Consortium for Electric Reliability Technology Solutions

Real-Time Voltage Security Assessment (RTVSA)

SUMMARY REPORT

Prepared For:

California Independent System Operator (CA ISO)

Prepared by:

Consortium for Electric Reliability Technology Solutions (CERTS)

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This activity was lead by Manu Parashar, Electric Power Group (EPG), with assistance from research performers Abhijeet Agarwal, EPG and Yuri Makarov, Pacific Northwest National Laboratory and Ian Dobson, University of Wisconsin.

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by part nering with RD&D entities, including individuals, businesses, utilities, and public or private res earch institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Real Time System Operations (RTSO) 2006 - 2007 is the final report for the Real Time System Operations project (contract number 500-03-024 MR041 conducted by the Consortium for Electric Reliability Technology Solutions (CERTS). The information from this project contributes to PIER's Transmission Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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1.0 Introduction

Over the past 40 years, more than 30 major blackouts worldwide were related to voltage instability and collapse. Among them, at least 13 voltage-related blackouts happened in the United States, including two major blackouts in the Western Interconnection in 1996 and a wide-scale blackout in the Eastern Interconnection in 2003. Several times, the blackout investigation teams indicated the need for on-line power flow and stability tools and indicators for voltage performance system-wide in a real-time. These recommendations are not yet completely met by the majority of U.S. power system control centers. The gap between the core power system voltage and reliability assessment needs and the actual availability and use of the voltage security analysis tools was a motivation to come forward with this project. The project's aim was to develop state-of-the-art methodologies, prototypes, and technical specifications for the Real-Time Voltage Security Assessment (RTVSA) tools. These specifications can be later used by selected vendors to develop industrial-grade applications for California ISO, other California Control Area Operators, and utilities in California.

An extensive analysis of existing VSA approaches was conducted. This included research by Consortium for Electric Reliability Technology Solutions (CERTS), surveys from the leading experts' opinion worldwide, feedback from industrial advisors, and brainstorm meetings with the projects' industry and academia consultants. A state-of-the-art combination of approaches and computational engines was identified and selected for implementation in this project. Subsequently, a multi-year project roadmap was developed which has guided the CERTS research on evaluating and demonstrating the recommended approaches on the California ISO test cases.

The initial framework of this project was originally formulated in close consultation with the California ISO. The key elements of the suggested approach which are the use of parameter continuation, direct methods, and the hyperplane approximation of the voltage stability boundary were approved by a panel of leading experts in the area in the course of a survey conducted by Electric Power Group, LLC (EPG) at the project's onset in 2005. These concepts were also verified in the course of face-to-face personal meetings with well-known university professors, industry experts, software developers, and included email discussions and telephone exchanges. CERTS industrial advisors approved these developments during various CEC Technical Advisory Committee (TAC) meetings conducted in the past years.

In 2005, the project development team successfully implemented the parameter continuation predictor-corrector methods. Necessary improvements were identified and developed. The Power Systems Engineering Research Center (PSERC) parameter continuation program and MATLAB programming language were used in the project. During 2006-07, research work included the implementation of Direct Methods to quickly and accurately determine the exact Point of Collapse (PoC), Boundary Orbiting techniques to trace the security boundary, the investigation of descriptive variables, and the validation of techniques for analyzing margin sensitivities. These techniques were tested using a ~6000 bus state estimator model covering the entire Western Interconnection and, for the Southern California problem, areas suggested by California ISO, and results were reported.

At the completion of the project, a functional specification document was developed which describes the design, functional and visualization requirements for a Real-Time Voltage Security Assessment (RTVSA) tool, as well as California ISO's preferences on certain implementation and visualization techniques.

2.0 Voltage Security Assessment (VSA) Surveys

2.1. Expert Recommendations

CERTS/EPG formulated a survey to reach out to the experts in the field of voltage security for comments, information, suggestions, and recommendations related to the VSA project. The surveys were sent to fifty-one experts in universities and in the power industry. Sixteen reviewers responded and their responses are summarized in Table 1. Eight of these respondents are from the power industry and eight are from academia. Four proposals for commercial software were also received from Bigwood, V&R, NETSSS, and ECI.

ISSUE	RESPONSES / COMMENTS	CONCLUSION
Voltage Security Assessment (VSA) (Hyperplanes for security regions)	- Online hyperplane possible - Not as unproven as interior point methods. - Ideally suited for phenomena that is local.	Hyperplanes well suited for VSA
Methodology for computing hyperplanes	- Loading & Generation Direction needed. - Stress path until voltage collapses. - At collapse, determine local boundary.	Use left eigenvector approach
Direct versus Time-domain methods	- Time domain iterative methods are proven and robust, capable of handling intermediate discrete actions/events. Example: Generator limits being reached Direct methods rely on simplistic models	Direct Method could be used for fine-tuning the security boundaries after an iterative set of continuation power flows
Weak elements identification	- Voltage collapses are concentrated in certain regions in the sense that the voltage falls more in those regions. There is no single element that collapses. That is, voltage collapses occurs system wide with varying participation from all the system buses.	The participation is computed from the right eigenvector of the Jacobian evaluated at voltage collapse corresponding to the zero eigenvalue.

Table 1: Survey 1 – University & Industry Recommendations on VSA Project

The consensus opinion was that the hyperplane approach to defining security regions was ideally suited for voltage instability assessment. Voltage instability is more of a local area/region phenomenon. Several participants in the survey felt that full blown time domain classifiers should augment the algorithms that utilize Direct Methods. An engineer from a utility in Northern California said that it was not clear how switching conditions could be revealed without "time domain" simulations. A utility from the South shared its experience that it was unable to develop suitable production metrics because of the integration of both continuous (load growth) and non–continuous (contingency) factors into a single metric. The computational methods to be used in VSA could be grouped into two broad classes – the Iterative Approach using Continuation Power Flows and the Direct Method. The Direct Method does not provide information on any discontinuous events when the stress parameter is increased. These discontinuous events occur when a thermal, voltage or reactive limit is reached.

