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On Voltage Stability Monitoring with Voltage Instability Predictors

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Abstract

After 15 years of use, voltage instability identification techniques based on determination of Thevenin-like equivalents have matured, but many issues remain. In this paper, some of them are addressed – computing, as well as some ideas about handling systems with pronounced transmission corridors (flowgates).

Introduction

Voltage stability is the ability of the load and the underlying transmission network to maintain power consumption (especially reactive power) within transmission and generation constrains. The consequence of system incapable of doing so is voltage collapse [1]. The model of voltage collapse requires knowledge of the entire system state. When the system state is known, any of the commonly used analysis techniques (direct, iterative or continuation methods) can provide the power margin to collapse in any given direction of the load change (short term load forecast). However, such methods are computationally time-consuming, which makes their use in real-time harder. Recent upgrades in national transmission system infrastructures (seen in US, China, and some European countries) will provide much better monitoring and control environment, but some of the challenges to a successful real-time monitoring and control will remain.

Voltage Instability Predictors (VIPs [2]) measure only local voltage and current phasors, from which the approximate two-bus equivalent networks can be calculated. A Thevenin-like equivalent can, based on the maximum power transfer principle, provide an indirect metric for the proximity of the critical point. The simplicity inherent to this approach is in using only local measurements; it requires no system-wide communication infrastructure. That advantage is also the main reason for the limitations in its accuracy and computability under some circumstances (interaction with load dynamics, for example).

In [2], the estimation of Thevenin equivalent parameters can be performed once two or more measurement sets are available. Least-square or recursive least-square methods are often deployed in finding these parameters. Reference [3] uses Tellegen's Theorem to derive a simple expression for Thevenin impedance which relies on two measurement sets. However, the expression is simply the outcome of a special case when applying least-square technique on two measurement sets. To avoid the use of recursive least-square, a new real-time Thevenin parameter identification scheme is proposed in [4]. The direction of change of Thevenin voltage as well as the amount of variation is updated each time based on a few simple rules. The identification method shows quick convergence with fine-tuned parameter. Reference [13] provides a comprehensive overview of various applications of VIP and derived techniques for voltage instability detection.

Generally, the voltage collapse may very likely occur before the magnitude of a specific load impedance drop to that of its corresponding Thevenin impedance. Impedance matching condition is met only by the first load reaching its maximum loadability limit. Voltage collapse occurs at this point and all other loads are yet to reach their own loadability limits. If we are to predict the onset of voltage instability by Thevenin parameters, we may well conclude that voltage instability occurs before meeting the impedance matching condition for most buses. However, the Thevenin-like impedance that VIP provides guarantees impedance matching at the critical point to voltage instability for all load buses. This nice property makes VIP capable of being a standalone local predictor.

The concept of using networked VIP to improve the accuracy of Thevenin parameter estimation was proposed in [9], [5]. By taking phasor measurements at two buses, better prediction of system trajectory to collapse can be made possible. In [6], the authors propose using phasor measurements at all load and generator buses to directly calculate Thevenin parameters. This approach, which preserves the characteristics of individual generator and load instead of lumping them into a single equivalent, is called 'multiport' Thevenin equivalent in [7]. The above approach is further developed in [8] where the effect of

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loads and the rest of the system (generators and network) on Thevenin equivalent is decoupled. The authors claim that the effect of all loads on the equivalent system is almost constant impedance. Therefore, the new 'Thevenin equivalent system' is not changing by much when no PV-PQ transitions (or other topology-changing contingencies) are taking place.

Reference [9] considers utilizing information collected from PMUs installed at generator buses for reactive power reserves margin and combining it with conventional instability predictor for a more comprehensive prediction. The scenario where VIPs are placed at both ends of transmission corridor is introduced in [10]. With some simplifying assumptions, VIPs at sending end of the transmission corridor can aid the identification of Thevenin parameter at the receiving end of the corridor in a real-time fashion.

Proven successful as a predictor to voltage collapse, the versatility of VIP has yet to be explored.

