PMU Measurement based Voltage Stability Assessment

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Abstract—The advent of Phasor Measurement Units (PMUs) has made it possible to monitor and assess the power system stability in a synchronized, faster and more accurate manner. Since the voltage and the current phasor measurements are readily available from the PMUs, the proposed work aims at exploiting these direct measurements in order to assess the voltage stability of the power system. At every operating point, the said measurements are utilized to find the critical power at which the voltage collapse is likely to occur. This critical power is, in turn, utilized to define a Voltage Stability Indicator (VSI). The proposed VSI is unity under stable conditions and reaches zero value as the system approaches to the voltage collapse point. The working of the proposed indicator has been demonstrated on a 5-bus test system which involves the long term dynamics of a load tap changer and over excitation limiter. The reactive power compensation required to prevent voltage instability is also discussed.

Keywords- Voltage stability, phasor measurement units, voltage stability limit, Synchrophasor technology.

I. INTRODUCTION

CONTINUOUS monitoring of the electrical grid is of utmost importance in order to ensure its safe and reliable operation. Conventional monitoring systems i.e., Supervisory Control and Data Acquisition (SCADA) systems result in asynchronous measurements which are usually updated once in 2-5 seconds. Because of their very low refreshment rate, SCADA has been unable to monitor the dynamic behavior of the power system grid. Synchrophasor Technology (ST), on the other hand, is relatively a new technology which provides the measurement of key electrical quantities such as three-phase voltages, currents, frequency, rate of change of frequency, etc, as fast as once per second of the system frequency. These phasor measurements are further time-stamped with the help of a common global time reference using Global Positioning Satellite (GPS) [1]. The synchrophasor measurements are taken by dedicated devices, named as Phasor Measurement Units (PMUs). Since the synchrophasor technology provides a synchronized instantaneous view of the power system, any abnormal behavior can be quickly identified and located.

The potential applications of the ST span over real-time power system monitoring, protection and control [2-4]. The scope of the proposed work is, however, limited to the assessment of the voltage stability using the phasor measurements which are readily available from the PMUs. Many factors like increase in system loading, reactive power limitation and dynamics of OLTC (on load tap changer) cause voltage collapse. When a contingency occurs in the power system, there is a sudden increase in reactive power demand which is met by generators and reactive power reserves like compensators. When these sources of reactive power (VAR) fail to meet the additional VAR demand, there is an uncontrolled decrease in voltage which results in voltage collapse [5].

Many conventional methods exist in the literature to assess the static voltage stability of a system such as the P-V, the Q-V curves, energy function based method, Continuation Power Flow (CPF) method, modal analysis, etc. [5]. With the advent of PMUs, many synchrophasor based models have also been proposed which utilize the PMU data to assess impending voltage instability at a load bus by finding the Thevenin equivalent of the rest of the system when seen from the load bus of interest [6-8]. A few sensitivity based methods like that of sensitivities of reactive power generation to reactive power loads have also been reported in literature [9-10]. It is shown that the sensitivities change their sign at the verge of voltage collapse. Recently a wide-area scheme has also been proposed in [11] where the voltage magnitude and the rate of change of voltage information, obtained through the PMUs, is utilized for detecting the impending voltage stability.

In the present work, a voltage stability indicator is devised using the voltage and the current measurements of a load bus which is assumed to be equipped with a PMU. As reported in [12], the V-I plots can be used to examine the voltage collapse and the maximum power transfer limit in a system. In the proposed work, therefore, the voltage phasor and the incoming current phasor measurements, at the present and some past operating points, are measured at the load bus using PMU. The measured data is then processed through least squares method to establish the voltage and the current relationship. Using the V-I plot, maximum load at which the voltage collapse would occur for a given operating point, is estimated, and maximum load value is in turn utilized to define a voltage stability indicator.

The paper has been organized in four sections. In section II the proposed method of voltage stability assessment is discussed. The simulation results of the proposed method on a 5-bus test system are demonstrated in section III and the main conclusions are drawn in section IV.
II. PROPOSED VOLTAGE STABILITY ASSESSMENT METHODOLOGY

It is a well established concept that at the voltage collapse point, load admittance is equal to the self admittance of the network [5]. The condition corresponds to the condition for maximum power transfer from the network to load at node-\(j\). The same concept has been exploited to derive a condition for finding the critical power at which the voltage collapse would occur but utilizing only the readily available PMU-measurements viz., the load voltage phasor and the incoming current phasor measurements.

