Real-Time Voltage Control
Under Stressed Conditions

See It Fast to Keep Calm

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AS THE ELECTRICAL UTILITY INDUSTRY ADDRESSES ENERGY AND environmental needs through greater use of renewable energy, storage, and other technologies, power systems are becoming more complex and stressed. Increased dynamic changes that require improvements in real-time monitoring, protection, and control increase the complexity of managing modern grids. In an effort to ensure the secure operation of power systems, more attention is being given to voltage management. Voltage management includes addressing voltage stability and fault-induced delayed voltage recovery (FIDVR) phenomena. Deployment of phasor measurement unit (PMU) technology, in combination with recently developed methodologies for tracking voltage behavior, has resulted in improved real-time voltage monitoring, protection, and control.

This article describes simple and accurate methodologies based on real-time measurement—and independent of the system model—designed for tracking both slow-developing and transient voltage stability conditions under various and changing system configurations. Tests with real-time supervisory control and data acquisition (SCADA) and PMU data, as well as data from comprehensive simulation studies, from the Bonneville Power Administration (BPA) and Southern California Edison (SCE) systems show very accurate detection as the system is approaching voltage instability. The calculated reactive power margin and other indices are easily visualized for operator awareness. For quickly developing disturbances, they allow the initiation of fast control and protection actions. This methodology also discriminates well between FIDVR and short-term

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voltage instability. Finally, a tool for properly modeling the complex voltage phenomena is described.

Quantifying Power System Stress

A power system is under stress whenever it is operated close to its limits. The level of system stress is inversely proportional to the level of system security. Operating the system in stressed conditions increases the probability of a chain of severe contingencies. The stressed conditions are not considered in traditional system security assessment, as confirmed by the number of large system blackouts over the past 20 years (see Table 1). To allow system operation at stressed levels and have the ability to react adequately to the consequences of these conditions, there is a need to quantify the level of system stress. This measure should reflect the impact of key factors influencing the system stress level. In addition, this measure should be intuitive, practical, and easy to visualize so that system operators can interpret it easily and respond quickly by initiating control and protection actions based on practical margins and thresholds. An appropriately chosen voltage stability index or indicator can serve the purpose of quantifying the level of system voltage stress (or system voltage security, as its inverse). As proximity to voltage instability is detected, appropriate control actions are required to prevent system degradation or contingency propagation. Many conventional control actions are not designed for quickly developing contingencies and may be too slow. Likewise, conventional methodologies and study tools may not be sufficient or fast enough to accurately initiate the type of reactive control currently deployed or may require accurate system models to be effective. There is a need to complement existing energy management systems and tools with the real-time approach described in this article for better system voltage management.

Voltage-Related Phenomena

Power system voltage problems with major impacts on the power system manifest themselves in two forms:

1) voltage instability
2) FIDVR.

Figure 1 illustrates these two phenomena.

Voltage Instability

Voltage stability is closely related to the notion of the maximum deliverable power that can be drawn by the system loads while preserving stable operation of the combined generation-transmission system. Voltage instability occurs when the combined generation-transmission system is unable to provide the power requested by the loads; this may be due to system outages and/or limitations in reactive power generation. Once it happens, it can evolve into further voltage collapse and cause system disruption. Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant portion of the power system. The form the voltage instability takes is influenced by the composition of the system load. A fast (short-term) instability—one that occurs within just a few seconds—can develop in situations when motor loads make up a large proportion of the local load, as illustrated in Figure 1.

Voltage instability, resulting in voltage collapse, has been reported as either a principal cause or an important part of the problem in many partial or complete system blackouts. Various examples have been documented. Table 1 lists some of these incidents, together with time frames, total load interruptions, and some of the societal and economic consequences.

FIDVR

A slightly modified definition of FIDVR, derived from the NERC Transmission Issues Subcommittee (TIS), is that FIDVR is a voltage condition initiated by a transmission, subtransmission, or distribution fault and characterized by the stalling of induction motors, initial voltage recovery after the clearing of the fault to less than 90% of precontingency voltage, and a slow voltage recovery lasting more than 2 s to expected postcontingency steady-state voltage levels.

table 1. Some documented voltage collapse incidents, 1995–2009.				
Date	**Location**	**Time Frame**	**Interrupted Load**	**Remarks**
11 November 2009	Brazil and Paraguay	68 s (after initial event)	24,731 MW	Voltage collapse in part of the system Number of people affected: 87 million
12 July 2004	Southern Greece	30 min	~9,000 MW	Number of people affected: ~5 million
23 September 2003	Southern Sweden and eastern Denmark	7 min	6,550 MW	Estimated cost: US$75 million (Sweden) Number of people affected: 4 million
14 August 2003	United States and Canada	39 min	63,000 MW	Estimated cost: US$7–10 billion Number of people affected: 50 million
May 1997	Chile	30 min	2,000 MW	—
10 August 1996	Western United States (WECC)	6 min	30,500 MW	Number of people affected: 7.5 million
8 June 1995	Israel	19 min	~3,140 MW	—

FIDVR is caused by constant-torque induction motor loads (mostly the single-phase motors in residential air conditioners) that stall in response to low voltages. The stalled motors draw excessive reactive power from the grid. This situation can further aggravate system conditions and cause a cascading system failure. A severe event can result in fast voltage collapse.

A typical FIDVR following a transmission network fault in the SCE system, as experienced at a 500-kV/115-kV substation, is illustrated in Figure 1(b). This figure indicates that immediately after the fault, voltage decreased to 78% of nominal voltage. The fault-induced low voltage caused air-conditioning units to stall; the stalled air-conditioning units kept the voltage from recovering to a nominal level. When the air-conditioning units' thermal overload protection switches tripped, the voltage recovered but overshot the nominal voltage (by 8.5% in the particular case shown in the figure). The high voltage is a result of the fact that the capacitor banks placed in service before or during the low voltage remained in service after large amounts of air conditioner load trips. This overvoltage caused another problem: the capacitor banks tripped off (at around $t = 172$ s). With the capacitors tripped off and the load returning, the voltage went up to a little above nominal voltage in this particular case.

Other important observations about FIDVR are:
✔ The deeper the initial voltage sag, the greater the increase in the reactive demand of motor loads.
✔ Voltage recovery is affected by the ability of the system to supply reactive power to the area of depressed voltage.

Table 2 lists some FIDVR incidents documented in the literature.