Computational Issues

When power system is in near steady-state conditions, the VIP evaluation should be paused since the difference between any two adjacent measurements is negligible. An alternative is to use very long (or infinite) measurement windows, but the time-lagging filtering effect of that may be prohibitive. On the other hand, if a disturbance or contingency event is detected, the resulting transient process may cause substantial error for the VIP evaluation. The reason for that is that VIP is supposed to reflect the impact of system changes, not the interaction of the local dynamics of the system (or measurement noise). The discontinuous controls, such as the controls of LTCs and over excitation limiter (OXLs), can also cause short transients. All of these dynamic processes could be magnified by the voltage-sensitive components in the system.

The performance of the least square error-based method is better than the recursive method [9] in capturing slow changes in stability condition. Both of the VIP algorithms require a set of voltage and phasor measurements covering similar system conditions but with appreciable difference. If the differences among the measurements are negligible, the sampling rate needs to be reduced in order to avoid static error and sampling of the near singular system. Since the recursive method has the advantage of using forgetting factor to control the window size, the risk of evoking static error could be reduced.

On the other side, if the effective window of any VIP algorithm covers the measurements from wider range of system conditions (such as pre- and post-contingency states), the VIP result could become inaccurate or unusable. The VIP algorithms assume the identical Thevenin model applied to all system states sampled within the sliding window (or they are indexed to sampling instants in the recursive mode).

Following a switching or similar transient event, subsequent transients may also cause error in the VIP result. During a transient process, the system state varies quickly. Moreover, the errors caused by a dynamic process could accumulate over time and eventually alter the steady-state VIP result.

Figure 1 demonstrates the limitation of the recursive VIP algorithm in handling abrupt changes and transients. The time-domain simulation is performed on the IEEE 39-bus dynamic model using PSS/E. The forgetting factor for the recursive least squares algorithm is set to be 0.95 or 0.99 for two simulation scenarios represented by a dotted black curve and a solid blue curve, respectively. The discontinuous changes in the voltage measurements correspond to the following events: two contingencies (at 100 seconds and 250 seconds), automatic OXL controls (at 120 seconds, 170 seconds and 390 seconds), and automatic LTC control (at 175s and 190 seconds). During discontinuous changes and subsequent dynamic processes, the VIP reacts by showing overshoot and subsequent over-damping. It is difficult to extract any constructive information about the changes in the voltage stability condition shown in Figure 1.

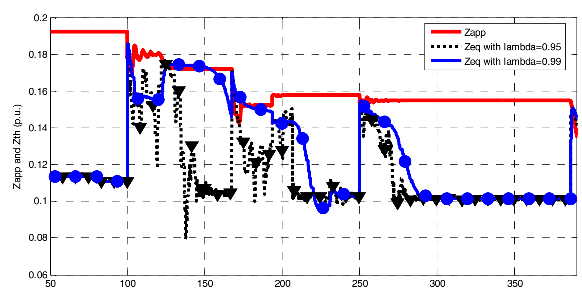

Figure 1. VIP evaluation using recursive approach for time-domain application.

Since the discontinuous changes and dynamic processes are the causes of false VIP results, a blocking trigger for VIP should be the identification of the onset and ending time for such events. A transient monitor with signal processing packages (such as wavelet toolbox) could be adopted to fulfill the task. Between the time frames of such events, special procedures should be designed to evaluate the trend of stability condition with reduced error and apply an adaptive, self-tuning algorithm to best track the system conditions and usability of the obtained VIP parameters.

Proposed Procedures and Examples

Modeling a system with flowgates

In this paper, a PMU-based VIP algorithm is proposed for voltage-stability monitoring of a system with pronounced longitudinal topology, represented by a transmission corridor (called flowgate hereafter). The application utilizes PMUs installed at the receiving end of all flowgates to measure the voltage and current phasors.

The concept can be expanded to a more complex network shown in Figure 1, where the generation plants supply the energy via subsystem A, which delivers it to the loads in subsystem B via a small number of flowgates which form the corridor of power transfer. Flowgates can be very long in a real system which limits the power transfer in the region.