The majority of responses favor the use of the hyperplane approach in determining Voltage Security Assessment. Also, the majority of respondents did not see hyperplanes suitable for determining Dynamic Voltage Assessment at this time. Small Signal Stability Analysis was considered to be a good first step for Wide Area Stability Monitoring and assessment using phasor measurements.

In summary, the primary recommendation for Real Time Voltage Security Assessment tool is to use the hyperplane approach in computing the corresponding security regions. Others are:

The computational engine for California ISO's VSA is recommended to be the Continuation Power Flow. This tool has been tested and proven by several researchers in commercial and non-commercial software.

An alternate recommendation is a hybrid approach, where a Direct Method could be used for fine-tuning the security boundaries after an iterative set of continuation power flows.

These recommendations were incorporated into the overall proposed roadmap and project plan for the project (Figure 1), which was formulated through discussions with California ISO and through active participation of CERTS performers Dr. Yuri Makarov and Prof. Ian Dobson over conference calls and in meetings.

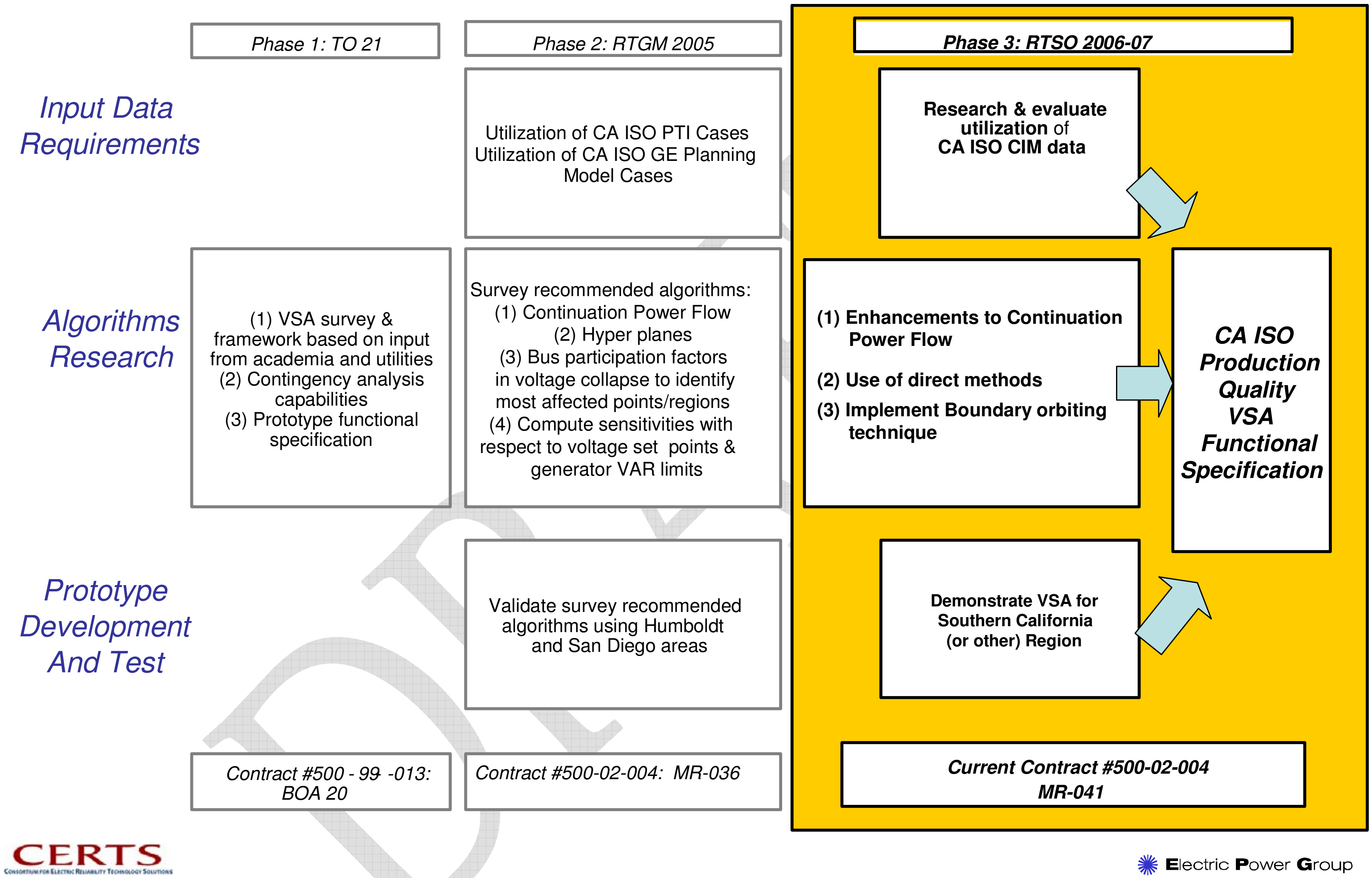

Figure 1: Multi Year Development Roadmap for California ISO Voltage Security Assessment (VSA) Project

2.2. Industry Best Practices

During the course of the project, a second survey was conducted among the vendors and utilities – the focus here was to evaluate existing power system voltage security tools and to identify the industry's best practices with the following goals:

- Survey interfaces and protocols that are currently used to import/export/exchange data, such as OPC or CIM/XML, in a power system simulation software, and thus, choose the one most appropriate for Real Time Voltage Security Assessment (RTVSA).
- Review available visualization capabilities within existing applications; identify the best available solutions and gaps between what is available and RTVSA vision.
- Assess processing capabilities of available applications, and recommend improvements for the RTVSA tool.

