A New Technique for on-line Monitoring of Voltage Stability Margin Using Local Signals

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Abstract—On-line determination of proximity of power system to voltage collapse is essential for operating the system with an adequate security margin. This paper presents a new method of estimating the voltage stability margin, which uses local measurements and calculates an index which is based on the basic definition of voltage stability. The proposed technique is very simple and straightforward. This technique uses the information about the current operating point and determines the voltage stability margin. The method was tested using IEEE 14-bus test system. The simulations were carried out for steady state voltage collapse and the technique was tested for a variety of operating conditions. The results show that, the proposed method can accurately predict the proximity to voltage collapse at each bus. The method is computationally efficient and suitable for on-line monitoring of voltage stability margin.

Index Terms—Voltage collapse, local measurements, on-line monitoring, load shedding.

I. INTRODUCTION

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ower utilities are now forced to increase the utilization of existing transmission facilities to meet the growing demand without constructing new lines. It is quite difficult to construct new transmission lines due to economic and environmental limitations [15]. This situation has resulted into deterioration of voltage profile. One of the major problems that may associate with such a stressed system is voltage instability or voltage collapse. Many incidents of system blackout due to voltage collapse have been reported worldwide [1, 2]. The consequence of voltage collapse may lead to a partial or full power interruption in the system. The continual increase in demand for electric power has forced utility companies to operate their systems closer to the limits of instability. This has increased the importance of implementing suitable and efficient techniques for on-line monitoring and prediction of possible voltage collapse in the system prior to its occurrence.

To operate the system with an adequate security margin, it is essential to estimate the voltage stability margin corresponding to the given operating point. The main problem here is that the maximum permissible loading of the transmission system is not a fixed quantity. It depends on various factors such as network topology, availability of reactive power support, generation and load patterns etc. All these factors continuously vary with time. Voltage magnitude alone cannot be used as an indicator of instability [3]. Sometimes during peak hours, voltage levels may fall due to heavy loading. This is just a low voltage condition and may not lead to voltage collapse. Therefore, on-line tracking of voltage stability margin is necessary to avoid system voltage collapse. If the stability margin is not adequate, proper actions must be taken to relieve the transmission system.

A review of the literature on methods or techniques reveals that various analytical tools based on different concepts have been proposed to predict the voltage collapse [4, 5, 14]. These indices provide reliable information about the proximity of voltage instability and the weakest bus/area in the system. Very few on-line methods have been proposed to predict voltage collapse and to take corrective action [3, 6, 7]. The conventional P-V and Q-V curves are widely used as a tool by the utilities for voltage stability analysis and for determination of maximum permissible loading. To generate these curves, large numbers of repetitive load flow solutions are required. Thus, these methods are time consuming and not computationally efficient. Several other methods such as modal analysis [8], L-index [9], bifurcation theory [10], energy methods [11] etc. have been proposed in the literature. All these methods involve significant amount of computations and therefore cannot be used for on-line application. Another drawback is that for all these methods the signals have to be derived from the generation and transmission networks whereas action has to be taken at the distribution level. Therefore, a strong communication link between SCADA system at transmission/generation level and the distribution system is essential.

In reference [3] a method for on-line monitoring of voltage collapse based on local measurements is suggested. It requires estimation of Thevenin parameters of the network using complex bus voltage and load current at two different load conditions. This method is modified in [6] to determine the Thevenin parameters from the bus voltage magnitude and the corresponding active and reactive components of the load power. Another approach to calculate the load to source impedance ratio is proposed in [7]. These methods are based on constant measurement of the load impedance $Z_L$ and estimation of Thevenin source impedance $Z_S$ based on the local measurements. However, determination of Thevenin parameters causes problems. The method described in this paper presents another approach to determine the voltage stability margin. The same equivalent circuit as in [3, 6, 7] has been used, but calculation is based on measuring the change in apparent power supplied to the load ($S$) with change in load admittance ($Y$).

