Chapter 5

GENERAL PRACTICES AND TOOLS

5.1 PRACTICES

Recognizing that voltage stability is a serious concern which must be examined during planning and operational studies, there is a requirement to develop practical study procedures, security margins, and criteria. The traditional approach to planning for voltage security relied on ensuring that pre-contingency and post-contingency voltage levels were acceptable for the system states under study. As a result, utilities have developed suitable voltage criteria which specify acceptable voltage limits. These criteria are largely based on equipment tolerances and although they ensure safe voltages, they generally provide no assurance that sufficient voltage stability margin exists. Put simply, a system may have very healthy pre-contingency and post- contingency voltage levels, but be dangerously close to voltage instability.

The relatively recent concerns for voltage stability have motivated the development of some study guidelines [1], [2]. The methods adopted will depend largely on the utilities' experience, policies, and regulatory requirements. For example, if studies show that voltage instability may occur when reactive reserves on specific generators reach certain values, the utility may use such measures as direct indicators of voltage security. The success of any such method depends on an understanding of the mechanism of, and proximity to, voltage instability for the particular system under a wide variety of possible conditions. This section provides some generalized guidelines for developing and applying security assessment methods.

5.1.1 Off-line Studies and On-line Studies

Voltage Stability (VS) margin is a measure of how close the system is to voltage instability. The approaches needed to assess margin will differ slightly between off-line studies (such as operation planning and discussed in detail in Chapter 3) and on-line studies (such as application of on-line voltage stability assessment tools in the EMS environment).

In the off-line environment, it is necessary to determine the margin for all design contingencies (such as single element outages, double outages of lines on the same tower lost by LLG faults, or double elements lost through breaker failure) for system conditions with all elements in service *and* for conditions with one or more elements out-of-service. Studying conditions with one element out-of-service is necessary to provide margin for the uncertainty of operating conditions. Because of maintenance and forced-outages, the actual system is rarely in a state with all elements in-service. Often, for study purposes, each out-of-service element is combined with each design contingency, to form a set of double contingencies which each may include unrelated elements such as loss of a line plus a generator. Care must be exercised in this case to account for the pre-contingency system readjustment which would normally occur for creating a new base case with one element out-of service.

For on-line studies, the system state and topology is known (or at least approximately known) through system measurements and state estimation. Therefore, it is necessary to study only the criteria contingencies *for all elements in service*. As a result, fewer scenarios need to be examined *and*, less margin may be required than for off-line studies in which the system uncertainty is greater.

Off-line VS study tools have matured over recent years [3], [4], and now on-line analysis tools are being developed to compute VS margins, verify that criteria is met, and suggest remedial actions necessary to meet the criteria [5]. One important aspect of practical VS assessment is the consistency between on-line and off-line assessment methods. While the two approaches may examine different scenarios and require different margins, the basic procedures, and models used should be consistent. This is essential to ensure the results obtained from off-line studies can be compared to on-line results. For example:

- For procedures: The use of PV or QV methods, or time-domain simulations, should be consistent in on-line and off-line studies. The definition of how margin is measured should be also equivalent.
- For models: The representation of loads, generator capabilities, field current limiters, switched shunts and tap changing transformers should be equivalent in on-line and off-line studies.

In the absence of on-line analysis capability, the off-line study results must be translated into operating limits and indices that can be monitored by the operators. The next section describes some technical guidelines for VS assessment, which can be applied for either off-line or on-line studies. The present industry practice is to use deterministic methods for stability assessment. With today's analytical methods and computer hardware, it is possible to assess a wide range of conditions and contingencies in reasonable computation times. However, probabilistic assessment methods and criteria may become necessary as interconnected models grow, controls become more complex (including remedial action schemes), and deregulation increases the volume and uncertainty of energy transactions.

5.1.2 Voltage Stability Margins and Criteria

In general, VS margins are defined as the difference between the value of a Key System Parameter (KSP) at the current operating condition and at the voltage stability critical point. Different utilities may use different KSPs from two main categories:

a) PV-based KSPs, such as an area load or power transfer across an interface

b) QV-based KSPs, such as reactive power injection at a bus or group of buses

Voltage stability criterion defines how much margin is deemed sufficient for voltage security of the system. It can be stated as “the system must be operated such that, for the operating point and under all credible contingencies, the VS margin remains larger than x% (or y MW/MVAr) of the KSP.” For example, when the KSP is defined as the area load, and the criterion is defined as 7% of this KSP, the system must remain voltage stable under all contingencies when the area load is increased by 7% above the given operating level.

In addition to the criterion for VS margin, utilities may establish other operating criteria for voltage security, including:

a) Voltage decline/rise criteria, which specify that bus voltages must remain within +x% and –y% of the nominal (or pre-contingency) values under all contingencies

b) Reactive reserve criteria, which specify that the reactive power reserve of individual or groups of VAr sources (generators and controllable shunts) must remain above x% of their reactive power output (or y MVAr) under all contingencies

The combination of the above criteria define the operating limits, or in other words, voltage secure operating range of the system.

As with any criterion, the VS criteria must be selected to provide adequate security without unduly restricting system operation. It is common to select different sets of criteria for different categories of contingencies. For example, the system may be required to have 7% load increase margin under single contingencies and only 3% load increase margin under double contingencies. The criteria appropriate for a given system can only be determined after extensive analysis of the system in order to establish the KSPs and the sensitivities of the system stability to changes in KSP values. An example of VS criteria can be found in [6].

5.1.3 Voltage Stability Assessment

In theory, either power flow-based (static) tools, such as the Voltage STABility program (VSTAB) [7], or time-domain simulation (dynamic) tools, such as the Extended Transient/Midterm Stability Program (ETMSP) [8], or the so-called Quasi-Dynamic (or Fast Time-Domain) simulation programs [9], can be used to calculate system VS margins. The dynamic tools must have appropriate models for the study of voltage stability, such as overexcitation limiter, thermostatically controlled loads and timing of transformer tap movements. The VS margins calculated using static or dynamic tools should be very close, provided that consistent device models are used in the two programs and that voltage instability does not occur during the transient period.

However, because of the high CPU time requirements for time-domain simulation (which may have to be run for 5 minutes or more), it is impractical to calculate VS margins for all the contingency cases in this manner. A practical approach is to use a power flow-based tool to calculate VS margins for the base case and all contingency cases, and use time-domain simulation only to bench mark the power flow results, and to determine the chronology of voltage instability, following a few selected critical contingencies.

5.1.3.1 PV-Based Margin Computation

With the KSP being defined as the system load, the process of calculating VS margins for the base case and the contingency cases is as follows (the same process applies to VS margin calculation with other KSPs):

(1) *Calculate VS margin for the base case using Static Analysis*. For PV Curve computation, the system load is increased step by step and at each step (load level) the power flow is solved. The voltage stability critical point is reached at the load level beyond which power flow solution does not exist. The increase in the system load from the initial operating point to the voltage stability critical point (nose of the PV curve) is the VS margin for the base case (see Figure 5.1-1).

At each load level, a generation dispatch scheme is used to supply the increased demand for active power and power flow solution is obtained with loads modeled as constant MVA and control of ULTCs and switchable shunts enabled.

(2) *Calculate VS margins for all the contingency cases using Static Analysis*. At each load level, after solving the power flow for the base case, the contingencies are applied one by one and the power flows are solved. The last load level where the post-contingency power flow solution exists is the post-contingency critical point and the increase in the pre-contingency system load from the initial operating point to this point is the VS margin for that contingency (see Figure 5.1-1).

Post-contingency cases are solved with loads modeled as voltage dependent. Depending on the time frame within which system performance is to be evaluated, and the actual system operation policy, a generation dispatch scheme (e.g., governor response, AGC, etc.) is used to balance the post-contingency powers and the control of ULTCs, automatically switched shunts and manually switched shunts are enabled or disabled.

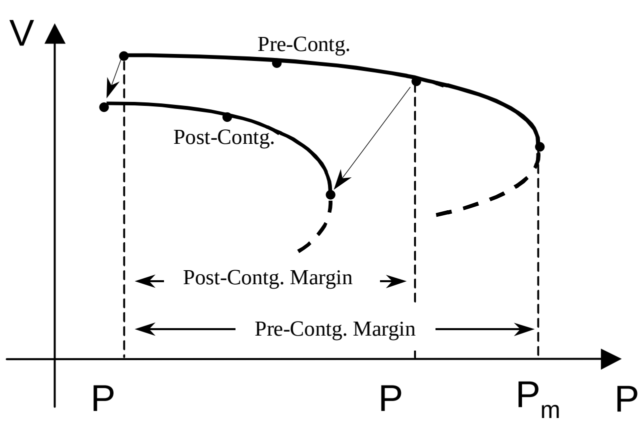


Figure 5.1-1. PV curves and VS margins.

(3) *Calculate VS margins for a few selected critical contingency cases using Time-Domain Simulation*. The approach is the same as that of step 2 above, except that the voltage stability of the system following a contingency is determined by time-domain simulation over an appropriate time frame (which may range from several seconds to tens of minutes.)

Starting with the solved cases corresponding to the different load levels, the system is disturbed by applying the contingency, and the system dynamic response following this contingency is calculated. If the time-domain simulation shows that the system reaches its post-contingency steady-state equilibrium point after a finite time period, the system is stable. If the steady-state equilibrium of the post-contingency system does not exist, time-domain simulation will show that the bus voltages continue to decrease and therefore the system is voltage unstable.

An operating point is voltage secure if

1. the VS margin of all contingencies meet the margin criterion,
2. the pre- and post-contingency voltages at that operating point meet the voltage decline/rise criteria, and
3. the pre- and post-contingency reactive reserve of specified sources at that operating point meet the MVAr reserve criteria.

5.1.3.2 QV-Based Margin Computation

In the above PV-based approach, the key system parameter defined for margin computation does not have to be limited to area load or interface flow. The KSP can easily be selected as any combination of real and reactive load, as well as generation, in one or more parts of the system. When the KSP is selected as the reactive load alone at one bus, the above procedure determines the QV margin at that bus, and when the KSP is selected as the reactive load at a group of buses, the same procedure determines the "Generalized" QV margin of the system.

However, traditionally, the QV margin at a given bus, under pre- or post-contingency conditions, is computed by the following procedure:

1. A fictitious synchronous condenser (generator) with unlimited reactive power is placed at the bus to control its voltage.
2. The scheduled voltage of the condenser is varied from Vmax to Vmin in descrete steps.
3. At each point (scheduled voltage) the power flow is solved and the MVAr output of the condenser is calculated.
4. The plot of MVAr output versus the scheduled voltage of the condenser is the well-known QV curve for that bus (see Figure 5.1-2). The amount of MVAr absorbed (negative of MVAr output) at the minimum point (bottom of the curve) is the MVAr margin at the bus.

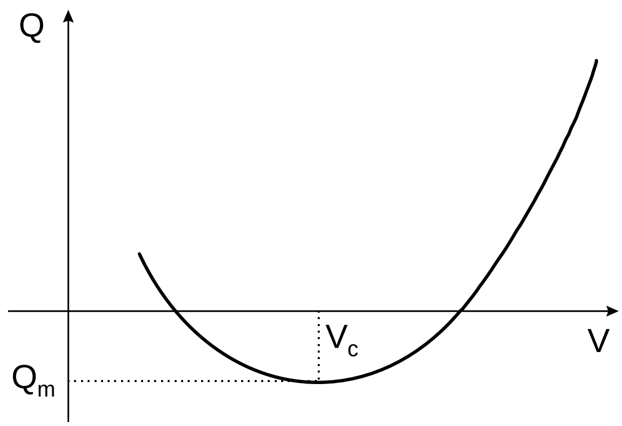


Figure 5.1-2. QV curve.

The reasons for popularity of this procedure are:

a) It is easy to use conventional power flow programs for this procedure.

b) The power flow solution at each voltage level converges easily because of the fictitious condenser controlling the voltage. Generally, the complete curve is computed, showing the stable and unstable operating regions.

The PV-based approach, with conventional power flow techniques, determines the stable part of the curve. Experience with VSTAB has shown that in this approach, repeated solutions with automatically adjusted step size, can reliably find the critical point (nose of the curve). Although continuation method can be easily applied to compute the unstable part of the PV or QV curve as well, in practice this is not necessary for determining the VS margin.