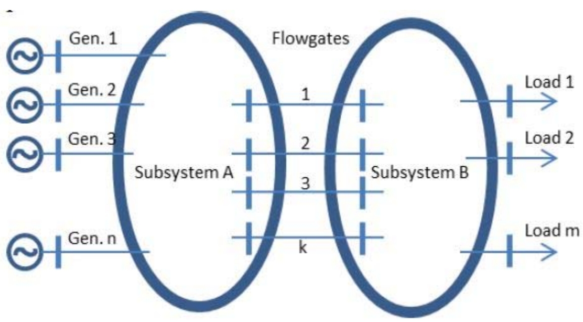

Fig. 2 Model of Flowgates connecting the two subsystems

New-England 39 bus system is used as test system in this paper. System diagram is shown in Figure 3. System parameters can be found in [11]. The system is modified by being divided into two subsystems connected by five transmission flowgates. The five flowgates are: flowgate 1: Bus 25-26, flowgate 2: Bus 2-3, flowgate 3: Bus 5-4, flowgate 4: Bus 13-14, flowgate 5: Bus 19-16. The two connected subsystems are referred to as generation side (left) and load side (right), respectively. Branch parameters of the five flowgates are modified, making them five times longer than in the original model where they represented relatively short lines.

Both generation and load sides have generators as well as loads, but the two subsystems are generation-dominant and load-dominant respectively, making the flowgates very important. In fact, 32.9% of base active power generation is from the load side, while the generation side possesses 45.2% of the total base active power load.

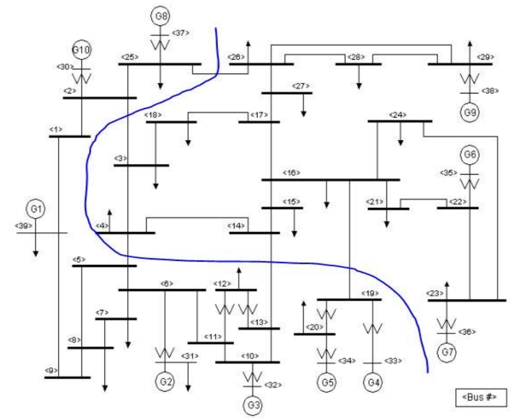
Fig. 3 New-England 39-Bus System with a cut

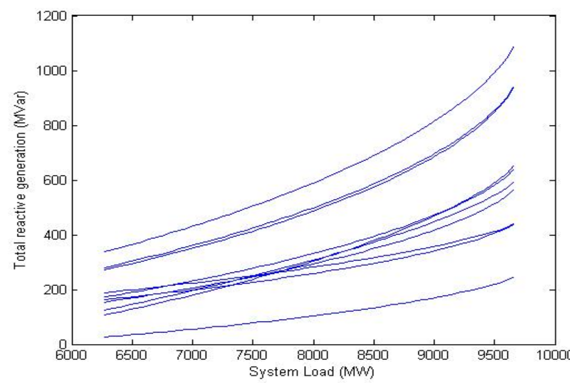

Fig. 3 Reactive generation in all power plants as a function of system load modeled as constant power injections.

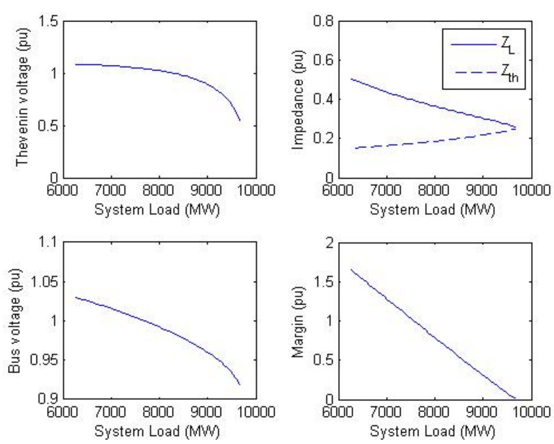

Fig. 4 Thevenin voltage, load & Thevenin impedance, bus voltage, and loading margin at bus 28

The base case system model has a total active power load of 6.15 GW. System is simulated with both active and reactive power while all loads grow proportionally, with a step size of 1% of base load, until the system collapses.

Figure 3 shows the system reactive generation, which, as expected, is nonlinear in nature because of the increasing system losses on transmission lines.

