Quantifying Proximity To Voltage Collapse Using The Voltage Instability Predictor (VIP)

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Abstract: In previous work concerning the Voltage Instability Predictor (VIP), the proximity to voltage collapse (or instability) was expressed in terms of distance between two voltage curves or between two impedance curves.

In this paper, a new measure, power margin, is introduced to describe the proximity to collapse in terms of power. The results of recent work on the effects of contingencies and system dynamics on the VIP are also presented, extending the prior work that assessed the effectiveness of the VIP under conditions of increased power transfers, using power flow simulations to examine voltage collapse conditions. These results show that the VIP algorithm successfully predicted voltage instability where conventional protection devices, using only voltage inputs, did not.

Keywords: voltage collapse, power margin, dynamic simulations, power system monitoring and control

I. INTRODUCTION

An escalating concern of the electric utilities is that increased power transfers and reduced transmission margins can lead to line overloads and voltage security problems. Many existing protection and control schemes are designed to cope with anticipated disturbances and can become ineffective when the system operating conditions are more severe than those considered in planning and design.

An important element of any protection and control scheme is to track, in real time, the proximity of the system to an insecure voltage condition. From the practical standpoint, selecting a detection method depends on what information is required. Many utility companies may not have an adequate information infrastructure (computing and communications facilities, system-wide measurements, etc.) to track voltage collapse, making it impractical to implement centralized schemes.

The Voltage Instability Predictor (VIP) is an algorithm that uses local measurements — station currents and voltages — to infer proximity to voltage collapse [1-3]. This algorithm can be implemented in microprocessor-based devices to form a line of defense at the local level and to provide information for coordinated control actions.

Since 1997, a research project has been conducted jointly by American Electric Power (AEP) and ABB. One major task of the project is to study the applicability of the VIP algorithm on the AEP network. This paper reviews the theory behind the VIP, the problems being faced by AEP and reports on the simulation results of the feasibility study on a realistic 7000 bus system. The numerical testing is part of the collaboration between AEP and ABB in the development of voltage security tools and techniques for AEP.

II. LOCAL DETECTION OF VOLTAGE INSTABILITY

A. Background and Motivation

Electric supply industry deregulation and utility competition transmission access are quickly becoming reality, with greatly increasing numbers of energy transactions. Parts of the existing bulk power transmission network are being loaded much differently from than planned or historically used. These changes will stress the transmission system to new levels with more economic significance.

Voltage instability is closely related to the notion of maximum loadability of a transmission network. To fully use existing transmission assets, transmission operator(s) track how close the transmission system is to its loadability limits. As line loading approaches loading limits, actions must be taken to relieve critical transmission paths. The main challenge is to determine the loadability of the transmission system, since this quantity is not fixed, but depends on network topology, generation and load patterns and the availability of reactive power resources. All of these factors can vary with time due to several factors, including changing transmission loading, scheduled maintenance, unexpected disturbances, and weather patterns.

Even though voltage instability is considered a "system" issue, a device that uses only local measurements could be used in mitigating the problem. Such a device would provide an attractive option for the power industry due to low cost and simplicity. This device may be used in two complementary roles:

1) it could be set to send an alarm or alarms to control center(s) when local measurements indicate a locally weak condition, and
2) as it encounters more severe conditions, it could be set to trip locally, with appropriate alarming.

Thus it could also form a fallback position or a safety net, e.g., acting if a centralized control/protection scheme fails for any reason, such as loss of communication channels

One control, that has been installed on the Pacific Northwest system [4], sheds load based on voltage level -- undervoltage load shedding. However, for many other systems, the difficulty of choosing setpoints (8 - 10% below normal voltage, etc.) poses a challenge. Some systems may ride through voltages much below the setpoint of the relay [5]. For other systems, the voltage can appear normal even though the grid is on the verge of instability. Thus voltage magnitude is often a poor indicator of instability, and a fixed setpoint may result in unnecessary action or failure to recognize an instability.

