algorithm.

II CLASSIFICATION OF POWER SYSTEM STABILITY

Power system stability is essentially the capability of the power system to maintain equilibrium with system variables in an acceptable range after being subjected to a wide range of disturbances no matter how small or large. The size of the disturbance influences the method of analysis and prediction of the stability. Voltage stability can be classified into the two following categories based on the size of disturbance [12].

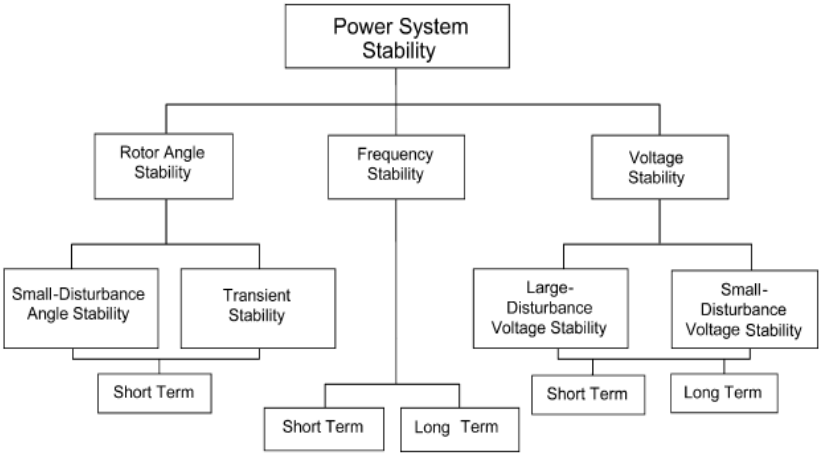

Fig. 1: Classification of Power System Stability

Large-disturbance voltage stability refers to the ability of a power system to maintain steady acceptable voltages following a large disturbance, such as system faults, loss of generation, or line tripping. The nonlinear response of a power system, including the interaction between numerous continuous and discrete control and protection devices, needs to be examined to determine large-disturbance voltage stability. Considering the nature of devices involved in a large system disturbance, the study period of interest may extend from a few seconds to tens of minutes.

Small-disturbance voltage stability refers to the ability of a power system to maintain steady acceptable voltages when subjected to small perturbations, such as incremental changes of system load. For the analysis of small-disturbance voltage stability, it is reasonable to consider the linearized system model around the operation point. Discontinuous models for tap changing transformers and other equipment may be replaced with approximate continuous models. The study period of small-disturbance voltage stability may range from minutes to hours [10].

Following, disturbances, the system voltages often do not return to the original level. Therefore, it is necessary to define the region of voltage level considered acceptable. The system is then said to have finite stability within the specified region of voltage level.

III VOLTAGE STABILITY ASSESSMENT

Modern transmission networks are more heavily loaded than ever before to meet the growing demand. One of the major problems associated with such a stressed system is voltage collapse or instability. There are many incidents of system blackout, due to voltage collapse [2].

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under all operating conditions. Voltage control and stability problems are now receiving special attention in many cases like under heavy loaded conditions. There may be insufficient reactive power causing the voltage to drop. This drop may lead to drop in voltage at various buses. This sort of abnormal voltage drop is referred as voltage instability. [3]

For many power systems, voltage stability assessment has become one of the most important types of analysis performed as a part of system planning, operational planning, and real time operations. Instability may occur in the form of a progressive fall of voltage of some buses [11].

i. In general voltage stability margin is defined as the difference between the values of the key system parameters (KSP) at the current operating condition and at the voltage stability critical point. Different utilities may use different KSPs from two main following categories:
    a. PV- based Key System Parameters, such as an area load or power transfer across an interface.
    b. Q-V based Key System Parameters, such as reactive power injection at a bus or group of buses.

ii. Voltage stability criterion defines how much margin is deemed sufficient for the voltage security of the system. It can be stated that “as the system must be operated such that for the operating point and under all creditable contingencies the VS margin remain larger than x% of the KSP.” For example, when the KSP, the system must remain voltage stable under all contingencies when the area load is increased by 7% above the given operating level. A practical approach is to use power flow base tool to calculate the VS margin for the base case and all contingencies cases. Mainly there are two methods by which VS margin can be computed:

a. P-V based margin computation and Q-V based margin computation

iii. P-V Curves.