Several vendors and utilities responded to the survey request, providing valuable information about their tool's interoperability, processing and visualization capabilities. Subsequently, the CERTS team followed up telephonically with the participants in order to better understand their system. The following conclusions have been drawn based on the information provided by utilities and vendors through the RTVSA survey. The detailed survey responses are provided in Appendix B.

Interfacing Capabilities		
→	Tool type	The tools are essentially standalone applications; however, they are 'transformed' into an EMS/SCADA (or on-line) application by automatically triggering the tool for each valid SE solution.
→	Data integration	For real-time data, flat text files are predominantly in use that are either copied to shared folder or transferred via FTP. Service-Oriented Architecture (SOA) and Enterprise Message Bus technologies are being developed by users. Historical data are stored either in historians or in shared folders. Some tools (such as V&R's POM) back up input data for offline studies, such as trend analysis or post-mortem analysis.
→	Data source	State Estimator
→	External data input & output formats	Flat text files (e.g., pss/e, pslf) are favored by most utilities and vendors. CIM/XML input is optional only for V&R's POM and Powertech's VSAT applications.
→	Input data model	Both node/breaker and bus/branch is common *Comment: Typically, a topology processor, which is internal to tools, converts a node/breaker model to bus/branch for power flow calculations. Hence, a node/breaker model is redundant unless it proves visually useful to operators and dispatchers.*
Processing Capabilities		
→	Simulations	- Bigwood's VSA&E and V&R's POM can perform all simulations (mentioned in the survey) in real time - ECI's QuickStab perform all the simulations, though most of them run manually - Bigwood's VSA&E, V&R's POM, and Powertech's VSAT are the only ones to display operating nomograms

→	Maximum number of buses supported	Sufficiently large
→	PF simulation speed	Less than a second for the majority (although this may vary depending on the number of buses, contingencies, processor speed, etc.)
→	*Recommendations (for a real-time tool)*	Monitoring thermal overloads, voltage deviation, voltage stability and dynamic security (including the one based on phasor measurement data)
Visualization Capabilities		
→	Common display formats	- Tabular (contingency list, corrective actions, voltage profiles, weak elements) - Graphical (bar charts for voltages, Mvar reserves, etc. , PV plots, bubble plots) - Geographical (voltage contours, interface flows, one-line diagrams)
→	Most useful visualization capabilities	- Operating nomograms for various system parameters (such as generators, loads & import/export limits) - Limiting contingencies - Security margins - Transfer limits bar charts - Graphical Interface flows - PV plots - SCADA trending charts - Alarming capability
→	Vendors have stated that their VSA application *is* being used by both real-time operators and dispatchers	

Table 2: Survey 2 – Evaluation of Existing RTVSA Tools & Industry's Best Practices

3.0 CERTS RTVSA Framework and Algorithms

The RTVSA application is based on an extensive analysis of the existing VSA approaches, by surveying the leading power system experts' opinion worldwide, and also with feedback from industrial advisors, to address many of the limitations of existing tools such as:

Many existing tools use *the power flow existence criterion* to compute the boundary. This has the dangerous potential to overestimate the actual voltage security margin in situations where the saddle node bifurcation, Hopf bifurcation, or transient stability conditions are violated before the power flow equations become divergent.

The limitations of P-V/Q-V plots that represent the load versus the voltage of a selected bus become apparent when voltage collapses are not concentrated in a few buses. Some voltage collapses are regional or involve the entire system. P-V curves are calculated using the power flow solutions by step-by-step increasing the loads. The "nose point" of the curve corresponds to the maximum power which can be delivered to the load. The bus voltage at this point is the critical voltage. If the voltage of one particular bus approaches the nose point faster compared to the other buses, it is assumed that the system voltage stability margin is limited by this bus. This information does not capture the extent to which all the variables participate in the voltage collapse.

Many of the existing voltage security applications are run in an offline analysis mode. The additional constraint that the voltage security assessment be performed in real time imposes new speed/performance requirements that can only be met through a combination of the state-of-the-art algorithms embedded within an innovative framework.

The mismatch between the core power system reliability needs and the availability of the VSA tools was a motivation to design the following special features into the RTVSA application.

3.1. Real-Time Voltage Security Assessment Framework

The most promising method for determining the available voltage stability margin in real time is based on piece-wise linear approximation of the voltage collapse boundary in coordinates of independent power system parameters (i.e. Hyperplanes). The approximating conditions are calculated off-line as a set of inequalities specific for each analyzed contingency:

$$\begin{cases} a_{11}P_1 + \ldots + a_{1n}P_n + b_{11}Q_1 + \ldots . b_{1n}Q_n \le c_1 \\ a_{21}P_1 + \ldots + a_{2n}P_n + b_{21}Q_1 + \ldots . b_{2n}Q_n \le c_2 \\ \ldots \\ a_{m1}P_1 + \ldots + a_{mn}P_n + b_{m1}Q_1 + \ldots b_{mn}Q_n \le c_m \end{cases} \quad (1)$$

The number of constraints m and the number of parameters P and Q included in each constraint are expected to be limited. Each face of the region approximates a part of the nonlinear region's boundary. The advantages to the proposed approach are:

- Fast and Convenient assessment: Having constraints (1) pre-calculated offline for each analyzed contingency, it is very easy to quickly determine in real time:
  - Whether the operating point is inside or outside the security region (by making sure that all approximating inequalities are satisfied)
  - Which constraints are violated (by identifying violated inequalities), and
  - What the most limiting constraints are (by calculating the distance from the current operating point to the approximating planes – see below).