Rest of the paper is structured as follows: Section II describes voltage stability of a simple two bus system.
Proposed technique for voltage stability margin estimation is presented in section III. In section IV simulation results are presented along with discussion. Implementation and important features of proposed technique are described in section V. Finally, conclusions are summarized in section VI.

II. VOLTAGE STABILITY

The voltage stability, also called as load stability refers to the ability of the system to maintain load bus voltages within acceptable limit, following some disturbance or change in power demand [12]. IEEE has given the formal definition of voltage stability as: It is the ability of a power system to maintain voltages so that when load admittance is increased, load power will increase, i.e., both voltage and power are controllable [4]. Voltage stability in its simplest form can be illustrated by considering the two terminal network of fig. 1. It consists of a constant voltage source $E_{TH}$ supplying a load $Z_L$ through series impedance $Z_{TH}$. This is representative of a simple radial feed to load or a load area served by a large system through a transmission line because any complex supplying system may always be reduced to the Thevenin equivalent circuit shown in fig. 1.

The magnitude of the current is given by –

$$I = \frac{E_{TH}}{\sqrt{(Z_{TH} \cos \theta + Z_L \cos \phi)^2 + (Z_{TH} \sin \theta + Z_L \sin \phi)^2}}$$  \hspace{1cm} (1)

This may be expressed as -

$$I = \frac{E_{TH}}{\sqrt{Z_{TH}^2 + Z_L^2 + 2 Z_{TH} Z_L \cos(\theta - \phi)}}$$  \hspace{1cm} (2)

Where -

$\theta$ = phase angle of impedance $Z_{TH}$ and
$\phi$ = phase angle of impedance $Z_L$

The magnitude of the receiving end voltage is given by

$$V_R = Z_L I = \frac{E_{TH} Z_L}{\sqrt{Z_{TH}^2 + Z_L^2 + 2 Z_{TH} Z_L \cos(\theta - \phi)}}$$  \hspace{1cm} (3)

The apparent power supplied to the load is

$$S = V^2_R Y \quad \text{where} \quad Y = \frac{1}{Z_L}$$

$$\therefore S = \frac{E_{TH}^2}{Z_{TH}^2 + Z_L^2 + 2 Z_{TH} Z_L \cos(\theta - \phi)}$$  \hspace{1cm} (4)

In Fig. 2, power $S$ is plotted verses the load admittance $Y$, assuming $E_{TH} = 1$ and $Z_{TH} = 1$. There are three curves which correspond to $(\theta - \phi) = 60^\circ, 90^\circ, \text{ and } 110^\circ$. As the load demand is increased by increasing $Y$, $S$ increases rapidly at first and then slowly before reaching a maximum, after which it decreases. For higher load demand, control of power by varying load would be unstable; that is, an increase in load admittance reduces power. These curves also show that the load power factor has a significant effect on the characteristics of the system.

If the derivative of the apparent load power $S_R$ is calculated against the load admittance $Y$, we get the following result.

$$\frac{dS}{dY} = \frac{E_{TH}^2 (1 - Y^2 Z_{TH}^2)}{(1 + Z_{TH}^2 Y^2 + 2 Z_{TH} Y \cos(\theta - \phi))^2}$$  \hspace{1cm} (5)

The condition for maximum load apparent power can be written as:

$$\frac{dS}{dY} = 0$$  \hspace{1cm} (6)

The solution of (6) confirms the well-known fact that at critical point of voltage instability

$$Z_{TH} = Z_L$$  \hspace{1cm} (7)

Fig. 3 presents equation (5) in graphical form again assuming
$E_{TH} = 1$ and $Z_{TH} = 1$.