The advantages of PV-based KSPs over QV-based KSPs are the following:

a) The PV-based KSPs, such as area load increase or power transfer across an interface, provide the system planners and operators with a direct and physical measure of voltage security of the system and show how much load or interface flow increase can be safely accommodated by the system.

b) In the QV approach, the way the system is stressed, i.e., injecting reactive power at one bus alone, is completely artificial and has no relation with the way the system is operated. It provides only an artificial measure of robustness at a given operating point. Small changes in the operating point can have significant impact on this measure due to the nonlinearity of the power system.

c) The voltage stability of the system can not be assessed completely by computing QV curves at a limited number of buses. In theory, the QV curve at every bus in the system has to be computed to give a complete picture of voltage stability margins. On the other hand, one PV curve computation with a global load increase can reveal the general stability margin of the system. Additionally, modal analysis at the nose of PV curve will identify those buses in the system where the voltage instability occurs.

5.2 ON-LINE FUNCTIONAL REQUIREMENTS

This section specifies overall functional requirements for on-line Voltage Stability Assessment (VSA). It is developed in a format that may be used as a generic starting point by a utility or an independent system operator (ISO) to develop procurement specifications for on-line VSA. It is also helpful as a starting point for use by the system suppliers to develop detailed design specifications.

5.2.1 On-line VSA Assessment

The on-line VSA package must determine the voltage security of the system in its given condition. The system is deemed voltage insecure if any credible contingency would cause violation of Voltage Stability (VS) criteria.

Different utilities have different VS criteria and different needs for on-line VSA. In general, the VS criteria may specify the required VS margins in terms of load increase, transfer increase, or other key system parameters, as well as required var reserves in different parts (zones) of the system.

The list of contingencies to be considered may have to be screened and/or augmented based on operating system conditions.

If the system is found to become voltage insecure for any credible contingency, preventive or corrective control actions must be sought to improve voltage security of the system. Preventive control actions move the system state to a voltage secure operating point. Corrective control actions would maintain voltage stability of the system in case severe or unforeseen contingencies happen.

Even when the system state is voltage secure, it is desirable to know how far the system state can move away from its operating point and still remain voltage secure. This is particularly true in the Transmission Open Access environment where computation of Available Transmission Capability (ATC) must take into account adequate static, dynamic, and voltage stability margins. When needed, control actions, similar to the preventive controls for contingencies, should be found to expand the secure region around the operating point.

Based on the above requirements, the on-line VSA package must provide the following basic functions:

- Contingency selection and screening
- Voltage security evaluation
- Voltage security enhancement

Besides assessment of voltage security of the present system state, the on-line VSA must assess voltage security of forecasted future states, and any specific state specified by the operator.

5.2.1.1 Contingency Selection and Screening

It is impractical and unnecessary to analyze in detail the impact of every conceivable contingency. Generally, only a limited number of contingencies might impose immediate threat to voltage stability and these might be quite different from the contingencies critical for transient stability, thermal overload, or voltage decline. It is required therefore to define a credible list of contingencies and provide the capability to both augment and screen the contingencies and select those most likely to cause problems, so that they will be assessed in detail.

5.2.1.2 Voltage Security Evaluation

The operators need to know whether the system operating conditions meet the VS criteria. The VS criteria may specify how far the system should be from the borderline of voltage instability in terms of load increase, transfer increase, or other forms of stress, when subjected to any of the selected contingencies. There might be other criteria that must be met as well, such as required MVAr reserves in different parts of the system and limits on post-contingency voltage declines.

There are also cases where computation of VS must be carried out in response to postulated conditions (e.g., to determine if a requested transmission service can be accepted).

In addition to evaluating the voltage security of the given system's operating point, it is also necessary to know the voltage secure region around this operating point. This information is useful when, for example, the system load is increasing or transfers are being increased, and the operator wants to know how much the load or transfer can increase while the system remains voltage secure. This is particularly important for determination and posting of the ATC.

These computations involve detailed analysis of all the selected contingencies at several system states. Static analytical techniques (power-flow based) can perform these computations in a majority of cases, but dynamic analytical methods (time-domain simulation) may be occasionally required.

5.2.1.3 Voltage Security Enhancement

If it is found that the system does not have sufficient voltage stability margin for one or more of the selected contingencies, actions must be determined to move the system state in such a way as to create sufficient margin. These preventive control actions will be taken before any contingency happens (pre-contingency system state). The on-line VSA should provide different control action alternatives, such as capacitor/reactor switching, generation re-dispatch, etc., and determine the impact of each control action on voltage security of the system.

In the event of multiple (or severe) contingencies, special corrective control actions may be necessary to prevent voltage instability. These generally impact customers (interruption of service or degradation of power quality) and therefore are reserved for use in response to very severe system disturbances. An example of a control action of this type is coordinated load shedding. The on-line VSA must be able to determine the best setting (location and minimum amount of required load shedding) for remedial action schemes involving automatic load shedding.

The on-line VSA must validate the effectiveness of the control actions. For corrective controls, this may require time-domain simulation of the events and control sequences. For acceptable performance in an on-line application, special time-domain simulation techniques are needed which are computationally much faster than the conventional methods and still capture the dynamics and timings important to voltage stability.

5.2.2 General Requirements

The on-line VSA function must operate in conjunction with the EMS environment to monitor the state of the power system periodically, on demand, and upon occurrence of significant changes in the state of power system, to ensure power system security against occurrence of predefined specific or generic contingencies. It should also be available in a study mode.

On-line VSA must allow automatic selection of specific contingencies from a predefined contingency list, based on actual system conditions. Generic contingency definitions must also be accommodated; on-line DSA should provide the capability to construct relevant contingencies based on the existence of recognizably vulnerable or stressed operating conditions in the system, and the nature, location, and degree of stress. This means that additional contingencies should be automatically added to the selected list of specific contingencies based on system conditions. Automatic contingency augmentation capability should also be provided to account for dependent contingencies (e.g., active arming for load shedding). The operator should be notified when contingencies are added or augmented automatically. The operator should have the capability to designate one or more specific contingencies to be selected for processing regardless of system conditions. The operator should also be able to designate one or more specific contingencies to be subjected to full processing (i.e., not be subjected to screening).

The selected contingencies should be classified into two groups, namely voltage stable (secure) and voltage unstable (insecure) contingencies.

Capability should exist to rank the contingencies according to indices or measures relevant to each of a predefined set of voltage security criteria.

The VSA function must determine the relevant operating limits (line loading limits, interface flow limits, export/import limits, and load change limits) to ensure voltage security of the system in the event of occurrence of any of the contingencies designated by the operator, the severe contingencies determined automatically through screening and ranking, or both.

The VSA function should compute indices quantifying the degree (margin) of voltage stability or instability of the system for contingencies designated by the operator, the severe contingencies determined automatically through screening and ranking, or both. Trends and evolution of system-wide indices, as well as indices per designated zone or area, should be available based on prior VSA executions to indicate whether system voltage security is improving or degrading.

Provisions should be available to accommodate automatic determination of preventive measures, and corrective actions.

Figure 5.2-1 shows the main components (modules) of on-line VSA. The Change Monitor triggers event oriented execution of the VSA function based on status and analog data received from SCADA. Alternatively, the available EMS Real-Time Sequence Control (RTSC) may be augmented to include triggering of on-line VSA execution through an EMS/VSA messaging mechanism. Contingency selection and contingency screening are configured separately to allow inclusion or exclusion of screening as suitable for the utility. If desired, they may be combined into a single module. Contingency analysis for voltage stability assessment may be configured to use either static (steady-state) analysis or dynamic simulation, depending on the characteristics of the contingencies of interest to the utility. Voltage security monitor determines the secure operating limits or operating regions to ensure adequate voltage stability margin. The security enhancement module assists in determination of preventive and/or remedial actions against voltage instability threat.

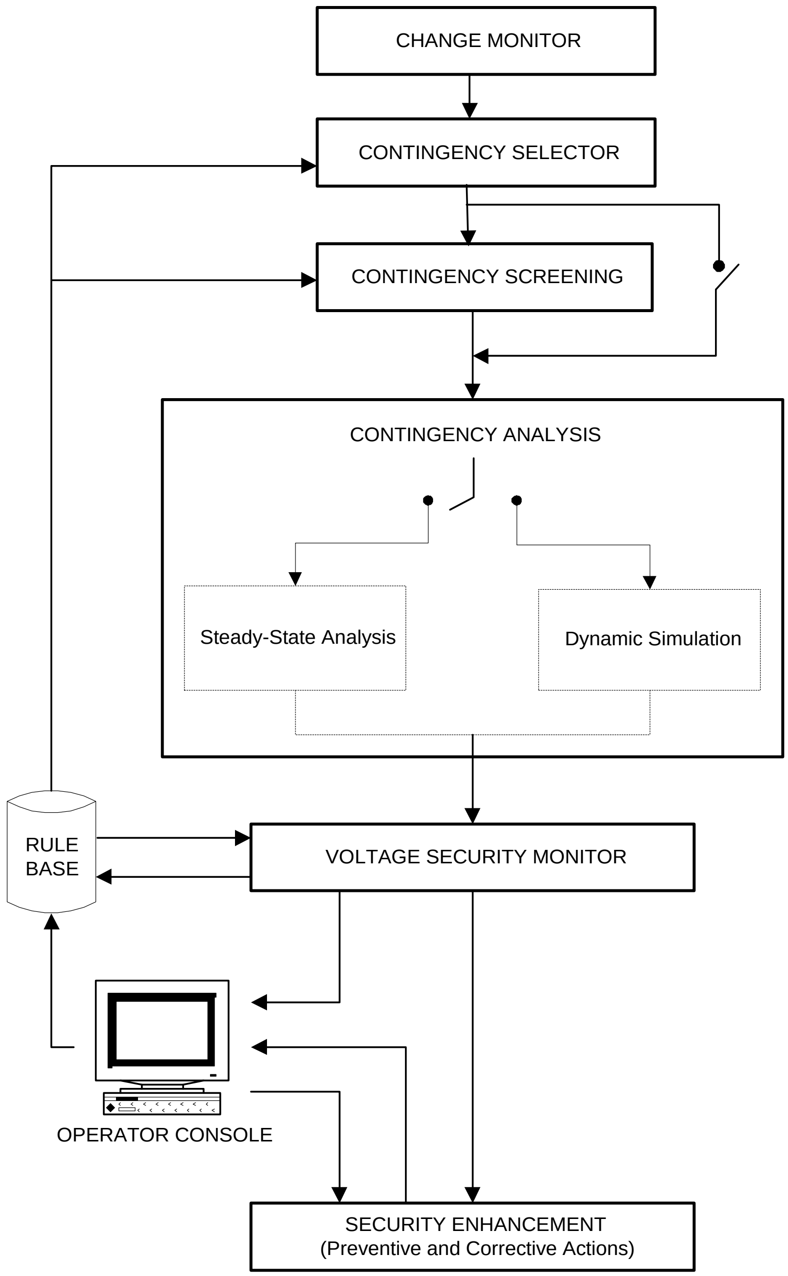


Figure 5.2-1. On-line VSA model.

5.2.3 Contingency Definition

A contingency consists of one or more events occurring simultaneously or at different instants of time, with each event resulting in a change in the state of one or more power system elements. A contingency may be initiated by a small disturbance, a fault, or a switching action.

The following types of switching actions should be supported in the definition of a contingency:

- Breaker opening/closing
- Shunt capacitor/reactor insertion and/or removal
- Series capacitor insertion or bypass
- Generator tripping
- Load shedding
- Transformer tap changing
- FACTS[1] device connectivity and operation
- Automatic transfer tripping (armed remedial action)

On-line DSA must provide the capability to automatically determine the initiation of some or all of the switching actions based on a combination of system conditions or events.

The capability should be provided to include one or more contingency type attributes or flags in the definition of a contingency to designate whether or not the contingency must be subjected to time simulation or static analysis.

5.2.4 Contingency Selection

The Contingency Selector should act as a filter so that only relevant and appropriate contingencies are processed each time VSA executes either in real-time or study mode. Starting with a list of pre-defined contingencies, the intent is to avoid unnecessary processing of any pre-defined contingency that can be pre-screened as irrelevant or non-critical under present operating conditions. In case the contingency list includes one or more groups of "similar" contingencies, whose relative severity can be logically established based on actual operating conditions, the Contingency Selector should be able to select the n most severe contingencies in each such group (with n user-adjustable; default n=1). Moreover, the Contingency Selector should have the capability to generate new contingencies (add to the list) based on operating conditions as determined by a set of rules. These specific conditions must be recognized automatically based on the operating data (SCADA) and the results of other functions (such as Static Security

[1] FACTS designates "Flexible AC Transmission System" devices, and is an EPRI trademark. This functional specification does not exclude other devices with similar features.

