A Novel Method for Voltage Instability Protection

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Abstract

The growing concern about wide area power system disturbances and their impact on power systems have reinforced interest in the new generation of system protection tools. Their application depends on their reliability, which, in turn, depends on the reliability of the hardware infrastructure on which they rely. In this paper, we propose a modification of a Voltage Instability predictor (VIP) [17], proposed some time ago. The modification provides a path for integration of a stand-alone, local protection devices with a potential system-wide action, and takes into account the voltage characteristics of the loads.

1. Introduction

Large power system disturbances, such as voltage collapse, and their consequences, represent a challenging problem for the industry. A major power system disturbance is mitigated via protection and control actions, required to stop the power system degradation, restore the normal state, and minimize the impact of the disturbance. The present control actions are not designed for a fast-developing disturbance and may be too slow. The operator must therefore deal with a very complex situation and rely on heuristic solutions and policies.

Unpredictable events can stress even the best-planned system beyond the acceptable limits. Some of the reasons for less than complete system reliability are: *i)* A very large number of possible operating contingencies; ii) Unpredictable changes in power systems, which may differ dramatically from the forecasts; iii) A combination of unusual and undesired events (for example, human error combined with heavy weather, terrorist acts, or other combination of events that would be considered very improbable in the earlier times of power system evolution); iv) Reliability design philosophy that is pushing the system close to the limits, imposed by both economic and environmental pressures.

Among the reasons for a slow implementation of system-wide protection and emergency control tools is that technologies necessary for implementation of a true distributed monitoring and control system have only recently become commercially available at the price levels that would make them viable for power system protection. Among those technologies are: real-time measurements of system state, such as phasor measurements (now commercially available from a number of vendors), accurate measurement synchronization techniques (usually based on non-military applications of GPS tracking systems), and reliable and fast communication infrastructure (based on wide area networks, like Sonet, implemented on fiber optics infrastructure, allowing fast latency times and reliability of communication on a par with conventional protection systems, which are mostly based on local measurements and actions, thus alleviating the need for such a sophisticated infrastructure).

In order to achieve the acceptability of the true system protection tools, it is necessary to provide them with "fall-back" positions (to enhance their functionality with conventional protection tools, based on local measurements, but functionally compatible and complementary with their more advanced functions). In such cases, a possible failure of the necessary hardware infrastructure would not preclude the system reaction to a disturbance, which would still provide a defense superior to the old, insufficient tools, such as undervoltage load shedding protection.

In this paper, we provide, as an example, illustration of an application in power system voltage stability emergency control, using a network of phasor measurement units deployed as an adaptive distributed monitoring and control tool. It is based on an assumed network of VIPs (Voltage Instability Predictors) [17], which were proposed earlier. The idea is to integrate the local action of the VIP (which could be described as an adaptive undervoltage load shedding scheme) with sharing of system-wide state information, thus allowing superior performance. We also investigate the implementation of real-time load parameter identification into the scheme to improve the accuracy of the system.

2. Voltage Stability

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subject to disturbance. A system enters a state of voltage instability when the disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage. The main factor causing instability is the inability of the power system to meet demand for reactive power.

The sensitivities of the power system variables (such as power flows, reactive generation) to the change in the system's state parameters become very large when a bifurcation point occurs in the parameter space. The qualitative structure of the system changes for any small variation of the parameter vector λ. The system model assumes dynamics of the synchronous machines and constant *PQ* loads, i.e.

$$g_1(\dot{\delta},\delta,\theta,\ V)=0$$

$$g_2(\delta,\theta,V,\lambda)=0$$

where g_1 describes real power balance and additional state equations of the generators and g_2 describes real and reactive power balance of the loads. The parameter vector λ represents the change in load power demands.

For the fixed value of λ, its equilibrium points are solutions of the system

$$g_1(\delta,\theta,V)=0$$

$$g_2(\delta,\theta,V,\lambda)=0$$

If $g = [g_1\ g_2]^T$ is linearized around an equilibrium point, and if we introduce $d\xi=[\delta\ \theta]^T$ the following relationship holds

$$g_\xi\ d\xi + g_V\ dV + g_\lambda\ d\lambda = 0$$

In the matrix form it is given by

$$\begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix}\begin{bmatrix} d\xi \\ dV \end{bmatrix} = -\begin{bmatrix} g_{1_\lambda} \\ g_{2_\lambda} \end{bmatrix} d\lambda$$

Singularity of the Jacobian matrix on the left side of the above equation implies the bifurcation, and shows that it is manifested by infinite sensitivity of the elements of the state vector with respect to changes in the loading parameters λ.