Fig. 3 also indicates the significance of load power factor on the characteristics of the system. Equation (5) indicates that $\frac{dS}{dY}$ depends on the Thevenin parameters and also on the magnitude and power factor of the load admittance. At no load i.e. when load admittance $Y = 0$, $\frac{dS}{dY} \approx E_{TH}^2 \approx 1$. Whereas, when $Z_{TH} = Z_L$, $\frac{dS}{dY} = 0$. Therefore, “maximum loading point” can be accurately monitored on-line just by computing the factor $\frac{dS}{dY}$. Normally, only the operating points below the maximum permissible loading point represent the satisfactory operating condition. Therefore, $\frac{dS}{dY}$ close to zero also indicates the proximity to “voltage collapse point”. The procedure for on-line estimation of voltage stability margin by measuring the variation of the apparent load power $S$ and the load admittance $Y$ is described in the following section.

III. PROPOSED TECHNIQUE FOR ESTIMATION OF VOLTAGE STABILITY MARGIN

Voltage stability margin can be increased by reactive power support. It can be provided by introducing shunt capacitors and/or Flexible AC Transmission System (FACTS) controllers at the appropriate location. However, the last option to avoid voltage collapse is the load shedding. As described in the previous section, to ensure voltage stability, the value of $\frac{dS}{dY}$ must always be greater than the critical value of zero. In actual practice, the minimum level of $\frac{dS}{dY}$ should be selected such that unexpected sudden change in $Z_{TH}$ and $Y$ should not cause voltage instability. In a power system, the load admittance is continuously varying. Variation in load is caused by natural tripping of load, operation of the on load tap changing devices etc. The approach proposed in this paper is based on the measurement of the change in apparent power supplied to the load $S$ and the load admittance $Y$. $S$ and $Y$ can be calculated easily from the voltage and current vectors measured at the HT side of the station transformer. From the measured values of $S$ and $Y$, the factor $\frac{dS}{dY}$ can be determined using the following expression:

$$\frac{dS}{dY} = \frac{S_2 - S_1}{Y_2 - Y_1}$$

Where,

$S_1, S_2 =$ Apparent power supplied to the load at the beginning and end of time interval
$Y_1, Y_2 =$ Load admittance at the beginning and end of time interval.

The time interval between two measurements may be about 500 ms. Thus, voltage stability margin can be monitored by on-line tracking of $\frac{dS}{dY}$ using (8). $\frac{dS}{dY}$ close to zero indicates the “maximum loading point” and also the proximity to voltage collapse.

IV. SIMULATION RESULTS AND DISCUSSION

The proposed method for on-line monitoring of the voltage stability margin of a power system was tested on IEEE 14-bus standard test system. System data is obtained from [13]. In this study the required local signals for various load conditions, are obtained from load flow simulations. The results obtained by the proposed method are briefly described in the following sections.

A. Gradual increase in load admittance at all the buses

For this study, all the loads were modeled as constant admittance loads and the load admittance at all the buses was gradually increased from the base case. The local signals found from load flow simulations were used to determine $\frac{dS}{dY}$. For determining $\frac{dS}{dY}$ only two successive data sets were used. The variation in total apparent power supplied to load with change in load admittance at various buses is shown in Fig. 4. Fig. 4 indicates that bus no. 14 has the lowest value of voltage stability margin for all load levels. Thus, bus no. 14 can be considered as the weakest bus in the system. This has been verified by simulating the system with all the loads modeled as constant power loads and determination of the weakest bus by other techniques like modal analysis, L-index and P-V curves. All the techniques show that bus no. 14 is the weakest bus in the system. Fig. 4 also indicates that bus no. 2, 5 and 4 are strong buses in the system. Fig. 4 shows the unstable operating
points with negative value of index also. This is due to the representation of loads as constant admittance loads.

Fig. 4. Variation of \( \frac{dS}{dY} \) with change in load admittance at various load buses of IEEE 14-bus test system.

