

Voltage Stability of Power System using PV Curve and PMU data



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Abstract: This paper describes a voltage stability indicator that can be used to determine the proximity to system collapse by power system operators. The proposed PV curve method to determine voltage instability is compared with the existing voltage collapse proximity index (VCPI). VCPI is indicative of critical transmission lines whereas the PV curve analysis is indicative of critical buses. Phasor Measurement Unit (PMU) data facilitates in quick calculation and presentation of the indices to the system operators. The drawbacks of VCPI and how PV curve method is better than VCPI are presented. The simulations have been carried out in Real Time Digital Simulator (RTDS™) using the New England IEEE 39 bus system. The indices accurately quantify the closeness of the power system towards instability. A slope monitoring method has been used to take restorative actions for the system to return to secure operating conditions.
Keywords: PMU, PV curves, RTDS™, Voltage collapse proximity index.

I. INTRODUCTION

Power system stability is the ability of a system, for a given initial operating condition, to regain a normal state of equilibrium after being subjected to a disturbance [1]. Power system stability problems have been discussed since 1920s. It is natural that for the most complex man-made system, thorough and extensive analysis has to be performed on anything which hinders the optimal operation of the power system. With the power system continuing to evolve and increase in complexity, it is imperative for system operators to monitor, analyze and if possible, predict system voltage collapses and generator rotor angle oscillations and suitable actions can be taken before the effects of the disturbance spread throughout the system.

Phasor Measurement Unit (PMU) technology is a growing field where high precision and time synchronized current and voltage measurements can be used for steady state and dynamic monitoring of the system as well as control and protection functions within a Wide Area Monitoring, Protection and Control (WAMPAC) system. A few countries, such as Ecuador [1] and Kazakhstan [2] have already

implemented such a system within their electrical grid and many other countries are introducing pilot projects to implement the WAMPAC system, as manufacture of PMUs are on a steady rise.

There are three types of system stability associated with the power system: *Voltage stability*, *Rotor angle stability* and *Frequency stability* [3]. The main factor contributing to voltage instability is the system loading. Excess loading over available generation in any part of the power system will likely lead to its deterioration. In an attempt to supply the excess load, the generators and their associated prime movers slow down. The tie lines are thus overloaded when they attempt to transmit the excess power, resulting in tripping of the lines. This causes separation of the system and eventually leads to instability.

In order to prevent the complete collapse of the system, under-frequency relays are used to automatically shed load in accordance with a predetermined schedule to re-achieve the load-generation balance in the affected area. Such actions must involve prompt response from the system operators in order to identify and preserve essential loads and enable the system to sufficiently recover from the instability. Hence, quick identification of most critical transmission lines during the disturbance phase is important to system operators to take corrective actions and restore the system equilibrium.

Many analytical concepts using different tools have been proposed in previous literature. The methods are broadly classified into two categories: *Jacobian based methods* and *System variables method* according to authors of [4] and [5]. In particular, Jacobian based methods which calculate voltage stability indices both offline [6], [7] and online [8], [9] are extensively part of the literature on voltage stability indices. Calculation of Jacobian is always computationally time-consuming, whether calculated online or offline. The System variables method is the most time efficient method for analyzing the voltage stability and hence a more suitable concept for system operators to have a better visualization of the power system. Voltage stability Index (VSI) [10], Voltage Collapse Proximity Index (VCPI) [11], Voltage Controllability indicator (VCI) [12] and many more indicators/indices and their comparison can be found in literature [4], [5] and [13]. Most of the methods involve offline simulations without capturing the true dynamics of the system, or they are employed for post-disturbance analysis which do not help system operators in early detection of instability.

A much researched method for identifying voltage collapse in power systems is the calculation of Thevenin's equivalent parameters, which is a system variables method. The concept of impedance matching (Thevenin's maximum power transfer theorem) is utilized to determine the point of voltage collapse. Phasor measurements of voltage and current make it possible for fast tracking of the

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Thevenin's equivalent parameters, and many authors have attempted to take advantage of this concept, but many of them have some form of drawback or criticism in the proposed concepts.

Determining the Thevenin's equivalent parameters through robust least square algorithm [14] suffers from large data window required to suppress oscillations, as pointed out by [15].

