Online Voltage Stability Analysis Using Synchrophasor Technology

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Abstract— Voltage instability has been a major problem in all the emerging power systems across the world. Several instances of blackouts in North America, including the 1996 Western Interconnection and the 2003 North East US /Canada blackout are primarily due to voltage collapse. So Monitoring and maintaining voltage stability in real-time is extremely important for operating a power system reliably. In this paper Synchrophasor technology is introduced. Synchrophasor technology has the capability to monitor voltage stability over a wide area in real time. In this paper different methods are introduced for finding the voltage collapse point in the system and also one new method given for identification of voltage collapse point.

Key words: Voltage stability analysis (VSA), Synchrophasor technology, Voltage stability index (VSI), Voltage Collapse Prediction Index (VCPI), S-Difference Criteria (SDC)

I. INTRODUCTION

In recent years, power system is being a large system and it is operated closer to their stability limits due to economic and environmental constraints. Maintaining a stable and secure operation of a power system is therefore a very important and challenging issue. Voltage stability problems normally occur in heavily stressed systems. Voltage instability is a major problem in all the emerging power system across the world. The voltage instability generally results in decreasing voltages. Sometimes the voltage instability may manifest as undamped (or negatively damped) voltage oscillations prior to voltage collapse. So it is very important to find a stability region which secure system from voltage collapse.

Voltage instability problem is always is distinguished by system voltage profile, heavily reactive line flows, inadequate reactive power support, heavily loaded power systems. Voltage collapse typically occurs right after an event which causes one of the upper conditions and it may last in time frames of a few seconds to several minutes, and rarely hours. Many methods have been developed in order to detect voltage stability in static security-stability assessment.

This paper presents several voltage stability analysis methods which are developed to monitor online voltage stability margins in power system using Phasor Measurements Units. By comparison and verification of those methods in real power system the better sight of those methods will be achieved in order to specify security margin and take proper remedial action. Hence, in the next section one online voltage stability analysis method will be formulated for a simple power system.

II. SYNCHROPHASOR TECHNOLOGY

Phasors are positive sequence vectors which are calculated from three phase voltages or currents. In the Synchro Phasor Technology. [1], the Phasors are time tagged and transmitted from PMUs located at remote substations or generating stations to a central repository called the Phasor Data Concentrators (PDC) where they can be time-aligned, compared, and stored. the comparison of these phasor data from different locations at a central location provides the real-time angular differences or system separation between the different parts of the grid. The phasors are sampled at high speed, typically between 30 and 120 samples per second, and thus are capable of monitoring the dynamics of the power system and provide an accurate wide area picture of the system. The Phasor Measurement Technology was originally developed in the early eighties by James Thorp, Arun Phadke, and Mark Adamiak at Cornell and American Electric Power.[2] The first implementation was produced at Virginia Tech in the late 1980’s under the direction of Dr. Phadke.

III. VOLTAGE STABILITY ANALYSIS

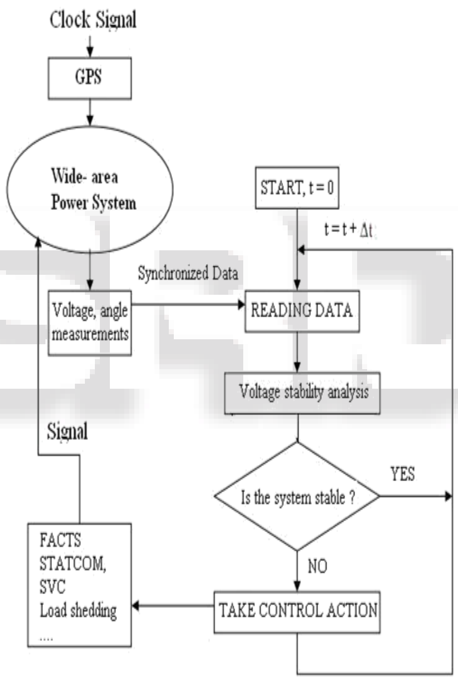

Fig. 1: VSA using synchronized phasors

Voltage stability methods have been developed in order to determine the point of voltage instability and describe how the system is close to voltage instability. Furthermore, it can used to recognize weak buses and the high risky areas involved for voltage instability. There are several methods to calculate these collapse point in real-time format by using PMUs data. [3]

- Jacobian based method
- Thevenin based method
- Voltage stability index method
- Voltage collapse prediction Index method
- S-Difference Criteria method

A. *Jacobian based method*

Voltage instability can be said to be the point where the load flow equations do not converge .A property of the bifurcation in the power system is that the load flow Jacobian of the system becomes singular at the bifurcation point. One or more real eigen-values of the system approach to zero as bi-furcation point is reached. The linearized steady state power flow relations of the power-system as used in Newton-Raphson power flow method are given by:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \qquad (1)$$