Tens of FIDVR cases were reported but not documented in available literature. SCE experienced a number of FIDVR cases: one event in 1990, four in 2004, three in 2005, 37 in 2006, and six in 2007. This number was so high in 2006
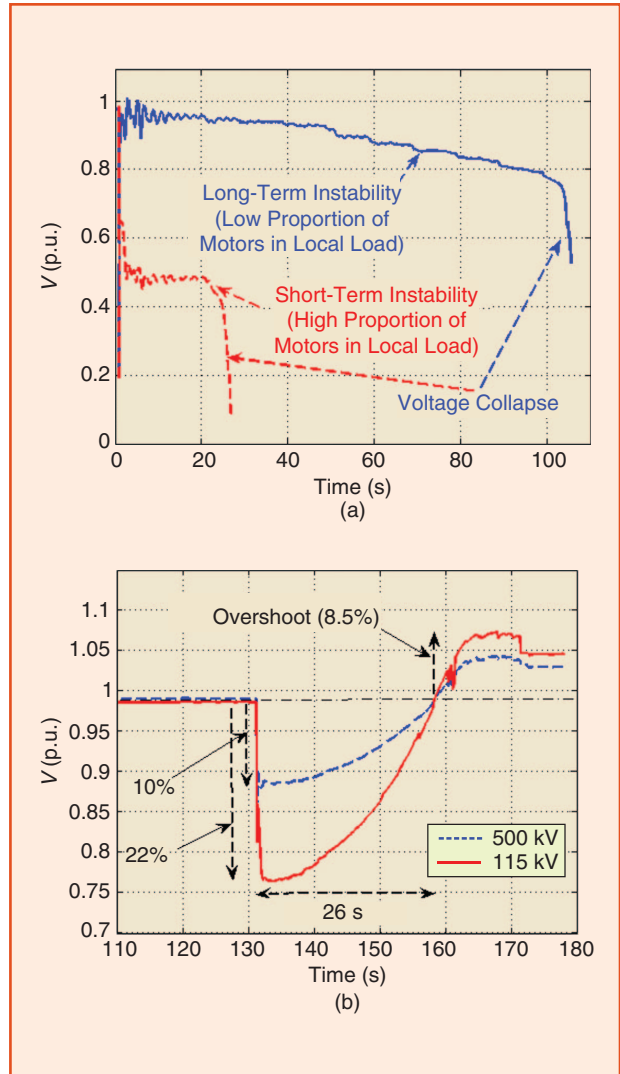

figure 1. (a) Voltage instability at a bus of the test system and (b) FIDVR at a 500-kV/115-kV SCE station.

| table 2. Notable FIDVR cases.				
Date	Utility/Location	Time Frame of Recovery	Interrupted Load	Remarks
28 July 2003	Arizona Public Service/Phoenix	Several seconds	440 MW	Generation loss: 2,600 MW Number of customers affected: 90,000
1 July 2003	Arizona Public Service/Phoenix	9 s	1,000 MW	Number of customers affected: 48,000
30 July 1999	Southern Balancing Authority/ Atlanta, Georgia	15 s	1,900 MW	Generation loss: 1,165 MW
5 August 1997	Southern California Edison/ Hesperia	20–25 s	3,500 MW	Lugo plane crash accident
29 July 1995	Arizona Public Service/Phoenix	20 s	2,100 MW	—
3 May 1994	Florida Power and Light Company/Dade County	8 s	450 MW	—
18 August 1988	Florida Power and Light Company/Miami	10 s	825 MW	—
22 August 1987	Tennessee Valley Authority/ Memphis	10–15 s	1,265 MW	—
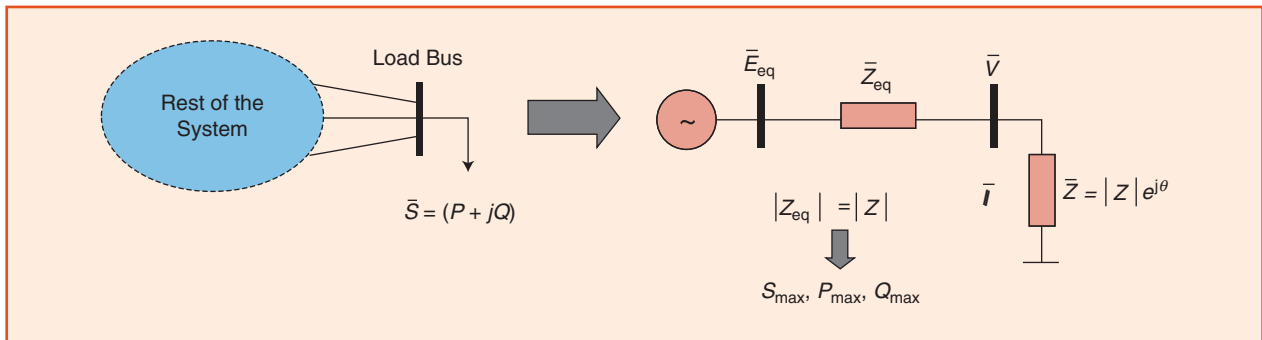
figure 2. Two-bus equivalent circuit.

due to hot and humid weather conditions, causing both an increase in high air-conditioning load and a large number of faults initiated by thunderstorms and lighting strikes. After a fault, a large number of air-conditioners would stall, causing a major voltage drop.

Voltage Stability Assessment

To avoid catastrophic outages and the huge economical and social costs caused by voltage instability and FIDVR, appropriate control and protection actions to mitigate these conditions are required. A voltage-related problem in the power system should be solved with control actions implemented through system operation, corrective controls, and/or emergency protection systems. Such solutions require accurate and fast voltage stability assessment.

Advanced voltage stability monitoring and instability detection schemes include two basic elements: collection of measurement data from PMUs or SCADA and preprocessing and computation of the proximity to voltage instability. The following section focuses on advanced voltage stability indices derived from the concept of a voltage instability predictor (VIP). The VIP method described here represents the enhancement of a concept first developed in the late 1990s. This new methodology results in major improvements in accuracy, numerical stability, implementation variants, and ease of use. This methodology has the following benefits:

✔ It offers simple, real-time voltage instability margin detection that is model-free.
✔ It works better than voltage-only methods but is simpler than any other alternative.
✔ It is much faster than EMS contingency analysis.
✔ It is easy to interpret and combine with other methods and indices.
✔ It enables the tracking of both slow changes and system dynamics using PMUs (e.g., 10–120 frames per second) or other measurements.

The New Methodology and Its Variants

The general VIP methodology is based on a representation of the power system as a two-bus equivalent circuit, as illustrated in Figure 2. The maximum deliverable power for such a system under a given load power factor is reached when the absolute values of the Thevenin and load impedance are equal, i.e., when $|z|=|z_{eq}|$.

The Thevenin and load impedance values are not constant; they vary, reflecting changes in power system operating conditions. It is critical to identify and follow these changes as they occur. This simple representation of the system parameters and their recursive estimation at the rate that the phasor data are measured enable a model-free approach in calculation of the stability margins in real time. Equivalent parameter identification at a high rate transforms the linear system of Figure 2 into a linear parameter-varying system, thus more adequately accounting for the nonlinearity present in real systems. The condition that the absolute values of the Thevenin and load impedance are equal can easily be used to estimate maximum deliverable power.

The VIP method has been extended for different system configurations, such as transmission corridors and load centers using measurements at both ends of the corridors or load center in-feeds. These extensions include better tracking of equivalent parameters, improved use of the measurements available for transmission corridors and load centers, computation of intuitive power margins, and simple visualization of system stability conditions.

The most interesting extensions for control center operators are power margins (measured in MVA, MW, and MVAR). A simple representation of these margins is the P-Q plane, shown in Figure 3. Two sets of margins are presented: *loading margins*, inherent to the concept of VIP, where the reactive loading margin, $\Delta Q_{loading}$, is of most interest. The active power loading margin is denoted as $\Delta P_{loading}$. Another set of reactive power margins, *Q-margin*, represented as ΔQ, is shown in Figure 3. It is related to the known concept of QV-analysis, but in this case it is computed and tracked in real time. The Q-margin is particularly suitable for FIDVR cases, since it provides the amount of reactive power that can be pulled out of the bus, corridor, line, cut-set, and so on. This is exactly what happens in FIDVR cases, when motors are pulling reactive power due to the drop in voltage.