B. Gradual increase in load admittance at bus no. 3

To investigate the effect of increase in active and reactive power load only at one bus, the load admittance at bus 3 was gradually increased. Again all the loads were modeled as constant admittance loads. The IEEE 14-bus test system was subjected to gradual active and reactive power increase by increasing the load admittance at bus-3. Fig. 5 shows the variation of \( \frac{dS}{dY} \) with respect to the change in admittance at bus 3. Fig. 5 shows that proximity to voltage collapse can be accurately detected by monitoring the value of \( \frac{dS}{dY} \).

Fig. 5. Variation of \( \frac{dS}{dY} \) with change in load admittance at bus-3 of IEEE 14-bus test system.

C. Gradual increase in load conductance at bus no. 9

To examine the effect of increase in active power load only at one bus, the load conductance at bus-9 was gradually increased. Load at bus no. 9 was modeled as constant admittance load whereas all the other loads were modeled as constant power loads. The IEEE 14-bus test system was subjected to gradual active power load increase at bus 9 by increasing the load conductance at the same bus. Fig. 6 shows the variation of \( \frac{dS}{dY} \) with respect to the change in load conductance at bus-9.

Fig. 6. Variation of \( \frac{dS}{dY} \) with change in load conductance at bus-9 of IEEE 14-bus test system.

D. Gradual increase in load susceptance at bus no. 9

To investigate the effect of increase in reactive power load only at one bus, the load susceptance at bus-9 was gradually increased. Load at bus no. 9 was modeled as constant admittance load whereas all the other loads were modeled as constant power loads. The IEEE 14-bus test system was subjected to gradual reactive power load increase at bus-9 by increasing the load susceptance at the same bus. Fig. 7 shows the variation of \( \frac{dS}{dY} \) with respect to the change in load susceptance at bus-9.

Fig. 7. Variation of \( \frac{dS}{dY} \) with change in load susceptance at bus-9 of IEEE 14-bus test system.

V. IMPLEMENTATION OF THE PROPOSED TECHNIQUE

The proposed method can be used for on-line monitoring of voltage stability margin as well as for off-line studies for power system planning. For on-line monitoring, the required data can be obtained from local measurements whereas for off-line studies it can be obtained from load flow simulations. Off-line study of the system using this technique will help the system planers to locate the areas in the system that are prone
to voltage collapse and appropriate measures can be taken to provide proper reactive power support. The bus at which the factor $\frac{dS}{dY}$ is close to zero is the weakest bus in the system.

Continuous on-line monitoring of the system by measuring the value of $\frac{dS}{dY}$ will help the system operators to take preventive measures in real time. Some of the preventive measures can be reactive power rescheduling, switching capacitor banks etc. The last option is load shedding. For practical applications there must be sufficient security margin. The choice of margin depends on the bus. For secure operation following steps may be followed:

1) If the level of $\frac{dS}{dY}$ becomes lower than certain set value, an alarm can be actuated.
2) If $\frac{dS}{dY}$ goes on reducing, the operation of transformer tap changing devices should be stopped.
3) If $\frac{dS}{dY}$ falls below a certain minimum value, then load shedding should be initiated.

Features of the proposed technique:
The proposed technique has the following important features:
- The proposed method is based only on local measurements so it can be easily implemented with digital relay. Other methods can only be implemented at the control center with communication links to the sub-station.
- The method is quite simple and straightforward and does not require any offline simulation and training.
- The technique can also be used for offline studies with load flow programs for system planning. It also identifies the weakest bus/area of the system which is prone to voltage instability.
- The method is computationally efficient and has a very high potential for on-line application.
- The calculation is based on the actual value of load admittance and the apparent power supplied to the load. Thus, it is not affected by the characteristic of the load.

VI. CONCLUSIONS
Estimating voltage stability margin on-line has always been a challenging problem for utilities because of nonlinearity. This paper proposes a simple and computationally efficient method for on-line prediction of voltage stability margin using some locally measurable quantities. The proposed method was tested on IEEE 14-bus test system. It was observed that the method can correctly estimate the voltage stability margin for various operating conditions. The method provides a very helpful tool to initiate corrective actions either at local stations or by the central control center via communication link.

REFERENCES