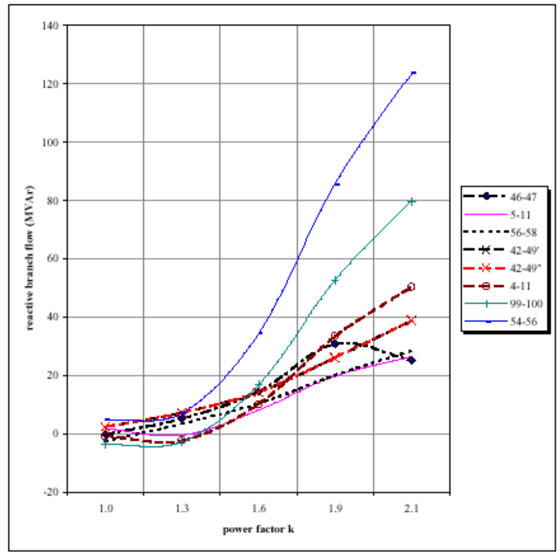

Figure 1. Dependence of the reactive line flows on the system loading level in the IEEE 118-bus system model.

The proximity indicators to voltage collapse may be defined in a number of ways. Their main purpose is to help detect the system's approach to voltage instability, when something still can be done to prevent the system break down.

Figure 1 shows the nonlinear change in reactive power flows in some of the transmission lines of the 118-bus system model, caused by the approach to bifurcation and PV-PQ transitions of various generators reaching their respective reactive capability limits. The simulation of approach to voltage stability is based of sequences of increasing load factors, for which the load flow calculations are performed.

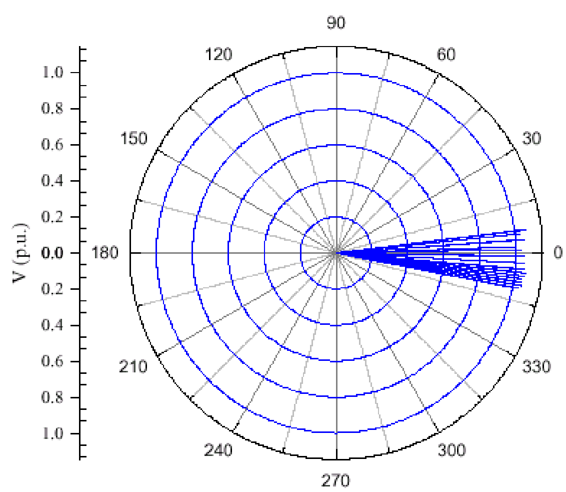

Figure 2. Phasor diagram of the 118-bus system in the state away from the voltage stability boundary.

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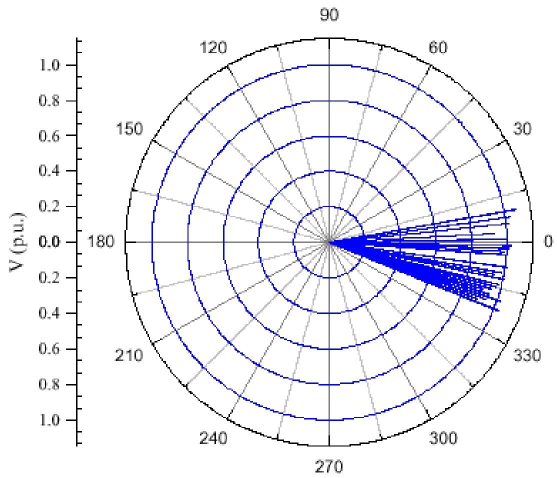

Figure 3. Phasor diagram of the 39-bus system close to voltage stability boundary.

Figures 2 and 3 show the phasor diagrams of the same system in the normal operating regime, and close to the voltage stability boundary. Even though the spans and magnitudes of both voltages and phase angles clearly show the dependence on the loading level, any proximity indicators directly based on the state (such as minimum singular value of the load flow Jacobian matrix) show a pronounced nonlinearity, especially at PV-PQ transition points of the generators.

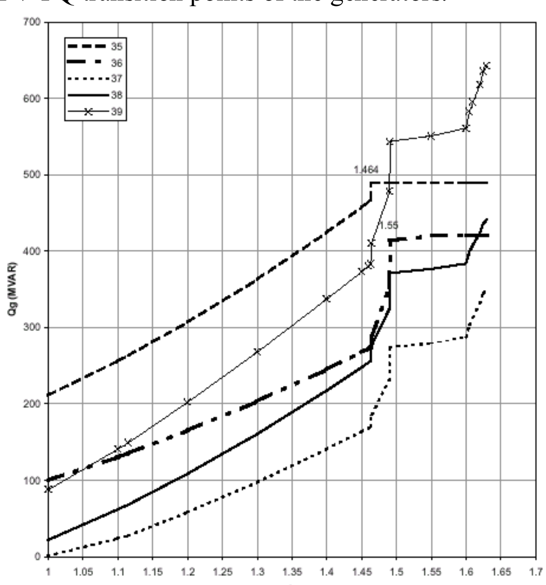

Figure 4. Reactive generation of the critical generators in the 39-bus system as a function of loading level.

