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DETERMINATION OF STATIC VOLTAGE STABILITY-MARGIN OF THE POWER SYSTEM PRIOR TO VOLTAGE COLLAPSE

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ABSTRACT

Voltage instability problems in power system are an important issue that should be taken into consideration during the planning and operation stages of modern power system networks. The system operators always need to know how far the power systems from voltage collapse in order to apply suitable action to avoid unexpected results. This paper propose a review of some static voltage stability indices found in the literature to study voltage collapse reveals that various analytical tools based on different concept to predict voltage collapse phenomena. These static voltage stability indices present reliable information about the closeness of the power system to voltage collapse and identification of the weakest bus, line and area in the power network. A number of static voltage stability indices have been proposed in the literature, but in this only four of them will be considered. The effectiveness of these indices is demonstrated through studies in IEEE 14 bus reliability test system. The results are discussed and key conclusion presented.

***Index Terms*—**stability margin, voltage collapse, P-V, Q-V, FVSI, LPQ, LSZ.

1. INTRODUCTION

An important subset of power system stability is voltage stability [1]. As electric utilities attempt to maximally use their transmission system capacities to transport real power, voltage collapse acts as a limiting factor [2]. Most voltage stability problems occur in response to large disturbances under heavy load conditions [3]. A voltage instability problem is a form of power system instability that occurs when the power system is incapable to sustain an adequate voltage level under an increasing load demand and/or configuration changes. *IEEE* defines voltage collapse as: the process by which voltage instability leads to loss of voltage in a significant part of the power system [4]. Voltage collapse in a power system may be caused by a variety of single or multiple contingencies such as a sudden removal of real and reactive power generation, a loss of transmission line or a transformer or an increase in the system load without an adequate increase in the reactive power. Frequently, both power industry engineers and academic researchers study system stability and planning by utilizing static load models (i.e. constant impedance, constant current, constant power, and combinations of these models) to represent the relationship between power and voltage. Because these load models are static and time invariant, they are not sufficiently accurate to describe the load behaviors under various operation conditions. The uncertainty regarding load composition and the sufficiency of these static loads models have been questioned in some publications [3, 15]. However, the load behavior is mostly dynamic, with the real and reactive powers being changed at any instant of time. In this paper static load models are considered. The natures of voltage control and voltage instability are local problems. However, the consequences of voltage instability results in progressive fall or rise of voltages of some buses [2, 6].

Voltage stability sometimes also called as 'Load stability'. Load stability is the lack of any power system to transfer an infinite amount of electric power to the loads. The inability of the power system to meet the demands for reactive power in heavily stressed systems to keep voltage at desired level is the main factor of voltage instability. There are other factors contributing to voltage stability such as the generator reactive limits, characteristics of the load, characteristics of the reactive power compensation devices and the voltage control devices action [5]. The reactive characteristics of the power system components such as AC transmission lines, transformers, and loads limit its capability to transfer maximum power. In addition, the power system may lack the ability to transfer power over long distances or through high reactance due to the constraint of a large of reactive power at some critical value of power or distance. Reactive power transfer is difficult due to extremely high reactive power losses that are why the reactive power required for voltage control is produced and consumed at the control area.

During the last decades, the phenomenon of voltage instability has been recognized many times all over the world and has been analyzed extensively. Several major network collapses caused by voltage instability problems were reported in France, Belgium, Sweden, Germany, Japan, the United States, Canada, and Iran [3, 6, 7]. During the last decade, voltage collapse phenomena have attracted more and more attention throughout the world, and several studies have been presented which relate to this problem [8, 9].

This paper propose a review of some static voltage stability indices found in the literature to study voltage collapse reveals that various analytical tools based on different concept to predict voltage collapse phenomena. These static voltage stability indices present reliable information about the closeness of the power system to voltage collapse and identification of the weakest bus, line and area in the power network. A number of static voltage stability indices have been proposed in the literature, but in this only four of them will be considered. The effectiveness of these indices is demonstrated through studies in IEEE 14 bus reliability test system. The results are discussed and key conclusion presented.