B. Foundation of the VIP Method

It is desirable for future devices to use not only voltage levels to detect voltage instability, but other locally available information as well. One such algorithm proposed is the VIP.

Figure 1 shows the concept of the VIP in a Thévenin equivalent system. No assumption has been made about the characteristic of the load.

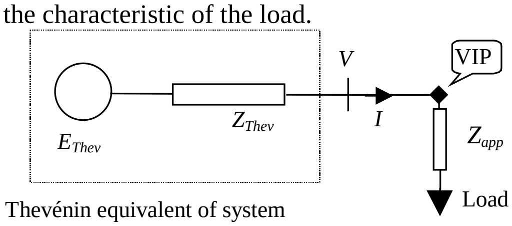

Figure 1: Local bus and system Thévenin equivalent.

From circuit theory, maximal power transfer occurs when $|\overline{Z}_{app}| = |\overline{Z}_{Thev}|$, where the apparent impedance $\overline{Z}_{app}$ is the ratio between the voltage ($\overline{V}$) and current ($\overline{I}$) phasors measured at the bus. When the loading is normal, the condition $|\overline{Z}_{app}| >> |\overline{Z}_{Thev}|$ holds. At the onset of voltage instability, the difference between the two impedances approaches zero. Tracking closeness to voltage instability, therefore, is done by tracking the distance between $|\overline{Z}_{app}|$ and $|\overline{Z}_{Thev}|$. This is the essence of the VIP.

One challenge in implementing the VIP concept is that $|\overline{Z}_{Thev}|$ is not a fixed quantity because it represents the rest of the system lumped together -- many different electrical entities, any of which can change status at any time. During impending voltage insecurity, $|\overline{Z}_{Thev}|$ grows (transmission becoming weaker) and/or $|\overline{Z}_{app}|$ diminishes (load becoming heavier).

In the simple case of Figure 1, the VIP based device is placed at a radial point in the network topology. This application is useful when there is a clear distinction between the "sink" and the "source", such as the upstream and downstream sides of a distribution station. However, typical transmission networks are highly meshed, making it difficult to locate a radial point. Consequently, work has been conducted to show the VIP to be applicable in non-radial cases; it can be placed on any line to determine if the flow has reached an insecure level [1].

C. Power Margin

When addressing voltage instability, a device using local measurements should sense the network strength and compare this against local loading to determine if any alarm or control actions should be taken. The VIP accomplishes this by tracking the distance between $|\overline{Z}_{app}|$ and $|\overline{Z}_{Thev}|$.

Since the proximity to voltage collapse (or instability) as expressed in terms of the distance between two voltage curves or the distance between two impedance curves can be somewhat non-intuitive, a more useful measure is therefore introduced. This new measure, power margin, describes the proximity to collapse in terms of power and can be looked upon as the power available to be pushed through the VIP location before the network collapses. To illustrate the concept of power margin, two practical contexts are given next.

In one context, the VIP is placed at a station feeding a radial load, such as the system represented in Figure 1. Here the user wants to know how much the station load may increase before the voltage collapses.

In another context, the VIP is placed on a line on a critical interface. The user would want to know how much power can be pushed through this line or across this interface before voltage insecurity becomes a concern.

Figures 2 and 3 elaborate on the concept of power margin. Figure 2 shows a scatter plot for *V* versus *I* (voltage magnitude vs. current magnitude), as loading changes on a portion of a system. The curve is typical for a multi-node system driven toward a collapse by a gradual increase of the loads: as the load increases, the voltage decreases.

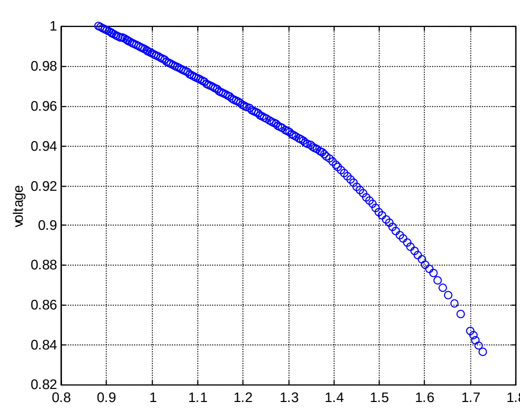

Figure 2: Scatter plot of *V* vs. *I*.