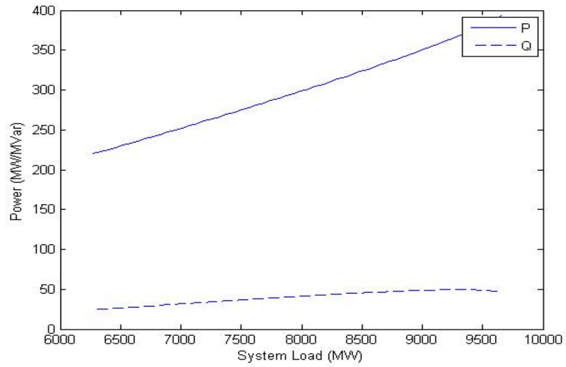

Fig. 5 Active and reactive power injection at the receiving end of flowgate 3 (bus 4) as the system loading grows up to critical level

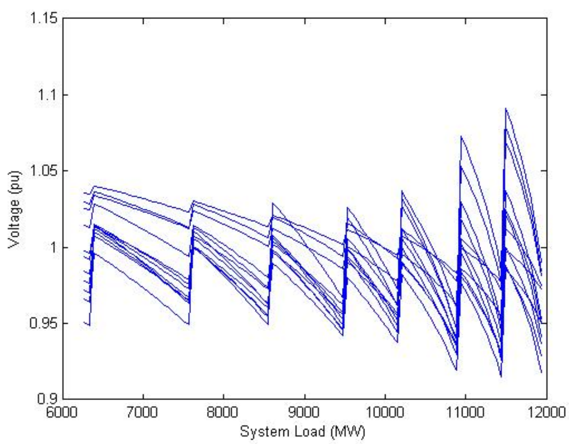

Fig. 6 Load bus voltage profile at load side of the system as the system loading grows up to critical level

Voltage control at load level can be achieved in various ways such as Thyristor Switched Capacitor (TSC) or Thyristor Controlled Reactor (TCR) based static var compensation [1] applied as series compensation on flowgates or as shunt compensation in some substations. We consider shunt capacitor compensation for some examples illustrated herewith, vastly cheaper than most alternatives. Shunt compensation is added when voltage at controlled load buses drops below 0.95 pu. Three load buses are equipped with capacitor blocks. Once they drop below 0.95, a shunt capacitance (1/3 pu) is added. By adding capacitance, voltage at the load bus is expected to be raised to at least 1 pu when the system load is not close to critical (more as the same blocks are added closer to critical load levels). The goal of this control is not just to maintain voltage in the transmission system, but rather to reduce transmission losses and improve the transmission capacity, and provide a challenging issue for VIP calculations.

Flowgate VIP calculations

In addition to conventional approach, VIP calculations are also performed at the receiving end of flowgates. They differ from the conventional ones in that the load (driving point impedance) is taken as the whole system behind the bus instead of the load at local bus, and the equivalent system is taken as the system in front of the bus (flowgate and generation side of the system). Given two measurement sets, the Thevenin parameters can be calculated as follows:

$$Z_{th} = \frac{V_2 - V_1}{I_1 - I_2}$$

$$E_{th} = V_2 + I_2 Z_{th}$$

Where E_{th} and Z_{th} are Thevenin voltage and Thevenin impedance, respectively. (V_1, I_1) and (V_2, I_2) are the two measurement sets. Voltages V_1 and V_2 are two snapshots of the bus voltages, whereas the currents I_1 and I_2 are obtained at the same instants as follows:

$$I = \left(\frac{S_{flowgate}}{V} \right)^*$$

Where $S_{flowgate}$ is the apparent power injected into the bus at the receiving end of the flowgate (through the flowgate). The only difference in the formulation of flowgate VIP calculation is the use of $S_{flowgate}$ instead of S_{load}.

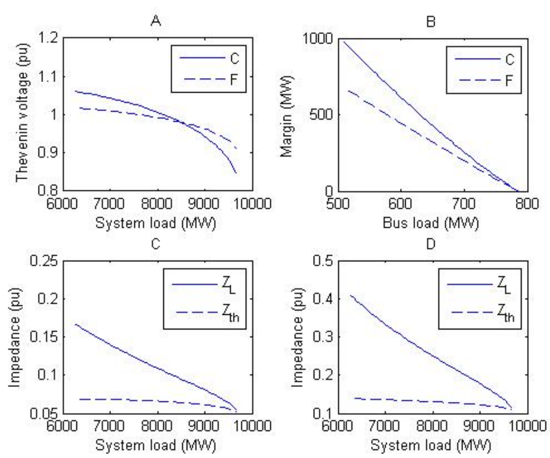

Fig. 8 Comparison between conventional VIP calculation (C) and flowgate VIP calculation (F) without voltage control. Figures show Thevenin voltage (A), loading margin (B), and load and Thevenin impedance (C and D) comparison at bus 4 (flowgate 3)