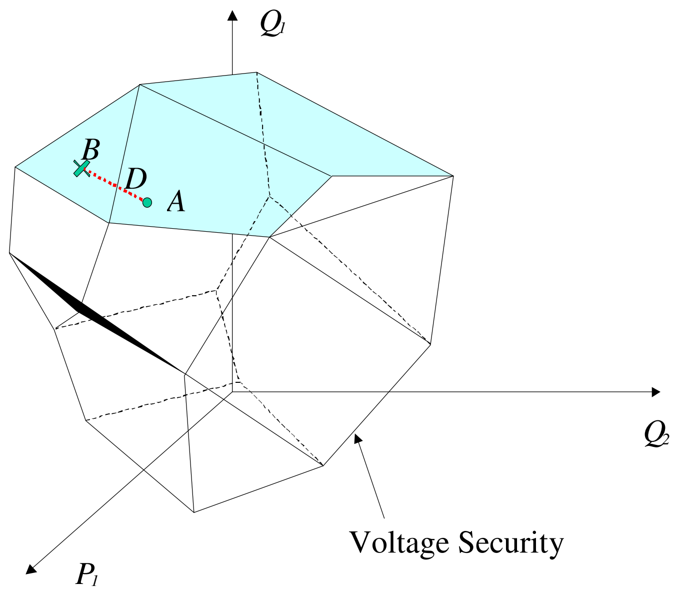

Figure 2: Conceptual view of Voltage Security Region

- Easy-to-Calculate Security Margin: The distance *d* from the current operating point *A* to the nearest constraint face *B* determines the MVA security margin[1]:

$$d_i = \frac{a_{i1}P_1^0 + \ldots + a_{in}P_n^0 + b_{i1}Q_1^0 + \ldots + b_{in}Q_n^0 - c_i}{\sqrt{a_{i1}^2 + \ldots + a_{in}^2 + b_{i1}^2 + \ldots + b_{in}^2}}$$

  Where the current operating point $A = \left[P_1^0, \ldots, P_n^0, Q_1^0, \ldots, Q_n^0\right]$

  The percent margin for each constraint i can be obtained based on a pre-established minimum admissible "MVA distance to instability" d^*:

1 We assume that the region is convex.

$$d_i^{\%} = \min \begin{Bmatrix} \dfrac{d_i}{d*} \times 100\% \\ 100\% \end{Bmatrix}$$

The resulting stability margin corresponds to the minimum distance, i.e. the distance to the closest constraint face:

$$D = \min_{(i)} d_i^{\%}$$

- Online computation of Parameter Sensitivities: The *normalized coefficients* of the set of hyperplane equations denoted by (1) are sensitivities that can be interpreted in several ways. These coefficients can be calculated trivially by the following mathematical expressions:

$$\frac{\partial D}{\partial P_j^0} = \frac{a_{ij}}{\sqrt{a_{i1}^2 + ... + a_{in}^2 + b_{i1}^2 + ... + b_{in}^2}}$$

$$\frac{\partial D}{\partial Q_j^0} = \frac{b_{ij}}{\sqrt{a_{i1}^2 + ... + a_{in}^2 + b_{i1}^2 + ... + b_{in}^2}}, \ j = 1, ..., n$$

where D is critical vector $\vec{D} = \vec{AB}$ - see Figure 2.

The different representations of these coefficients include:

1. The locations in the network where the most sensitive controls are needed
2. The left eigenvector nullifying the power flow Jacobian matrix at the point of collapse
3. This eigenvector has an identical representation to *Lagrangian multipliers*[2] at PoC

3.2. CERTS RTVSA Algorithm Overview

The important concepts that are used in the CERTS RTVSA algorithm are stress direction (procedure), descriptor variables, state space, and parameter space.

The *stress direction (procedure)* specifies how the system parameters change from their base case values as a function of a scalar amount of stress. For example, generation and load participation factors can define a stress direction and the amount of generation can give a scalar amount of stress --- these together can specify the changes in the bus power injections that is, any system state along the stress direction can be associated with certain value of a stress parameter such as

[2] This representation is well suited to imply a 'Locational price' for an ancillary service such as the distance to voltage collapse specified in terms of dollars. Lagrangian multipliers specify the sensitivity of the constraints so that a constrained optimization problem becomes an unconstrained optimization problem – see Eric W. Weisstein. "Lagrange Multiplier" from MathWorld - A Wolfram Web Resource. http://mathworld.wolfram.com/LagrangeMultiplier.html

the percent of the total load increase in an area. Each specific direction and value of the stress parameter uniquely defines the system state. This implies certain fixed patterns for varying the system generation and loads (for example, load participation factors, sequence of generator dispatch, and others – detailed examples can be found in this report). Stress directions can include some local system stresses addressing a particular voltage stability problem area, and global stresses such as the total load growth and the corresponding generation redispatch in the system.

Descriptor variables reflect the most influential or understandable combinations of parameters (or derivative parameters) that influence the voltage stability margin. Examples are the total area load, power flows in certain system paths, total generation, and others (the system operating nomograms' coordinates are good examples of descriptor parameters). In the simplest case, descriptor parameters can include some primary system parameters such as nodal voltages and nodal power injections. Descriptor variables help to adequately address global and local voltage stability margins without involving thousands of primary parameters. Certain subsets of descriptor variables can correspond to some local voltage stability problem areas.

The *state space* includes all system nodal voltage magnitudes and voltage phase angles.