In terms of "impedance margins", the distance to collapse is the difference between the value of Z_{Thev} at the corresponding time instant and the ratio V/I. However, as described earlier, an "impedance margin" is a non-intuitive quantity, and it is better to address the distance in terms of "power margin".

To illustrate this, Figure 2 is repeated in Figure 3 with added points, lines, and shaded areas:

- the dotted curve represents the overall shape of the *V-I* scattered plot,
- the present point, labeled "*c*", lies on the dotted curve with "Area *abcd*" equal to the power (MVA) observed by the VIP now, and
- the straight line extrapolated from *c* through f represents the projected behavior of the (*V,I*) points with "Area *aefg*" the (forecasted) maximum power using a linear forecast.

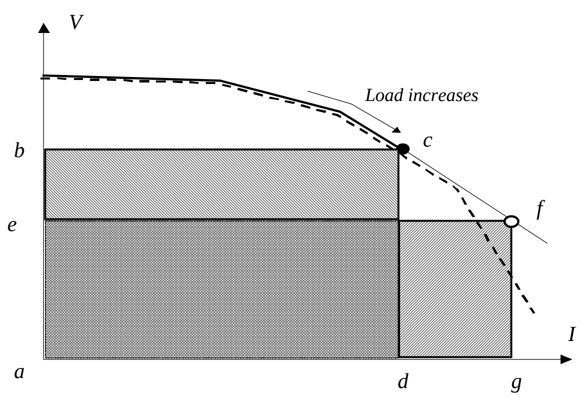

Figure 3: Representation of MVA margin.

The difference between the maximum power using the linear forecast and the current power observed by the VIP is the power margin and can be expressed as:

$$\Delta S = \frac{(V_t - Z_{Thev} I_t)^2}{4 Z_{Thev}}$$

where (V_t, I_t) is the current measurement set and Z_{Thev} is the current Thévenin impedance.

1) Power Margin Accuracy

The forecast margin is computed based on linear extrapolation of recorded data. The forecast is exact if the network equivalent stays unchanged and if no limiting devices act. In Figure 3, the "forecast" line coincides with the "true future" line (dotted) for some time after the present time. Thus for the near term, the forecast power "Area *aefg*" remains unchanged and is a good estimate. However, as soon as the "true future" curve makes a turn, a new forecast line must be built, and this would change the value of "Area *aefg*". The new value for "Area *aefg*" will be smaller than the old one. If there are no topology changes, this forecast is always optimistic.

2) Improving the forecast using history data

The linear forecast as described above is used when the VIP has no knowledge of potential line loading changes. However, if the loading beyond its present point has been encountered in the past, the VIP can produce more accurate margins. For example, the entire dotted line in Figure 3 could be available in the memory of a VIP device due to previously recorded data. Instead of using the linear forecast ("Area *aefg*"), the VIP could use the dotted curve as the forecast.

III. Overview of AEP Region

AEP, based in Columbus, Ohio, is a global energy company and one of the United States' largest investor-owned utilities, providing energy to 3 million customers in seven states, with 1999 revenues of $US 6.2 billion.

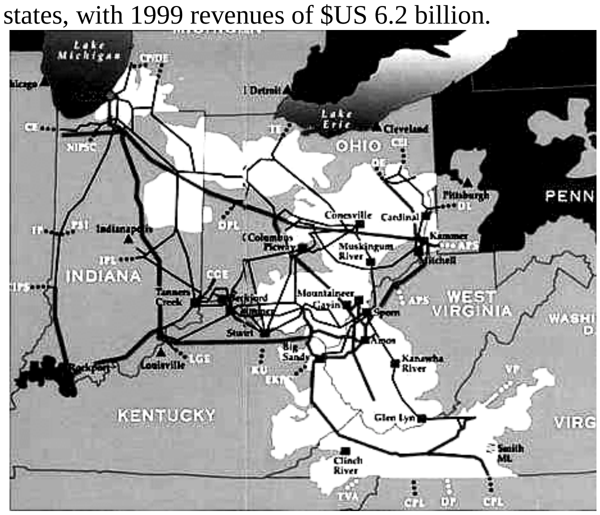

Figure 4: Map of AEP Service Area.