Where J is jacobian matrix is the same as conventional Jacobian matrix. Voltage instability is known to be a reactive power flow problem. Hence, if the changes in P are neglected, by setting $\Delta P = 0$, the corresponding Q-V sensitivity matrix can be found as,

$$\Delta Q = \left[J_{Q,V} - J_{Q,\theta} J_{P,\theta}^{-1} J_{P,V}\right]\Delta V = J_R \Delta V$$

The modal analysis on reduced Jacobian matrix JR is used for voltage instability detection. If all the eigen values of the Jacobian matrix are positive, the system is voltage stable. Any of the eigen values approaching zero is to approaching voltage instability point, Here Jacobian method is applied for 5 bus power system. Figure 2 shows the eigen value of bus 4th when increase the reactive load at all the bus keeping active power constant.

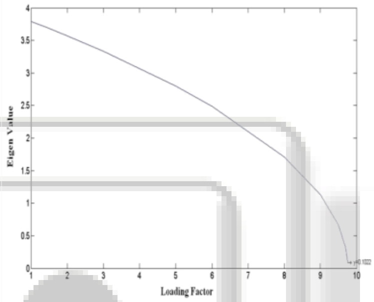

Fig. 2: 4th Bus Eigen value for varying the reactive power of all the load buses

B. Thevenin based method

Consider the two bus system with load impedance given by $Z_1 = R_1 + jX_1 = (V_1)^2/(P_1 - jQ_1)$ and system impedance given by Z = jX. If a constant power-factor load is considered, the maximum power flow is at the instant when $|Z_l| = Z_j$

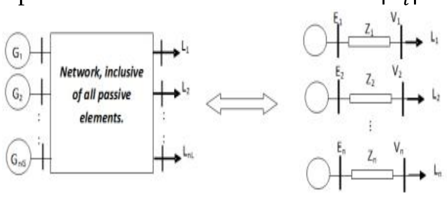

Fig. 3: Illustration of Thevenin-based methods

Figure 4 shows $Z_{th} = Z_{load}$ for 2 bus system when increase the reactive power and keeping the active power constant.

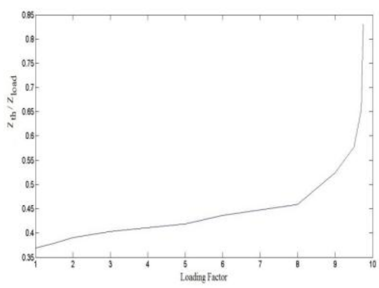

Fig. 4: Zth=Zload for varing the reactive power of the load buses

C. Voltage stability index method

The VSI is derived from the voltage quadratic equation at the receiving bus on a two-bus system. The general two-bus representation is illustrated in Figure 5. The symbols are explained as follows [4]

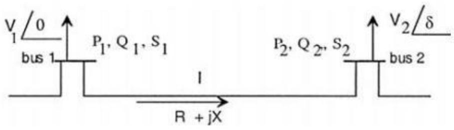

Fig. 5: Two-bus power system model

Taking the symbols i as the sending bus and j as the receiving bus. Hence, the fast voltage stability index, VSI can be defined by:

$$VSI_{ij} = \frac{4Z_{ij}^2 Q_j X_{ij}}{V_i^2 X_{ij}}$$

If the value of VSI exceeds unity, then the corresponding line is very much unstable. So for safer operation of the system, the Voltage Stability Index (VSI) should be less than unity.Figure 6 shows the VSI for weakest branch in 5 bus system when increase the load at all the bus.

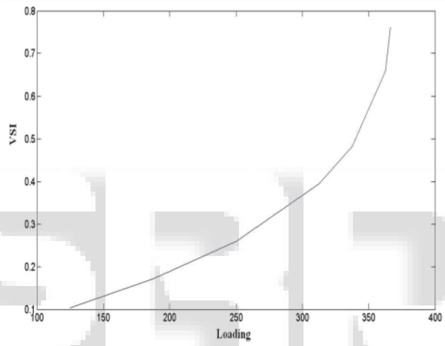

Fig. 6: VSI for weakest branch with increased loading at all load buses

D. Voltage collapse prediction Index method

The technique is derived from the basic power flow equation. The technique is applicable for any number of buses in a system.[5] It needs the voltage phasor information of the participating buses in the system and the network admittance matrix. Using the measured voltage phasors and the network admittance matrix of the system, the voltage collapse prediction index (VCPI) is calculated at every bus. For an N-bus system the voltage collapse prediction index (VCPI) is obtained at bus k, which is given by,

$$VCPI_{kth\ bus} = \left| 1 - \frac{\sum_{\substack{m=1 \\ m\neq k}}^{N} V'_m}{V_k} \right| \qquad V'_m = \frac{Y_{km}}{\sum_{\substack{j=1 \\ j\neq k}}^{N} Y_{kj}} V_m$$

Where, V_k is the voltage phasor at bus k V_m is the voltage phasor at bus m Ykm is the admittance between buses k and m.