When considering voltage stability, the relationship between transmitted P and receiving end V is of interest. The voltage stability analysis process involves the transfer of P from one region of a system to another, and monitoring the effects to the system voltages, V. This type of analysis is commonly referred to as a PV study.

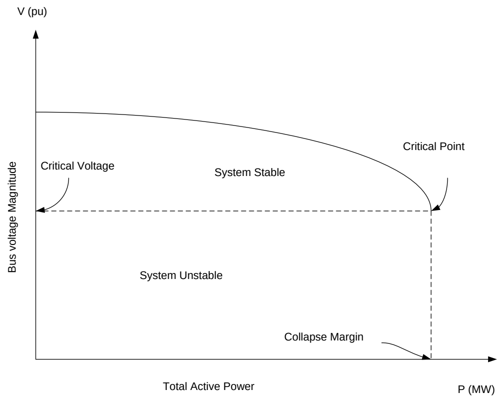

Fig. 2: P-V curve

The Figure shows a typical PV curve. It represents the variation in voltage at a particular bus as a function of the total active power supplied to loads or sinking areas. It can be seen that at the “knee” of the PV curve, the voltage drops rapidly when there is an increase in the load demand. Load-flow solutions do not converge beyond this point, which indicates that the system has become unstable. This point is called the Critical point. Hence, the curve can be used to determine the system’s critical operating voltage and collapse margin. Generally, operating points above the critical point signifies a stable system. If the operating points are below the critical point, the system is diagnosed to be in an unstable condition.

iv. Q-V Curves.

Voltage stability depends on how the variations in Q and P affect the voltages at the load buses. The influence of reactive power characteristics of devices at the receiving end (loads or compensating devices) is more apparent in a QV relationship. It shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions.

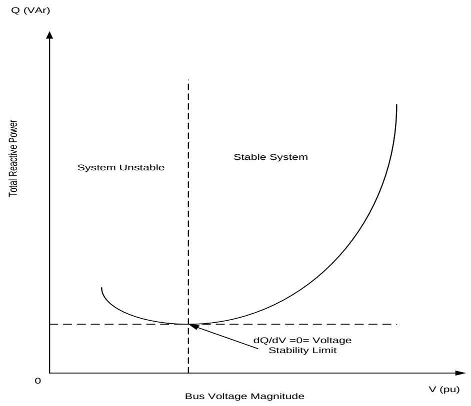

Fig. 3: QV curve

Figure shows a typical QV curve, which is usually generated by a series of load-flow solutions. Figure shows a voltage stability limit at the point where the derivative dQ/dV is zero. This point also defines the minimum reactive power requirement for a stable operation. An increase in Q will result an increase in voltage during normal operating conditions. Hence, if the operating point is on the right side of the curve, the system is said to be stable. Conversely, operating points in the left side of the graph are deemed to be unstable.

IV STABILITY STUDY VIA SENSITIVITY ANALYSIS

A common approach in doing sensitivity analysis is to define a stability index and then study how the different parameters affect this index. By using sensitivity techniques, useful information about the relationship between state, control, and dependent variables can established. Sometimes the sensitivity might not be directly defined with respect to a certain stability index, and is therefore referred to as parametric sensitivity. Since the system performance degradation often leads to loss of stability, parametric sensitivity is also used in sensitivity based stability analysis. At a normal operating state, sensitivity analysis provides information about how different parameters influence stability. Certain control measures can be designed to prevent the system from instability. Sensitivity analysis is well suited for evaluating the effectiveness of the controls. [11]

i. Modal Analysis

Modal analysis involves calculation of eigenvalues and eigenvectors of the power flow Jacobian. A system is voltage stable at a given operating condition if for every bus in the system, bus voltage magnitude increases as reactive power injection at the same bus is increased. A system is voltage unstable if for at least one bus in the system, bus voltage magnitude decreases as the reactive power injection at the same bus is increased. In other words, a system is voltage unstable if V-Q sensitivity is positive for every bus and unstable if V-Q sensitivity is negative for at least one bus [4].