The AEP transmission system consists of 22,000 miles of high-voltage lines, including 2,022 miles of 765,000-volt lines. AEP operates the most interconnected transmission system in North America and has more than 140 interconnection points providing more than 60,000 megawatts of tie capacity to 29 utilities.

The AEP Southern Transmission Region (STR) serves customer demands in parts of West Virginia, Virginia, Tennessee, and Kentucky. The electricity requirement of customers in this area is more than three times the area's generation capacity. Consequently, the transmission facilities extending from the northern portion of AEP system into the STR are essential to meet the STR area customer requirements. AEP has found that, for certain credible contingencies on the transmission system in Virginia and West Virginia, there will be unacceptable consequences characterized by severe low voltages, excessively high power and Mvar flows, and likely splitup within the US-Canada Interconnection (EI). These concerns have been described in a report from the US Secretary of Energy to President Clinton, and have been reviewed by the three affected regions of the EI (MAAC, SERC, and ECAR) [6]. AEP is working with the states of

Virginia and West Virginia to construct additional transmission facilities to minimize the effects of the expected growing electric consumption in AEP's Southern Transmission Region. AEP is also considering a number of remedial/mitigating measures, including planned shedding of firm customer load in that region. AEP is considering the VIP device as a part of its work to address the issues of maximizing its transmission capability and minimizing the risk of uncontrolled wide-spread cascading failure due to voltage collapse phenomena. This work supplements AEP's immediate conventional work in the Southern Transmission Region to: a] improve the voltage support capabilities of power plants; b] improve system operating controls, including remote switching of transmission voltage control equipment, and c] install an automatic load shedding process as a last resort to minimize the impact of the voltage collapse. AEP is seeking ways to provide a more reliable estimate of the proximity to voltage collapse in the transmission system. The goal is to attain a modern, real-time protection and control system that helps the company's transmission grid to reliably meet customer demand. AEP sees the VIP device and its concept as an effective arena for this investigation and likely deployment.

IV. CASE STUDIES

To address the issue of voltage collapse, ABB and AEP are working in a joint research project to develop tools and techniques for reliable prediction of proximity to voltage collapse and for operation of the system to avoid or mitigate the collapse. The VIP concept has been tested on a 2001/02 winter peak 7000 bus power flow case used by AEP in planning studies. This section presents results of initial work on the effects of contingencies and system dynamics on the VIP, and initial results of tests using field-recorded data.

A. Dynamics Simulations

Previous work [1-3] assessed the effectiveness of the VIP under conditions of increased power transfers, using power flow simulations to examine voltage collapse conditions. The present work extends that by adding the effects of system dynamics including generator excitation systems and voltage and frequency dependent loads.

Voltage collapse was simulated on the AEP system with multiple contingencies including loss of generation and loss of critical transmission lines over a period of time [6,7]. The system was initially simulated in steady state conditions for 0.5 seconds before the first contingency (simultaneous line outages). The next contingency (loss of generation) was applied at 12 seconds with sequential contingencies (line outages) occurring every 10 seconds afterward (22 sec., 32 sec., etc.) until the system splits up at t = 52 seconds.

During these simulations, VIP devices were placed at selected load buses and on selected lines, each processing local measurements (bus voltage and line current). As can be seen in Figure 5, a VIP device located at the Baker station predicts that the system becomes unstable at approximately t = 25 seconds when the power margin becomes zero.

