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Fast and Real-Time Algorithm to Detect Impending Voltage Instability

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Abstract: With the ongoing increase in transmission line capacity, power systems operate at the verge of their stability limits. Thus there is a need for fast and accurate algorithms to monitor the voltage stability for sudden changes in operating conditions. This can be accomplished by the utilization of real-time data sampled by Phasor Measurement Unit (PMU) with GPS time-stamping, for the development of Thevenin's equivalent model. Developed algorithm is valid for any type of load model and has been tested under different scenarios.

Keywords: Voltage Stability, Thevenin's equivalent, ZIP model, PMU, VSAI.

1. INTRODUCTION

Detection of Voltage instability is very crucial in a power system. It is a dynamic phenomenon caused by an uncontrollable voltage drop after a disturbance has occurred in the power system. If it is neglected, it may direct to voltage collapse. Thus monitoring of voltage stability at regular and short intervals is obligatory. This is done by power system modeling and analysis. Taking into account the several blackouts and voltage collapses occurring due to the continuous expansion of transmission system, there is a need to tracking the dynamic changes in states of the power system if the data is collected for shorter time intervals. Thus modeling of the system must be real-time data and the calculated stability indices thereafter must be fast enough to monitor the voltage stability of the entire system. Conventional methods in assessment of voltage stability include minimum singular value approach, Eigen value approach, and calculation of various indices, based on power flow. These methods fail in real-time monitoring as they require large computational time.

Synchrophasor technology provides time-stamped voltage and current phasors that are synchronized by Geostationary Position Satellite (GPS). Measurements obtained at different locations spread over wide area of the system provides vital information in handling the power system stress and assessment of impending voltage instability by proper voltage stability indices. In [1], multilayer Feed Forward Neural Network (FFNN) is trained by the PMU data. The network then calculates Fast Voltage Stability Index, Voltage Profile Index and Line Stability Factor. Voltage stability monitoring is performed using these indices. Reliability of the PMU measurement-based stability indices is enhanced with accurate and fast modeling approach. [2] Discusses impact of various load modeling and composition on power system voltage stability with PMU data by calculating Fast Voltage Stability Assessment Index, Voltage stability assessment indices, Line Stability Index. These are used to define transfer limits of the power system.

In [3], Paniagua, et. al., have developed methods to detect voltage instability by Thevenin's Equivalent of the large power system. Effectiveness of the algorithm was discussed by applying at nodes of transit, terminal load, and voltage controlled nodes. In [4], parameters of Thevenin's equivalent are tracked by discrete Kalman filter (DKF) and Unscented Kalman Filter (UKF) based on PMU measurements. It was

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shown that the proposed algorithm tracked the change of system dynamics quickly and more accurately. In [5], single-port Thevenin's equivalent model is built and voltage stability margin is computed by the cubic spline extrapolation technique given that the generator reactive power limits. Real-time voltage stability monitoring assessment is based on grid transformation and the modeling of the Thevenin's equivalent of the considered power system that are based on PMU measurements. Thus the effect of magnitude and phase error in these measurements on calculated voltage stability indices is examined in [6]. Similarly in [7], the uncertainty quantification by incorrect phasor measurements based on two impedances is discussed. Effect of this uncertainty on voltage stability assessment is analyzed using the Voltage Instability Predictor (VIP) method.

2. PROPOSED METHODOLGY

Algorithms available for examining online voltage stability over a wide area system are based on calculating Thevenin's equivalent parameters iteratively. During the period considered, they assume that changes in the parameters at the load bus under consideration and that the remaining system remains unaffected. This is not true in case of sudden contingencies. Such algorithms take long time to compute the indices and also suffer from convergence issues under various contingency conditions. The proposed method to calculate voltage stability analysis index (VSAI) is based on development of Thevenin's equivalent non-iteratively using local measurements. It is based on data taken at one time and not over a time-period making it fast. It is capable of handling any composition of loads. Algorithm for the proposed method is:

Step 1: Obtain line data and bus data of the concerned power system.

Step 2: Store PMU measurements-magnitude and angle (in radians) of V_L, I_L.