Analysis). The Contingency Selector should also be able to augment a contingency definition based on active arming of remedial action schemes. It should also recognize “must select” contingencies. The must-select list should be dynamic; for example, it should automatically include any contingencies that in the previous VSA execution required remedial action arming.

The Contingency Selector rules should be applicable to any power system data quantity that Contingency Selector can obtain or derive from the EMS and/or VSA database. To support both real-time and study VSA, this includes data from SCADA, the State Estimator, Static Security Analysis, OPF, and any Operating Orders coded in the EMS/VSA environment. Different rules should be possible for real-time and study analysis. Mathematical operations applicable to Contingency Selector's current and past data quantities must be supported. Logical as well as algebraic statements should be possible.

The Contingency Selector must support rules that check whether each contingency's related data quantities represent a certain status and/or range-of-operation condition that warrants activation or deactivation of the contingency. In real-time mode, these checks should be possible on an instantaneous, trend, rate-of-change, or time-duration basis. This should include the ability to evaluate changes in the power system data since the last execution of real-time VSA. Where appropriate, the limits that may be used to define an applicable range of operation should be maintained separately in the VSA database or otherwise obtained from the EMS. The ability to construct rules that combine multiple power system conditions via one or more logical statements should be supported. The Contingency Selector should also activate/deactivate contingencies based on Static Security Analysis results, using generic or user-defined rules.

5.2.5 Contingency Screening

Contingency screening may be required to reduce the number of contingencies selected by the Contingency Selector before carrying out further detailed analysis.

A number of voltage stability indices introduced in Chapter 4 may be computed via computational short-cuts to help rank the selected contingencies in an approximate order of severity, or identify harmless contingencies that need not be subjected to further analysis. Alternatively, rule-based criteria may be used as experience is built up with the system. Finally, the contingency screening module may be entirely disposed of if the Contingency Selector adequately filters the list of possible contingencies.

The design of the on-line VSA should be flexible and modular to accommodate easy adaptation of contingency selection and screening to the specific utility requirements. In particular a number of screening and ranking criteria should be provided for selection by the user. The user must have the capability to include or exclude screening separately in the study mode and in the real-time sequence execution of on-line VSA.

5.2.6 Contingency Analysis

The Contingency Analysis module should provide the capability to select the method of analysis most suitable for the utility. Both static (steady-state) analysis and dynamic simulation methods should be provided[2].

Static analysis may include power flow methods, sensitivity analysis, as well as traditional local analysis (e.g., V-Q and P-V curves). Dynamic simulation should provide for analysis of both fast and slow dynamics, preferably with automatic time step adjustment. It should accommodate generator and governor dynamics, field current limiting dynamics, load restoration dynamics, tap changing time delays, AGC, and prime mover dynamics.

The user must have the capability to designate the analysis method to be used for all contingencies, or on a per contingency basis. In the latter case the method of analysis may be included as part of the contingency definition as specified in Section 5.2.3, Contingency Definition.

The results of contingency analysis must include classification of each contingency as voltage stable or unstable. Depending on the method of analysis selected, a measure of voltage stability margin should also be provided. Moreover, if the method of analysis permits, sensitivity of the stability margin with respect to designated operating parameters of interest may be computed.

The capability must exist for iterations between the Contingency Analysis module and the Security Monitor. Both manual and automatic iterations should be provided for. In automatic iteration, the Security Monitor will modify designated parameters (e.g., system load) and trigger a run of Contingency Analysis. This will permit the Security Monitor to determine secure operating limits or regions in terms of operating parameters which are of interest to the operators, rather than in terms of indices which may be meaningful only to the analysts.

5.2.7 Voltage Stability Criteria

Voltage security (or insecurity) of the power system should be assessed based on voltage security criteria of interest to, and accepted by, the utility. Lack of sufficient voltage stability margin as defined by the voltage stability indices defined in Chapter 4, Voltage Stability Indices, should be identified.

The user must have the capability to have a contingency which results in islanding or necessitates automatic load shedding beyond a designated threshold, to be identified explicitly or labeled as insecure even though the remaining part of the system meets voltage stability requirements.

For a practical example of VS criteria used in a utility environment, review [6].

[2] Contingency Analysis as defined here must not be confused with Steady-State Security Analysis which deals only with steady-state contingencies. Here the contingencies are of a dynamic nature, but the method of analysis may be static or dynamic.

5.2.8 Security Monitor

Security Monitor must support voltage security analysis, in both the real-time and study modes, by interpreting and presenting to the user the VSA contingency analysis results from the following perspectives:

1. Which contingencies result in voltage insecurity?
2. Which of the insecure contingencies are the most limiting (for the system as a whole or for specific zones and areas under study), and where?
3. What is the overall voltage security condition of the power system as a whole, or of specific zones or areas under study, as measured by one or more individual or composite voltage security indices?
4. Is the overall voltage security condition of the power system getting better or worse as evidenced by tracking appropriate voltage security indices?
5. Do projected short-term operating conditions, such as scheduled interchange or interface flows, suggest that the overall voltage security condition of the power system is going to get better or worse?

Security Monitor should also provide the capability for direct (scan rate) monitoring of voltage and generator reactive power and reactive reserve for designated generators or plants.

5.2.8.1 Security Monitor Capabilities

Security Monitor should have the ability to apply multiple user-specified rules to assess the voltage security condition of the power system. The rules should operate on the pre- and post-contingency power system data and/or the voltage security indices that Security Monitor must calculate using the Contingency Analysis module. The rules must allow multiple conditions associated with the data and indices to be combined via one or more logical statements.

Security Monitor must be capable of establishing the margins, sensitivities and other signatures that it needs in order to calculate the various operating limits of interest to the user, such as those needed for computation of available transmission capability (ATC).

The VSA Operating limits may be assumed to be of the box type (i.e., max/min limits). However, the capability to determine secure operating regions (interdependent operating limits or simultaneous transfer limits) must be provided for each pair of operating parameters designated by the user, with a third parameter selected by the user to produce a family of operating regions.

The user must have the ability to review Security Monitor's results via tabular and graphical displays. Presentations should include the insecure contingencies ranked in order of severity and a convenient means of comparing contingencies on the basis of their relevant voltage security indices, operating limits, and remedial actions. A convenient means of tracking the overall voltage security condition of the power system must also be included.

The user must have the ability to review Security Monitor's voltage security index definitions and security assessment rules. On-line modifications of these definitions and rules must be possible in the study mode.

5.2.8.2 Direct (Scan Rate) Monitoring

The on-line VSA is expected to run normally as part of the real-time sequence, starting the State Estimator (SE) solution, as explained in Section 5.2.11. It may be set to execute following each SE solution or a multiple thereof. Therefore, in its normal execution, the on-line VSA results are based on system snapshots obtained once every few minutes (5 minutes to 30 minutes depending on the specific implementation; 20 minutes being a reasonable reference value). Direct monitoring of specific bus voltages or generating unit reactive power refers to scan rate (or multiple scan rate) monitoring of such quantities, and would be best classified as a SCADA function. The relevant data update periodicity would be in the range of 2 seconds to 30 seconds depending on the implementation (10 seconds being a reasonable reference value).

The Security Monitor should provide the capability for the operator to monitor designated bus voltages, as well as generator and static var system reactive power and reactive reserve. Depending on the design of the interface between the on-line VSA and the SCADA systems, this capability may require either opening a window into the SCADA system from the on-line VSA environment, or scan rate (or multiple scan rate snapshot) data transfer from SCADA to the on-line VSA.

Reactive power and reactive reserve monitoring capability should be provided for individual units, groups of units, and power plants for which SCADA scan rate data is available.

The capability should be provided to graphically display the selected monitored quantities and their trend with time. The capability should also be available to have composite voltage security indices computed and displayed accordingly.

5.2.9 Security Enhancement

Security Enhancement includes both Preventive and Remedial Actions. The VSA functions should assist the operator in determining the needed security enhancement measures.

5.2.9.1 On-line Determination of Preventive Actions

The preventive actions will consist of manipulating a coordinated set of “controllable parameters” in the pre-contingency state consisting of the following:

- Voltage/VAR rescheduling
- Network element switching
- Generation rescheduling
- Start-up of certain units (e.g., synchronous condensers)
- Adjustments of operating reserves on certain units
- Adjustment of interface flows across specifically designated interfaces

- Adjustment of HVDC and FACTS device control set points
- Curtailment of certain loads (interruptible loads, load control schemes, etc.)

Mechanisms for arriving at the final preventive action decisions may consist of one or a combination of the following:

a) User-suggested preventive actions,

b) rule-based preventive actions, and

c) preventive actions obtained through a security-constrained optimal power flow (SCOPF).

The information available from the base-case VSA execution run may provide sensitivity data and limit data that are helpful in preventive action considerations. The sensitivity data could be in the form of a "sensitivity matrix" that relates incremental changes in the "controllable parameters" to the incremental changes of "output variables". The latter may include voltage security indices and/or physical variables of interest (line flows, inter-area transfers, bus voltages). Limit data is obtained for specific critical variables (e.g., interface flows across designated transmission corridors) by the Security Monitor using several iterations with the Contingency Analysis module to arrive at the exact limit. The limits could be of the "box" type, i.e., upper and lower limits for a given variable, or in the form of operating regions (interdependent limits or simultaneous transfers).

Once the decision for preventive action is made, a simulation check should be made to verify that the resulting conditions would be secure. Otherwise, corrections to that decision should be made and the results tested until an acceptable condition is arrived at.

5.2.9.2 On-line Determination of Remedial Actions

The main objective of on-line remedial action determination is to determine appropriate arming for the remedial action schemes in case the preventive actions and/or the present active arming is not adequate to ensure system security. The proper arming for individual contingencies can be determined separately. The corresponding remedial action may involve shedding different combinations of load groups at one or several substations depending on the contingency, and the actual operating conditions.

Often many different arming schemes are possible to ensure voltage stability. If the impact on the post-contingency operation is the same, then for operator's convenience, it is desirable to have VSA recommend only incremental changes with respect to the existing active arming. However, when the number of required incremental changes (in a single VSA execution, or cumulatively over successive VSA executions) exceeds a threshold (user-enterable), it would be advisable to have VSA ignore the existing active arming, and determine a new arming scheme. Accordingly, for on-line determination of remedial actions, provisions must be available for both "Flat Start Arming" and "Incremental Arming" as defined below.

In Flat Start Arming, the VSA is performed assuming that all remedial action schemes are initially disarmed. For those contingencies that cause voltage insecurity, an "optimal" subset of arming schemes is sought with the objective to arm the smallest amount load shedding to achieve the desired voltage stability margin. This may be determined through the sensitivity analysis, whereby the changes in voltage stability margins are related to various possible control actions. Flat Start Arming is performed following a large change in system operating conditions, on demand, or once every n (user-enterable) VSA cycles.

In Incremental Arming, the current arming state is retained and is automatically considered by the on-line VSA. Depending on VSA results, an armed scheme may be disarmed if the corresponding voltage stability margins are high enough, and vice versa. The incremental arming patterns are determined so as to minimize the number of changes in the active arming, while ensuring system stability. Any sensitivity derivatives computed in this case are evaluated with the existing active arming.

The operator must in any case have the capability to request a graphical comparison of the existing active arming and the one recommended by the VSA function.

In the study mode, the engineer/analyst should be able to study possible remedial action arming options that would lead to system security. Both flat-start and incremental arming capabilities must be provided. The VSA system must have the tools to allow easy modification of the arming patterns.

5.2.10 Modeling and Data Requirements

This section specifies modeling and data requirements of the VSA function. Some of these requirements may be in line with the utility's existing EMS models and data; others may have to be added for on line VSA purposes.

5.2.10.1 Modeling Requirements

The VSA will require the following classes of models:

- Network Models
- Device Static Models
- Device/System Dynamic Models
- Load Models
- Fault/Control Models

A description of the requirements for each model type is presented below.