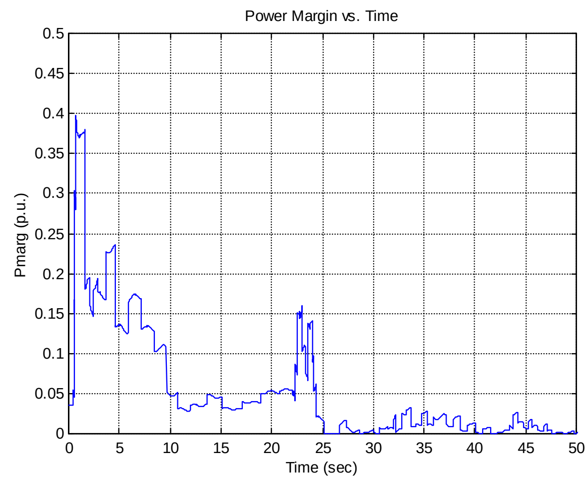

Figure 5: Power Margin at the Baker station – simulation study

Comparing Figure 5 with the voltage profile at the Baker station in Figure 6, one can see that voltage is not a good indicator of system instability. As discussed above, the system fails much later (t=52 sec.) when it splits up.

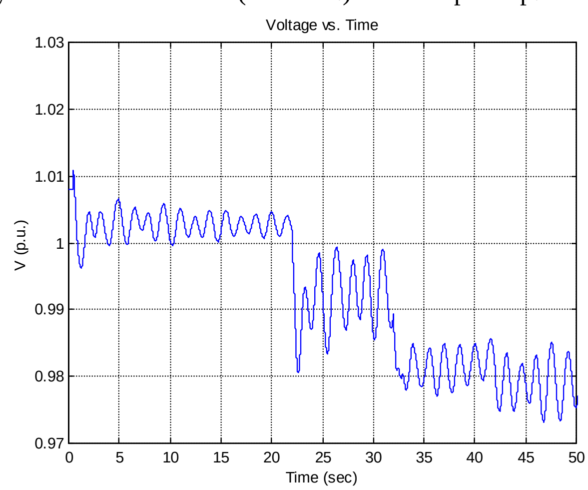

Figure 6: Voltage Profile at 765 kV Baker station – simulation study

B. Recorded Data

The next stage of development is to perform field-testing. Consequently, further testing of the VIP algorithm were made using data from AEP dynamics recording devices. This work should validate the robustness of the algorithm given the noisy signals found in transmission stations. This work is underway, with some initial results shown in Figure 7 and Figure 8. These figures provide results of the VIP algorithm using data from a station in AEP's Southern Transmission Region.

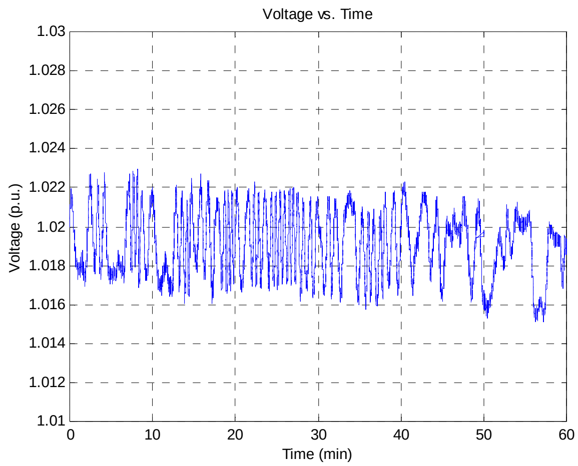

Figure 7: Voltage Profile recorded at the Jackson's Ferry station.