2. STATIC VOLTAGE STABILITY INDICES FORMULATION

2.1. P-V and Q-V Curves

P-V and Q-V curves are used to analyze steady state voltage stability which is the stability of the power system in normal operation. The performance of the power system when subjected to disturbances is studied with the help of dynamic stability criteria. Figure 1 shows the general character of a P-V and Q-V curves. The curve shows the voltage falls as the demand increases. The 'nose' of the P-V and Q-V curve identifies the maximum load demand that can be served (active or reactive power limit) and the associated critical voltage. The upper part of P-V and Q-V curve is considered to be stable whilst the lower part is considered to be unstable. Consequently, normal operation of any power system in stability region is limited to the upper part of the curve. In addition, normal loading margin P_{margin} between the maximum permissible demand and the nose is usually used as static voltage stability indicator. The load flow analysis is used to determine the maximum permissible demand by gradually increasing the load until the flow fails to converge. The power system will reach its voltage instability limit when any increase in active or reactive loading demand results in the system operating point crossing the nose of the P-V and Q-V curves.

2.2. Line Stability index LQP

Line stability index LQP proposed by A. Mohamed et al. [10] derived based on the power transmission concept in a single line, in which the discriminant of the voltage quadratic equation is set to be greater than or equal to zero to achieve stability criterion. On the other hand, if the discriminant is smaller than zero, the roots of the quadratic equation will be equal to zero, that means the system under analysis inter the instability region. Figure 2 shows a single line diagram of two-bus power system where the LQP index derived from. In which:

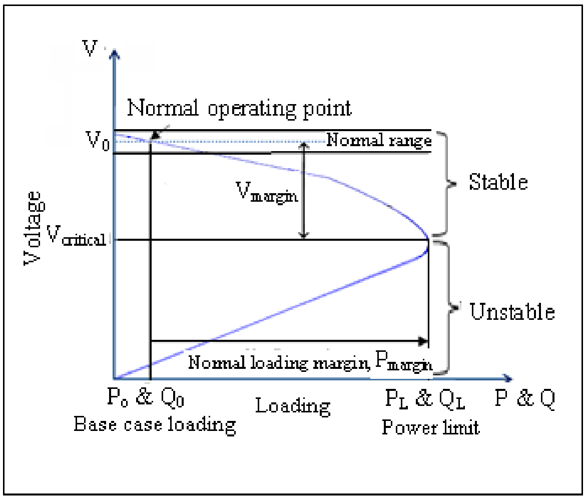

Figure 1 general character of a P-V and Q-V curves

2.3. Line Stability index LQP

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- V_i, the sending end voltage
- V_j, the receive end voltage
- $Z_{ij}=R_{ij}+jX_{ij}$, the transmission line impedance
- $S_i=P_i+jQ_i$, the sending end apparent power
- $S_j=P_j+jQ_j$, the receiving end apparent power

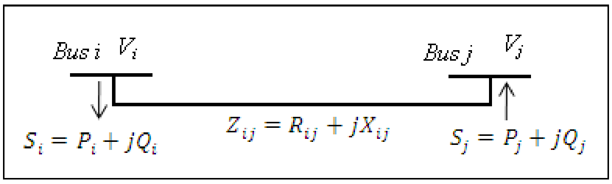

Figure 2 Single line diagram of two bus system

The static line voltage stability index for this model can be defined as follows:

$$LQP = 4\left[\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right)\right] \leq 1 \qquad (1)$$

In order to keep the power system operation in stability region, the line stability index LQP should be kept less than 1 or LQP ≤ 1.

2.4. Line Stability index (Fast Voltage Stability Index (FVSI))

The line stability index FVSI was proposed by Musirin [11] derived based on the concept of power flow through a single line stated in previous section and it is given by:

$$FVSI = \frac{4ZQ_j}{V_i^2 X} \leq 1 \qquad (2)$$

Evaluating FVSI, the line with value close to 1 is ranked as the most critical line of bus in the power which may lead the whole power system to voltage collapse. FVSI can be used also to identify the weakest bus in power system based on the maximum loadability on a load bus. The bus with minimum loadability is ranked as the weakest bus in the power system which is the suitable location for reactive power compensation for improving steady state voltage stability margin in the power system.

2.5. Line Stability index LSZ

Line stability index LSZ was proposed by Jalboub et al. [12] is formulated from the quadratic equation derived from a two-bus network and is computed using the apparent power and the line impedance as stated in previous section and it is given by:

$$LSZ = 2\frac{|Z_j||S_J|}{|V_i|^2 - 2|Z_j|\left(P_j \cos\theta + Q_j \sin\theta\right)} \leq 1 \qquad (3)$$

The LSZ index shows how far the load buses from their voltage stability limit and hence the most sensitive bus can be identified according to maximum loadability. The transmission line with largest value of *LSZ* is taken as the weakest line and the bus with minimum loadability is taken as the weakest bus and must receive special care to maintain voltage stability within a certain limit.