(1) *Network Models.* There are two types of network models that will have to be present, namely, internal and external models. The internal model includes representation of lines, generators, transformers, loads, DC converters and shunt/series devices, as well as the status of breakers, and configuration of bus arrangements in substations. The main purpose is to be able to adequately represent switching operations in contingencies and possible remedial action schemes. The external model network may consist of two sub-networks, namely: (i) the inner external (or buffer zone), where the identity of the external network model elements is preserved, and (ii) the outer external, where reduced models are used. Depending on arrangements for data exchange with other transmission

control centers, little or no real-time data may be available about the external model. There may be a need to change the external model occasionally based on available scheduling information, seasonal variations, etc. One or more external models may be required to account for various operating conditions in the system based on scheduling data or seasonal variations. For both the internal and external subsystems, busses are grouped into zones. Power transfer interfaces from any zone to an adjacent one must be easy to identify for purposes of interface flow and transfer computations.

(2) *Device Static Models.* The static models are load-flow models of device/element representations. The following static models should be supported at a minimum :

- Lines: represented as pi-sections, possibly with unsymmetrical line charging
- Transformers: represented as pi-sections whereby the various impedance/admittance components may be explicit functions of tap settings. Three winding transformers must be properly modeled, including any associated tap changers.
- Phase-shifting transformers: represented by complex tap ratios, allowing both shift in angle and change in voltage magnitude
- Generators: represented as a real-power source together with a reactive power capability curve as a function of terminal voltage.
- Shunt elements: represented by their impedances/admittances
- DC lines: represented as real-power injections, with defined MVAr vs MW characteristics
- Static Var Compensators (SVCs): represented by static gain and maximum/minimum limits
- Loads: represented by the ZIP model, i.e., as a combination of constant impedance (Z), constant current (I), and constant real/reactive injection (P) components

(3) *Device/System Dynamic Models.* The device dynamic models to be considered are as follows:

- Generator dynamic models including the following:
  - Machine mechanical dynamic equation (swing equation with damping)
  - Machine electrical dynamic equations
  - Excitation systems of various types
  - Governor systems of various types
  - Selected prime mover models (selection to be based on response times)
  - Power system stabilizers
- DC Line dynamic models including various controls
- SVC dynamic models

- FACTS devices including modeling of their connectivity and time delays
- ULTC transformers: to include time delays associated with tap-changing controls.

Flexibility must be provided to accommodate user-supplied device models easily.

(4) *Load Models. L*oad models should include the following features:

- Nonlinear voltage dependence either as in the ZIP standard model (i.e., combination of constant impedance, constant current, and constant power) or as a general polynomial in voltage
- Large induction motor loads
- Slow thermostatically driven loads (heating/cooling)

(5) *Fault/Control Models*. This modeling requirement includes the following:

- Relay models: for those relays which may operate due to a disturbance (e.g., load shedding relays).
- Modeling of control actions in remedial action schemes

5.2.10.2 VSA Data Requirements

VSA data requirements consist of data for the above models, additional data needed by the VSA system as a whole, and specific real-time data needed exclusively by the on-line VSA function.

A. Model Data Requirements

(1) *Network Models*. These include connectivity/topology information for lines, transformers, shunt/series devices, and generating units. Additional network data will include:

- Limits on bus voltages for each voltage level for normal and emergency operation
- Bus configurations in substations as functions of breaker status (for internal network)
- Zone data

(2) *Device Static Models*. The following data will be needed:

- Line pi-section impedances/admittances data
- Line thermal limits, both normal and emergency
- Transformer pi-section data including tap settings with impedance/admittance components as explicit functions of tap settings
- Transformer limits, both normal and emergency
- Phase-shifting transformer data and limits, both normal and emergency

- Generator static data: minimum and maximum ratings, nominal terminal voltage, reactive power capability curve as a function of terminal voltage and coolant conditions
- Shunt element impedances/admittances and ratings
- DC lines: voltage levels, ratings
- Loads: default ZIP load partition ratios at nominal voltage (for the Z, I, and P components), load limits, and default power factors

(3) *Device/System Dynamic Models*. The following device dynamic model data requirements must be met as a minimum:

- Generator dynamic model data:
  - Machine mechanical parameters: inertia constant and damping coefficient
  - Machine electrical parameters: transient/subtransient reactances and time constants, saturation model data
  - Excitation systems: data for each model available in standard power system stability analysis programs such as EPRI's ETMSP
  - Governor systems data for each model available in standard power system stability analysis programs such as the EPRI ETMSP
  - Selected prime mover model data (selection to be based on response times)
  - Power system stabilizer gains, time constants and limits
- DC line dynamic model data including those for various controls and their parameters
- FACTS device data (compatible with those available in EPRI ETMSP)
- ULTC transformers and phase-shifters: time-delays associated with tap-changing controls

Flexibility must be provided to accommodate data for the user-defined models in a flexible user-friendly manner.

(4) *Load Models*. Load model data should include the following as needed:

- Percentages of Z, I and P for each load bus and for real and reactive powers independently (percentages specified for nominal base case conditions)
- Coefficient for polynomial representation of loads as function of voltage
- Large induction motor loads data
- Slow thermostatically driven load data (including time delay, time constant, gain, and sensitivity factors)

(5) *Switching/Control Models*. The switching/control data requirement may include the following:

- Relay model data including timing of breaker operation, protective action schemes, etc.

- Model data of control actions in remedial action schemes. Also, this may include threshold values for various arming schemes.

B. System Data Requirements These consist of additional data to accommodate various VSA execution parameters and to compensate for missing and erroneous data. The VSA execution parameters should accommodate at least the following:

- Cycle period for the overall VSA function
- Threshold triggers for automatic VSA execution (e.g., system load change beyond a threshold, status change for major devices/lines, etc.)
- Convergence parameters (thresholds and iteration counts)
- Screening and ranking parameters and data

C. VSA Specific Real-Time Data The real-time data needed by the VSA system will be supplied by the SCADA/EMS database. The following additional types of real-time data needed by the VSA may or may not be available in the existing SCADA/EMS. A decision must be made for each utility VSA implementation regarding the need for and cost-effectiveness of additional telemetry or data exchange to support on-line VSA. The minimal requirements are as follows:

- Status of the Generator AVR (ON/OFF)
- ULTC tap changer status (Blocked/Un-blocked)
- ON/OFF status of power system stabilizers
- Arming status of remedial action schemes
- Status of FACTS devices.

The status of selected equipment in the external system, which may or may not be available in the existing SCADA/EMS database, may also be required.

D. Default Data The VSA system should have the capability to fill in missing data using appropriate default values. It must also detect and flag erroneous data based on reasonability checks. The user must be able to fill in the correct information and must have the option to use default data.

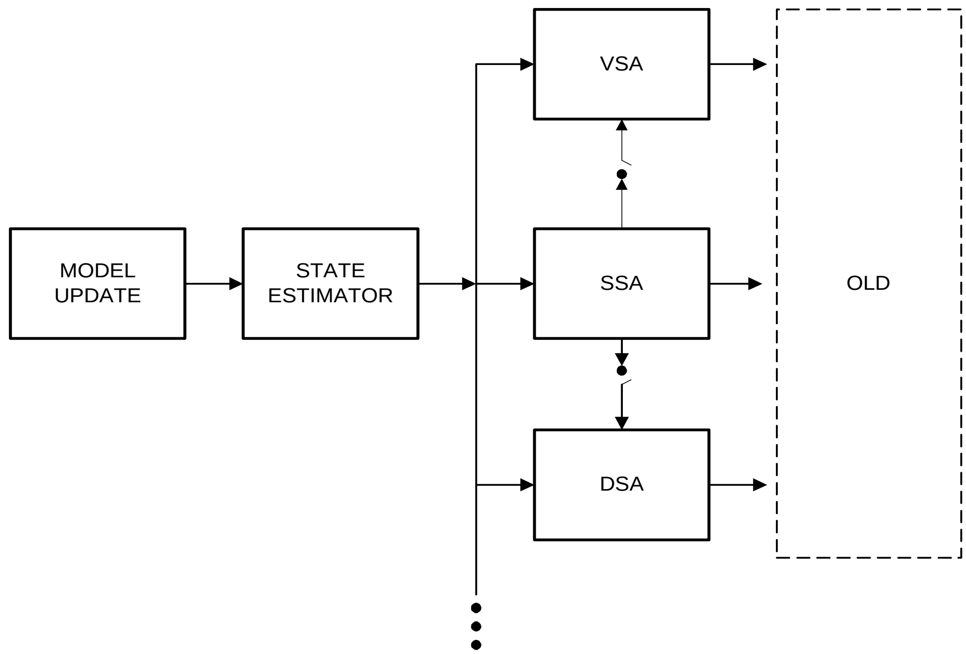
5.2.11 On-Line VSA Execution Modes

The VSA function must be able to execute periodically, on demand, and upon occurrence of significant changes in the state of the power system. It should also be available in the study mode.

5.2.11.1 On-line VSA Execution Control Requirements

In the on-line mode (referred to also as real-time execution mode) the VSA must execute in conjunction with the real-time sequence control (RTSC), which coordinates execution of the network security application functions available in the EMS environment. Figure 6-2 shows where on-line VSA fits in the EMS real-time sequence.

The EMS RTSC design is expected to provide the flexibility for the operator to have an execution of the State Estimator (SE), and possibly the Steady-State Security Analysis (SSA) function be automatically triggered to precede each VSA execution.



SSA = Steady-State Security Analysis
VSA = Voltage Stability Analysis
DSA = Dynamic Security Analysis
OLD = Operating Limits Determination

Figure 5.2-2. Real-time sequence VSA execution.

A. On-line VSA Execution Triggers The following triggering mechanisms for on-line VSA execution should be available:

(1) *Periodic Execution*. It is expected that the provisions in the EMS RTSC, will allow the user to specify the execution periodicity of the on-line VSA based on absolute time (e.g., on the hour, 20 minutes past the hour, etc.), time lapse since the last VSA execution (e.g., 20 minutes after the last VSA execution), or multiples of periodic State Estimator executions (e.g., after every other SE execution). For each utility the existing EMS RTSC capabilities will be used to trigger periodic on-line VSA execution.

(2) *Event-driven Execution*. The on-line VSA must execute upon changes in the operating state of the power system detected by a "Change Monitor" that triggers the RTSC execution. These changes should include the following:

- Changes in system topology
- Variation of load, generation, or interface flow level beyond designated thresholds
- Changes in the arming pattern of automatic corrective devices, whenever applicable
- Changes in the status of reactive resources (ON/OFF)
- Changes in the status of generator AVR, blocked transformer taps, etc., where telemetered
- Change of state (ON/OFF) of stabilizers on the machines.

The user must be able to specify a time delay associated with each group of event triggers, so that VSA execution starts only after the system has settled down to a steady-state and the corresponding base case is available from the State Estimator.

(3) *On-demand Execution*. The operator must be able to request execution of on-line VSA at any time. In case VSA is already executing the operator must be accordingly notified, and should be given the option to have the requested on-demand VSA execution queued or ignored.

B. VSA Execution Abort The operator should be able to abort VSA execution at any time regardless of the triggering mechanism that started the execution.

It should be possible to assign execution and abort priorities based on the type of triggering mechanism that started the current VSA execution, and the source of the incoming execution or abort request. For example, it should be possible to have any periodic VSA execution aborted by any event trigger, and have any periodic trigger ignored or queued when an event triggered VSA run is executing. It should also be possible to have a forced execution mode such that if VSA has not run to completion for a period of time (specified by the user, and longer than normal VSA execution periodicity), a forced execution is started ignoring subsequent execution abort requests (except for manual abort).

C. Execution Control The operator should be able to use a simple display block diagram to include or exclude contingency screening for on-line VSA execution. The operator should also have the possibility to observe the on-line VSA execution results (interface flow limits, generation limits, etc.) and authorize or prevent their use by other EMS functions. The operator should also have the capability to enable automatic transfer of the on-line VSA results for use by other EMS or SCADA applications.

The analyst/engineer must have the capability to enable/disable either static analysis or time simulation for Contingency Analysis for all contingencies. If both are enabled, the contingency type flag described in Section 5.2.3, *Contingency Definition*, will prevail.

D. Validity of VSA Results The on-line VSA should have the capability to determine (and warn the operator) when the results of the most recent VSA execution are no longer valid due to changes in the system or arming conditions. It is normally expected that the Change Monitor will initiate VSA execution under these conditions. However, it is also possible that the VSA executions triggered by the Change Monitor do not run to completion for some time due to frequent changes in system conditions. The operator should then be notified that the available VSA results are no longer valid.