The (independent) *parameter space* includes all nodal power injections (for P-Q buses) and real power injections and voltage magnitudes (for P-V buses).

The voltage stability boundary can be comprehensively (and uniquely) described in the parameter space (and the state space), but in this case the description would involve thousands of variables. Descriptor parameters help to reduce the dimensionality of the problem by considering the most influential combinations of parameters (or derivative parameters).

The *descriptor parameter space* includes all descriptor parameters. Since the points in the descriptor parameter space can be mapped into the points of the parameter and state spaces in many different ways (because of the limited number of descriptor parameters space dimensions), certain fixed system stress procedures should be introduced to make this mapping adequate and unique.

The developed RTVSA algorithms consist of the following steps (which has been illustrated in a flowchart under Figure 3):

1. **Initial system stressing procedure** for a given stress direction **to reach a vicinity of the Point of Collapse (PoC)** in this direction. This step is implemented using the Parameter Continuation Method. The Continuation Method is one of the most reliable power flow computation methods; it allows approaching the PoC and obtaining the initial estimates of system state variables needed for the subsequent steps. The selected form of the continuation methods includes predictor and corrector steps.
2. **The direct method** is used then **to refine the PoC location** along the initial stress direction (the continuation method would require multiple iterations to find the PoC with the required accuracy). At least one of the power flow Jacobian matrix eigenvalues must be very close to zero at the PoC.

3. **The inverse iteration method or Arnoldi algorithm** is applied **to find the left eigenvector corresponding to the zero eigenvalue at PoC**. The left eigenvectors are used to build the set of approximating hyperplanes.
4. **The stability orbiting procedure is then applied to trace the voltage stability boundary along a selected slice.** This procedure is a combination of a predictor-corrector method and the transposed direct method.
5. In case of divergence, the algorithm is repeated starting from Step 1 for a new stress direction predicted at the last iteration of the orbiting procedure. Divergence may be caused, for example, by singularities of the stability boundary shape along the slice.
6. For a given voltage stability problem area and the corresponding descriptor parameters, **the "sliced bread procedure" is applied to explore the voltage stability boundary and build the set of approximating hyperplanes**.

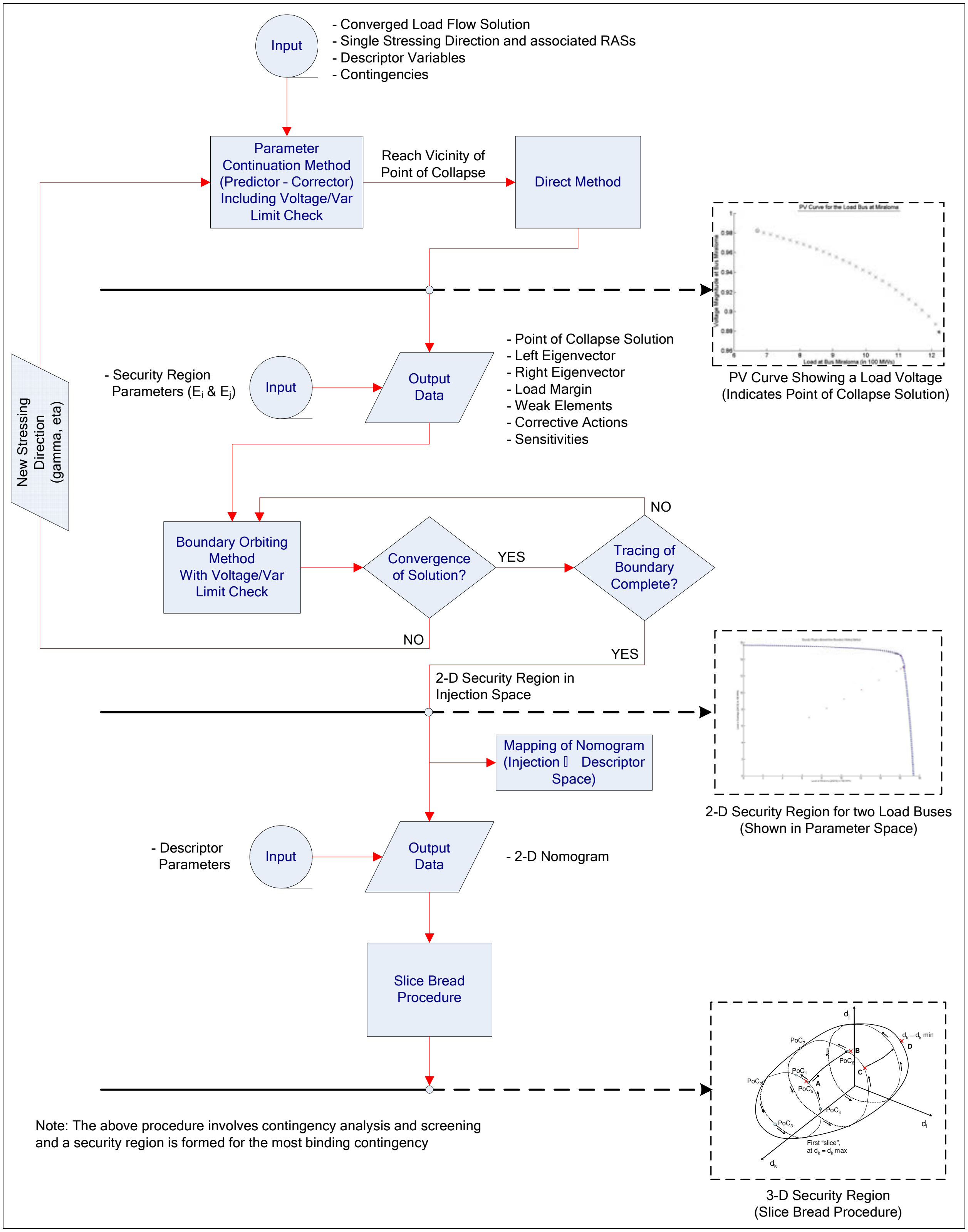

Figure 3: RTVSA Algorithms Flowchart

The developed RTVSA algorithm performs voltage security assessment calculations under both offline and real-time modes.