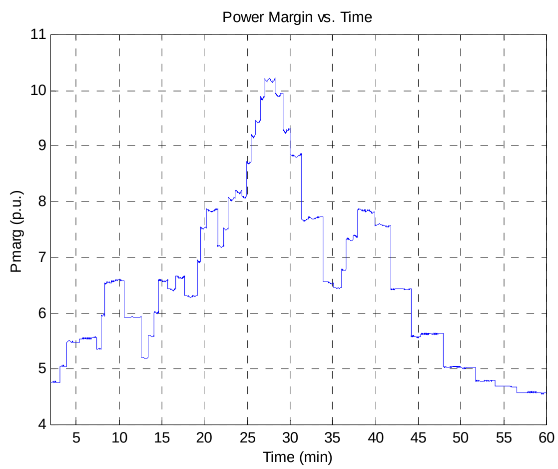

Figure 8: Power margin recorded at the Jackson's Ferry station.

V. CONCLUSIONS

This paper presents a new method to calculate the proximity to voltage collapse using the VIP algorithm, with results from studies applying the new method to the 2001/02 winter peak AEP system and field-recorded data. These simulations show that the VIP algorithm successfully predicted voltage instability where conventional protection devices, using only voltage inputs, did not.

VIP based devices can serve as an essential group of monitoring devices, continuously reporting to a control center. At first, standalone VIP devices can be installed to sense local conditions, send alarms, and record its performance under field conditions. After field experience validates the concept, they can be installed to work automatically, issuing alarms and/or control actions to a local actuator. When the VIP device acts, it will report to the control center to inform the operator an activity has taken place. The communications requirements for this form of reporting (binary output corresponding to status changes) are modest. In each of these local modes, this device can act autonomously, implicitly coordinated with other device, as underfrequency load shedding relays do.

In the longer term, as a more sophisticated communication system becomes available, the VIP devices will report the proximity of voltage collapse to control center(s) where that information, with other device information, will be used to implement coordinated action schemes.

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VII. BIOGRAPHIES

Navin Bhatt (SM '82) earned his MSEE and Ph.D. degrees from West Virginia University, Morgantown, WV, and joined AEP in 1977. At AEP, he has been involved in analytical studies in the area of power system dynamics, including voltage security, generator controls, stability and system restoration. He has written several IEEE and other technical papers. Presently, he is the Manager - System Dynamics Analysis, responsible for organizing and directing the activities related to transmission system performance analysis for short- and long-term planning horizons, in order to ensure dynamic security of the AEP power system. He is a member of the Eta Kappa Nu and Sigma Xi honor societies, a Senior Member of IEEE, a member of the IEEE Power Engineering Society, and a Registered Professional Engineer in the State of Ohio.

Danny Julian (S '88, M '92, SM '99) received his BSEE and MSEE degrees from Clemson University in 1991 and 1992 respectively. After working for GE Harris Energy Control Systems, he joined ABB at the ELECTRIC SYSTEMS TECHNOLOGY INSTITUTE in 1997. He is a registered Professional Engineer in the States of Florida and North Carolina with areas of interest including computer applications in power systems, power system planning, operations and control and economics and optimization of power systems. He is also a member of the Eta Kappa Nu and Phi Eta Sigma honor societies, a Senior Member of IEEE and a member of CIGRE.

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William Quaintance (S '87, M '92) received his BSEE from North Carolina State University and MSEE degree from Clemson University in

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Richard P. Schulz (F '90) earned BS degrees in Mechanical and Electrical Engineering from Lehigh University and an MS Engineering degree from Union College in 1966. He joined General Electric in 1959, and worked for 25 years in electric utility application engineering in Schenectady, NY. In 1987, Mr. Schulz joined the System Planning Dept. of American Electric Power as a Staff Engineer. Mr. Schulz's work is centered in the areas of power system dynamics and monitoring for planning and event reconstruction. He has authored or co-authored over 40 papers, is active in committee work of CIGRE and the IEEE Power Engineering Society, and is licensed as a Professional Engineer in New York and Ohio.

Khoi Vu (M '91) received BSEE, MSEE and Ph.D. degrees from the University of Washington. He was a visiting faculty at Clemson University during 1991-93, and is now with the ABB Corporate Research AS in Oslo, Norway. His areas of interest in power systems include stability, computer-based protection and control, and power quality.