Consider that the \(V\) and \(I\) measurements are available at a very fast rate from the PMU, and around a given operating point-Q, the voltage \(V\) can be expressed as a function of the current \(I\) by the following \(m\) order polynomial:

\[
V = f(I) = \alpha_0 + \alpha_1 I + \alpha_2 I^2 + \ldots + \alpha_m I^m
\]  \quad (1)

The magnitude of the apparent power, \(S\), of a load bus-\(j\) can be calculated as:

\[
S = V \times I
\]  \quad (2)

Using (1), (2) can be rewritten as:

\[
S = g(I) = \alpha_0 I + \alpha_2 I^2 + \alpha_3 I^3 + \ldots + \alpha_m I^{m+1}
\]  \quad (3)

For maximum power transfer,

\[
\frac{\partial S}{\partial I} = 0
\]  \quad (4)

In other words, (4) can be simplified as:

\[
\alpha_0 + 2 \alpha_1 I + 3 \alpha_2 I^2 + \ldots + (m+1) \alpha_m I^{m} = 0
\]  \quad (5)

The solution of (5) results in the value of current at which maximum power can be transferred to the load bus-\(j\). Let this solution be termed as \(I_{mx}\). The corresponding magnitude of the apparent power, \(S_{mx}\), can be obtained by substituting the value of maximum current, \(I_{mx}\), in (3), i.e.,

\[
S_{mx} = g(I_{mx})
\]  \quad (6)

Once \(S_{mx}\) is evaluated, the distance of the any operating point-Q from the collapse point-C, as shown in Fig. 1, can be calculated as:

\[
\vartheta = \frac{S_{mx} - S_Q}{S_{mx}}
\]  \quad (7)

Under nominal operating conditions, \(\vartheta \approx 1\) and as the operating point moves towards the nose point C, the value of \(\vartheta\) reduces, and finally as the operating point-Q coalesces with nose point-C, the value of \(\vartheta\) becomes zero, as shown in Fig. 1. The value of \(\vartheta\) indicates the voltage stability of a power system, and it has been termed as a Voltage Stability Indicator (VSI) in the rest of this paper.

\[
\begin{align*}
\vartheta & = 1 \\
Q & \quad \vartheta = 0
\end{align*}
\]

Fig. 1 Movement of VSI along nose curve

A. Finding the \(\alpha\) coefficients:

It is to be noted that the determination of the maximum loading, \(S_{mx}\), and hence the VSI, at any given operating point-Q, requires the values of coefficients \(\alpha\) in (1) for various load buses. These coefficients can easily be determined from the voltage and current measurement data by considering a data window (in this work, it is considered to be 1 second) around the operating point-C. This data can easily be obtained from local measurements provided by PMUs. Once the data in the set time-window is buffered, the least squares curve-fitting technique [13] can be applied to obtain the polynomial that represents the function \(f(I)\) in (1). Practically, the measured data may have some errors or noises and the least square estimation will also minimize that effect of measurement noise. The set of past data can be processed through the least squares curve-fitting technique as follows:

Let \(V\) be a vector of measured voltage magnitudes at the \(n\) time-instants in the time-window and let \(A\) be the vector of \(m\) unknown \(\alpha\) coefficients, and let \(I\) be the current matrix such that:

\[
[I]_{(n,m)} \times [A]_{mx} = [V]_{mx}
\]  \quad (8)

The coefficients of the polynomial (\(\alpha\)) can be obtained from the following equation that minimizes the measurement errors or noises:

\[
[A] = ([x]^T[x])^{-1}[x]^T[y]
\]  \quad (9)

After the coefficients of the polynomial are calculated, the critical load and VSI are calculated from (1)-(7).

Clearly, as the system conditions vary, so do these \(\alpha\) coefficients, and thereby the VSI. The frequency of updating these coefficients depends upon the time window chosen.
III. SIMULATION RESULTS

The proposed methodology is tested on a 5-bus test system [5], as shown in Fig.2. The system is simulated in PSCAD 4.2.1. In Fig.2, Bus-1 shows the Thevenin equivalent of a remote system, Bus-2 depicts one generator, and one load at Bus-5 is fed through a transformer equipped with LTC. Most of the load power is provided by the remote system (Bus-1) through a long, double-circuit transmission line.

The load, at Bus-5, behaves as a constant current load of 141.4 MVA and the on load tap changer (LTC) has different delays on its tap changes. For the generator at Bus-2, a 6th-order synchronous generator model is used, together with its speed governor, Automatic Voltage Regulator (AVR), and Over Excitation Limiter (OEL).

Fig.2 5-bus test system [5]

The OEL has an inverse-time characteristic. A disturbance occurs at t=1s, in which a line between buses 1 and 3 is tripped. The system response is obtained by variable-step numerical integration. Therefore, the voltage and the current phasor data, which effectively is a time-series data (and practically will be obtained from the PMU installed at the load-bus), is obtained from the time-domain simulation (TDS). All measurements are sampled every 0.1 s. This sampling rate is higher than needed for tracking long-term voltage instability, but compatible with Synchrophasor technology.