5.2.11.2 Study-Mode Execution Control Requirements

In the study mode, the user must be able to execute the VSA function using a save case steady-state or system snapshot.

The real-time VSA mode should continue while studies are being executed. The user must have the capability to modify the save case conditions, choose an existing contingency list, add, delete, or modify contingencies, modify arming schemes, include or exclude contingency screening, and change VSA execution parameters and thresholds. The user must also have the possibility to select or construct a specific contingency to be analyzed without processing or modifying the contingency list.

5.2.12 On-line VSA User Requirements

The user requirements for the integrated VSA function are stated in this section. Both general user requirements and specific requirements for various user groups (operators, operations planners/engineers, and managers) are discussed in this section.

5.2.12.1 General VSA User Requirements

This section presents user requirements common to all users, i.e., operators, operations planners/engineers, and managers.

A. User Interface Environment The VSA should have an effective and user-friendly graphic user interface with point and click features, pull-down menus and Windows. Modern graphics should be used for the quick assessment of complex situations.

The VSA user interface should provide facilities for effective and efficient monitoring of the various indices, margins and trends together with provisions for implementation of preventive action recommendations, and arming of automatic corrective actions (such as comparison of existing and recommended arming).

The VSA should be able to store the results of insecure cases and the associated state estimator base cases automatically when these appear in the on-line mode (controlled by the real-time sequence control). These cases should be archived for future analysis and consideration by the Engineer.

In both on-line and study modes, the capability must be provided to show the run time since the start of the VSA execution, as well as the progress of the VSA run (e.g., screening in progress, the number of contingencies processed so far, the number of remaining contingencies to be examined, etc.).

A waiting symbol on the screen is required. Hard copy output capability is required for both tabular and graphical displays.

B. User Interaction The following display capabilities must be provided as a minimum:

- Displays that indicate the available VSA execution control parameters, their current value, and their default value.

- Displays that graphically show the variation of a voltage stability index with a given interface flow, the critical interface flow limit for a single contingency, and its envelope curve for all contingencies processed during VSA execution.
- Displays that show the unacceptable (insecure) contingencies for the previous VSA executions.
- Displays that indicate the “new” insecure contingencies that were not identified as insecure in the previous VSA run, and the previously insecure contingencies that are no longer insecure.

C. Save Case Capability The user must be able to request the on-line (real-time) or study mode VSA data and results to be saved.

A save case should include the following data and parameters:

1. The pre-contingency steady-state base case. The base case may have been generated under real-time sequence control (State Estimator solution, possibly augmented by other VSA or EMS satellite functions, to provide a VSA base case), or via a study power flow solution.
2. Additional status and analog data needed by the rule base (e.g., remedial action arming status).
3. All VSA execution parameters (tolerances, thresholds, etc.) and configuration (e.g., screening bypass).
4. The contingency list selected/produced by the Contingency Selector.
5. VSA results generated according to the execution parameters. The user must have the capability to call up a menu to select the VSA results to be saved. This should include the capability to select a variable category, and item, as follows:
   - Screening results (contingencies discarded or retained).
   - Ranked lists of severe contingencies along with the value of the ranking index for each ranking index used.
   - Overall VSA summary results, including grouping of contingencies into voltage stable (secure) and unstable (insecure), final ranking of severe contingencies, interface flow limits, recommended remedial action arming, etc.

D. User Documentation The VSA user documentation should address, among other things, the following items:

1. What each function is supposed to do.
2. How to adjust data, parameters, options, etc., and what happens once those adjustments are made.
3. Descriptions of how to accomplish various tasks using the system and how to use its features. These need to be very clear step-by-step instructions.

4. The documentation should be self-contained and not reference other publications, except for general information.

An on-line “Help” facility is required to explain to the user all commands, functions, uses, outputs and any other features of the VSA package.

5.2.12.2 Operator Requirements

This section presents specific user requirements for the operators.

A. Operator Interaction The on-line VSA environment should be easy to understand and manipulate. Specifically the following facilities should be provided:

1. The on-line VSA must be initially consistent with operating orders (See Section 5.2.13.1) based on off-line analysis. New features, whether based on indices or the use of modern graphic facilities, should take into consideration the structure and contents of the current operating orders so that the transition to the on-line VSA is smooth and credible.
2. The operator should have the ability to include or exclude screening in on-line VSA execution.

B. Security-Related Information Provided to the Operator As a minimum, the following security-related information should be provided to the operator:

1. Operating limits associated with a prescribed set of contingencies, i.e., generation limits, VAR support limits, voltage stability margins, reactive margins, etc.
2. Transfer limits on important individual or simultaneous interfaces.
3. Coordinated action to affect various transfers securely against voltage instability threat.
4. Sensitivities of changes in the voltage stability limits/margins to specific operator actions (if available).
5. Time trends associated with expected system changes which would allow the operator to estimate the time available for intervention with a given operator-initiated measure.
6. Warning when the current VSA results are no longer valid due to changes in power system conditions. This can be implemented via an appropriate alarm that indicates that system conditions have changed and that prior VSA results are no longer valid.
7. System trend information indicating whether things are getting better or worse. This trend information is to be based on changes in key system indices and customized for indices applicable to the utility.

C. Applications of the On-Line VSA Function The operator should be able to utilize the on-line VSA for the following applications:

1. Compute the VSA limits needed to determine Available Transmission Capability. This will be realized by incorporating VSA limits along with thermal limits,

Steady-State Security Analysis (SSA) limits, and Dynamic Security Assessment (DSA) limits in an Operating Limit Determination (OLD) function. The OLD function (which is not part of VSA) may accommodate box-type operating limits or inter-dependent limits (operating regions).

2. Outage dispatching for possible outages of generators, lines, transformers and reactive groups. This entails a study mode application of the VSA function.
3. Incorporation of critical contingency results in relevant on-line application software like the optimal power flow.
4. Preventive actions: list of possible preventive measures for operator decision together with the "cost" associated with each measure.
5. Arming: Arming recommendations for coordinated automatic corrective action to ensure "vigilance" against the contingencies of concern.
6. Corrective Action: following the possible occurrence of critical contingencies, a list of potential corrective measures should be made available.

D. Direct (Scan Rate) Monitoring Using a window into the SCADA system, or otherwise, the operator should be able to monitor designated bus voltages, as well as generator and static var system reactive power and reactive reserve for individual units, groups of units, and power plants for which SCADA scan rate data is available.

The capability should be provided to graphically display the selected monitored quantities and their trend with time, along with relevant computed composite voltage security indices.

5.2.12.3 Operations Planners/Engineers User Requirements

These include all of the user requirements stated in Sections 5.2.12.1 and 5.2.12.2 (for the operators), except Section 5.2.12.2.D, plus the following:

1. Ability to adjust certain system parameters: this may apply to selection of fewer or more contingencies, together with the ability to construct system scenarios for study purposes.
2. Ability to include or exclude time domain simulation for Contingency Analysis.
3. Ability to recreate an actual event and study its validity against measured data.
4. Capability to perform model reduction/equivalencing for operator's use. The model reduction capability may be an off-line tool, but the VSA should offer the possibility to test the impact of choosing different external models, and compare them.
5. Capability to compare cases to other utilities through standardized inputs and outputs and the ability to interface with time-simulation stability programs. (This will be a feature to be specified separately for each utility's VSA specification if needed.)

6. Capability to compare cases against each other through appropriate graphical means that focus on the key parameters associated with various comparisons (e.g., indices, margins, sensitivities and trends).

Provisions should exist for efficient and easy-to-carry-out database maintenance, including the ability to define specific and generic contingencies, and to modify the contingency list, the network, device models and the rule base.

5.2.12.4 Managers User Requirements

This category of user requirements includes the following:

1. Summary reports on system performance as provided by the voltage stability indices and their corresponding time evolution.
2. Reports on actual vs. computed results to assess validity of the results. These are study reports based on Engineer's activities in cases of severe events on the system.
3. Reports on critical events.
4. Summary logs of critical variables.

5.2.13 Interface Requirements

This section addresses the main VSA interface requirements with other automated functions.

5.2.13.1 Consideration of Existing Automated Operating Orders

The operating orders involving determination of the interface flow limits and/or arming of remedial action schemes may be available in an automated environment at the utility. In this case, most probably an automated table look-up process is available. Since the states in the look-up table cover only sample operating conditions, usually interpolation, extrapolation or scaling follows the table look-up process to adapt the table look-up results to the prevailing operating conditions. The VSA rule base should be able to accommodate such rules. VSA should interface with the Automated Operating Order subsystem to obtain information regarding selected contingencies, interface flow definitions, interface flow limits, and the arming scheme. It should provide the capability to compare the operating limits, and arming, obtained by applying the operating orders, with those obtained based on VSA execution.

5.2.13.2 Interface With EMS Functions

On-line VSA should be capable of using the output results of existing host-EMS functions such as State Estimator, Dispatcher Power Flow, and Optimal Power Flow to establish the power system conditions to be analyzed by VSA. These conditions may take the form of a power flow solution that represents the state of the actual power system or the state of a projected or study version of the power system.

In the real-time mode, VSA must typically interface with State Estimator results. Other options exist, however, that depend on host-EMS capabilities. For example, if actual security violations are detected by State Estimator, Optimal Power Flow may execute automatically to determine appropriate corrective action. The host EMS may then run its Steady-State Security Analysis function. In which case, if the corrective action is projected to give rise to a power system state with contingency problems, Optimal Power Flow may run once more to determine appropriate preventive action. This means that the user may wish to run VSA on a power flow solution established from:

a) actual real-time conditions, as reflected in the State Estimator solution,

b) conditions corresponding to "steady-state" corrective actions, or

c) conditions corresponding to "steady-state" preventive actions.

VSA implementation should allow the user to coordinate VSA execution with the host-EMS real-time sequence accordingly.

In the study mode, VSA should typically interface with Dispatcher Power Flow results. Host-EMS studies using Optimal Power Flow may also be possible. Therefore, VSA implementation must allow the user to demand the execution of VSA on any study power flow solution that can be created or retrieved via host-EMS facilities.

Further, in real-time or study mode, VSA should use both the power system model and the power flow results of the EMS function to generate and initialize the VSA power system model that will serve as a base case and hence starting point for subsequent VSA processing.

VSA should also be capable of using the output results of the host-EMS real-time and study Steady-State Security Analysis functions. For example, for a given power flow solution, the corresponding Steady-State Security Analysis results may help VSA determine the relevant contingencies it should analyze.

VSA should use real-time sequence results as they are generated in response to the existing demand, event, and periodic execution mechanisms that serve steady-state security analysis in the host EMS. In addition, however, VSA should be capable of using the output results of host-EMS functions such as remedial action arming status, the Operating Orders, etc., to determine if a change in the status of breakers and/or corrective device arming should trigger execution of the EMS real-time sequence solely for VSA purposes. In this case, the flexibility to execute a subset of the normal real-time sequence should be provided (e.g., execution of State Estimator without subsequent execution of Optimal Power Flow and Steady-State Security Analysis).

The ability of existing EMS functions to access VSA output results should also be provided. This should include the use of recommended operating limits (interface flow limits) and recommended corrective-device arming status and associated threshold levels.

5.2.13.3 Interface with EMS Services

VSA should interface with EMS services to obtain real-time or study power flow solutions, corresponding power system models, and the other results from SCADA and Automated Operating Orders that it needs. These services should provide facilities to output VSA user messages such as convergence or voltage insecurity warning messages, and provide EMS access to VSA results such as interface flow limits.

To permit direct (scan rate) monitoring of designated voltage or reactive power quantities, data interface to SCADA should have the capability to transfer selected SCADA telemetered or computed data to VSA every scan cycle (e.g., 2 seconds) or a user-selectable multiple thereof (e.g., every 10 seconds).

5.2.14 Sizing and Performance Requirements

The sizing requirements are the basis for the VSA performance testing assuming that high performance Workstations are used. In exceptional cases where the sizing requirements of a utility exceed those stated below, the VSA software should be capable to handle the required sizing with proportionally reduced performance. The maximum sizing requirements for such parameters are indicated below in parentheses.

5.2.14.1 Sizing

The VSA design must be modular and parametric, with sizing parameters that permit easy adjustment by the utility Engineer. Dependent sizing parameters (e.g., dimensions of work matrices, etc.) should be automatically adjusted, and should not require adjustment by the Engineer.