The *offline calculations* produce an approximated voltage stability region (a 2-D, 3-D, or a higher dimensional nomogram) bases on multi-directional stressing situation presenting the interaction and tradeoffs between different stressing directions. The pre-calculated voltage stability region is an inner intersection of stability regions for the set of user-specified contingencies. The offline calculations should be conducted periodically (ideally, several times a day) to update the approximated voltage security region and to reflect the most recent changes in the system.

The *real-time calculations* are conducted in real time (after each converged State Estimation cycle) to determine the current or future position of the system operating point against the walls of the approximated voltage stability region, and to calculate such essential security information as the available stability margin (distance to instability), the most limiting contingency, the most dangerous system stress directions, weak elements causing potential instability, and the recommended preventive and enhancement controls that help to increase the margin in an efficient way.

Note: The *offline* calculations can also be conducted in real time if a few stressing directions representative of the actual system loading, given by the real time dispatch schedule, planned outages, and load forecast, and/or predetermined stresses are to be considered separately. In such a scenario, the available security margins, distance to instability, the most limiting contingency, weak elements causing potential instability, and the recommended preventive and enhancement controls that help to increase the margin in an efficient way can be obtained in real-time using the algorithms proposed in this document.

3.3. Some Special Features of the RTVSA Application

The underlying concepts are applicable to the simple one-dimensional approach or the more complex multi-directional stressing to explore the entire voltage security region in the parameter space or in full P-Q injection space.

The RTVSA tool has the ability of analyzing the effects of multiple transfers. There are no restrictions in distributing the source and sink over a large number of buses in geographically distant locations in the system. A non-local treatment of congestion[3] is crucial because conservatism causes costly curtailment of profitable power transfers and a suboptimal use of the transmission system.

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[3] Congestion can be quantified more precisely as the combined effect of multiple power transfers exceeding the transfer capability of the transmission system.

The RTVSA algorithm[4] in the initial stages uses the parameter continuation method, which is one of the most reliable power flow methods capable of reaching the point of collapse on the power flow feasibility boundary. New variables called the continuation parameters are added and represents a position of a power flow operating point along some power system stress direction in the parameter space. The *predictor step* consists in an incremental moving of the power flow operating point along the state space trajectory, based on the linearization of the problem. The *corrector step*, that follows each predictor step, consists in elimination of the linearization error by balancing the power flow equations to some close point on the nonlinear trajectory.

The RTVSA algorithm also uses Direct methods for finding the PoC quickly and accurately, which combines the parametric description of the system stress and the power flow singularity condition expressed with the help of the Jacobian matrix multiplied by a nonzero right or the left eigenvector that nullifies the Jacobian matrix at the collapse point. In principle, the Direct Method avoids implementing a loading procedure. There may be problems of finding the initial guesses of the state variables and the eigenvector that may be resolved by initial loading the system along the stress direction. By doing so, the initial guess of variables can be obtained. Many inaccuracies of the step-by-step loading methods that do not exactly converge to the PoC will be avoided by implementing the Direct Method. There are savings in computational expenses because of the absence of iterations even though the Direct Method solves a problem almost double in dimension to the step-by-step loading methods.

The RTVSA algorithm determines the "right eigenvector" and the "left eigenvector" at the PoC. The weak elements are based on the right eigenvector and provide the extent to which variables participate in voltage collapse. This determines weak areas and also whether the collapse is an angle collapse. Large sensitivities of the margin to PoC indicate controllable parameters. These are represented by the left eigenvector and can be quantified for suitable corrective action by ranking the increase in margin with respect to a unit MW or MVAR in generator response.

Sensitivity computations relate changes in data to changes in transfer capability. The uncertainty in the transfer capability due to uncertainty in the data can be quantified to reveal which data is significant in the transfer calculations.

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4 The RTVSA algorithm falls into the class of non-divergent power flow methods that manipulate the step size of the Newton-

Raphson method. If the power flow mismatches indicate divergence, the step size is reduced until convergence occurs or the step

becomes very small. A very small step size is considered to be an indicator of the point of collapse.

3.4. Algorithm Simulation and Validation Results

The selection of the critical parameters influencing the voltage stability margin and stress directions was conducted based on engineering judgment. The stress directions were defined using the sink-source and balanced loading principles. This means that the generators and the loads participating in each stress scenario are identified, as well as their individual participation factors; the participation factors are balanced so that the total of MW/MVAR increments and decrements is equal to zero. This allows avoiding re-dispatching of the remaining generation. Based on the California ISO recommendation, two study areas were selected for verifying the prototype VSA algorithms: the Humboldt and San Diego problem areas.

The San Diego region within Southern California suffers from voltage stability issues, and hence, forms a good test case. California ISO provided the CERTS team with the 5940 bus (1188 generators) State Estimator generated load flow solution on October 23, 2006 that spans the entire Western Interconnection and includes all buses/lines at or above the 115 kV level. Only elements below the 115 kV level and external to the California ISO have been equivalenced. Within the California ISO jurisdiction, some of the lower voltage levels are also covered. Hence, this case precisely models the southern California region being studied.