Figure 4 shows the reactive generation levels of some of the heavily loaded generators in the 39-bus systems as it approaches the stability boundary. The points of reactive generation capability limits of the machines instantly affect the reactive generation of the other generators, and their sensitivity with respect to the loading parameter(s), as can be seen in Figure 5.

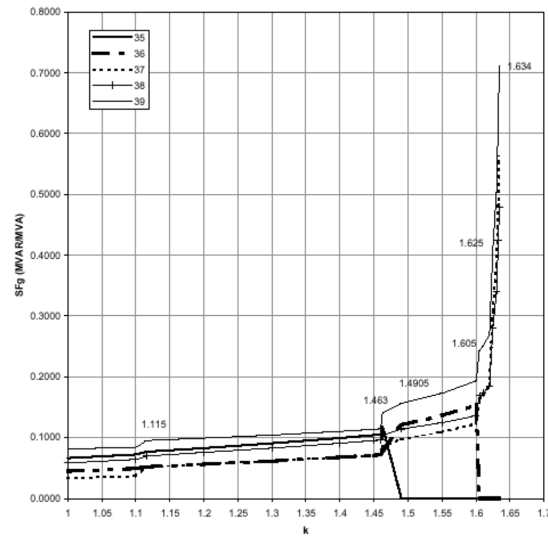

Figure 5. Sensitivities of the generated reactive power of the generators in the 39-bus system (in MVAr/MVA) with respect to the system loading.

2. Technology Infrastructure

The idea of a wide area protection system relies on certain technology, which assumes certain level of performance. The following is a brief overview of the enabling technologies that the proposed, as well as future, solutions to the voltage stability problem can be assumed to rely on.

2.1 Phasor Measurements

Phasor measurements are well known by now. The essential feature of the steady state phasor measurement is that it measures positive sequence (and negative and zero sequence quantities if needed) voltages and currents of a power system, with synchronized measurements being obtained at different measurement locations. Recursive Discrete Fourier Transform (DFT) calculations are normally used in phasor calculations on sliding time windows.

$$\tilde{X}_1^{new} = \tilde{X}_1^{old} + k_a \Delta x_a + k_b \Delta x_b + k_c \Delta x_c$$

Here, $\tilde{X}_1^{new}$ are the positive sequence phasors, and the k_x are appropriate Fourier coefficients. The Δx_i are the changes in the samples of the various phase quantities. The synchronization is achieved through a Global Positioning Satellite (GPS) system. It is possible to use other synchronization signals, if these become available in the future, provided that a sufficient accuracy of synchronization could be maintained. If the system model is known, dynamic phasor concept may be used [18], but practical implementations of such a concept require careful consideration in protection, where at least some of the model parameters are unknown. If dynamic phasor is possible to be implemented, however, such monitoring would provide the best input for real-time control of the disturbance.

A typical synchronized phasor measurement system configuration requires several functional components. The GPS transmission provides precise timing pulses, accurate to within 100 ns. Pulses are received by the receiver section, which delivers a phase-locked sampling clock pulse to the Analog-to-Digital converter system. The sampled data are converted to a complex number (in rectangular coordinates), which represents the phasor of the sampled wave form. Phasors of the three phases are combined to produce the positive sequence measurement. Typical resulutions of the A/D converted samples is 16-bit, which is sufficient for the dynamic ranges of the most of the signals dealt with in the power systems, although higher resolutions may be available for special applications.

2.2 Communications

Communications systems are crucial in a wide area relay system. These systems distribute and manage the information, which is then used for analysis and control/protection of the network [12], [13].

To meet the reliability and security requirements, the communications network needs to be designed for fast, robust and reliable operation. A number of factors contribute to achieve these objectives: type and topology of the communications network, communications protocols and media used are among the most important. The communications system speed, expressed in bits per second in digital systems or hertz in analog systems, is a function of the communication protocol and the media bandwidth, the frequency and volume of information communicated and the handling of communication errors.

Presently, electrical utilities use a combination of analog and digital communications systems for their operations consisting of: power line carriers, radio channels including microwaves, leased/ switched/ dedicated phone lines and optical multiplexers. Providing that the type and volume of information that needs to be transferred is adequate, any of these systems will perform well in a wide area protection and control system.

Optical systems offer the best performance as a communication medium to an electrical utility. That is due to its immunity to electromagnetic interference and signal fading, and its extremely large bandwidth, which allows for transfer of large quantities of data in real-time. Typical data transfer latency times expected in large scale applications are of the order of 1-10 ms between any two points in the system.

3. Novel Voltage Stability Protection Method

In 1997, we presented [17] the method that employs only local measurements to estimate the proximity of the system to voltage. The method is proposed for relay application.

Based on the local measurements – bus voltage and load current phasors – the proposed algorithm produces an estimation of the strength/weakness of the transmission system connected to the bus, and compares that with the local demand.