This new calculation scheme highlights the importance of flowgates. Normally, flowgates are long lines and have large impedances, and they constitute a considerable portion in the Thevenin impedance equivalent, providing that the impedance referred to the generation side of the system is not too large compared to the flowgate series impedance. If this is the case, then the distance between load and Thevenin impedance will indicate the additional power transfer capability of the flowgate. However, the new scheme is not rigorous conceptually, as the equivalent system and the aggregate load overlap. This hinders the convergence of load and Thevenin impedance at critical point. This may be desirable when remedial actions need to be taken on some flowgates (series compensation) as the system approaches critical point, distance between the two impedances serve as a running indicator for choosing between flowgates, discussed in the following section.

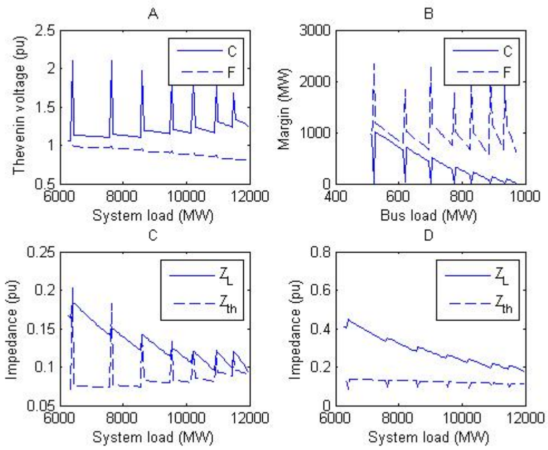

Fig. 9 Comparison between conventional VIP calculation (C) and flowgate VIP calculation (F) with voltage control. Figures show Thevenin voltage (A), loading margin (B), and load and Thevenin impedance (C and D) comparison at bus 4 (flowgate 3).

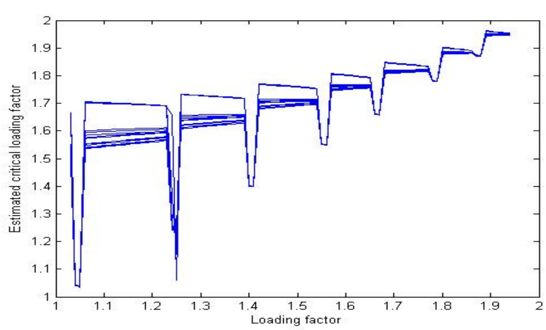

Fig. 10 Corrected estimated critical points at all load buses.

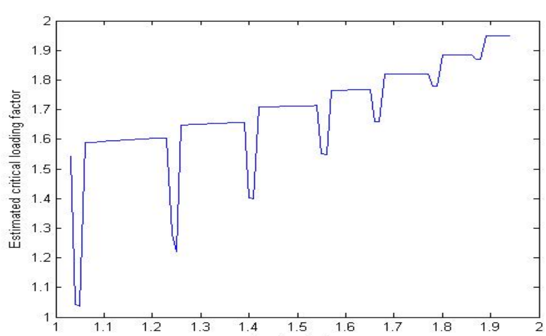

Fig. 11 Aggregate (average) of estimated critical points at load buses.

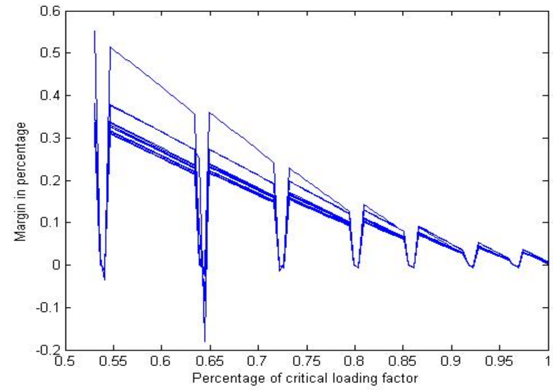

Fig. 12 Corrected margin estimations at load buses.