Step 3: Find equivalent Thevenin's impedance, Z_{Th} and voltage, V_{Th} of the given circuit as seen from load bus L [10].

Figure 1 shows a 2-bus Thevenin's equivalent circuit of the power system under consideration. Maximum power transfer from source to load happens in the case of

$$Z_L = Z_{Th} \tag{1}$$

Where

$$\bar{Z}_{Th} = R_{Th} + jX_{Th} \tag{2}$$

$$\bar{Z}_L = Z_L\angle\theta = R_L + jX_L \tag{3}$$

This circuit shows the complete system "seen" from the considered bus.

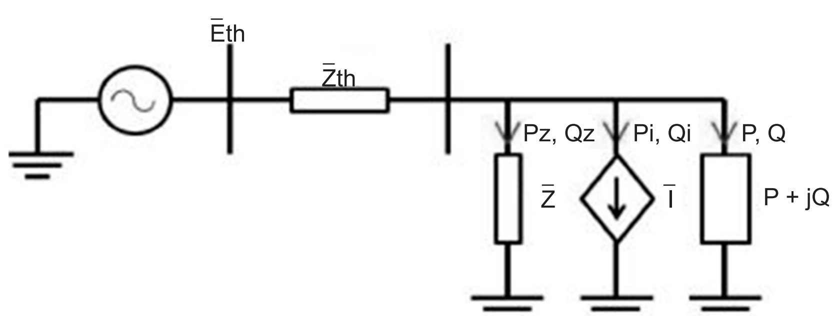

Figure 1: Thevenin Equivalent Circuit for ZIP load, as seen by load bus

According to the phasor diagram show in Figure 2 the following relationship holds:

$$\vec{E}_{Th} = E_{Th}\angle\beta \tag{4}$$

$$\vec{V}_L = V_L \angle \theta \tag{5}$$

and

$$\vec{I}_L = I_L \angle 0° \tag{6}$$

$$E_{Th} - I_L Z_{Th} = V_L \tag{7}$$

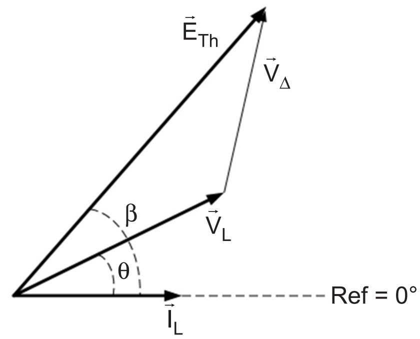

Figure 2: Phasor Diagram of the Two-Bus Equivalent Circuit

'*n*' Values of V_L, I_L are recorded by varying phase angles of the generator. Equation (7) in Matrix form is:

$$AX = B \tag{8}$$

where

$$X = \begin{bmatrix} E_{Th} \\ Z_{Th} \end{bmatrix} \tag{9}$$

The solution for Equation (8) is obtained using the Least Mean Squares technique as $X = (A^T A)^{-1}(A^T B)$. Correct values of E_{th} and Z_{th} are obtained with constant power type loads.

Step 4: For ZIP loads, Thevenin's equivalent parameters must be computed as:

$$E_{eq.} = \frac{E_{Th} - (I \times Z_{Th})}{1 + \dfrac{Z_{Th}}{Z}} \tag{10}$$

where $z = \dfrac{V_L^2}{P_Z - iQ_Z}$, $I = \dfrac{P_I - iQ_I}{V_L^*}$

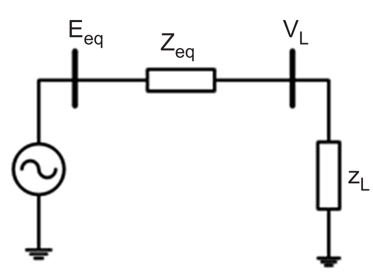

Figure 3: Modified Equivalent Circuit

Step 5: Calculate Voltage Stability Analysis Index (VSAI):

$$VSAI) = \left| \frac{E_{eq.} - V_L}{V_L} \right| \tag{11}$$

According to the proposed algorithm, calculated index values of VSAI close to "0" indicate a voltage stable system and those near "1" are a sign of less voltage stable system.