3. SIMULATION SETUP

3.1. Test system description

The voltage stability analysis was conducted on IEEE 14 bus reliability test system to permit comparability with other indices. It consists of five synchronous machines with IEEE type-1 exciters, three of which are synchronous compensators used only for reactive power support. There are 11 loads in the system totaling 259 MW and 81.3 Mvar. The dynamic data for the generators exciters was selected from [13].

Figure 3 shows the single line diagram for the test system. The reactive power loading is increased gradually at chosen bus each time until near to voltage collapse keeping the loads on the other buses constant. From the results, the proposed index *LSZ* was calculated at each line for every load change.

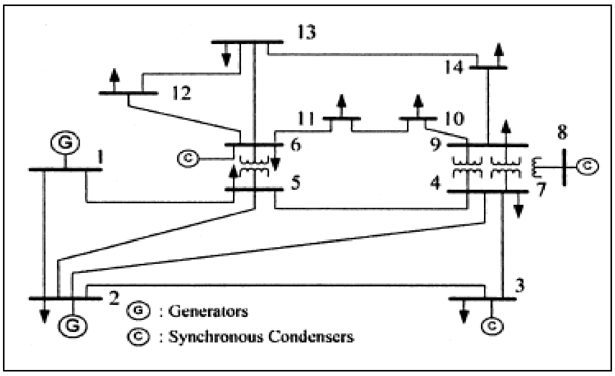

Figure 3 single line diagram for IEEE 14 bus test system

3.2. Experiments

To assess the static voltage stability of the proposed test power system the flowing steps are performed:

- Weakest bus identification based on the selected static indices.
- Voltage collapse point identification based on P-V and Q-V curves.
- Static stability margin determination.

4. RESULTS AND DISCUSSIONS

4.1. Weakest bus identification

In order to determine the weakest bus in the power system, the IEEE 14 bus reliability test system described in previous section is simulated and load flow equations are solved with the help of Matlab program to study the effectiveness of the selected indices. The stability index was calculated for all buses but only buses 10, 12, and 14 are presented here because they are ranked as the weakest buses in the test system. Figure 4 (a, b, c) shows static voltage stability indices FVSI, LQP, and *LSZ* are plotted versus reactive power load change together with the load voltage for selected load buses (10, 12, 14). From the graph appeared that bus 14 is the weakest bus in the system because they reach their stability limit for minimum loadability.

Maximum reactive power margin at different buses in 14 bus IEEE RTS is shown in Figure 5. Since bus 24 has the smallest maximum loadability compared with the other buses, it considered the most critical bus in the system and it's ranked as the weakest bus.

4.2. Voltage collapse point identification

Different P-V and Q-V curves can be computed depending on the system parameters chosen to plot these curves. The family of P-V and Q-V curves shown in the following figures is plotted by maintaining the sending end voltage constant for 14 bus IEEE RTS which is the