Equation represents the condition for voltage collapse at the kth bus. The right-hand side of equation is termed as the VCPI, which will vary from 0 to 1. If the index is 0, the bus is voltage stable and if the index is 1 the voltage at a bus has collapsed. Figure 7 shows VCPI of 5 bus system with varying the loading of all load buses

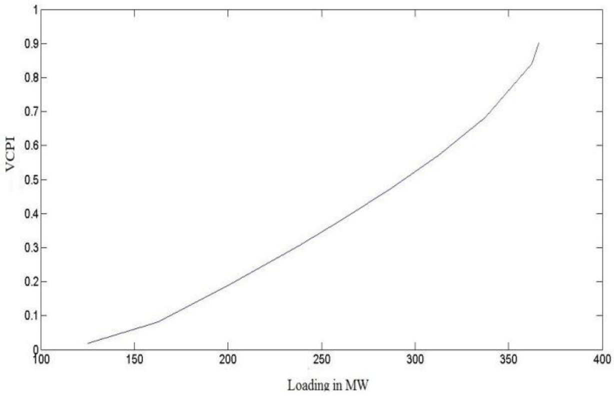

Fig. 7: 5th bus VCPI when increasing the loading of all load buses

E. S-difference criterion (SDC) method

The most stressed line of the system will be the one which shall consume most of the apparent power fed through the receiving end of the line. The concept used is that in the vicinity of voltage instability point an increase in the apparent power in the sending end will not result in any increase in the apparent power in the receiving end [6]. If j is the receiving end of the transmission line, the apparent powers received at the receiving end at the

Instants t_k and t_{k+1} are:

$$S_j^{(k)} = V_j^{(k)} I_{ji}^{(k)^*} \qquad (3)$$

$$S_j^{(k+1)} = V_j^{(k+1)} I_{ji}^{(k+1)^*} \qquad (4)$$

The difference between the two can be approximated to:

$$\Delta S^{(k+1)} = \Delta (VI^*)^{(k+1)} \qquad (5)$$

$$\Delta S^{(k+1)} = V^k \Delta I^{(k+1)*} + I^{(k)*} \Delta V^{(k+1)} \qquad (6)$$

Therefore, at the voltage instability point

$$V^k \Delta I^{(k+1)*} + I^{(k)*} \Delta V^{(k+1)} = 0 \qquad (7)$$

Therefore, SDC for a line ij is defined as,

$$SDC_{ij} = \left|1 + \alpha e^{j\emptyset}\right| \qquad (8)$$

Where,

$$\alpha = \left|\frac{V^k \Delta I^{(k+1)*}}{I^{(k)*} \Delta V^{(k+1)}}\right| \quad And\ \emptyset = \angle \frac{V^k \Delta I^{(k+1)*}}{I^{(k)*} \Delta V^{(k+1)}}$$

At the collapse point SDC for at least one line should tend to equal to zero in limit. The minimum of the SDCs i.e. SDC_{min}, is the indicator to be monitored for voltage instability monitoring of the system. Figure 8 shows the SDC value for most critical buses in 14 Bus systems with load increase at all the load buses.

Load Range	SDC of 5 most critical buses in 14 Bus system				
132 MW	BUS 4	BUS 5	BUS 9	BUS 10	BUS 14
158 MW	16.058	16.319	11.361	11.233	9.850
198 MW	9.866	10.868	7.004	7.062	6.398
225 MW	4.887	5.285	4.945	4.800	4.181
264 MW	8.994	8.959	7.982	8.353	7.135
303 MW	8.123	7.985	6.399	6.698	5.634
343 MW	5.788	5.537	4.764	5.009	4.261
383 MW	4.034	3.815	3.474	3.705	3.216
396 MW	2.906	2.726	2.574	2.724	2.376
422 MW	2.417	2.238	2.188	2.373	2.082
449 MW	1.714	1.565	1.608	1.761	1.576
475 MW	1.030	0.937	1.026	1.124	1.038
482 MW	0.482	0.4237	0.498	0.558	0.529
485 MW	0.254	0.2343	0.271	0.299	0.297
486 MW	0.028	0.006	0.039	0.007	0.003

Fig. 8: Critical buses in IEEE 14 bus system with increasing load at all load buses.

IV. CONCLUSION

In this paper we have examined four traditional methods for finding the voltage collapse point and proposed one new synchronized Phasor measurement based voltage stability method described in this paper. In thevenin method calculation of thevenin impedance at load bus is very difficult for higher bus system. In Jacobean method Eigen value changes with slack bus. In VSI and VCPI method index value should not exactly near to one at collapse point so this four methods are not accurate for online voltage stability analysis so in this paper one new SDC method described. In this method using current and voltage sample at different time instant voltage stability and voltage capacity of bus measured and from the result we conclude that this method is most suitable for online voltage stability monitoring.

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