The closer the local demand is to the estimated transmission capacity, the more likely to occur is the voltage instability. This information can be used for load shedding as well as other applications. The method is very attractive since it is very simple and can be applied in *real time*. It does not require the network information to be known (topology, loads, generators, etc.). On the other hand, the controls that use only local data are low cost and simple to build.

The algorithm that is used in voltage stability estimation was called, somewhat optimistically, Voltage Instability Predictor (VIP), even though there is no guarantee that its actions, based on local measurements only, would indeed coincide with the onset of a system-wide voltage instability. We propose to enhance the original VIP algorithm with a simple communication strategy, which may represent the bridge between a completely self-contained protection system, and the one that would truly use the system-wide monitoring information on a complete system model.

3.1 Real-time Equivalent of the System

The local voltage stability monitoring and control method is based on a two-bus equivalent, where one of the buses is the slack bus supplying a load over a single branch, as shown in the Figure 6. The line and source system is represented by an impedance

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$\tilde{Z}_{eq} = R_{eq} + jX_{eq}$ and voltage phasor $\tilde{E}_{eq}$, respectively. $\tilde{E}_{eq}$ and $\tilde{Z}_{eq}$ represent the equivalent of the network seen from the terminals of the load bus of interest

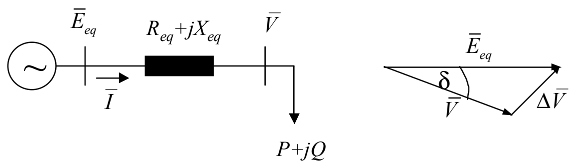

Figure 6. Load bus and the rest of the system represented with a source and a line, and the corresponding line diagram.

Simple calculation shows that at the voltage stability point, the equivalent impedance Z_{eq} is equal to the load bus impedance Z given as a ratio between the voltage $\tilde{V}$ and the current phasor $\tilde{I}$ measured at the bus, i.e, $Z = |\tilde{V} / \tilde{I}|$ [17].

$$Z_{eq} = Z$$

To assess the load bus distance to collapse, the corresponding agent has to track the parameters of the equivalent source $\tilde{E}_{eq}$ and impedance $\tilde{Z}_{eq}$ that model the rest of the system lumped together, and monitor the Impedance Stability Index (ISI) or Voltage Stability Index (VSI) defined below. The values close to one are indicative of the proximity to voltage collapse and can be used to pinpoint the system area directly associated with the collapse problem. Obviously, the smallest value among all *ISI* determines the stability of the whole system.

$$ISI = \frac{Z_{eq}}{Z} \qquad VSI = \frac{V}{\Delta V}$$

Notice that V and ΔV represent high and low voltage solution at a load bus. At the collapse point $V = \Delta V$. The value of parameters $\tilde{E}_{eq}$ and $\tilde{Z}_{eq}$ are not constant, but vary slightly and reflect changes in the power system loading.

A phasor measurement device can also determine the load margin from any current operating point to the tip of the power-voltage curve, where voltage collapse can take place. The power margin is equal to

$$\Delta S = ZI^2 - Z_{eq}I^2$$

and represents the extra MVA that can be delivered to the load before voltage collapse occurs. The ratio between the power supplied by equivalent source $S_{eq} = E_{eq}I$ and the power actually consumed by the load $S = VI$ will reveal power lost in the transmission. This ratio rapidly increases as the system approaches the voltage collapse. Please note that in the above discussion, the model of the load is implicitly assumed to be constant power injection, because only such load experiences voltage collapse at the peak of the power-voltage (nose) curve. We will extend our consideration to other types of loads later in the text.

3.2 System Parameter Identification

The relationship between unknown parameters of the voltage source $\tilde{E}_{eq}$ and line $\tilde{Z}_{eq}$ modeling the rest of the system seen from the load bus is expressed with the following equation:

$$\tilde{V} = \tilde{E}_{eq} - \tilde{Z}_{eq}\tilde{I}$$

After separating the imaginary and real parts above, we obtain the system of two linear equations with four unknowns, i.e., $\tilde{E}_{eq} = E_r + jE_i$, and $\tilde{Z}_{eq} = R_{eq} + jX_{eq}$.

$$\begin{bmatrix} V_r \\ V_i \end{bmatrix} = \begin{bmatrix} E_r \\ E_i \\ R_{eq} \\ X_{eq} \end{bmatrix} \begin{bmatrix} 1 & 0 & -I_r & I_h \\ 0 & 1 & -I_h & -I_r \end{bmatrix}$$

where $\tilde{I} = I_r + jI_i$, and $\tilde{V} = V_r + jV_i$.