One of the most notable of the extensions to the VIP method is calculation of the reactive power margin in real time (computed as the amount of reactive power that can be

increased from the current operating point before reaching the voltage stability boundary). This compares favorably with the traditional Q-V analysis method used by many power utilities (an off-line and time-consuming method). Another reason to use the VIP method comes from FIDVR and concerns the fact that the motors are pulling reactive power from the system. The voltage stability boundary shown in Figure 3 is assumed to be quadratic and is easily derived from known maximum deliverable apparent power. Both the voltage stability boundary and the operating point are recomputed and refreshed once a new measurement set is available, allowing for easy visualization and tracking of voltage stability conditions. The method is of course capable of computing and visualizing loading power margins, thus offering greater flexibility in stability monitoring and detecting conditions of instability.

Further improvements to the classic VIP approach, in which power margins are monitored at individual system load buses, are being implemented for transmission corridors and load centers (see Figure 4).

Real-Time Voltage Control

To maintain an acceptable voltage profile across the network, power systems are equipped with control devices acting as continuous-feedback controls of substation voltages. These control devices are automatic voltage regulators (AVRs) that vary the excitation of rotating generators. Although such devices are not designed to deal with the large contingencies likely to take place in stressed conditions, they still provide useful support in these conditions. This is particularly true for AVRs that regulate high-side voltages of generator step-up transformers through compensation of their leakage reactance. The compensation AVR is more effective than other types because it regulates voltages closer to the loads.

In order to deal with large contingencies, additional discontinuous corrective controls are needed. These discontinuous controls are initiated based on a predetermined
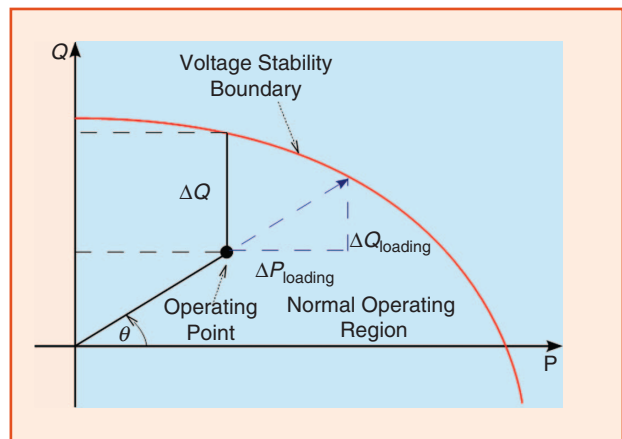

figure 3. Voltage stability power margins in P-Q plane: loading ($\Delta Q_{loading}$) and Q-margin (ΔQ).

threshold of the system stress indicator. Figure 5 shows a real-time, measurement-based voltage control scheme. An important part of this control scheme is the measurement system's ability to capture key system variables at fast rates. A well-designed real-time voltage control scheme should be able to detect the onset of the problem rather than relying on observation of its consequences (e.g., by monitoring voltage magnitudes). The chosen indicator should provide the thresholds for initiation of discontinuous control action. Such an approach should be better than voltage magnitude monitoring (which may be inaccurate when detecting proximity to voltage instability) and as simple as possible for easy interpretation and understanding. Indicators with physical meaning, like the ones derived from the VIP method, provide both the required accuracy and simplicity.

Corrective voltage control in real time aims at saving the system after an unexpected contingency actually occurs and a voltage-related problem is detected. In principle, corrective voltage controls, in case of voltage instability, are used to push the system to a new equilibrium by increasing the
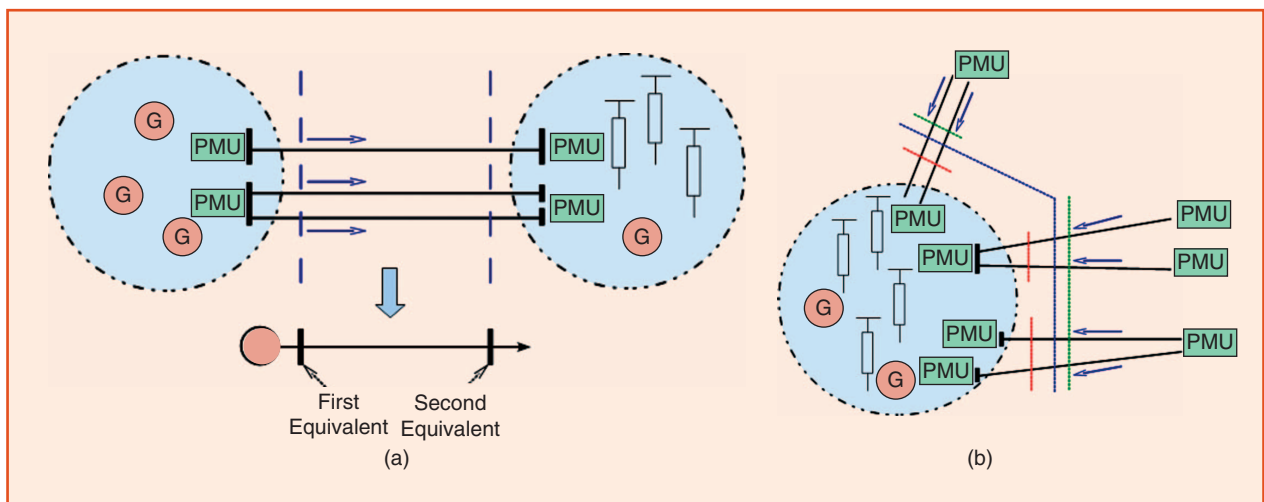

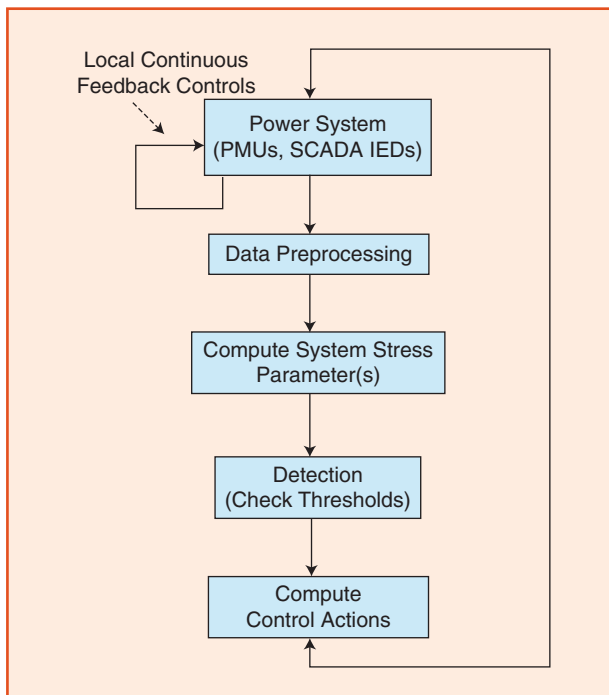**figure 4.** (a) Corridor and (b) load center concepts.

figure 5. A real-time voltage control scheme.

maximum deliverable power or reducing the load consumption. This approach is efficient for both short-term and long-term instability. Another approach, efficient for long-term instability, is to stop the load restoration mechanism.