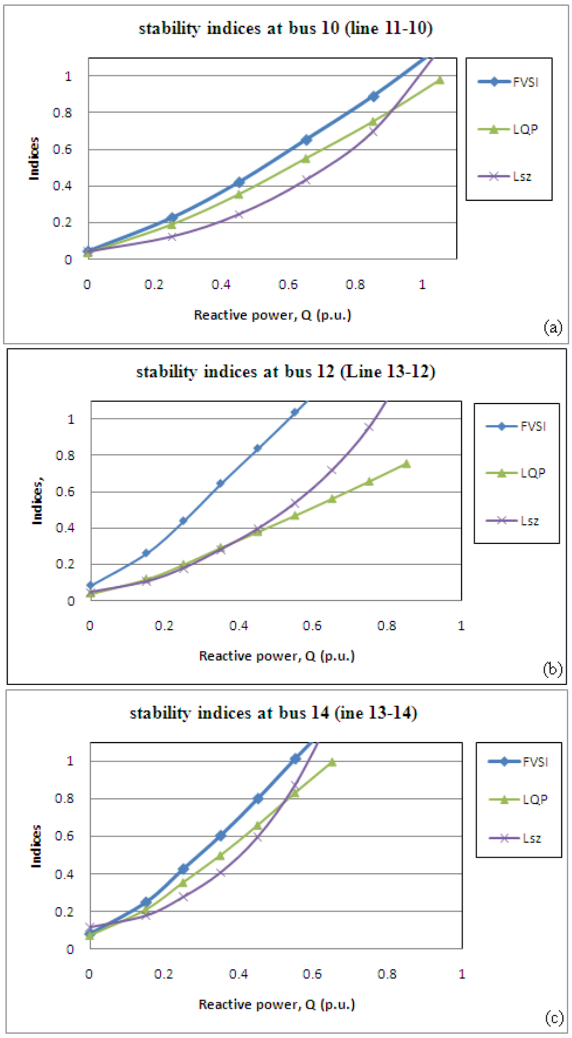

Figure 4(a,b,c) FVSI, LQP, and LSZ, vs reactive power loading at buses (10, 12, and 14)

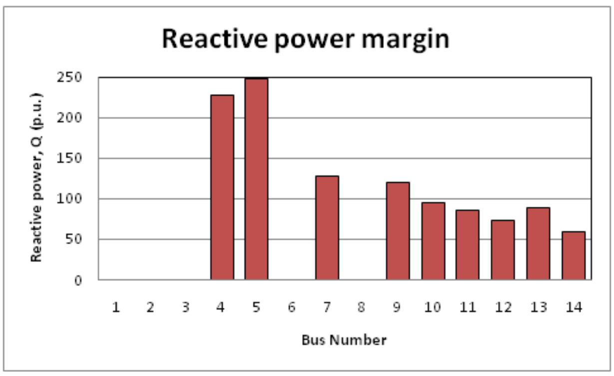

Figure 5 Reactive power margin in 14 bus IEEE RTS

weakest bus in the test system as described in weakest bus identification section, while the load at the receiving end is varied at a constant power factor and the voltage at the receiving end is calculated. The processes starts from the current operating point (base case), which indicates the initial load level of the power system. In each step, a load flow for the power system is performed. This processes continuo until the voltage collapse occurs.

The voltage at bus 14 in 14 bus IEEE RTS is tested from the operating point to the collapse point versus the network growth has been shown in Figure 6. In this figure, increasing the load level has been performed through increasing the active and reactive loads at bus 14 by the same step values. As seen from Fig. 1, by increasing the load level, the bus voltage decreases until the voltage collapse occurs.

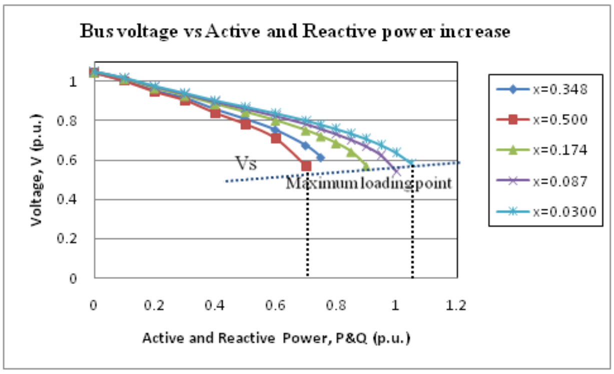

Figure 6 maximum loading points in case of active and reactive load changes

Figure 7 shows P-V curves at bus 14 for 14 bus IEEE RTS. Each curve in the figure is plotted at constant power factor by increasing the active power gradually until maximum loading point is reached, which is also referred to as the maximum system loadability, which in turn corresponding to a singularity of the Jacobian power flow equations. Any attempt to increase the active power beyond its maximum values, the result is a voltage collapse of the system.

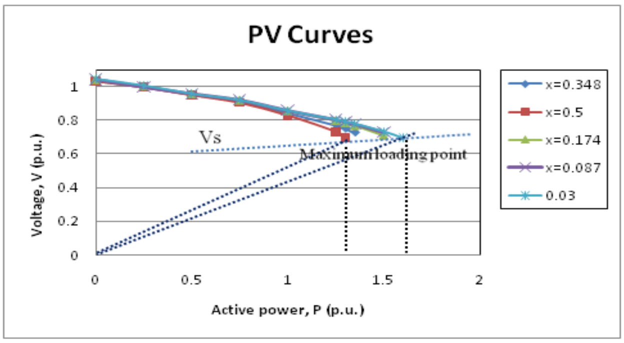

Figure 7 maximum loading points in case of active load changes

Figure 8 shows Q-V curves at bus 14 for 14 bus IEEE RTS. Each curve in the figure is plotted at constant power factor by increasing the reactive power gradually until maximum loading point is reached. Q-V curves give the maximum reactive power demand at a particular bus that can be increased before the system suffers a voltage collapse.