Having the time tagged sequence of voltage and current phasor measurements, we can determine the unknowns by using a parameter identification algorithm, such as recursive least-squares (RLS). Note that all of the above quantities are functions of time and are calculated on a sliding window of discrete data samples of finite, preferably short length. The other important factor of the calculation is the need for a change in the system, for only different system states can provide useful information for identification of the system equivalent. This constraint, however, does not represent a major obstacle, for if the system stays in the same operating point, its steady state does not change, and voltage collapse cannot occur. As soon as there is a change of the system state that can lead to deterioration of its voltage stability, we will be able to determine the parameters of the system equivalent, and proceed with the decision regarding any protective actions (load shedding, etc.)

The monitoring device based on the above principle can be used to impose a limit on the loading at each bus, and sheds load when the limit is exceeded. It can be also used to enhance existing voltage controllers. Coordinated control can be obtained if communication is available.

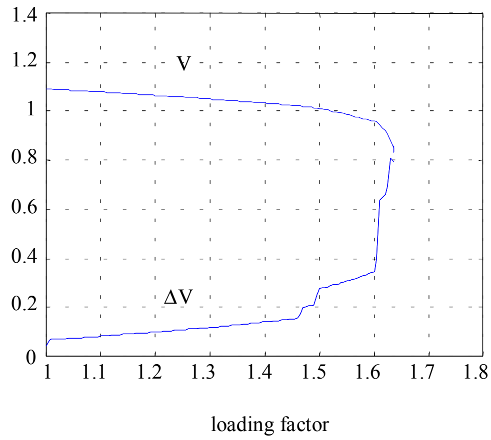

Figure 7. Measurement of the load voltage V and equivalent system voltage ΔV obtained at bus 7 of the 39-bus system during proportional system loading.

To illustrate local and enhanced voltage stability monitoring, we use the standard IEEE 39-bus system. Loading is simultaneously increased at all load buses. Limits of reactive power generation are taken into account. Voltage collapse occurs for the proportional multiplicative loading factor equal to 1.634. The recursive least squares (RLS) algorithm is used to track the time-varying parameters of the system equivalents. The parameters of the equivalents change with operating conditions. This is especially true when the reactive generation limits are encountered. Therefore, the older data should be less relevant than newer data. This is accomplished with a forgetting factor $\lambda<1$, since it gives larger weight to more recent phasor measurements.

Figure 7 shows how voltages across the load (V) and the system equivalent (ΔV) can be used for comparison against voltage collapse, which occurs when they are equal. Figure 6 can also be used to rationalize the use of VIP relay as an adaptive undervoltage load shedding device, which can be triggered when the difference between V and ΔV is below certain threshold, rather than when V reaches below certain level (which is a trigger in the conventional undervoltage load shedding applications).

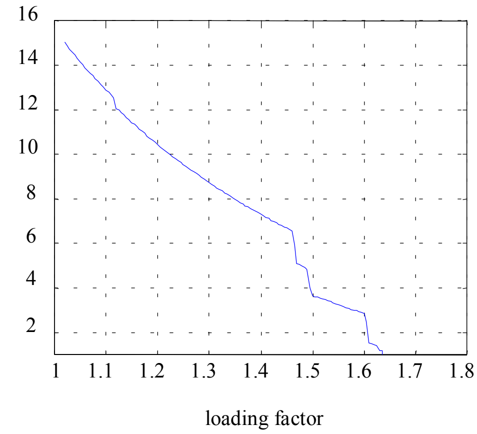

Figure 8. Estimation of the loading margin VSI at bus 7 of the 39-bus system during proportional system loading.

Figure 8 shows the benefits and disadvantages of the loading margin VSI, a ratio of V and ΔV, as defined previously in the text, calculated on the same bus 7, for which the data are shown in Figure 7. It is clear that the margin would be close to linear were there not the PV-PQ transitions in the system, which are causing the discontinuities in the model and, consequently, voltages ΔV.

Current operating state k	# Unit switching from PV to PQ mode	# Unit that will next switch form PV to PQ mode	Load factor estimate k^e	Estimation error (%)
1	-	30	1.120	0.43
1.115	30	32	1.554	6.23
1.463	32	35	1.493	2.08
1.4905	35	36	1.659	3.28
1.605	36	33	1.639	0.88
1.625	33	34	1.647	0.81
1.634	34	-	-	-

Table 1. Estimation of the next PV-PQ transition of the generators based on the present pattern of generation, and knowledge of the reactive margins.

Since the critical points are the transition points, we propose to estimate those by transferring the reactive margin information from all the generators to all of the

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VIP devices, so that the VIPs possess the knowledge of approximate points of discontinuity (at some of which the actual collapse may occur). By receiving the reactive margin information from the generators, estimates of PV-PQ transitions can be made, based on the knowledge of actual reactive generation.