Reduced Jacobean Matrix

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

Where,

ΔP= Incremental change in bus real power

ΔQ=Incremental change in bus reactive power injection

Δθ=Incremental change in bus voltage angle

ΔV=Incremental change in bus voltage magnitude

$$\begin{bmatrix}j_{11} & j_{12}\\ j_{21} & j_{22}\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} = \begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}$$

System voltage stability is affected by both P and Q. However, at each operating point we keep P constant and evaluate voltage stability by considering the incremental relationship between Q and V. This is analogous to the Q-V curve approach. Although incremental change in P are neglected in the formulation, the effects of changes in the system load or power transfer levels are taken in to account by studying the incremental relationship between Q and V at different operating conditions.

ii. Sensitivity Analysis via CPF

The Jacobian matrix of Equation (6) becomes singular at the voltage stability limit. Consequently, conventional power flow algorithms are prone to convergence problems at operating conditions near the stability limit. The Continuation Power Flow analysis overcomes this problem by reformulating the power flow equations so that they remain well-conditioned at all possible loading conditions. This allows the solution of the power flow problem for stable as well as unstable equilibrium points. [12]

The continuation method is a mathematical path-following methodology used to solve systems of nonlinear equations. Using the continuation method, one can track a solution branch around the turning point without difficulty. The continuation power flow captures this path following feature by means of a predictor-corrector scheme that adopts locally parameterized continuation techniques to trace the power flow solution paths. [11]

iii. Eigen Value Sensitivity

The eigen value analysis gives information about small signal stability of the current operating point. Therefore the sensitivity of the critical eigenvalue with respect to system parameters is often needed to design coordinated control to prevent instability.

$$[J_R] = [\xi]\,[\lambda]\,[\eta]$$

$$[|V|] = [\xi][\lambda]^{-1}\,[\eta]\,[\Delta Q]$$

$$[|V|] = \left[\sum i \frac{\xi_i \eta_i [\Delta Q]}{\lambda_i}\right]$$

Where [ξ i] = right eigen vector of [JR]

[η i] = diagonal eigen value matrix of [JR]

Suppose λi is the critical eigenvalue of interest, its sensitivity with respect to any parameter p. Eigen value sensitivity can be applied to any eigenvalue of critical interest, therefore oscillatory as well as collapse type instability can all be addressed by this approach. For voltage collapse analysis, one can apply this to minimum zero crossing eigenvalue λmin [13].

iv. Voltage Stability Index

System operators would always like to know how far the network is from voltage collapse point for smooth and reliable operation of power system. Voltage stability index is formulated which assess the state of a distribution system from the view point voltage collapse [4]. It is based on a simple solution of quadratic equation r_1+jx_1 between bus i and bus i+1 of the radial distribution system may be represented by an equivalent circuit model as shown in fig.[4].

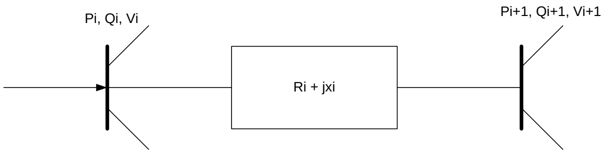

Fig. 4: Voltage Stability Index.

$$L_i = \frac{4\sqrt{((P_{i+1}^2 + Q_{i+1}^2)(r_i^2 + x_i^2))}}{V_i^2} \leq 1$$

The system is closed to the voltage collapse when the value of voltage stability index approaches unity. On the other hand, more the value of the indicator close to zero, the system is more stable.

Any interconnected network can be reduced to an equivalent two bus network by keeping the sending end voltage constant and considering Ps and Qs as total and reactive power generation respectively connected with receiving end active and reactive load, PR and QR respectively by an equivalent impedance of req+jeq.

Here, when developed VSI is applied to the two bus equivalent system of the multi bus system, it can be represented as,Voltage stability level of the total interconnected system can be measured using proposed VSI and thereby appropriate action may be taken if the value of index would become nearer to unity [5,7].

V CONCLUSION

A common approach in doing sensitivity analysis is to define a stability index and then study how the different parameters affect this index. Certain control measures can be designed to prevent the system from instability. Sensitivity analysis is well suited for evaluating the effectiveness of the controls. By using sensitivity techniques, useful information about the relationship between state, control, and dependent variables can established.

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