The analysis [15] itself is valid for EHV systems as the transmission line resistance is not taken into account. Modelling the system as a coupled single port network [16] to determine Thevenin's equivalent parameters takes into account only static voltage stability.

The authors in [17] and [18] propose a method about maximum load point, where the sign change in the eigenvalue propose a sensitivity computation method to determine the reactive power sensitivity from the snapshot of the system states obtained from the PMU measurements. The proposed method inherently explains about an eigenvalue tracking determines the requisite criterion for long-term voltage stability. But this work does not use dynamic models to predict system response. Also, sensitivities are calculated based on the *Jacobian* of the system state trajectory, whose disadvantages are mentioned previously.

There is also a third category of methods called *Time series* method. Calculation of Lyapunov exponent [19], [20] and cubic-spline extrapolation technique [21] are some time series methods for evaluating voltage stability. These methods also involve exhaustive computational abilities.

Voltage Collapse Proximity Indicator (VCPI) is one of the simpler tools that can be used which can utilize PMU data with its fast sampling rate to provide system operators with an early indication of voltage collapse, and take some preventive actions at the onset of instability [22]. This index gives us the stability of the system based on the line power flows.

The PV curve concept can be used to determine the weakest bus in the system. The VCPI index can be used to verify the results of the PV curve method. The verification method is given in a later section.

This paper is organized as follows: The concept of voltage stability indicator (VCPI) derived from PMU measured impedance is outlined in Section II. Section III presents the simulation setup of the IEEE 39 bus system along with standard exciter and turbine governor models and the procedure for initiating instability in the system. The results of the VCPI stability index are also shown. The correlation between PV curves and VCPI is given in Section IV. Section V accounts how instability can be prevented using the slope monitoring of the PV curves. Section VI gives a conclusion to the study.

The paper does not consider the essential problems like communication infrastructure and phasor measurement pre-processing. It is assumed that the voltage and current phasors obtained from the PMUs are time synchronized without any loss of data.

II. VOLTAGE STABILITY USING TWO PMUS

A. Real-time impedance calculation using PMU data

PMU data can be used to calculate the impedance (and admittance) of a transmission line. This requires the placement of PMUs at both ends of the transmission line, and

the impedance is calculated based on the current and voltage measurements [11]. The expression for line impedance of a transmission line modeled as a PI-section, as shown in Fig.1 [22], is given by (1).

$$Z\angle\theta = \frac{(V_s\angle\delta_s)^2 - (V_r\angle\delta_r)^2}{(V_s\angle\delta_s)(I_r\angle\theta_r) + (V_r\angle\delta_r)(I_s\angle\theta_s)} \quad (1)$$

Where V_s at an angle δ_s is the sending end voltage phasor, V_r at an angle δ_r is the receiving end voltage phasor, I_s at an angle θ_s is the sending end current phasor and I_r at an angle θ_r is the receiving end current phasor. This type of impedance calculation is immune to weather conditions and changes in topology of the system, due to the fact that it is calculated based on voltage and current phasors [22].

B. Voltage stability index/indicator

There are various methods of measuring the proximity of a system to voltage collapse. The Voltage Collapse Proximity Indicator (VCPI) [4], [5] is based on the maximum allowable power flow across a transmission line and for a two bus system with PMUs at both ends, and the expression is given by (2).

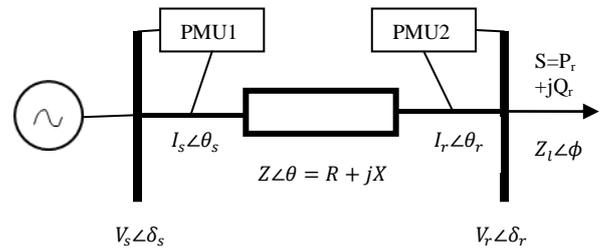


Fig. 1. Impedance Calculation with PMUs at both ends of the line.

$$VCPI = \frac{P_r}{P_{\max}} = \frac{P_r}{\left(\frac{V_s^2}{Z}\right) \left(\frac{\cos\phi}{4\cos^2\left[\frac{\theta-\phi}{2}\right]}\right)} \quad (2)$$

Where P_r is the real power at the receiving end of the line, $Z\angle\theta$ is the value of line impedance calculated from (1), $Z_l\angle\phi$ is the impedance seen at the receiving end which can be calculated from P_r and Q_r .