3. SIMULATION RESULTS AND NUMERICAL STUDIES

The ability of the proposed algorithm to compute Voltage Stability Assessment Index to work under various contingencies or load increase is demonstrated by considering a 3-bus system. Relevant data is given in Tables 1 and 2. A PMU is installed at bus-3 and the PMU measurements for 24 samples are tabulated in Table 3. This gives a direct measurement by PMU at bus 3. Voltages and currents at bus 1, 2 can be determined indirectly as PMU placed at bus 3 ensures full observability of the power system.

Table 1
Transmission line Data

Line No.	*From Bus*	*To Bus*	*R (p.u)*	*X (p.u)*	*G*	*B (p.u.)*
1	1	2	0.05	0.2	0	0.025
2	1	3	0.02	0.15	0	0.02
3	2	3	0.02	0.15	0	0.02

Table 2
Load data for the considered power system for the 24 time samples

Time	*P (p.u)*	*Q (p.u)*	*Time*	*P (p.u)*	*Q (p.u)*	*Time*	*P (p.u)*	*Q (p.u)*
1	1.02	0.11	9	1.311	0.142	17	0.977	0.106
2	1.04	0.112	10	1.285	0.139	18	0.987	0.107
3	1.061	0.115	11	1.259	0.136	19	0.977	0.106
4	1.273	0.138	12	1.247	0.135	20	0.997	0.108
5	1.248	0.135	13	1.234	0.133	21	1.017	0.11
6	1.26	0.136	14	1.222	0.132	22	1.037	0.112
7	1.286	0.139	15	1.198	0.129	23	1.058	0.114
8	1.286	0.139	16	0.958	0.103	24	1.079	0.117

Table 3
Phasor Measurements recorded at Bus 3

Time	*V (p.u.)*	*Angle (Radians)*	*Time*	*V (p.u.)*	*Angle (Radians)*	*Time*	*V (p.u.)*	*Angle (Radians)*
1	0.996	–0.068	9	0.956	–0.136	17	1.001	–0.067
2	0.996	–0.07	10	0.967	–0.144	18	0.997	–0.055
3	0.989	–0.065	11	0.952	–0.133	19	1	–0.052
4	0.984	–0.094	12	0.954	–0.133	20	0.939	–0.203
5	0.988	–0.089	13	0.984	–0.077	21	0.938	–0.209
6	0.99	–0.09	14	0.986	–0.084	22	0.933	–0.221
7	0.992	–0.082	15	0.989	–0.09	23	0.993	–0.07
8	0.986	–0.09	16	1.01	–0.062	24	0.997	–0.057

Power system is analyzed for various conditions at a particular bus and stability assessment [9] is done by tracking the changes in calculated values of corresponding VSAI as shown in Figure 4. During the sudden occurrence of any contingency, an increase in the value of Voltage Stability Index towards unity indicates the impending voltage instability.