In the case of FIDVR, transmission network–level solutions are:

✔ guiding the system to a new operating point with acceptable voltage magnitudes (voltages within the normal operating range), which can be achieved by increasing the maximum deliverable power or by shedding load

✔ limiting the impact of the fault, which is usually achieved by quicker clearing of the faults and sectionalizing a tightly coupled transmission system.
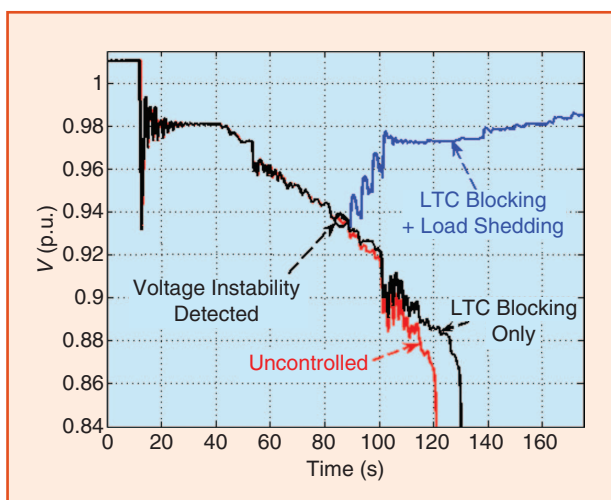

figure 6. Effects of some emergency voltage control actions.

Corrective real-time voltage controls can be divided into two major categories:

✔ The first category includes controls that are event-based, using control actions assessed off-line through simulations of postulated scenarios. This type of control is initiated upon recognition of specific system conditions (events) and does not readjust its actions in response to the system's evolution.

✔ The second category includes controls that are response-based, assessing the severity of the disturbance through measurements and adjusting their actions correspondingly. These controls do respond to the system's evolution, and they repeat some actions if the actions taken previously are not sufficient to resolve the problem. This approach makes the control scheme more robust.

Emergency control is a special type of corrective control designed to deal with extremely stressed system conditions. This control can be both event-based and response-based.

Various control devices and actions can be used to achieve the control objectives described above. The effectiveness of a number of different control devices and actions in voltage-related problems is summarized in Table 3.

Usually, LTC controls are not able to save the system but do postpone system collapse, providing extra time so that other controls can stabilize the system, as illustrated in Figure 6. A real advantage of LTC controls is that when they are combined with other control types, such as load shedding, they usually help decrease the amount of the other controls necessary to achieve a satisfactory result, as shown in Figure 6.

Load shedding is an effective measure for voltage-related issues. Load-shedding schemes can be implemented based on local data (typically one or several bus voltages, in some designs complemented by other signals) and/or on wide-area measurements. Figure 6 also illustrates the effectiveness of load shedding in stabilizing the system upon detection of developing long-term voltage instability. Voltage source converter devices such as STATCOM (especially the D-var type) and D-SMES are very efficient in controlling voltages during periods of short-term instability. Standard versions of these devices connected to distribution networks are more cost effective than larger devices connected to transmission networks. The effectiveness of large shunt capacitor banks can be improved by selecting and using only the groups of capacitor banks required. Additional short-term capacity offers benefits and should be exploited in the case of short-term instability. Renewable energy resources, if capable of producing both active and reactive power with the help of a power electronics interface, can provide cost-effective local voltage support to boost the local bus voltage during FIDVR.

Voltage Control Implemented in a System Integrity Protection Scheme (SIPS)

A robust corrective emergency control against voltage instability and FIDVR requires a combination of the controls

table 3. Effectiveness of control devices and actions.					
	Voltage-Related Problem				
Control Device or Action	**Long-Term Voltage Instability**	**Short-Term Voltage Instability**	**FIDVR**	**Additional Short-Term Capacity**	**Remarks**
Load tap changer (LTC) blocking, reversing, locking, and voltage set point reduction	*				Voltage set point reduction most efficient among tap controls; slow response
Emergency control of generator voltages	*			Yes	Efficient when an AVR with line drop compensation is used; fast response
Synchronous condenser	*	*	*	Yes	Very efficient for long-term instability and FIDVR; expensive (capital costs are US$30–35/kVAR, high operating costs); adjustable-speed active power control efficient for short-term instability; fast response
Supervar (a type of synchronous condenser)	*	*	*	Yes	High-temperature superconducting wire (rotor); lower operating costs than for standard synchronous condenser; fast response
Switched shunt capacitors	*	*	*	Yes	Generally slow response; fast response (0.15–0.75 s) in case of short-term instability needed; relatively cheap (capital costs are US$8–10/kVAR, low operating costs)
Static var compensator (SVC)	*	*	*	Yes (very short for high-voltage SVC)	Expensive (capital costs are US$30–50/kVAR, moderate operating costs); fast response
Static compensator (STATCOM)	*	*	*		Expensive (capital costs are US$50–55/kVAR, moderate operating costs); fast response
Dynamic var (D-var)	*	*	*	Yes	A type of STATCOM; scalable and mobile; fast response
HVdc modulation		*			Control of reactive power consumption in the converter transformers; fast response
Fast fault clearing		*	*		Fault clearing of eight cycles (0.13 s) or less
Load shedding (direct or through undervoltage)	*	*	*		Fast response (1.5 s) in case of short-term instability needed; direct load shedding based on an indicator other than voltage
Direct load control	*		*		Thermostatically controlled loads particularly attractive; load relief to start faster controls
Emergency demand response scheme	*		*		Accurate assessment of load available for shedding difficult
Transmission system sectionalizing	*		*		Limits load affected
Energy storage: superconducting magnetic energy storage (SMES) and distributed SMES (D-SMES)	*	*	*	Yes (D-SMES)	D-SMES offers cost-effective solution; fast response
Renewable sources	*		*		High operating costs; local support provided; fast response
Plug-in hybrid electric vehicles (PHEVs)	*		*		Inherent energy storage potential; potential to participate in emergency demand response (when in vehicle-to-grid, or V2G, mode)

given in Table 3 with coordination and adaptation of individual devices. The trend in corrective emergency control is toward integration of voltage control in a SIPS. The idea of a SIPS is to use measured local and system-wide information at a processing location to initiate actions counteracting the propagation of major disturbances in the power system. A distinguishing feature of the SIPS approach is that it serves the overall power system (or a strategic part of it) in order to preserve system stability, maintain overall system connectivity, and/or avoid serious equipment damage during major events. A SIPS may require multiple detection and actuation devices and communication facilities.

Voltage instability and FIDVR corrective controls within a SIPS should be focused on the design of response-based controls, acting in a closed loop and based on algorithmic decisions. These controls should also strike a balance between control actions taken locally and those taken centrally.