The ratio of P_r and P_{\max} (the maximum power that can transferred through the line), represents the proximity of the voltage collapse. As the power flow on a particular line reaches to its maximum limit, voltages fall below their normal operating limits which would result in tripping of the line, through the protection system or by the operator. Hence, higher the value of VCPI (near unity), greater is the system vulnerable to voltage collapse.

The ratio of P_r and P_{\max} (the maximum power that can transferred through the line), represents the proximity of the voltage collapse. As the power flow on a particular line reaches to its maximum limit, the line is more likely to trip and voltages fall (or rise) below (or above) their normal operating limits. Hence, higher the value of VCPI (values near unity), greater is the system vulnerable to voltage collapse.

SIMULATION SETUP FOR DETERMINING VCPI The New England IEEE 39 bus test system [23], which consists of 10 synchronous generators, 46 lines (including transformer connections) and 31 loads is used to demonstrate the effectiveness of the indicator mentioned in Section II. All the generators are supplemented with standard models of exciters (IEEE Type DC1A) and turbine-governors (IEEE Type 1). The loads are modeled as static loads. The total loading of the system is 61,495 MW and 14,089 MVAR.

13 PMUs are placed in the system according to optimal placement strategy given in [24]. An additional 13 PMUs are to be placed at the other ends of the respective transmission lines, for real time impedance calculation using PMU data as shown in section II.

Simulation is carried out on RTDS™, where virtual PMU models are available. The virtual PMU blockset in RTDS™ can support up to 24 PMUs. Hence, only 24 buses are considered for PMU placement. A set of three phase voltages and three phase currents are provided as input for each PMU and the phasor magnitude, phasor angle, frequency, rate of change of frequency and fraction of second (or second of century) are outputs. The circuit diagram in RTDS™ is shown in Fig. 2.

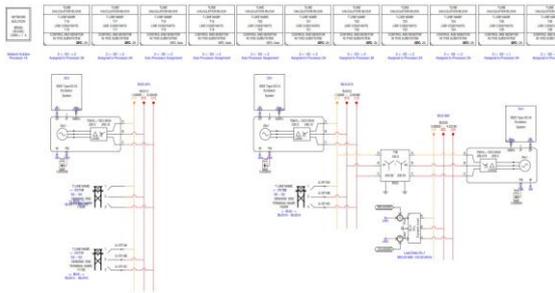


Fig. 2. Circuit diagram in RTDS™ (Note: The figure only shows part of the system)

The electrical power output of each generator in steady state is given in Table I.

TABLE-I
STEADY STATE POWER OUTPUT OF GENERATORS

Generator connected to Bus No.	P (MW)	Q (MVAR)
30	245.957	187.949
31	547.170	756.591
32	644.407	264.554
33	627.286	169.992
34	503.752	201.851
35	620.045	299.321
36	555.017	129.182
37	534.204	41.957
38	823.970	123.002
39	1099.650	68.339

The loads are increased uniformly with a rate of 3% for every second so that the loading on the generators increases to simulate the condition of instability.

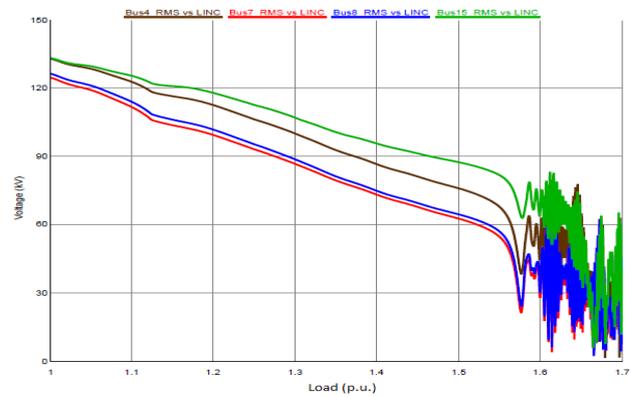


Fig. 3. Phasor magnitudes of bus voltages with respect to percentage increase in load (PV curves of selected buses).