The generation stressing process adopted by the VSA tool involves generators with the participation factors calculated based on their maximum generation capacity:

$$Participation\ Factor\ of\ Gen_k = \frac{Pgen_{\max}(Gen_k)}{Pgen_{\max}(Total)}$$

This participation factor for generators are dynamic, as they change once a generator reaches its maximum generation limit and is left out of the equation.

The participation factors for the loads are calculated using their base case $Load_k$ (in MWs), whereas the load power factor is maintained constant:

$$Participation\ Factor\ of\ Load_k = \frac{Base\ Load_k}{Total\ Load\ of\ the\ Stress\ Vector}$$

The distributed slack bus model includes all buses in the system except the ones that participate in the stress vector. This model reacts to the active power mismatch that is caused by the stressing procedure and generation contingencies. The participation factors on the distributed slack buses are calculated proportionally to the $Pgen_{max}$ of generators.

Parameter continuation predictor-corrector method was chosen as the preferred method capable of reaching the vicinity of point of collapse on the power flow feasibility boundary. The addition of new variables called continuation parameters determines the position of an operating point along some power system stress direction in the parameter space. The predictor step consists of an incremental movement of the power flow point along the state space trajectory, based on the linearization of the model. The corrector step, which follows each predictor step, consists in the elimination of the linearization error by balancing the power flow equations to some close point on the nonlinear trajectory.

Figure 4 below shows the PV curve (real load vs. voltage magnitude plot) for a load bus that was part of the load stress vector in the RTVSA algorithm. The crosses are the predictor-corrector solution points as the algorithm traces the curve to reach the vicinity of the voltage instability point denoted by a star.

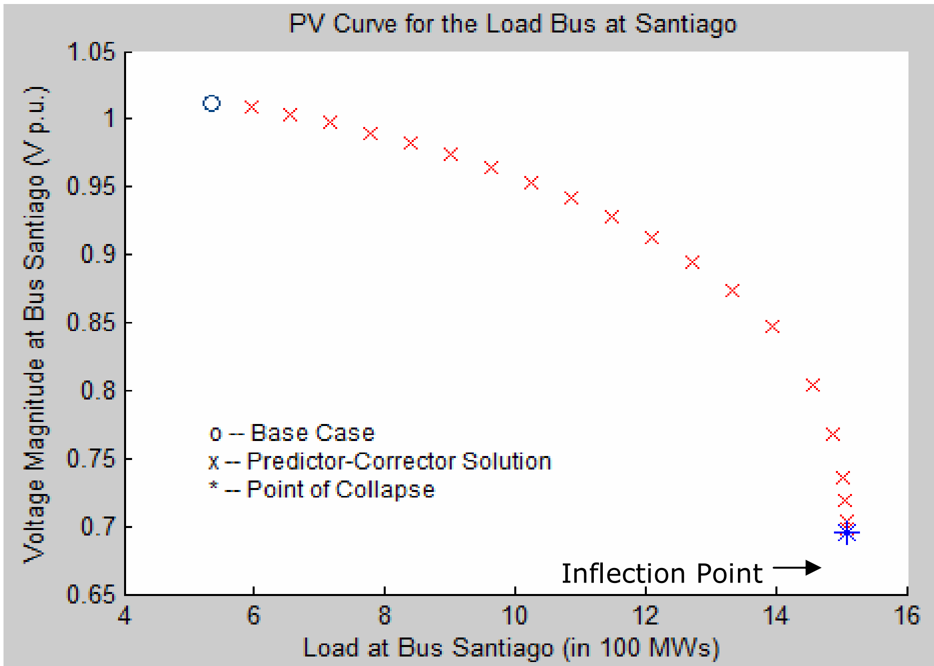


Figure 4: PV Curve for a Load Bus

Similarly, the parameter continuation method can also be illustrated for a 2D stressing scenario for two loads in the San Diego region as shown in Figure 5 below:

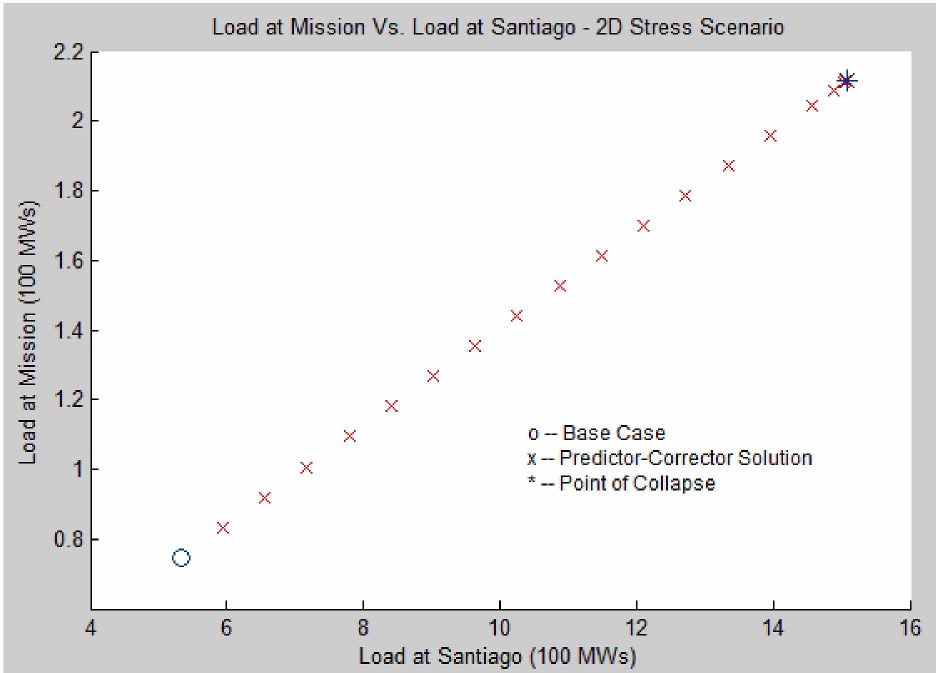
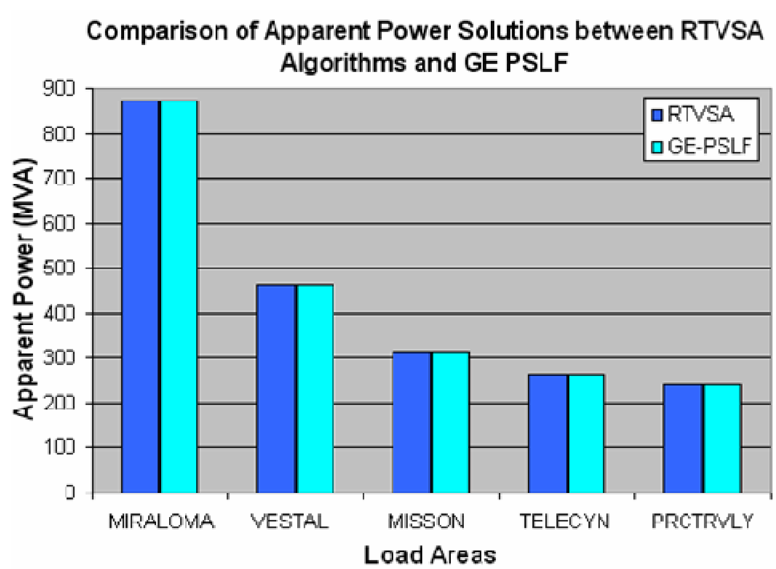