Figure 7 illustrates a hierarchical wide-area protection architecture for emergency voltage instability and FIDVR control integrated in a SIPS. For example, a local SIPS could collect voltage measurements at key buses and take actions on loads, shunt capacitors, and SVCs based on predefined rules and settings (usually, voltage thresholds). A system-wide SIPS collects the measurements from all measured buses in the system and detects approaching instability based on this wide-system view. Once developing instability is detected, the system-wide SIPS extracts all the information at the critical point and sends new parameter settings to the local SIPS, making overall protection adaptive with respect to the system state and contingency. The local SIPS keeps predetermined thresholds as backup in case of a communication failure from the system-wide SIPS.

Test Results

The key to any of the operational, control, and protection measures described above lies in assessing voltage stability margins using methodologies such as the improved VIP. These methodologies require comprehensive testing under complex system configurations and conditions before being deployed. The new VIP methodology has been comprehensively tested using real-world PMU and SCADA measurements and off-line system simulations in the BPA and SCE systems and under various conditions (local load, transmission corridor, load center). Such tests have included recordings of past system events and the output of time sequence power flow (TSPF) for dynamic off-line system simulations. An improved TSPF tool was developed as an add on to a conventional positive sequence load flow (as described later in the article). Although improvements could be made to any positive sequence load flow tool, GE PSLF software was used for the following tests. Results showed that the methodology works correctly for all test cases:

✔ It has the ability to detect instability even if voltage close to nominal.
✔ Results are comparable with those from detailed, model-based, off-line QV analysis and are very accurate close to the instability boundary.
✔ There were no false alarms.

Results also showed that the methodology discriminates between FIDVR and short-term voltage instability. FIDVR cases (without voltage collapse) are accurately detected
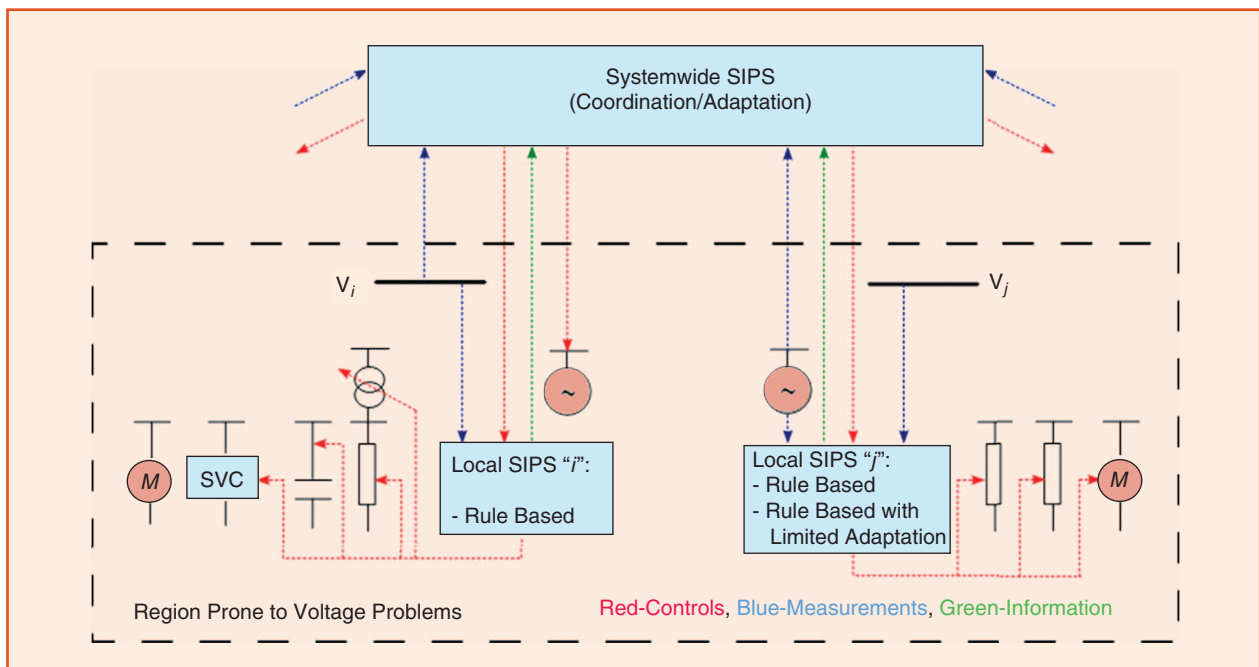

figure 7. A hierarchical SIPS for voltage-related problems.

despite the fact that the voltage is low for some time. The test results are described in more detail below.

Figure 8(a) displays a load center configuration in the BPA system and the results of voltage instability detection using a version of the VIP method. The event is shown in Figure 8(b) in terms of voltage magnitude at the bus in load center; in Figure 8(c), the time evolution of Q-margin is compared with the results of the BPA Q-V analysis tool; and Figure 8(d) provides a simple visualization of the VIP results in the P-Q plane. From Figure 8(c) it can be seen that Q-margin results, as compared with Q-V analysis, are very accurate when the system is close to the voltage stability boundary. Away from the boundary, differences with respect to Q-V analysis results were observed.

The results given in Figure 8 were obtained using outputs of simulations performed using time sequence power flows and correspond to a scenario with linear load increase in the load center and a line tripping in a generation-dominant area. These disturbances trigger the switching of several shunt capacitors in both the generation area and load center. Computed Q-margin illustrates that all switching is accounted for, as well as important system events such as line tripping. The same holds true for other VIP-derived quantities (equivalent load and system impedances and their ratio). A contraction of the voltage stability boundary can be observed after the line tripping, as illustrated in Figure 8(d).