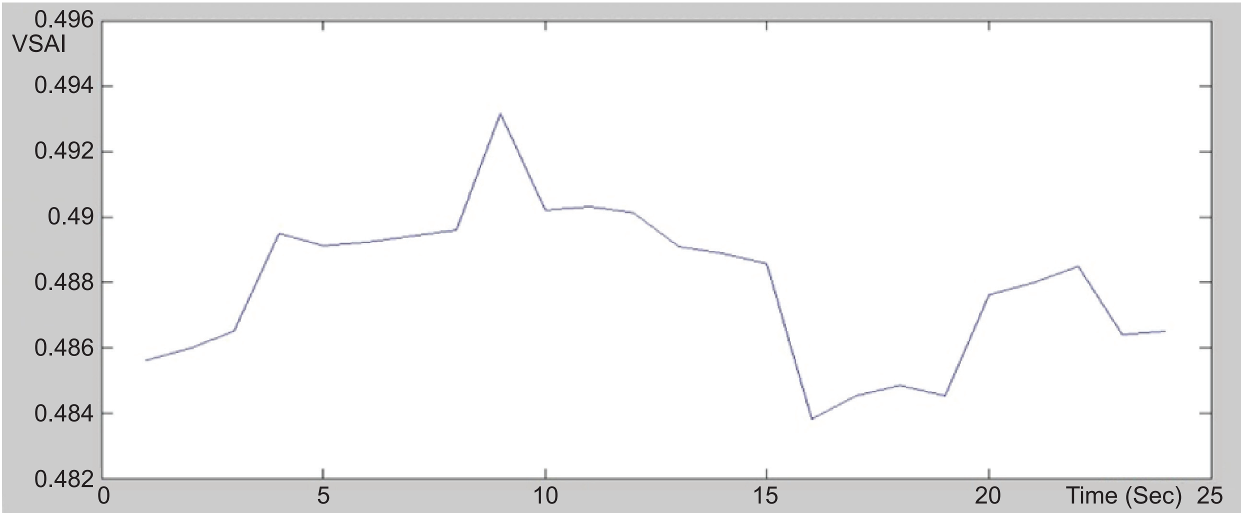

Figure 4: Variations in VSAI for various test conditions

Case 1: At 4th Second, load is increased by 20%: When the load is increased 20% at bus 3, voltage magnitude at that bus drops. For the required power level, instability occurs due to insufficient power available at the bus to maintain constant frequency and desired terminal voltage. From stability point of view, the bus is weakened. Weakening of the bus, leading to instability at the monitored bus is clearly shown from the increase in its VSAI value. Figure shows that VSAI changes from 0.4863 to 0.4890 indicating voltage instability at the monitored bus.

Case 2: At 9th Second, Generator-1 is turned OFF: When the generator unit is switch off then from the graph we can say that VSAI value changes from 0.4890 to 0.493 indicating voltage instability. This is due to lack of power to meet the desired demand and the voltage collapse point occurs.

Case 3: At 13th Second, Generator-1 is turned ON: When the generator unit is switched on to supply then the VSAI value changes from 0.493 to 0.4887 which shows stability.

When there is an addition of generator unit, the generating capacity is increased for given available demand, so that optimal power (maximum) is delivered to load. This leads to increase in stability.

Case 4: At 16th Second, load is decreased by 20%: When the load is decreased then the VSAI value changes from 0.4887 to 0.4852 reflects voltage stability. This is due to for a given available power and if the load is decreased maximum power can takes place which gives voltage stability or load stability. Voltage collapse of a load area is possible without loss of synchronism of a generator.

Case 5: At 20th Second, transmission line 3 is disconnected: When the transmission line is tripped then the VSAI value increased from 0.4852 to 0.4883 which gives voltage instability. This happens due to more reactive power to be transferred by less number of transmission lines thus generally stressing the lines is more results in voltage instability.

Case 6: At 23rd second, transmission line 3 is switched in: When the transmission line is switched in then the VSAI value decreased from 0.4883 to 0.487 which shows stability. This is due to for a given reactive power to be transferred by more number of transmission lines so the stress on each line is less which gives stable voltage to load.

4. CONCLUSION

In this paper, the voltage stability monitoring algorithm considers load models of various types viz., constant impedance, current and power type. Thus it is highly suitable to real-time power system networks. The proposed algorithm calculates Thevenin's equivalent parameters of the system as seen from the load bus based on PMU data at one instant. In this way, it eliminates the need for the past data to calculate voltage stability index. Thus it is fast and quite accurate in detecting any slight conditions leading to voltage instability. Simulation results demonstrate that the presented algorithm is capable to rapidly recognize possible voltage instability in a power system for various contingency conditions and load changes.

Table 4
Details of the test conditions and stabilty

Event No. and Time	*Nature of event*	*Variation in VSAI during event*	*Status of Voltage stability*
at 4s	20% load increase	0.4863 to 0.4890	Less stable
at 9s	Switch OFF generating unit 1	0.4890 to 0.493	Less stable
at 13s	Switch ON generating unit 1	0.493 to 0.4887	Stable
at 16s	20% load decrease	0.4887 to 0.4852	Stable
at 20s	Switch out transmission line 3	0.4852 to 0.4883	Less stable
at 23s	Switch in transmission line 3	0.4883 to 0.487	Stable

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