The generators can then use the information from the time-varying VSI, or ISI indicators to estimate the power, or time margin (if load forecast is known), but if such margin is estimated beyond the closest estimated PV-PQ transition, such transition is used as the next immediate critical point. The modified VIP algorithm can therefore be described as follows:

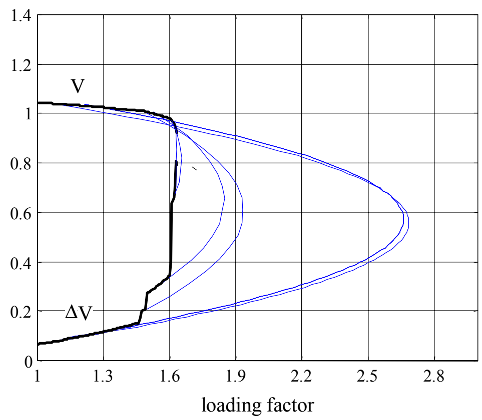

Figure 9. VIP-based estimates of the power margin depend critically on the PV-PQ transitions of the generators in the system (calculated upon step 2 recommendation below).

1. Perform the local measurements and calculate the system and load parameters, as well as ISI and VSI indicators.
2. By using the 2-bus equivalent model, calculate the power margin using the currently available recent data (after the last PV-PQ transition).
3. Receive generator reactive generation and reactive margin data. Estimate the minimum margin to the next PV-PQ transition.
4. Whichever of the (2) or (3) is smaller, represents the current estimate of the critical margin.
5. If current critical margin is based on (2), check whether it is smaller than a given set of thresholds to activate the control and protective actions.
6. If current critical margin is based on (3), request information from the system coordinator whether the next estimated PV-PQ transition is a critical one. If so, deploy protective and control actions upon checking current margin against the set of thresholds.

The Figure 9 illustrates the process of determining the voltage stability margin. To be consistent in this example as in all previous ones, we used the multiplicative proportional loading factor as a parameter that drives the system to voltage stability limit. Hence, we "measured" the margin in terms of system loading, and not in terms of time. The thick solid lines in the Figure represent the voltage load curves traced at bus 23. The points on the thin line knees indicate estimates of the critical points, and therefore voltage stability margins. As the system moves toward the stability limit and the generators encounter Q-limits, the estimate of the system margin becomes more accurate. In our example, the initial estimate for the voltage stability margin was 2.68, and final 1.63.

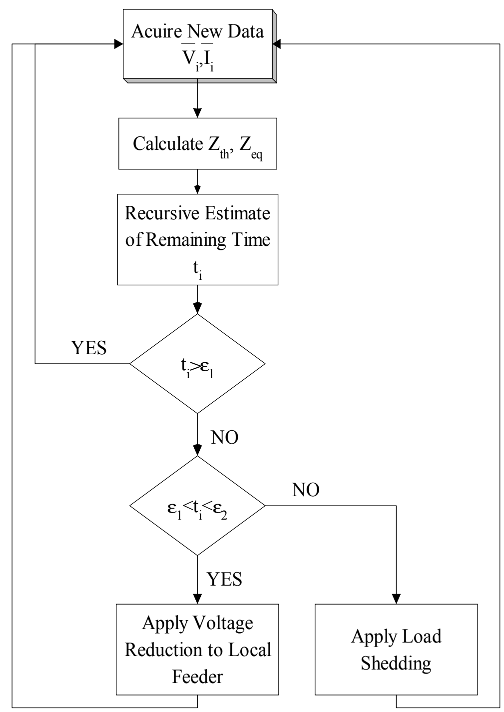

Figure 10. Voltage stability margin estimate flow chart.

The *ISI* index is predictable in the sense that it decreases significantly as the system moves closer to the collapse point. However, its nonlinearity makes it impractical for prediction of proximity to collapse. However, having more "predictable" shape voltage magnitude V at a load bus can be used in combination with ΔV to estimate the distance to voltage collapse from a discrete number of successive operating points by using a curve-fitting technique. The proposed method to get the "time or power margin" to the voltage collapse as "seen" from the terminals of a bus i can be explained as in the flow chart on the next page. The estimated time margin is expressed as the period in minutes upon which the system might experience collapse. Since, the ΔV might be very sensitive to device limits, the estimate has to be revised after any sharp change in the ΔV value.

First, at any given (current) time instant, we obtain new voltage and current phasor measurements, and calculate the elements of the two-bus equivalent, as shown above.

Then, from the knowledge of a discrete number of previous and current operating states, we approximate the voltage load curves by a nonlinear function, whose form is a function of the load characteristics. To fit the function, a minimum of two points on each curve is necessary.

Upon finding the approximate voltage load curve, every PMU locally estimates the collapse point (peak of the nose curve) and time when it will be reached, as seen from the corresponding load bus, if short term load forecast information is available.