VIP Performance for FIDVR and Short-Term Voltage Instability

The simplicity of the VIP method and its reliance on basic circuit equations motivated an assessment of its capabilities in FIDVR and short-term voltage instability cases. This assessment was further motivated by the fact that voltage recovery is affected by the ability of the system to supply reactive power to the area with depressed voltages. This suggests that the ratio of the system strength to local load can give a good indication of FIDVR, and this is exactly the essence of the VIP method. Its capabilities have been assessed on the BPA and SCE systems in different situations, using PMU recordings of past system events
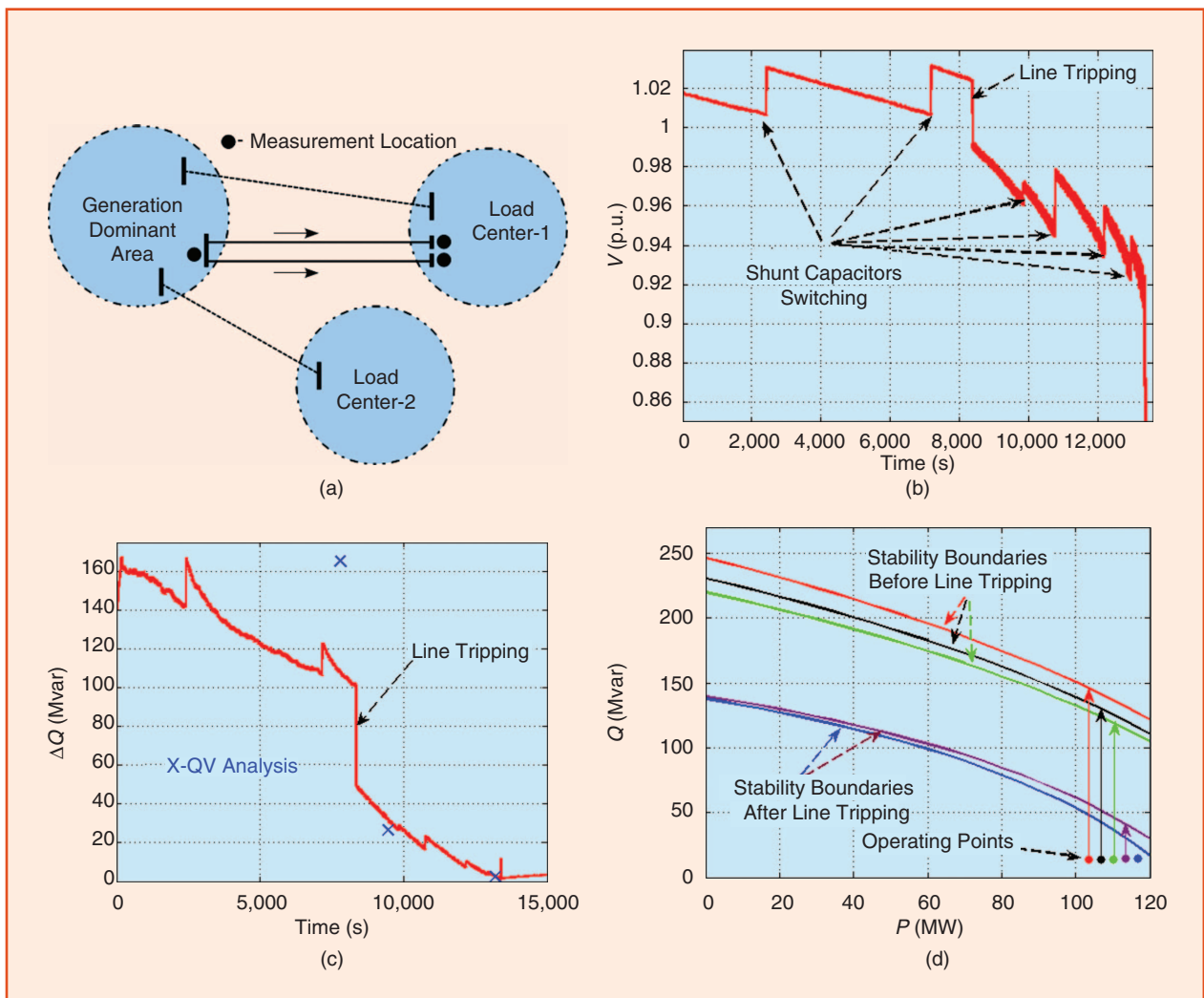

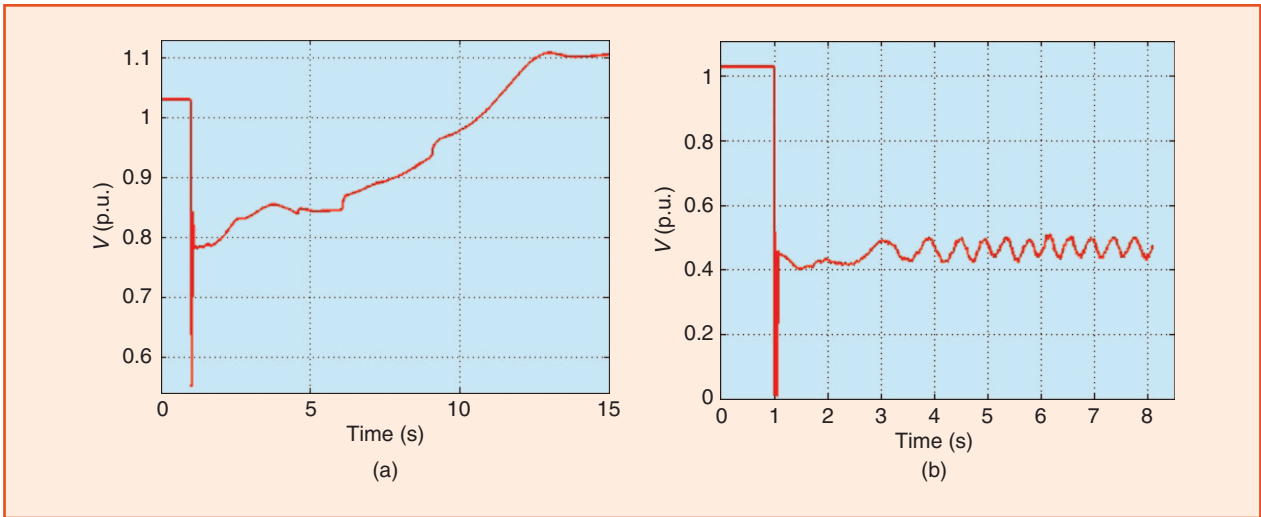**figure 8.** VIP results for a BPA system load center.

figure 9. An FIDVR event and a short-term instability after transmission faults at a 230-kV BPA station.

as well as the output of dynamic simulations performed in a PSLF tool. Figure 9 displays voltage magnitudes in a 230-kV station belonging to the BPA system for two different simulated transmission system faults (one resulting in FIDVR and another in short-term voltage instability). The faults have been simulated in the PSLF tool; relevant variables were recorded every 0.033 s to mimic a realistic PMU rate.
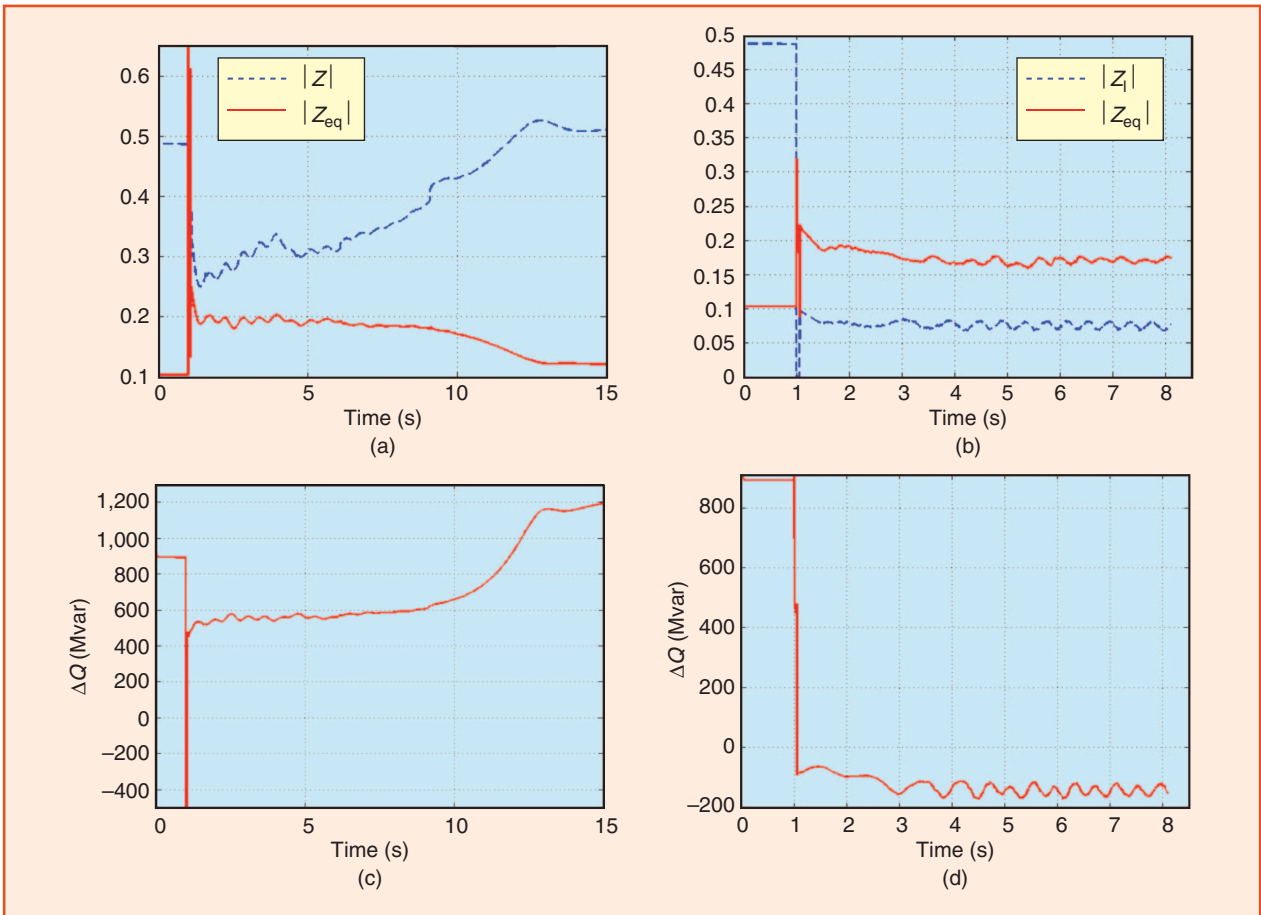