As seen from Figures 6, 7, and 8 by increasing the load level, the bus voltage decreases until the voltage collapse situation occurs. These curves are known as the nose curve [14], the nose or the last point of which represents voltage collapse. The voltage stability margin value is the horizontal distance between the current operating and voltage collapse point. This distance determines the voltage stability margin in the load domain. The voltage stability margin in the load domain indicates the power system maximum loadability in terms of voltage stability. Generally, voltage stability margin value of a system depends on three factors [14]; the configuration of the power system, its load scenario, and its generation scenario. The configuration of the power system determines the values of load and generation at buses and also indicates how different buses are connected to each other. That is, by means of the configuration, static analysis data used by load flow at the current operating point can be identified. Furthermore, the load scenario means that the load level including the active and/or reactive power at which buses should be increased. Also, the generation scenario indicates that the active power of the generating buses should be increased. Therefore, the load and generation scenarios determine how the current operating point of the power system with fixed configuration is being changed. In other words, the load and generation scenarios indicate where the voltage collapse point for a power system with fixed configuration is occurred.

4.3. Static stability margin determination

In order to identify the static stability margin, the Q-V curves is plotted at constant power factor together with the selected static voltage stability indices as shown in Figure 9, It is clear from the figure; the voltage stability margin starts from normal operating point (about 0.8 p.u.) [13] to the voltage collapse point (about 0.6 p.u.) and the reactive power loading margin varies between 0.55p.u. and 1.28 p.u.

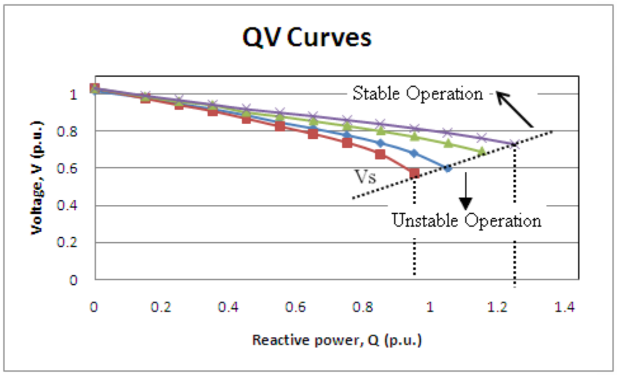

Figure 8 maximum loading points in case of reactive load changes

The only way to save the power network from voltage collapse is to minimize the reactive power load or connect additional reactive power sources such as shunt capacitors and/or FACTS systems at the suitable locations. The most effective way for power network to improve the voltage profile and static voltage stability margin is by introducing FACTS system. However, in order to get suitable performance from the FACTS systems, proper location of these equipments in the power network is very important. It found that the best location for the compensation systems for improving steady state voltage stability margin is the weakest bus in the power system network [16, 17].

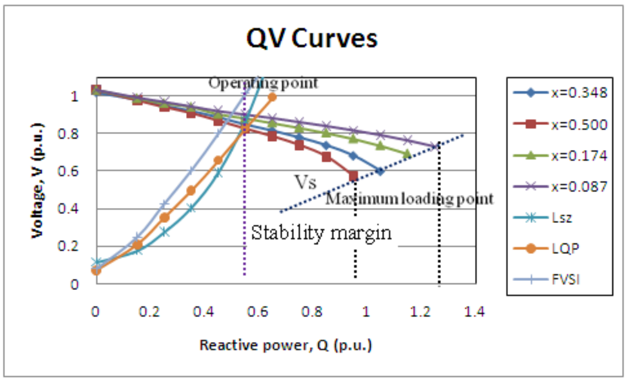

Figure 9 static stability margin determinations

5. CONCLUSIONS

This paper presents a comparative study and analysis of the performance of some selected static voltage stability indices. These indices can be used as indicating parameters to show how far the power networks from voltage collapse. In order to investigate the effectiveness of these indices, IEEE 14 bus reliability test system was used. The simulation result detects clearly the stressed condition of the lines, identifies with degree of accuracy the weakest buses prone to voltage collapse and determines the static stability margin of the power to work in save operation. The simulation results shows that bus 14 is the most critical bus in the system and it’s ranked as the weakest bus. The most effective way for power network to improve the voltage profile and static voltage stability margin is by introducing FACTS system. However, in order to get suitable performance from the FACTS systems, proper location of these equipments in the power network is very important.

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