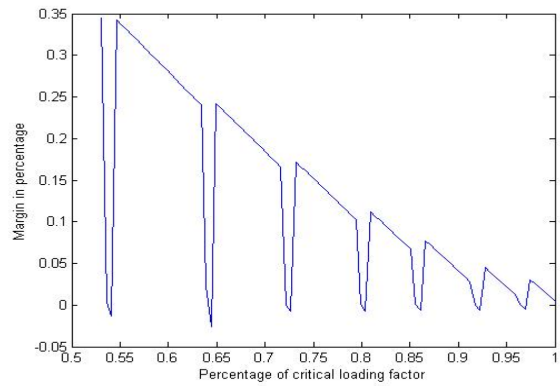

Fig. 13 Average of corrected margin estimations at load buses.

By applying simple transformation t directly to Thevenin parameters calculated using VIP algorithm [9], direct estimate of the loading margin is possible (assuming a known pattern of load increase and taking into account the approximate nature of the model).

As can be seen from Figures 8b and 9b, absolute values of margin are not very accurate. However, for conventional VIP margins, it is observed that they all approach zero at the critical point in a linear linear fashion. This suggests that linear extrapolation of estimated margin changes might provide a better estimation of margin. Estimated loading power at critical point is obtained solving for intersection between extrapolated time-dependent (VIP-derived) [9] margin curve and x-axis (bus load or loading factor). Margin estimation can be further improved by averaging the margin estimates obtained from most, or all all load buses (broadcasting the results within the network of VIP processors at different load buses). Simulation results for critical load estimation are shown in Figures 10 and 11, and estimated margins are shown in Figure 12 and Figure 13. Linear extrapolation of the margin curve is achieved by using only the last two calculated margins, which in essence is the current slope of margin. The discontinuities are caused by the voltage control actions (switching of the shunt capacitor blocks at load substations), and the slopes of the estimated margins reflect the increases in critical load levels obtained by deploying reactive reserves in the system.

Flowgate VIP in remedial action formulation

Remedial actions, including network compensation, are called for well before the system approaches the critical point to trigger voltage collapse. Among them, line series compensation may be used to decrease transmission line impedance carrying power over long distance [1] by deploying capacitors installed in series with transmission lines. Particularly interesting future solution to this problem may be the application of distributed series compensators [15], which can be installed along transmission corridors to provide a substantial amount of compensation in both inductive and capacitive directions, effectively providing a tool for controlling load flows (and redistributing the flows through the flowgates, as an example). While such devices are still in experimental stage of development, they are approaching commercialization, and the issues are being resolved related to their successful deployment (monitoring, control, communication between the devices, interaction with protective relaying, etc.).

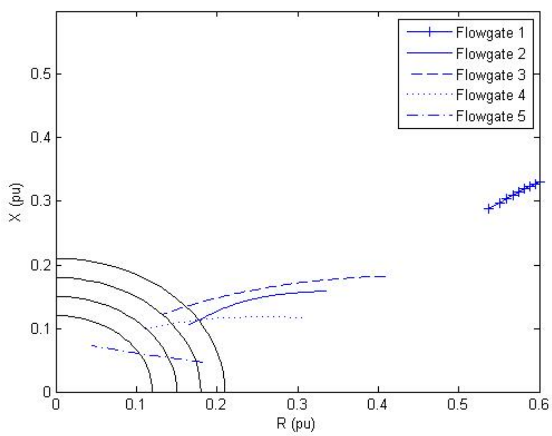

Fig. 14 Trajectories of $Z_L - Z_{th}^*$ at the receiving end of flowgates.

Should heavily loaded flowgates threaten to become the limiting factor of power transfer and a possible cause of transfer capacity or voltage instability, series compensation applied to flowgates may be carried out. Effectiveness of series compensation at different flowgates is indicated by their margin sensitivity (as per [9] and the modification proposed in the previous text). Therefore, the flowgate with highest margin sensitivity should be compensated first, without jeopardizing the overall capacity to transmit power to the load-dominant part of the system. The difference between load impedance and the complex conjugate of the Thevenin-like impedance (both obtained from flowgate VIP calculation), $Z_L - Z_{th}^*$, is proposed here as an indicator to margin sensitivity of series compensation. Although only a Thevenin-like quantity (as pointed out in the introduction), Z_{th} obtained from flowgate VIP calculations is close to its true counterpart (when the driving point impedance is the actual load at the point of measurement). The distance between the two impedances describes the possible metric for distance to voltage collapse, as the convergence of the two marks the onset of voltage instability. The trajectories of $Z_L - Z_{th}^*$ at five flowgates are shown in Figure 7. Those which make the closest approach to the origin are deemed to be the most critical from the standpoint of line loadability.