figure 10. Load and equivalent impedances and Q-margins following transmission network faults at a 230-kV BPA station. (a) and (c): FIDVR; (b) and (d): short-term instability.

For both cases, the results of voltage condition monitoring, using derived quantities from a transmission corridor, are shown in Figure 10 and can be described as follows:

✔ For the FIDVR case, load and equivalent impedances do not cross each other except during fault-on conditions, as shown in Figure 10(a). Q-margin remains positive, except during fault-on conditions, as illustrated in Figure 10(c).

✔ For the short-term voltage instability case, load and equivalent impedance cross each other, as can be seen in Figure 10(b). Reactive margin becomes and remains negative right after the fault, indicating an unstable case, as shown in Figure 10(d).

✔ There was no false alarm for the FIDVR case, despite the fact that the voltages are considerable depressed.

✔ The results during fault-on conditions should be discarded.

In summary, the new VIP method accurately discriminates between a voltage-stable case (FIDVR is considered a voltage-stable case) and an unstable case.

Based on this new methodology, a real-time voltage stability monitor GUI, providing a valuable visualization tool for system operators, was developed and installed at SCE. A snapshot of this display is shown in Figure 11.

TSPF Simulation

The increased complexity of today's power systems imposes new challenges in using existing dynamic simulation tools in the process of real-time voltage control design. First, a transient stability run is not feasible for studies requiring an hour or more of simulation time. Second, the models used in transient stability runs are not usually considered to be as accurate as those used in power flow studies, and these modeling errors may be magnified in stability simulations involving hundreds of thousands of time steps. Consequently, there is a need for a simulation tool that bridges a gap in the available set of analysis tools between static power flows and full-blown transient simulations. TSPF is such a tool; it is suitable for studying controllers and system control actions with long time constants. The modeling and CPU time requirements for TSPF simulation are much less than for traditional transient simulation, and the modeling environment can be made to be more flexible.

TSPF is used to model a sequence of events in a static model of the power system. It does not model dynamic phenomena as dynamics are typically defined in the contemporary vernacular, but TSPF could be used to study the onset of voltage instability. The entire purpose of the TSPF simulation is to implement the many new control algorithms. There
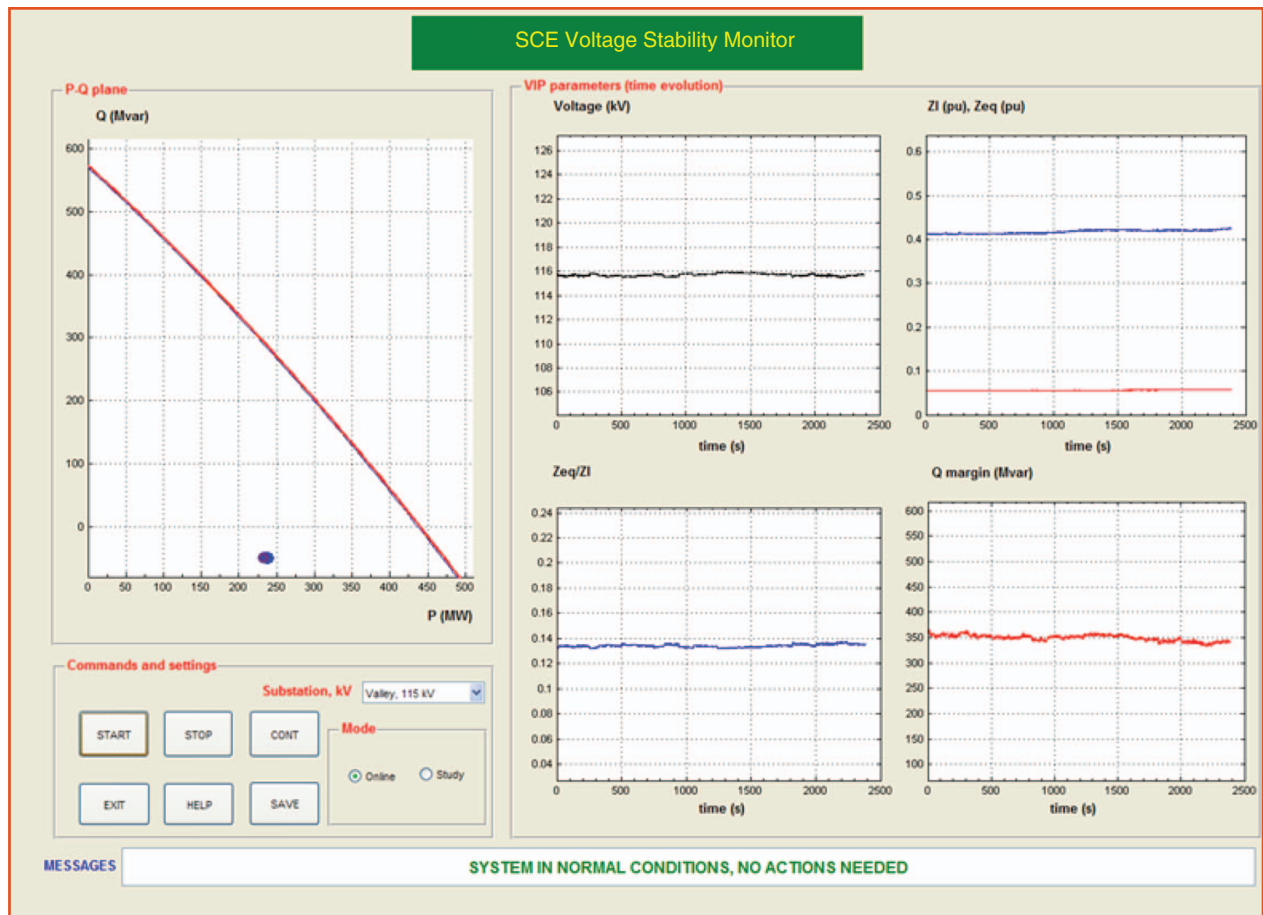

figure 11. The SCE voltage stability monitoring application GUI.

are no standard models for these new controllers, and more are expected to emerge. A specific implementation of TSPF is detailed in Figure 12, in terms of computational environments chosen, program flow and file transfers.