1. Network size:

Buses	2000 (Max. 10 000)
Branches	3000 (Max. 12 000)
Generators	500 (Max. 1500)
Induction Machines	200 (Max. 1000)
ULTCs	500 (Max. 1500)
Phase Shifters	50 (Max. 300)
Multi-terminal HVDCs	20 (Max. 50)
SVCs	50 (Max. 200)

2. Monitored interfaces: 5 (Max. 50)

3. Contingencies:

Number of specific contingencies	300 (Max. 2000)
Number of power system elements involved per contingency	100 (Max. 1000)

4. Save case storage requirements:

   Number of VSA executions to be saved:

   - Real-time sequence executions (for 4 days): 300
   - Study save cases: 100

   Number of contingencies per VSA execution: 300

5.2.14.2 Performance Requirements

The performance requirements stated below are based on the expected sizing requirements (not the maximum values) stated above and reasonable performance scenarios. The VSA hardware platform is assumed to consist of a high performance Workstation. The following VSA execution parameters are assumed:

1. VSA execution periodicity: 20 minutes
2. Mix of contingencies: 300 contingencies with different degrees of complexity, including no more than 30 severe contingencies (i.e., such that a good contingency selection/screening process would not select more than 30 contingencies for full processing).
3. VSA execution: VSA execution will include contingency selection, screening, classification, ranking, and limit determination, as well as computation of the preventive, arming, and corrective actions.

There must be no misclassification of an insecure contingency as secure. The operating limits determined should be accurate within 2 percent of the limits that would be obtained from analysis of the same initial steady-state, and contingencies, using off-line detailed models and tools, and involving trial-and-error changes in the interface flows of interest.

5.2.15 Expandability

The VSA design must be modular and must comply with accepted guidelines of open system architecture (operating system, programming language, database, graphic user interface, and application program interface guidelines). The VSA design must be flexible and expandable to accommodate additions and changes, particularly for preventive, arming, and corrective actions, their determination and coordination in subsequent developments of the on-line VSA.

5.3 TOOLS

In recent years several tools have been developed for the assessment of voltage stability or security of power systems. Some of these tools are in everyday use in the operation of large complex systems. This section includes the following tools as described by their respective developers:

1. ASTRE from University of Liege, Belgium.
2. AVS from University of New South Wales, Australia.
3. CPF/EQTP from Iowa State University, USA.
4. UWPFLOW from University of Waterloo, Canada.
5. VOSTA from Polytechnic of Milan and University of Pavia, Italy.
6. VSA from Siemens, USA.
7. VSAT from Powertech Labs Inc., Canada.

5.3.1 ASTRE

ASTRE[3] is a voltage stability/security tool for system planners, operation planners and control centers. It is well suited to off-line studies involving a large number of simulations, as well as to on-line applications.

5.3.1.1 Applications and Main Functions

ASTRE performs several types of studies relevant to voltage stability/security analysis:

- Contingency evaluation
- Loadability limit computation
- Secure operation limits, i.e. pre-contingency limits on power transfers considering the impact of contingencies
- Small-disturbance (eigenvalue, eigenvector) analysis of instability mode
- Determination of optimal *post*-contingency remedial (corrective) actions: Minimal post-contingency load shedding
- Determination of optimal *pre*-contingency remedial (preventive) actions: Minimal generation rescheduling, minimal pre-contingency load shedding.

5.3.1.2 Computational Techniques

The heart of ASTRE is a Quasi Steady-State (QSS) time simulation. This fast time-domain method, outlined in Section 3.1.3 of this report, consists of replacing the short-term dynamics, considered infinitely fast, by equilibrium (i.e., algebraic) equations, while focusing on the long-term dynamics. The method is well documented in [10]-[14]. It has been carefully validated with respect to multi-time-scale (i.e., full) simulation on the Hydro-Quebec [13] and EDF systems. It combines the advantages of time-domain methods (accuracy, handling of dynamic controls, interpretability of results, possibility to obtain information on the instability mode, etc.) with the computational efficiency of static (mainly load flow type) methods.

ASTRE is also interfaced with a full dynamic simulation package (see below).

5.3.1.3 Features

The software is made up of three modules (in practice three executables communicating through files): (i) A full AC power flow used for generating stressed pre-contingency operating points, taking into account possible pre-contingency actions while the system is being stressed; (ii) a QSS simulation module for the simulation of a list of contingencies at a given stress level, with criteria checking during and at the end of the simulation; (iii) and a module aimed at calling the first two, according to the Simultaneous Binary Search (SBS) logic. This module allows to "replay" any

[3] French acronym for "Analyse de la Securité de Tension des Réseaux Electriques" (Power network voltage security analysis)

combination of system stress and contingency, launches the computation of post-contingency remedial actions and determines pre-contingency remedial actions.

(1) *Contingency Evaluation*. The system response to contingencies is determined using the QSS fast time-domain simulation.

(2) *Loadability Limits*. These are determined imposing a smooth ramp of load increase and checking the small-disturbance stability through the sign of sensitivities computed along the system trajectory.

(3) *Secure Operation Limits (SOLs)*. For a given system stress (changes in load and/or generation, power transfers, etc. which make the system weaker) and predefined contingencies, a SOL corresponds to the maximum value of the stress such that the system can withstand any of the contingencies. SOLs can be easily interpreted insofar they refer to pre-contingency parameters that operators can either observe or control. SBS is used to determine the SOL corresponding to the most severe contingency(ies) (obviously, the limits of the other contingencies can be computed as well).

(4) *Contingency Filtering and Screening*. The SBS itself is organized so as to quickly get rid of the harmless contingencies during the computation of the SOLs. In addition, if the dynamics allow, a post-contingency load flow (with proper handling of generator reactive power limits and frequency control) can be used to screen contingencies at maximum stress and discard the harmless contingencies.

(5) *Remedial Action Determination.*

- Pre and post-contingency load shedding: An automatic procedure first analyzes the optimal shedding location, then determines the minimal amount of load shedding. This analysis can be repeated for various shedding delays, in the post-contingency approach.
- Generation rescheduling: Sensitivities of load power margins to active power injections are used to build a set of linearized security constraints, that can be embedded in a standard Optimal Power Flow. Two simplified versions of this OPF are included in ASTRE: Minimum generation rescheduling and minimum linear production costs.

5.3.1.4 Models

With the QSS technique, the system evolution is approximated by a succession of short-term equilibrium points. At each point, the network power flow equations are solved together with equations stemming from the equilibrium conditions of the short-term dynamics of generators, AVRS, governors, SVCs, etc. For instance, the saturation, speed droop and voltage droop effects of generators are reproduced, giving access to generator field currents for checking and enforcement. Please refer to [11] for a detailed description of QSS models.

The dynamics are driven by continuos processes (e.g. load increase, generic load power restoration models) as well as by discrete devices (e.g. load tap changers, overexcitation limiters, automatically switched shunt compensation, secondary voltage controllers, thermal tripping of lines, undervoltage load shedding, etc.)

5.3.1.5 Interfaces

(1) *Input data*. Interfaces are available to translate the load flow data files written in IEEE, PTI, RP600 or EUROSTAG format into the ULg format used by ASTRE. The dynamic data files are also in this ULg format.

It is also possible to re-use the data files of existing full dynamic simulation programs. For instance, an interface picking up the relevant QSS data into the dynamic data files of the ST600 package is in use at Hydro-Quebec; another one is under development to do the same with PSS/E.

Finally, a coupling between full and QSS simulations has been recently developed in collaboration with Hydro-Quebec. Following a large disturbance, this combined tool allows to test the short-term (or transient) period with full detailed simulation and, if the system has survived this period, to switch to QSS simulation to test long-term voltage stability, once the fast transients have died out. The switching is made transparent to the user.

(2) *Reports*. The program yields listings, time plots, bar charts (e.g., for voltage profile display) and display on one-line diagrams. Graphical display is performed outside ASTRE, using company software or general packages such as GNUPLOT and MATLAB, etc.

5.3.1.6 Computational Environment

There are basically two versions:

1. A “character-mode” version, well suited to intensive number crunching. This version has been integrated into other power system packages under Unix and Windows NT.
2. A PC version, with a full Windows user interface. This version has been used as stand-alone and is currently being considered for voltage security analysis within an EMS environment.

The models of the above quoted systems rank from 600 to 2500 buses, all allowing an interactive and real-time use. The most up-to-date figures are available in [15].

5.3.2 AVS

AVS is a dynamic system voltage stability program aimed at the planning and development of large interconnected power systems to successfully withstand the effects of unpredictable multiple contingencies. The program incorporates a strategy that can safeguard grid integrity and maintain system voltage stability. It is intended for use by the operation planners and system planners.

5.3.2.1 Applications and Main Functions

AVS is able to analyze post-disturbance effects caused by multiple contingencies that endanger system voltage stability on extensive interconnected power systems. With any multiple contingency the program produces a series of outputs, each corresponding to one of the post-disturbance sequential dynamic changes. At each dynamic step, parameters for the entire power system network can be retrieved and the program gives the option to print any or all of this information. The program offers summary tables of selected parameters at each step.

5.3.2.2 Features

The program can be used on a Personal Computer (PC) and incorporates an adaptive control strategy appended to a load flow that can deal with networks of 15,000 busbars. The program would be used like conventional load flow programs by inserting the network data file for the power system to be examined.

Additional information is also required, such as the timing of automatic transformer tap changers and similar parameters as well as nominating measures, such as load shedding to deal with post-disturbance events. This extra information is provided for the special control strategy that has been able to respond to multiple contingencies, anywhere on the EHV grid, and initiate the appropriate measures that would maintain grid integrity and regain viable operating conditions. This control strategy is able to initiate each of the post-disturbance dynamic changes for which a separate program output is produced. They include both continuous changes, such as tap changing as well as the selected measures, such as load shedding. If, in using the program, no measures or inadequate measures are selected the program will continue to the point just prior to the loss of angular instability (and collapse). The program has been made sufficiently robust so as to achieve convergent solution for severe multiple contingencies, the starting point of the post-disturbance dynamic series of evaluations. It allows studies on the entire interconnected network and so avoids the erroneous reactive power assessments that follow from network simplifications. The advantage of the program as a planning tool is its faster turn around as compared to conventional dynamic study programs in which turbo-generator governor actions are included.

The control strategy has been shown to be effective by a number of network studies with multiple line outages. For example, when 5 lines were opened simultaneously on an EHV grid with a 15,000MW demand, the control strategy initiated measures, including 1000MW of load shedding, for regaining a viable operating state [16], [17].

The control strategy incorporated in the program has been devised to respond and adapt to multiple contingencies of the severity which have led to severe voltage instability incidents in power systems throughout the world. It thereby vaults beyond the limitations of prevailing planning criteria that consider only single and double contingencies, and are unable to deal with the unpredictable multiple contingencies that have occurred in reported incidents. The new strategy is intrinsically simple and could be developed into a "system protection arrangement" for automatically safeguarding system voltage stability. Such an arrangement could be retrofitted to a power system at a modest cost as it is based on inexpensive control measures in contrast to present approaches for which large capital expenditures are required to reinforce power systems with the current approaches that use planning criteria. It would then allow higher power flows on EHV lines now constrained by operational security measures against system voltage instability which, in any case, have not avoided power system collapses.

5.3.2.3 Method of Use

The program input would typically be an unfavorable generating schedule that produces heavy power flows on lines of the EHV interconnection and, using this load flow as reference, the planning engineer would then choose severe multiple contingencies, such as outages of heavily loaded lines. For each of the multiple outages, the program would automatically generate a series of load flows, each corresponding to a dynamic change, and continuing until automatic measures had regained voltage stability. The dynamic study sequence is programmed to stop when measures have reduced the level of excitation, so that not one unit's rotor current exceeds its continuous rating, the point when voltage stability has been regained. Information with the program proposes measures suitable for controlling voltage stability.

An important reason for using the program would be as a stepping stone for implementing a "system protection". Apart from confirming that the strategy would be effective on the power system under study, the program offers two new and vital avenues for a system protection.

Firstly, because there is no adequate history of multiple contingencies and collapse, the program would provide a sufficient number of such incidents to allow the calibration of the parameter changes required for directing the necessary responses of the system protection.

Secondly, the program can be used to select cost-effective measures, appropriate to the power system under examination as well as the best timing of their actions.