As can be seen from the figure, flowgate 5 is closest to the origin and flowgate 1 is the furthest, which is consistent with their margin sensitivity w.r.t. series compensation obtained from simulation results in Table 1. The biggest improvements in post-compensation loading factor are achieved when series compensation is applied to the flowgates having $Z_L - Z_{th}^*$ closest to the origin.

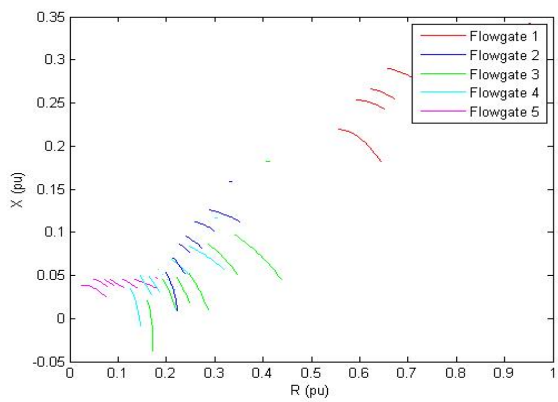

Fig. 15 Trajectories of $Z_L - Z_{th}^*$ at the receiving end of flowgates when voltage control actions are performed in the system.

Table 1. Loading factors at critical load level with 30% series compensation active at corresponding flowgates (critical loading factor is 1.57 when no compensation is added)

Gate	**Gate 1**	**Gate 2**	**Gate 3**	**Gate 4**	**Gate 5**
Loading factor	1.58	1.61	1.60	1.60	1.64

VIP as a trigger for remedial actions

Contingencies such as loss of flowgates will decrease the loading margin substantially as flowgates are main the pathway of power transfer. Knowing the approximate updated margin to critical point when contingency occurs is important. A method of estimating the new margin in case of the single flowgate contingency is presented in this section. It is useful to be able to approximately assess those margins, especially in the case when system is exposed to the unusual conditions not studied beforehand.

The rationale behind this method can be found in [12] where it is stipulated that loading margin changes nearly linearly or quadratically with respect to various system control parameters, such as shunt capacitance, import power into critical area, etc. It can be shown empirically that there is also a nearly linear relationship between line admittance and loading margin. Therefore, if two sets of margins are obtained for two different values of line admittances, the margin for any value of admittance, including zero (line out of service) can be roughly estimated. The only obstacle to getting the approximate margin with contingency would be to obtain the second margin with different line admittance. This can be done when small distributed series compensators [14] are deployed at the flowgates. In such a case, adding a small amount (say, 3 percent) of series compensation to the line provides an opportunity for the needed second margin estimate without significantly changing the system state in the process. Given two margins m_1 and m_2 corresponding to line admittances y_1 and y_2, the relationship can be obtained as

$$m = \frac{m_1 - m_2}{y_1 - y_2} y + \frac{m_2 y_1 - m_1 y_2}{y_1 - y_2}$$

and the estimated new margin with the loss of flowgate would be

$$m = \frac{m_2 y_1 - m_1 y_2}{y_1 - y_2}$$

Simulations have been performed to test the validity of the proposed method. As loss of flowgate 5 would create an island and jeopardize the system immediately, this contingency is ignored. Only margins corresponding to the loss of flowgates 1-4 are estimated. VIPs are placed at the receiving end of the flowgates. Since the receiving end of flowgate 4 is a tie bus (bus 14), VIP sensor is placed at the nearby bus 15 instead, connected to the receiving end of flowgate 4. Series compensation of 3% is added briefly to the flowgate so that a new margin with different line admittance can be obtained. Flowgate contingency margin is thus obtained using the above formula. The results show that the linear extrapolation is a potentially useful tool in estimating the new margin, especially when the system is close to the critical point. Relatively small margin estimation errors which are observed in Table 3 are quite acceptable if the remedial actions are triggered (as they should be) at sufficiently high margin threshold. For example, the critical loading factor following contingency of flowgate 1 is estimated to be 1.49 at loading factor of 1.1, and the estimate slowly grows to 1.53 at the loading factor 1.4 and beyond. Since the true value of critical loading factor is 1.52, assuming any margin larger than the estimation error would result in timely deployment of remedial actions. Approximate estimates of loading margin are particularly useful when the system state differs from those estimated in the offline studies (say, due to unforeseen contingencies or other system conditions).