4. Control Actions

Obviously, the system collapse margin corresponds to the minimal value of the time margin estimated at every load bus. If time margin is grater than some predefined threshold value, the PMU will assume its bus not to be critical, and system to be stable. However, time margin value between two threshold values, which we may refer to as "warning" and "emergency", would be a trigger to the PMU to take immediate corrective actions at the local bus, such as voltage reduction, to prevent the system collapse. A PMU will take more severe control actions, such as load shedding, if the time margin is lower than the "emergency" value.

The effect of the control actions will be sensed immediately through new measurements of the voltage and current phasors at the corresponding load bus. This allows a PMU to evaluate the effect of its control actions and adjust them in response to the changes of estimated margin.

The example shows that monitoring of the generator Q-limits is also an important part of the above procedure, for every PV-PQ transition caused by activation of generator excitation limiters would change the load margin estimates, sometimes radically. Since the procedure described above could be implemented at every load bus, redundancy of those estimates is taken advantage of to create a voting scheme for protective and emergency control actions.

5. Load Models: ZIP

For the steady-state analysis, depending on availability of the data, we model the loads as a constant impedance load (Z), a constant current load (I), a constant power (P), or a mixture of the three (ZIP model):

$$P_L = kP_0\left[A_1 + A_2\frac{V}{V_0} + A_3\left(\frac{V}{V_0}\right)^2\right]$$
$$Q_L = kQ_0\left[B_1 + B_2\frac{V}{V_0} + B_3\left(\frac{V}{V_0}\right)^2\right]$$

where $A_1 + A_2 + A_3 = B_1 + B_2 + B_3 = 1$; P_0 and Q_0, the so-called nominal load powers, are the load real and reactive powers consumed under nominal conditions i.e., at the reference voltage V_0 and the nominal frequency. The actual or consumed load powers P_L and Q_L are the powers consumed by the load under existing conditions of voltage V and frequency. The value k is an independent demand variable called loading factor.

6. Voltage Stability Limit for Mixture Loads

To study the system voltage stability for the different load compositions, a simple 2-bus system is considered. The system consists of a generator (E = 1.0), which supplies a load with a ZIP load model, at constant power factor through a transmission line (R= 0.02; X= 0.05). The nominal active and reactive load powers are P_0= 50 MW and Q_0= 20 MVAr, while the reference voltage is V_0= 0.985. For short notation, load is rewritten as

$$P_L = k(P_{con} + aV + \alpha V^2)$$
$$Q_L = k(Q_{con} + bV + \beta V^2)$$

where the subscript "con" indicates the constant load power component.

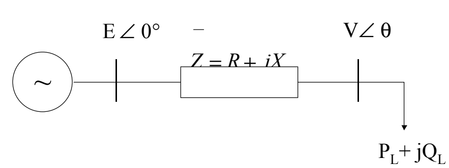

Figure 11. 2-bus system with constant voltage source supplying a load through a single transmission line.

A simple calculation for the system shown in Figure 11 gives a relationship between the voltage magnitude at the load bus V and the load active P_L and the reactive Q_L

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powers:

$$V^4 + V^2\left[2(P_L R + Q_L X) - E^2\right] + Z^2\left(P_L^2 + Q_L^2\right) = 0$$

The system becomes voltage instable at the operating point *C* at which the load characteristic is tangent to the system *PV* curve. This is equivalent to the singularity of the system Jacobian.

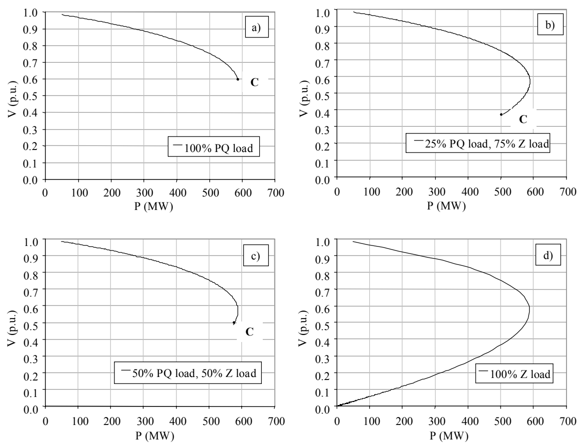

Figure 12. System PV curves and bifurcation points for the various mixtures of the constant power and impedance loads in a simple two-bus system equivalent calculated by VIP.

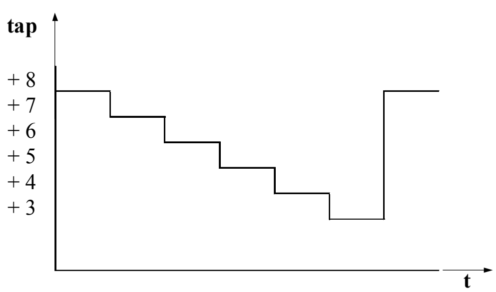

Figure 13. A sequence of tap changes used to determine the load voltage characteristics.(variable lengths may be used in practice)

It is, therefore, possible to reach beyond the maximum load margin point, toward reducing the overall load, before reaching the bifurcation point and collapsing the system. We propose to periodically calculate the system load characteristics in order to be able to assess the true bifurcation point. Since any such calculation requires a voltage disturbance, the load parameters can be obtained from intentional switching of the tap changer at the load terminals (or elsewhere, so that a usable voltage disturbance can be produced).