The PV curves (the variation of bus voltage with percentage increase in loading) of some selected buses is shown in Fig. 3. It can be seen that the nose point of the curves is approximately at 1.6 p.u. (or 160% of initial loading value) at 20 sec (since load ramping is 3% per second), when the entire system loses its stability after this point.

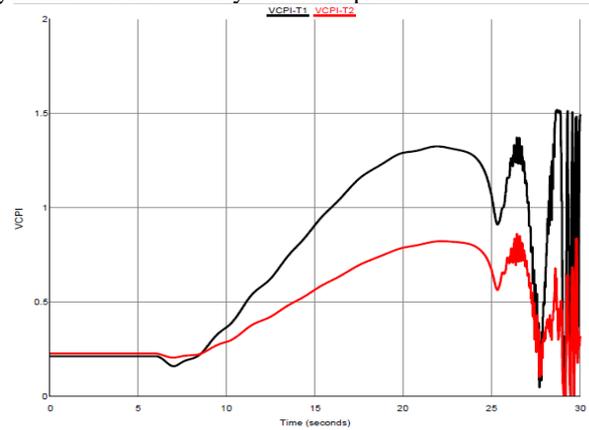


Fig. 4. Variation of VCPI for two lines with increase in percentage loading.

Fig. 4 shows how the value of VCPI increases with increase in percentage loading. The VCPI for transmission line T1 at the point of instability (160% loading) is 1, whereas the VCPI for transmission line T2 is much lesser (around 0.7) at the same instant of time. Hence, it can be concluded that the line T1 is more sensitive to voltage collapse than the line T2. Also, the instability occurs at around 20 seconds after base loading conditions which matches with the loading percentage at instability (160%) as seen in Fig. 3. Table II shows the VCPI values for the transmission lines where PMUs are placed. Based on their relative values (compared to 1.0), it can be seen which lines are more prone to collapse for a disturbance.

TABLE-II
RANKING OF VCPI AT 160% LOAD

Line No.	Line name	VCPI value
T1	1 – 2	1.2870
T2	1 – 39	0.7735
T3	39 – 9	0.8836
T4	16 – 19	0.5669
T5	25 – 26	0.4053

T6	23 – 24	0.5525
T7	22 – 21	0.4221
T8	29 – 28	0.2045
T9	5 – 8	0.4391
T10	4 – 14	0.1222
T11	10 – 13	0.2342
T12	16 – 17	0.1695

III. RELATION BETWEEN PV CURVE AND VCPI

The VCPI is used as a measure of the maximum loadability of the line. When the load is increased across the system in a uniform manner, the most critical line can be determined. In order to use this concept on buses, instead of increasing all the loads simultaneously, only the load at a particular bus is increased (one at a time) from the base case up until the maximum allowable limit or until the bus voltage reaches the minimum allowable limit [25]. This procedure is carried out at all the load buses in the system (since the load buses are the ones with relatively low voltages). The VCPI values are measured for all the lines connected to the load buses. The results shown here are for the four most critical buses (buses 4, 7, 8 and 15) and the lines connecting these buses.

TABLE III
VCPI CALCULATION AT LOAD BUSES

Bus number	Percentage load increase (%)	Bus voltage at loading limit (p.u.)	Maximum VCPI among lines connected to bus
4	114.1	0.8948	0.9000
7	38.6	0.7774	1.1060
8	54.3	0.8322	1.0440
15	162.2	0.8865	0.6192

As seen from Table III, buses 7 and 8 are the most critical buses in the system. The value of VCPI reaches 1, the voltage reaches very low values and the percentage load increase, or loadability at both these buses is very low. Since bus 7 has the lowest loadability value before reaching instability, it is considered to be the weakest bus. The PV curves for the aforementioned four buses, which validate this result is given in Fig. 3.

One of the drawbacks of the VCPI is the fact that two PMUs are required for determining the index value. Only a single PMU is required for determining the PV curve at a bus. The VCPI also cannot be used at buses connected by transformer branches. This indicates that the PV curve method is a more efficient indicator than the VCPI method. The following section presents how system instability can be avoided using slope monitoring method.