Table 3. Extrapolation of critical loading factor for a flowgate contingency based on margins at different flowgate admittances (all margins are in pu, tables show flowgates 1, 2, 3, and 4 in consecutive order, their true critical points after contingency (loss of this flowgate) are 1.52, 1.38, 1.41, and 1.38)

Loading factor	No compensation margin	3% series comp. margin	Estimated critical loading factor
1.1	0.6650	0.6688	1.4900
1.2	0.5151	0.5184	1.4938
1.3	0.3699	0.3726	1.5033
1.4	0.2296	0.2318	1.5331
1.5	0.0954	0.0969	1.5337
1.51	0.0823	0.0838	1.5343
1.52	0.0694	0.0708	1.5373

Loading factor	No compensation margin	3% series comp. margin	Estimated critical loading factor
1.1	1.1101	1.1210	1.3353
1.2	0.8440	0.8543	1.3587
1.25	0.7159	0.7258	1.3729
1.3	0.5914	0.6009	1.3883
1.35	0.4709	0.4799	1.4012
1.38	0.4006	0.4093	1.4170
1.4	0.3547	0.3632	1.4248

Loading factor	No compensation margin	3% series comp. margin	Estimated critical loading factor
1.1	1.6166	1.6349	1.3050
1.2	1.2250	1.2415	1.3383
1.25	1.0367	1.0522	1.3571
1.3	0.8359	0.8684	1.3770
1.35	0.6773	0.6906	1.3995
1.38	0.5745	0.5872	1.4128
1.41	0.4745	0.4864	1.4279

Loading factor	No compensation margin	3% series comp. margin	Estimated critical loading factor
1.1	1.1268	1.1384	1.3349
1.2	0.8569	0.8673	1.3627
1.25	0.7269	0.7367	1.3781
1.3	0.6006	0.6098	1.3947
1.33	0.5267	0.5355	1.4057
1.35	0.4783	0.4868	1.4136
1.38	0.4070	0.4150	1.4263

Conclusions

Various VIP procedures for estimation of proximity to voltage instability [13] have been used for over 15 years. There are many flavors and variations in implementing the VIP principle.

Among the difficulties in successfully applying the VIP is exposure to various transient switching modes which can interfere with the calculation and render the results unusable. Filtering and robustness introduced by using various recursive and redundant procedures provide limited benefits and require that an adaptive calculation approach be used to avoid the pitfalls in the incoming data streams. In general, the quality of VIP is compromised when the system state is frequently disrupted by switching or other discontinuity-inducing transients. On the other hand, the selection of the sampling rate and other parameters needed for successful application of VIP should account for sufficient time needed for system to change appreciably so that the obtained Thevenin-like equivalent is due to the load changes and system topology rather than random fluctuations of the load or measurement noise.

When the power system operates by supplying power to the bulk load via a number of transmission corridors (flowgates), approximate VIP calculations can be used to estimate the impact of flowgate contingencies. In the absence of frequent transients in the system, such approximate calculations can be quite useful in the absence of (or during the wait to obtain) more accurate data. They can be used to trigger some emergency controls, such as series compensation of flowgates and deployment of additional reactive support in the network. When using such calculations, it is assumed that the flowgates are equipped with some (preferably distributed) series compensators, similar to the one discussed in [14]. Such devices are still in experimental stage of development, but possess high attractiveness for deployment in systems similar to the one analyzed in this paper. When controls of distributed compensators are appropriately coordinated and coupled with VIP calculations, the procedures for maximizing the system transmission capacity or voltage stability margin can be effected via load flow redistribution. That controlled deployment sequence could be defined completely heuristically by combining the ordered sequence of switching distributed compensators with VIP measurements across network and making adjustments upon obtaining the results.

Also, a modified VIP calculations can be applied to the flowgates, but measuring driving point impedances in the direction of the bulk load rather than the local load. In such cases, the norm of the difference between driving point impedance and the complex conjugate of the Thevenin-like equivalent represents a measure of criticality of the flowgate (those that are closest to full loading capacity are having the smallest difference between driving point impedance and the complex conjugate of the Thevenin-like equivalent – a condition which can be somewhat mitigated by adding series compensation to the flowgates.

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