5.3.2.4 Computational Techniques

The program performs a full time simulation of power system operation using a full AC power flow. The program implements advanced models and controls of all voltage control devices (generators, SVCs, transformers, etc.), especially their time and overload characteristics.

5.3.2.5 Interfaces

The user interface is the standard Windows Graphical User Interface. System data is entered via text files. The planner is then able to modify control strategies online, with results presented both in windows as graphs and tables, or to files. The results for each time step comprise all the operational data that would be required to re-create a network model: voltages, generator quantities, transformer taps, etc.

5.3.2.6 Performance

The program is capable of performing simulations on networks up to 15,000 Busbars in size. On a standard PC, the complete dynamic simulation typically takes less than 10 seconds (CPU) for a 100 busbar network, and 2 minutes (CPU) for a 1000 busbar network. This then means that the planner can perform a significant number of simulations of different contingency combinations and control strategies in less than a day.

5.3.3 CPF/EQTP

Continuation Power Flow (CPF)/Equilibrium Tracing Program (EQTP) is an off-line voltage security analysis package intended for use by system planners, operation planners and educational institutions.

5.3.3.1 Applications and Main Functions

The program can trace PV curves for any given operating condition and scenario and provide margin sensitivity information. It also provides transfer limits for various transactions. It can handle large scale practical power systems.

5.3.3.2 Computational Techniques

CPF uses power flow based formulation while EQTP uses differential and algebraic based formulation.

Advanced bifurcation based techniques are incorporated to solve nonlinear algebraic equations. The program takes advantage of sparsity based iterative solvers. The program is well conditioned near the nose point.

EQTP solves system differential and algebraic equations simultaneously so that all the system variables including the state variables and the algebraic variables are obtained in one step.

The program identifies system voltage collapse point during the direct equilibrium tracing process, without rebuilding the system dynamic Jacobian matrix and costly checking its singularity. The voltage collapse point thus identified is rigorous in the sense of small disturbance stability

The following references provide the details regarding CPF [18] and EQTP [19] programs. Sensitivity analysis is given in references [20], [21]. The control strategies are given in references [22], [23]. The techniques related to bifurcation are discussed in [24], [25].

5.3.3.3 Features

The program is well suited for understanding the mechanism of voltage collapse as well as the development of corrective or preventive control strategies, such as how to reschedule real power generations, carry out secondary voltage controls, and as a last resort, shed loads to mitigate voltage collapse.

Some of the salient features of the program are:

- PV curve automatic tracing:
  - Provides true maximum power point by considering relevant dynamic factors
  - There is no need for slack and PV buses
- Sensitivity analysis (qualitative):
  - Screens the contingencies that may lead to voltage collapse

  - Locates the weak areas
  - Identifies the critical generators

- Margin sensitivity (quantitative):
  - Provides voltage stability margin estimation

- Unsolvable cases:
  - Can solve unsolvable cases created by a line or generator outage

- Available Transfer Capability as limited by voltage stability:
  - Simulates simultaneous multi-area transactions
  - Provides transaction sensitivity; identifies and ranks the transactions that are detrimental to voltage stability

- Preventive and corrective strategies against the voltage collapse:
  - Strategies for minimum load shedding
  - Strategies to maintain a certain voltage stability margin

- On-line voltage stability monitoring and control:
  - Developing methodologies to utilize off line studies for on line implementation

5.3.3.4 Models

Dynamic models include synchronous generator (two axis model), prime mover, speed governor and excitation control system. Field and armature current limits as well as generator real power limits are included. Generators are modeled to regulate their own respective generator terminal bus.

The governor speed-droop characteristic and the automatic voltage regulator (AVR) steady-state characteristic are fully modeled for each generator so that the assumptions for slack (infinite) generator and PV generators are eliminated. The program supports voltage and frequency dependent load models; this includes constant P-Q, constant I, constant Z, or combination. Tap changer and switchable shunt models are supported.

Three types of HVDC models are incorporated: (i) Power controlled, which keeps the power transfer at the set value; (ii) voltage controlled, which keeps the voltage magnitude on sending end or receiving side buses at the set value; and (iii) current controlled, which keeps the direct current at the set value.

The program is flexible enough to include any other model of interest.

5.3.3.5 Interfaces and Computational Environment

The program can read the data in IEEE common data format. Some modifications are needed to read PTI data format. A graphical user interface is under development for presenting output results.

The program can work either on PC or on a Unix based workstation.

5.3.4 UWPFLOW

UWPFLOW (University of Waterloo Profile FLOW) is mainly a research tool that has been developed at the University of Waterloo, Canada, in collaboration with the University of

Wisconsin-Madison, USA [26]. The program has been primarily designed for researchers working in voltage stability analysis of power systems; however, given the characteristics of the program, it can be and has been used in planning studies of power networks.

5.3.4.1 Applications and Main Functions

The program allows to perform a variety of voltage stability analyses mainly for off-line studies. It basically performs multiple power flows using detailed steady-state models of the various system elements to calculate local bifurcations associated with system limits or singularities in the system Jacobian, and thus determine voltage collapse points of a power system as well as its transfer capability limits (ATC) [27], [28].

The program produces nose curves, also known as PV/QV or voltage profile curves, in MATLAB format, so that plots can be readily generated with the help of this program. Other output to allow for further studies using MATLAB and AWK, such as sensitivity analyses to determine the best locations for Flexible AC transmission (FACTS) controllers such as SVCs, STACOMs or TCSCs, are also generated together with code files for easy post-processing of this information. For example, the program yields various types of Jacobians and related left and right eigenvectors associated with the smallest eigenvalue at any loading point; it generates tangent vectors at different loading levels; etc.

UWPFLOW also produces several of the voltage stability indices described in Chapter 4, which can be used to further study the stability of the network, especially when using energy function based indices [28]-[30].

5.3.4.2 Computational Techniques

UWFLOW basically uses detailed models to perform accurate steady state and standard power flow calculations in power systems. The program is designed to compute nose curves and collapse points using multiple power flows, continuation methods and/or direct methods, which are discussed in detail in Chapter 4. Given the detailed representation of various power system elements, the program can also be used to determine the progression of steady state points as system conditions change; a new feature is being currently added to the program to be able to perform these types of studies automatically.

The program is based on a robust Newton-Raphson numerical technique and uses the full system Jacobian and sparse matrix manipulation techniques to perform its computations. The parameters that control the numerical solutions and convergence criteria are given default values to guarantee accuracy at the expense of time performance; however, the user can change these values at will to stress either the computational accuracy or to speed up the program.

5.3.4.3 Features

The main technical features of UWPFLOW are:

- It can be used to compute the maximum loading margin, i.e., the “distance” to a voltage collapse point [31].
- Generates full voltage profiles or nose curves [31], [32].

- Yields a variety of output data and files to readily carry out additional studies such as contingency ranking and sensitivity analyses to determine the best location for shunt and series compensation [33].
- It allows to model in detail a variety of system elements in steady state, including their controls and limits, as described below. Hence, the margins to collapse produced by the program can be considered as "true" steady state stability margins, as long as the system does not present an oscillatory problem (Hopf bifurcation) [34].
- Given the available models, the steady state solution of the system can be traced in "time" as the system changes.

5.3.4.4 Models

The program is able to read WSCC/BPA ac-dc input data files [35], as well as IEEE common format files [36], and input data files based on Italian data formats for power flow and optimization programs (INPTC1 DAT files and COLAS ADD files). Hence, in addition to the "standard" power flow models for generators, transformers, transmission lines and loads included in all of these formats, the program is also able to represent:

- Remote controlled PV buses. Using this feature, secondary voltage controlled, as defined by ENEL [37], has also been implemented.
- ULTCs and phase-shifters for local and remote V, P and Q control.
- Area interchange control.
- Switched-reactance controlled buses.
- HVDC links, including all its controls and limits [31], [38].
- Accurate steady state models of FACTS controllers, including their main controls and limits [39]. Models of SVCs, TCSCs and STATCOMS are already included, and new controllers are being added.
- Voltage dependent load models based on EPRI's SSSP models [40].
- Steady state models of generators, including their AVR and Prime-mover controls as well as its limits. Thus, armature and field current limits, as well as P, Q, and S power limits can be defined. The program is also able to simulate a distributed slack bus.

UWPFLOW has no limitations on system size, other than those imposed by memory limitations in the corresponding computational environment, i.e., RAM and swap space.

5.3.4.5 Interfaces and Computational Environment

The program has been developed in C and C++ and designed to run in WINDOWS and UNIX environments. It has been successfully used to study ac/dc/FACTS networks on PC and HP, DEC, and SUN SPARC workstations, generating full nose curves and a variety of other information for post-processing in realistic systems in reasonable times (e.g., for the “full” Italian system, modeled using a 670-bus system, full nose curves can be obtained in a PC-PENTIUM II running WINDOWS in about 50s).

In WINDOWS, the program runs under its own GUI and can be used together with its on-line manual. In UNIX, it runs as a standard command-line program; the manual is available in PDF format in this case. In both computational environments, the program can be executed using standard DOS and UNIX script files; this feature is used to run the tutorials provided with the program.

A large variety of command-line flags are available, so that the user can control the solution process in detail. Numerical tolerances, limits, system controls, etc., can be redefined or turned on and off using these flags to improve convergence characteristics or to speed up the computation.

Input data must be provided as text data files using a variety of typical formats, as previously indicated, as well as specially designed ones, as explained in detail in the on-line program manual and tutorials. The program generates a variety of output data that is either written onto the WINDOWS GUI or UNIX terminal, or into text files, depending on the command-line options, for post-processing with the help of MATLAB M files and/or AWK scripts generated by or available with the program. For example, the program does not create its own graphical nose curves, but rather generates an M file to obtain the corresponding plots using MATLAB.

5.3.5 VOSTA

The VOSTA (VOltage STAbility) program was developed at the Polytechnic of Milan and the University of Pavia to perform off-line computations for voltage security assessment and enhancements for short-term applications [41]. It is mainly intended for research applications, but operation planners could also make good use of this program.

5.3.5.1 Application and main functions:

In the security assessment module, the program simulates a load ramp. The load is distributed among the load areas following coefficients given by a load forecast (load pattern) and, within each area, among the load busses following the initial load level in each bus. Correspondingly, active power is produced by generators according to economic dispatch coefficients. Using a steady-state model, the total system load is calculated before a non convergence of the power flow occurs. Therefore, the output of the procedure is the voltage collapse distance (MW and MVAr margins) of operation points scheduled days or hours in advance. The same procedure can also be used, changing the loading pattern and the generator coefficients, to determine the maximum loadability of an area and the maximum power that can be transferred from area to area, as well as the maximum loading of a particular line or of a set of lines.

The security enhancement module preventively calculates the remedial control actions to be taken during severe or emergency alarm states [42], [43]. These remedial actions include rescheduling of generator voltages, re-dispatching of real power outputs, blocking of taps in ULTC transformers feeding the loads at MV levels, lowering the voltage targets of the consumers, switching reactive compensation devices, shedding loads, etc.

5.3.5.2 Computational techniques

VOSTA makes use of several indices to determine the security level of the power system with respect to voltage collapse. In particular, the following indicators can be calculated:

- The sensitivity value of the global reactive power production of all regulating units with respect to the reactive load increase in the whole system.
- The sensitivity value of the reactive power generation of an area with respect to the area reactive load.
- The sensitivity value of the pilot node voltage of an area with respect to the area reactive load for Secondary Voltage Regulation (SVR) applications.
- The maximum eigenvalue of the inverse of the power flow Jacobian complete and reduced matrices.
- The maximum singular value of the inverse of the power flow Jacobian complete and reduced matrices.
- The sensitivity matrix and the eigen (singular) values of the matrices that define the area characteristics in the presence of SVR.
- Some of the indices described in Chapter 4, particularly the quasi-linear index discussed in Section 4.3.3 [44].

The indicators mentioned above are calculated during the ramp process after each step, together with a full power flow solution for each operating point. A steady-state model is used taking into account the system equation nonlinearities as well as the discontinuities of the Jacobian matrix entries associated with active generator capability limits and ULTC transformer actions. The steady-state responses of ULTC transformers, the voltage dependence of real and reactive loads, and the response of AVRs and SVR are also accounted for.