In order to demonstrate the efficacy of the proposed method, following two cases have been discussed:

- Unstable line outage leading the voltage collapse
- Stable contingency

1) Line outage leading to the voltage collapse: In this case, the capacitor near the load is taken to be 1μF, and a situation is considered where OEL acts before LTC by adjustment of exciter time constant (T_E) of the generator at Bus-2 and the corresponding voltage waveform is shown in Fig.3. Here OEL is hitting at t=20s so that the excitation is limited to withdraw the voltage support at load. After OEL action, LTC starts acting thereby trying to meet the reactive power demand near the load or the voltage support near the load. This cascaded effect results in a voltage instability which finally results in a voltage collapse at t=198s.

Figure 4 shows the real power transferred to the Bus-5 as a function of time. It can be seen from Fig.4 that the real power reaches a maximum value (i.e. the maximum power transfer limit) at t=142.49s.

The voltage and the current phasors are obtained from the TDS results. The said measurements are then utilized to calculate the proposed Voltage Stability Indicator (VSI) at Bus-5, as discussed in Section II. The time-window used for the calculation of the proposed VSI is set to be 1 second. α coefficients are calculated using the V and I data over 1-sec time window. It is to be noted that α coefficients do not remain constant all the time. Their values change as the system conditions change. As an example, in the present simulated case, prior to hitting the OEL of the generator, the functional relation between V and I in one particular time-window was as follows:

\[ V = -0.00099 - 0.01431I + 0.344I^2 \]

However, after t=20s, the V-I relation in one time-window was changed to:

\[ V = 7.409 - 6.464I - 1.6518I^2 + 0.707I^3 \]
The VSI results so obtained are shown in Fig. 5. It can be observed from the results that initially under stable conditions, VSI was at unity value. As the system conditions start deteriorating, VSI value declines, and at \( t = 142.5 \)s, i.e. the time where the maximum power transfer limit is reached, VSI hits the zero value. In Fig. 6, voltage is plotted as a function of load active power. Q-V curve is shown in Fig. 7. The curves shown here are post disturbance P-V and Q-V curves. Before and after the OEL action, as well as in between successive tap changes, the system reaches short-term equilibrium (STE) points.

![Fig.5 VSI results at Bus-5](image1)

![Fig.6 P-V curve at Bus-4](image2)

![Fig.7 Q-V curve at Bus-4](image3)

2) **Stable contingency:** In this case, everything is kept the same as in case 1 except that the value of capacitance near load is now considered to be 5\( \mu \)F. As expected, in this case the voltage stability condition improves, and the collapse does not occur even though the quantum of disturbance remains same.

Similar to case 1, the OEL acts before LTC thereby withdrawing voltage support near the load after OEL action LTC starts acting there by trying to restore the voltage near the load. Unlike the earlier case here at \( t = 135 \) s the voltage restores hence it avoids voltage collapse. In this case the value of capacitance is increased so that it provides more reactive power to the load unlike the previous case in which the value of capacitance is lower.

![Fig.8 Voltage profile at Bus-4 with reactive power compensation](image4)

The voltage evolution, in this case, is shown in Fig. 8, and Fig. 9 depicts the time variation of the reactive power. It is observed that the voltage stabilizes after 135s and the action of LTC stops at this instant. This results in prevention of Voltage collapse though the instability persists until 135s.
The Voltage Stability Indicator’s results are shown in Fig.10. Following the contingency, the VSI declines to a value of 0.2. However, it is clear from the plot that after the voltage gets stabilized, the VSI value settles to a new value of 0.8.

IV. CONCLUSIONS

This paper proposes a new indicator to assess the static voltage stability limits of a system. Only the PMU measurements have been utilized for the said purpose. Using the voltage and current measurements over a time-window, relationship between these two quantities is established using least square method. The V-I relationship so obtained is then used to find out the critical loading of the system. The method has been illustrated on a five-bus system and the results are compared with the conventional methods of assessment of static voltage stability like P-V curves and Q-V curves. The simulation results are found to be in good agreement with the results of the conventional methods. The advantage of the proposed method lies in the fact that it does not require any network information, and it purely works on the measurements which are accurately and quickly available by at the substation equipped with PMUs.

REFERENCES


Imran Sharieff is presently a doctoral student in Indian Institute of Technology Ropar, Punjab. His research interests include PMU applications in power systems, wide area monitoring and optimization techniques for power systems. Ranjana Sodhi received the Ph.D. degree from the Indian Institute of Technology Kanpur, in 2011. She is currently an Assistant Professor in the Department of Electrical Engineering, Indian Institute of Technology Ropar, Punjab. Her research interests include wide area monitoring systems, voltage stability assessment and control, power system deregulation, and application of optimization techniques to power systems.