Implementation of the tool requires a flexible programming environment. Such computational environments include GE's PSLF, MATLAB, and Excel. MATLAB provides a programming environment familiar to many engineers as well as a robust plotting and display capability. File-based exchange of variables is preferred over memory-based methods for the implementation purpose. Memory-based methods would include programming pipes
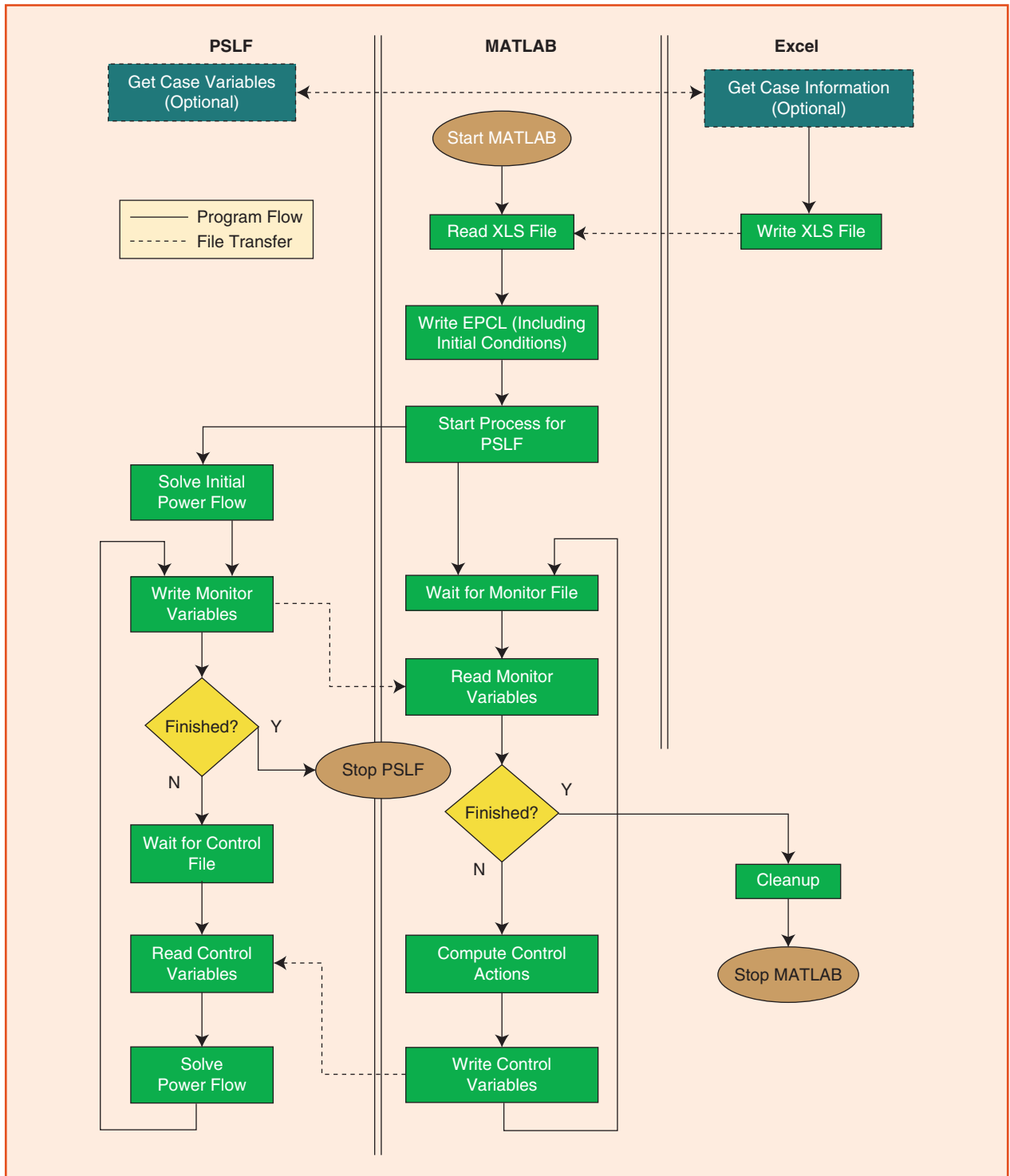

figure 12. A specific TSPF implementation.

between the programming environment and the power flow solver engine.

TSPF simulation cannot be used to study anything that requires dynamic models, including anything that involves frequency response or that invokes governor action. For some future implementation of a TSPF, however, it may be possible to solve a sequence of governor power flows rather than classical power flows.

Conclusions and Future Improvements

This article has analyzed the need for accurate and fast voltage stability assessment and real-time voltage control and protection devices and actions as elements of comprehensive system voltage management to prevent voltage problems. It has been demonstrated that the new, improved VIP methodology can be deployed so as to make use of currently available technology (such as synchronized measurements) and enable additional benefits, especially with continuous technological advancements. The advantages of this new VIP methodology in determining proximity to voltage collapse are:

- ✔ It is a model-free approach, offering easy interpretation of results.
- ✔ It can be implemented in several variants, including those for the bus, transmission corridor, and load center.
- ✔ It offers calculation of Q-margin and other indices for accurately and quickly detecting proximity to voltage collapse.
- ✔ It is easily combined with and offers a useful complement to other methods and indices.
- ✔ It is capable of initiating model-based contingency analysis, e.g., by generating alarms for the operator.
- ✔ It can reliably distinguish FIDVR from voltage instability, even if voltage is very low.

The method's advantages regarding practical deployment include its ability to process data from different sources (PMUs, SCADA, and simulation outputs). It takes immediate advantage of available data and scales up well with increased numbers of PMUs. Another benefit is its simplicity of implementation in various hardware devices and control center software tools. Excellent results have been achieved from system tests on slowly changing system operating conditions and in tracking system dynamics after large disturbances using actual PMU and/or SCADA data and system simulations.

Furthermore, the complexity of today's power system has given rise to a need for a new simulation tool to bridge the gap between traditional static and dynamic analysis tools. The TSPF tool, when used judiciously, is expected to become a useful addition to static power flows and full dynamic simulations. The increased deployment of wind, solar, and other renewable generation as well as energy storage and electrical vehicles will have a major impact on power system performance and consequently on voltage management.

Synchronized measurements, fast and secure communications, and powerful computational facilities are gradually being deployed in modern power grids. These new and continuously improved technological solutions, combined with algorithmic developments, will provide improved and comprehensive solutions for voltage instability and FIDVR monitoring, protection, and control.

For Further Reading

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