5.3.5.3 Features

After the security assessment step, VOSTA can determine the best control actions to give the system a sufficient security level [45]. This computation is activated when the maximum singular value σ_{max} of the inverted PF Jacobian exceeds a threshold level that depends on the power system considered.

The preventive control actions taken into consideration in order to reduce σ_{max} are:

- Rescheduling of generator terminal voltages.
- Rescheduling of the pilot bus voltages in case the of SVR.
- Rescheduling of real power generation.
- Rescheduling of the reactive power compensation devices.

The first three goals are attained by controlling the busses that influence the behavior of σ_{max} the most; the computation is based on the second order information given by the sensitivities of σ_{max} with respect to any system parameter and makes use of a linear programming procedure. The rescheduling of the reactive compensation devices takes into account the cost of reactive resources and adopts a minimization technique.

In case of emergency, the load shedding strategy can be adopted, based on a linear programming function that minimizes the cost of the load curtailment. All these features can be used together with area or bus limits on the supplied real and reactive power.

Based on the techniques used for voltage collapse analysis, contingency analyses can also be performed [46]-[48]. VOSTA can exploit the features of the above mentioned second order sensitivities in order to detect the most critical branches, i.e., the branches whose tripping can cause voltage collapse. A first step is the ranking of the most dangerous lines; this can be done adopting a simplified model that transforms the analyzed branch in a real and reactive power injection at the branch terminals. The variations of σ_{max} determined through sensitivity calculations give an idea of the level of importance of each contingency considered. Similar results can be obtained with respect to branch admittance variations.

As the voltage/reactive problem is a highly nonlinear problem, usually the ranking is not sufficient by itself for understanding the "margin" of the system in case of contingency. For this reason, a quantification procedure has been introduced in VOSTA in order to define, in case of critical lines, the amount of reduction of real and reactive power needed to avoid voltage collapse in case of tripping. This is obtained by adopting an iterative procedure based on repeated power flow solutions.

The possibility to define the load increase profile to simulate a load ramp, and the generators that participate on that ramp give also the possibility to determine the maximum amount of real and reactive power that can be transferred securely from area to area or from bus to bus before voltage collapse (TTC, ATC) [49]. Of course, this maximum limit is calculated taking into account system nonlinearities, reactive power limits of generators, maximum and minimum voltage limits, and local and global control constraints.

5.3.5.4 Models

The models adopted in VOSTA are based on the steady state conditions. The steady state equations are taken into account both for the network (the full power flow equations), and for the control systems modeled (AVRs, SVR, generator limits, etc.). Machine and load dynamics are not taken into account. Currently, VOSTA makes it possible to study power systems of up to 1500 buses.

5.3.5.5 Interfaces and Computational Environment

The input data are given to the program in three files, namely, a binary file containing the data of the network (branch impedances, characteristics of the loads, data of the controlled buses, etc.); an ASCII file that defines the functions that the user would like to run; and an ASCII file that holds information about the controls and the relevant set points.

The program results are given as ASCII files that contain the information requested by the user, based on the performed studies.

Part of the program is now integrated with the SICRE environment, which is used for planning and operation analyses by the Italian System Operator.

VOSTA currently runs on Digital Alpha and Unix workstations. A PC version is currently under development.

5.3.6 VSA

The Siemens Voltage Stability Analysis (VSA) package provides power system operators and engineers an on-line tool to identify voltage stability problems. The VSA application can perform analysis based on State Estimator or Power Flow cases, thus providing results for current conditions or any future conditions of interest. VSA allows the operator/engineer to examine the effects of load, power transfers or other conditions on voltage stability.

5.3.6.1 Application

VSA is intended for use in an operations environment (real-time or operational planning). It can support analysis of current system conditions or postulated conditions.

5.3.6.2 Computational Techniques

A Continuation Power Flow (CPF) based on full AC power flow solution to incorporate the effects of reactive power flows, voltage limits and voltage collapse is used. Security margins are defined as the difference between the initial MW load and the collapse point MW load minus a specified MW back-off value. The margins are obtained by running Continuation Power Flow as the system is stressed by increasing the load in the sink and generation in the source. VSA utilizes Load-Tap-Changing transformers, Voltage Control Capacitors and Reactors and generator MVAR and phase shifter controls.

5.3.6.3 Features

Some features of the VSA application are:

- Flexible source/sink combination definition
- Contingency screening for improved performance
- P-V and MVAR reserve plots
- Base case and limiting contingency case collapse levels
- Monitored bus voltage values at collapse point
- Weak bus identification using Eigenvalue analysis

VSA can analyze multiple system changes simultaneously. The user can setup and study several distinct combinations of sources and sinks along with selected monitored buses and contingencies.

The analysis consists of the following steps:

- Contingency selection

- Contingency screening and ranking
- Contingency evaluation

The first step consists of selecting the contingencies to be analyzed. The large list of selected contingencies is then screened and ranked using fast ranking algorithms. Finally, contingencies flagged as potentially harmful during the screening and ranking phases are studied in detail using a specialized power flow. The output of this process is Limits to collapse in terms of MW load changes.

The voltage collapse studies of interest correspond to the medium term framework. Siemens has considered and adopted the implementation of quasi steady state methods based on the use of special purpose power flow analysis tools and modal analysis. The main tool for voltage stability analysis is a power flow program enhanced with continuation methods. The continuation power flow (CPF) is used for the computation of margins to collapse from a given operating point.

The following analytical tools are provided:

- Modal and sensitivity analysis methods to determine the nature of the equilibrium point as obtained from a state estimation solution reflecting the current power system condition.
- Continuation Power Flow to trace the PV-curves and determine the critical equilibrium point on this curve, and to compute stability margins.

5.3.6.4 Interfaces

The user interface for VSA provides the following capabilities:

- Retrieving real time State Estimator (SE) and study mode power flow solutions
- Multiple source/sink combinations allowing analysis of different operating scenarios
- Interactive source/sink definitions
- Contingency selection
- Monitored bus selection
- Display of results in both plot and tabular format
- Defining and modifying voltage security criteria
- Defining and modifying execution parameters

Output results are available from the detailed analysis. The result summary includes:

- The most limiting contingency
- Collapse MW level
- The most limiting contingency collapse MW level
- Critical voltage at monitored buses

The plotting facility allows the plotting of PV curve for any selected bus and source/sink combination. System MVAR Reserve plots are also provided based on selected generators.

Detailed unit reactive output summary provides tabular display showing all the unit reactive power output at the initial and critical point. The display also shows the actual and critical MVAr reserves for a group of critical units.

Detailed output of the solution can be generated for any solution point on the P-V curve. This output is provided to support the analysis of results. The available summaries include:

- Bus voltage summary for all buses
- Unit reactive output summary
- ULTC, VCC, VCR summaries
- Station tabular output

Results of the eigenvalue analysis are available to support identification of weak buses.

5.3.6.5 Computational Environment

VSA is supported on both NT and UNIX platforms. The VSA application is integrated with the Siemens suite of network applications. They can be implemented as a stand-alone system, as part of a full EMS or as an add-on to an existing system.

5.3.7 VSAT

The Voltage Security Assessment Tool (VSAT) determines the voltage security of a given system state as well as the security limit of any number of power transfers [50]-[53]. It is designed for use by the system planners and operators in off-line (stand-alone) or on-line (connected to a control center EMS) environments.

5.3.7.1 Application and Main Functions

For a given operating point, such as the snapshot of the on-line power system (provided by the State Estimator) or any other state of the system (future state or in a study mode), VSAT:

- Determines if the system remains voltage secure should any contingency occur.
- Determines the security limit of any specified power transfer in the system.
- Identifies the critical contingencies and the type and location of insecurities.
- Determines the best (most effective) remedial control action for returning an insecure operating point (transfer level) to a secure state.

5.3.7.2 Computational Techniques

The main computation technique for voltage security assessment in VSAT is the full AC power flow solution with the Fast Decoupled (FDPF) method. Voltage stability of the power system is indicated by the existence of the power flow solution when the generator VAr capabilities, action and limits of control devices, load models, etc. are properly represented. With the automatic step reduction, FDPF is capable of reaching the nose of the PV curves without numerical difficulties. Unlike some other tools which compute a post-contingency PV curve by increasing the load/generation after the contingency is applied at the base point (using Continuation Power Flow or conventional methods), VSAT traces the pre-contingency PV curve (with proper account of manual and automatic control actions) and then at each point applies the contingencies (which might be solved by different control options, e.g., switchable shunts frozen) to determine if that point is secure or not.

VSAT also includes the Fast Time Domain (FTD) simulation module which computes the Quasi Steady State response of the system to disturbances [10]. This method properly accounts for the chronology of events and slow dynamics of control and protective devices relevant to voltage stability of the power system.

Modal Analysis computes the bus participations from the eigenvectors of the reduced QV Jacobian matrix at the collapse point to identify the location of voltage instability in the system [54].

Remedial Action selection is based on the sensitivity of the security violation(s) to each control. The sensitivities are computed from the pre- and post-contingency Jacobian matrices.

5.3.7.3 Features

- *Contingency Screening*: For each transfer or stress, VSAT screens the long list of contingencies and selects the most severe ones that will be considered in the security assessment and transfer limit computation. The method described in [55] is very efficient and reliable (never misranks the contingencies).

- *Security Criteria*: The security is determined based on several criteria. The main criterion is that
  - The system must remain voltage stable under all contingencies

  Other criteria that can be enforced by the user are:
  - The system must have a given margin to instability, i.e., it must remain voltage stable when the load (and generation) increase by a specified MW (PV margin) and/or MVAr (QV margin) amount at specified regions of the system (or any other specified stress in the system)
  - The pre- and post-contingency bus voltages must remain within specified limits
  - The pre- and post-contingency VAr reserve of selected sources must remain within specified limits
  - The pre- and post-contingency loading of lines and transformers must remain below their thermal rating

- *Transfers*: Each transfer consists of one source and one sink (one-dimensional transfer) or two independent sources and one sink (two-dimensional transfer). Each source or sink may consist of one or more groups of loads or generators. For one-dimensional transfers, the source and sink are increased in equal steps until the security limit is reached (PV curve computation). For two-dimensional transfers, the security limits of all possible combinations of transfer between the two sources and the sink are determined. Different contingencies and security criteria can be specified for different transfers.
- *Remedial Action*: The control actions are selected from the specified list of available controls, such as capacitor and reactor switching, generator voltage setting, transformer tap setting, load shedding, etc., based on the priority specified for each group of devices. VSAT first determines the best preventive (pre-contingency) action considering all contingencies and all security violations. If these can not prevent insecurity under some contingencies, VSAT then determines the best corrective (post-contingency) action for each of those contingencies.
- *Distributed Processing*: VSAT Server (engine) can be installed on several computers on the network. VSAT Client (controller) automatically keeps track of available servers and distributes the transfer limit computations among the free servers. When there is one transfer limit to be computed, the contingency solution for that transfer is distributed among the servers [56].

5.3.7.4 Models

- All conventional and advanced models of devices and controls are supported by the power flow engine, including HVDC, FACTS, generator capability curves, etc.
- Power-flow data in PTI, IEEE, BPA and other formats are supported.
- Post-contingency load models can be any combination of constant power, current and impedance or any exponential function of voltage.
- Each contingency can include multi outages of lines, generators, loads, shunts, etc.
- Governor response and AGC dispatch options are provided for contingency solution.
- FTD accepts the dynamic data with the full range of models and retains those components that are relevant to voltage stability (overexcitation limiters, tap changers, etc.)
- VSAT can handle systems as large as 32000 buses.

5.3.7.5 Interface

VSAT client has a Graphical User Interface for setting up cases, entering data, controlling the program execution and viewing and plotting the results. Data for VSAT is provided in a set of ASCII files. In on-line application, the persistent data (e.g. security criteria) reside on the VSAT local disk while the power-flow and other non-persistent data is prepared by external applications (e.g. State Estimator) and passed to VSAT for security assessment. EMS or other applications can exchange messages or files with VSAT to initiate the computations, interrogate the status of each case and retrieve the results for display or storage on other media.

5.3.7.6 Computational Platform

VSAT Client runs on PC Windows 9x or NT. The computation engine can run on PC or Unix systems. On one Pentium II 450 MHz PC, the security of a 15000-bus system with 20 contingencies is determined in 30 seconds and the security limit of one transfer (PV curve with 20 contingencies) is computed in about 4 minutes. The execution time reduces almost linearly with the number of computers running VSAT Server simultaneously.

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