IV. VOLTAGE STABILITY USING PV CURVES (VOLTAGE STABILITY USING ONLY ONE PMU)

In the PV curve method of determining voltage stability of a network, the nose point of a PV curves depicts the point of voltage collapse of the network. When there is a smooth increase in the load, the point where the load characteristic becomes a tangent to the PV curve is defined as the loadability limit of the system. In other words, the tangent (in this case the derivative of the PV curve) is a good indicator for the proximity of voltage collapse, as described in [26].

The *tangent (derivative of the PV curve)*, is relatively constant up till the nose point. At the nose point, the tangent escalates to a very high value (becomes infinite for an ideal PV curve). But the tangent line is different for different buses in a system, since the PV curve is different for different buses. A more general notion is the *second derivative* concept. The second derivative at a point indicates the shape of the curve at that point. Since the general shapes of PV curves are the same (refer Fig. 3), this indicator can be used to determine the nose (critical) point on the PV curve. When the tangent remains constant, the second derivative hovers close to zero. When the critical point of the system is reached, the second derivative value deviates appreciably from zero, indicating a change in the shape of the curve. This indicator can be used to detect the approach of the critical point.

The double derivative value of the PV curve can be used to monitor the system for voltage instability and take appropriate corrective actions (such as tripping of loads) when the value deviates appreciably beyond zero. Both tangent and double derivative at the four buses mentioned in Section IV (buses 4, 7, 8 and 15) are monitored continuously as shown in Fig. 5. The procedure for creating instability is the same as that described in Section III. When both the slope and rate of change of slope shoot up towards infinity (∞), it is safe to say that the nose point of the PV curve has reached.

A limit of -3 acts as a safety net to compensate for the non-linearity in the PV curve when real-time simulation is performed, as zero can only be considered in ideal cases. At the instant the double derivative value drops below -3, 1.5% of the total system load is tripped. This provides a sufficient margin for the voltages to recover to a new operating point, as shown in Fig. 6.

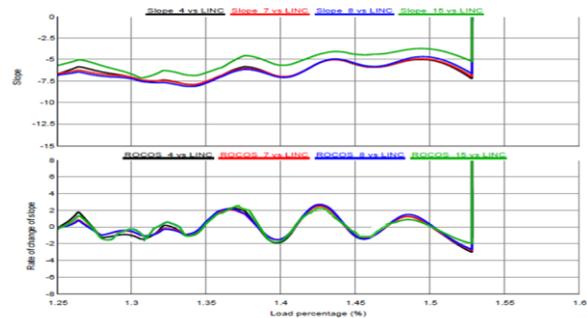


Fig. 5. Slope and Rate of change of slope (ROCOS) against percentage loading.

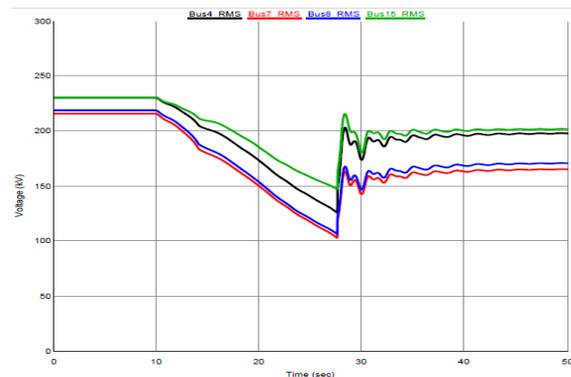


Fig. 6. Voltage recovery at the buses after load shedding.

V. CONCLUSION

The phenomenon of instability in the power system presents a challenge to system operators. The identification of instability just before its occurrence would greatly help operators take timely corrective actions to minimize the effect or even prevent it. PMUs help in identification of such disturbances owing to their fast sampling rates. In this paper, two voltage stability indicators, VCPI and PV curves, are discussed and computed using data from the PMUs placed in the IEEE 39 bus standard system. The VCPI is used to determine critical transmission lines and the PV curve is used for determining critical buses.

The VCPI requires larger number of PMUs to implement than the PV curve method, in which it is sufficient to place PMUs at load buses. Additionally, the VCPI method does not work on transformer branches. It cannot determine instability due to transformer overloading.

Using the PV curves slope and double derivative monitoring method, the onset of instability can be deduced and system operators can take corrective actions, like tripping selective or non-critical loads for the system to recover to stable operating conditions.

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