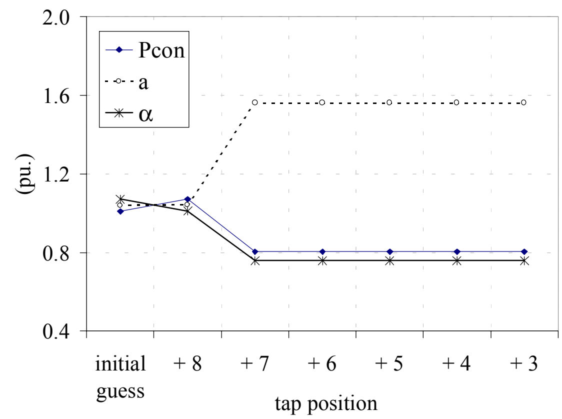

Figure 14. Active load parameters P_{con}, a and α curves for 25% P, 25% I, 50% Z load as a function of the tap position in the load identification experiment.

The number of taps and the magnitude of the voltage disturbance may be needed to be more substantial if the measurements possess even a small degree of error (noise). This necessitates emphasizing the importance of using as precise a measurement system as possible, and providing the system with as large voltage disturbance as practically possible, without jeopardizing the system itself. The experiment shown in Figure 14 was performed on bus 3 of the 39-bus system model, assuming it was equipped with a tap changer at the load terminals.

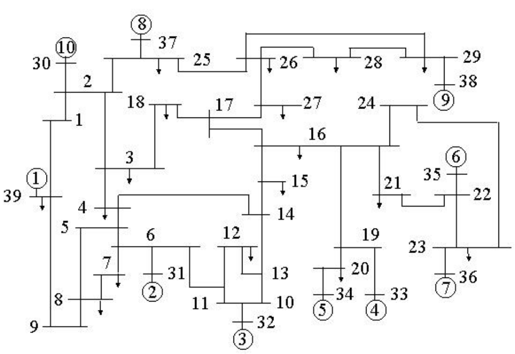

Figure 15. IEEE 39-bus system used in simulations.

Once the load characteristics are known, we can look at their impact on the load margin to voltage collapse. The voltage stability limit for an N-bus system depends on the load characteristics and the available reactive power reserve. The voltage instability cannot occur when all loads are of the impedance type and the units have enough reactive power reserve that PV-PQ transitions never happen. In all other cases, the system has a voltage stability limit.

In a large system, voltage stability indicator (VSI) can be defined as a minimum value of the voltage stability load bus indices (index VSI_i is assumed to correspond to bus i):

$$VSI = \min_{i \in \alpha_{PQ}} \{VSI_i\}, \quad (0.1)$$

where α_{PQ} represents a set of the system load buses.

The proposed voltage stability indicator has been tested on modified New England 39 bus power system. The loads have been considered voltage dependent. The active and reactive load increase was simulated in all load buses. The increase in real power generation was proportional to the increase in the active system load. Initially, the reactive power generation has not been limited and the loads of all load nodes has been increased simultaneously. Later, 39-bus system with the same loading conditions was tested at limited reactive power production.

[1]PQ load	[2]I load	[3]Z load	k*	k**
100 %	0 %	0 %	2.213	1.634
75 %	0 %	25 %	2.450	1.7163
50 %	0 %	50 %	2.739	1.8022
25 %	25 %	50 %	2.9	1.8495
25 %	0 %	75 %	3.079	1.8920
10 %	0 %	90 %	3.295	1.9477
0 %	0 %	100 %	3.433	1.9856

[1] $A_1 = B_1$; [2] $A_2 = B_2$; [3] $A_3 = B_3$. * no Q limits ** Q limits taken into account

Table I. Critical system loadings for IEEE 39-bus system with respect to the different load types.

7. Conclusions

The expansion of the conventional protection system into a true wide area protection system should be done with full consideration of the added hardware and software complexity, and provision for the partially functioning system to operate (without communication, or with partial communication capability). In this paper, we have evolved the concept of the Voltage Instability Predictor (VIP) relay [17] to a higher level of complexity, by allowing for limited communication of measurement data (from generators to VIP devices), which allows VIP devices to estimate the PV-PQ transitions of the system generators and determine the critical load margins on the basis of that information. In such an arrangement, VIP relays effectively become software agents, which not only calculate the local load margins based on local voltage and current measurement, but also refine the validity of their calculation by acquiring the information on generator reactive margins. Furthermore, VIPs act as actuators of load identification, and incorporate that information in voltage instability algorithm to enhance the accuracy of protective and remedial actions.

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