Figure 5: Load at Mission vs. Load at Santiago

In order to verify the results of the parameter continuation algorithm, the GE PSLF simulation engine was modified to incorporate the RTVSA stress vectors as well as the participation factor calculations, among other minor changes. The source and the sink vectors were stressed[5] to reach the point of voltage instability. The result of this comparative study revealed that the Point of Collapse solutions obtained from GE PSLF were indeed very close to that of the RTVSA algorithm as shown in Figure 6, Figure 7 and the comparison chart in Table 3 below:



5 GE PSLF uses Brute-Force method to determine the Point of Collapse solution

Figure 6: Comparison of Power Solutions (at PoC) between RTVSA & GE PSLF

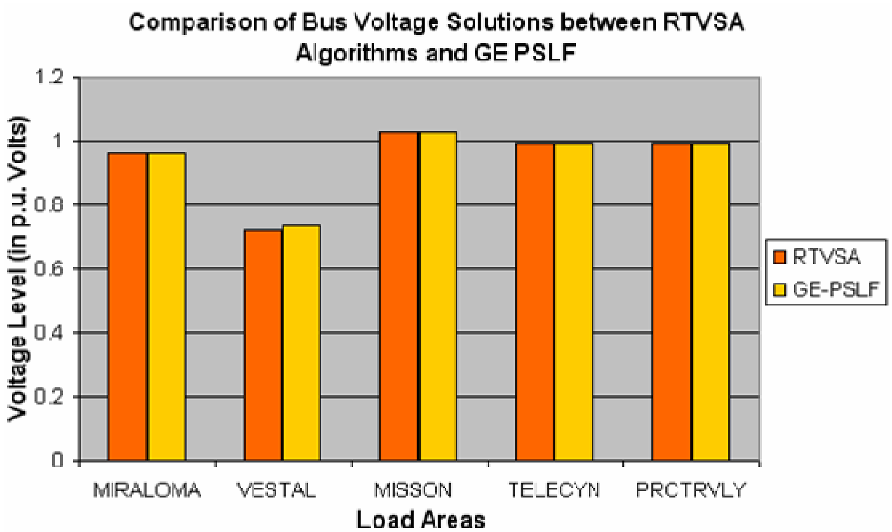


Figure 7: Comparison of Voltage Solutions (at PoC) between RTVSA & GE PSLF

Loads	% Difference in Power	% Difference in Voltage
Miraloma	0.04%	0.09%
Vestal	-2.19%	0.22%
Mission	0.02%	0.19%
Telegraph Canyon	-0.01%	0.30%
PRCTRVLY	0.02%	0.33%

Table 3: Percentage Difference between RTVSA and GE PSLF Calculations

3.5. Direct Method

Direct methods for finding the Point of Collapse in a given direction combine a parametric description of the system stress, based on the specified loading vector in the parameter space and a scalar parameter describing a position of an operating point along the loading trajectory and the power flow singularity condition expressed with the help of the Jacobian matrix multiplied by a nonzero right or the left eigenvector that nullifies the Jacobian matrix at the collapse point. Unlike the power flow problem, this reformulated problem does not become singular at the point of collapse and can produce the bifurcation point very accurately.

In principle, the direct method allows finding the bifurcation points without implementing a loading procedure. There is, however, a problem of finding the initial guesses of the state variables and the eigenvector that may be resolved by initially loading the system along the stress direction. By doing so, the initial guess of state variables can be obtained. To evaluate the initial guess for the eigenvector, the inverse iteration method has been recommended to calculate the eigenvector corresponding to the minimum real eigenvalue. The RTVSA code, however, utilizes Arnoldi's algorithm in Matlab software, also known as 'eigs' function, for simulation purposes.

The accuracy and advantage of the Direct Method algorithm has be shown with the help of the two plots below, wherein the Direct Method algorithm (Figure 9) is capable of determining the solution point (Point of Collapse) in one step, compared to 18 iterations taken by the Predictor-Corrector algorithm (Figure 8).

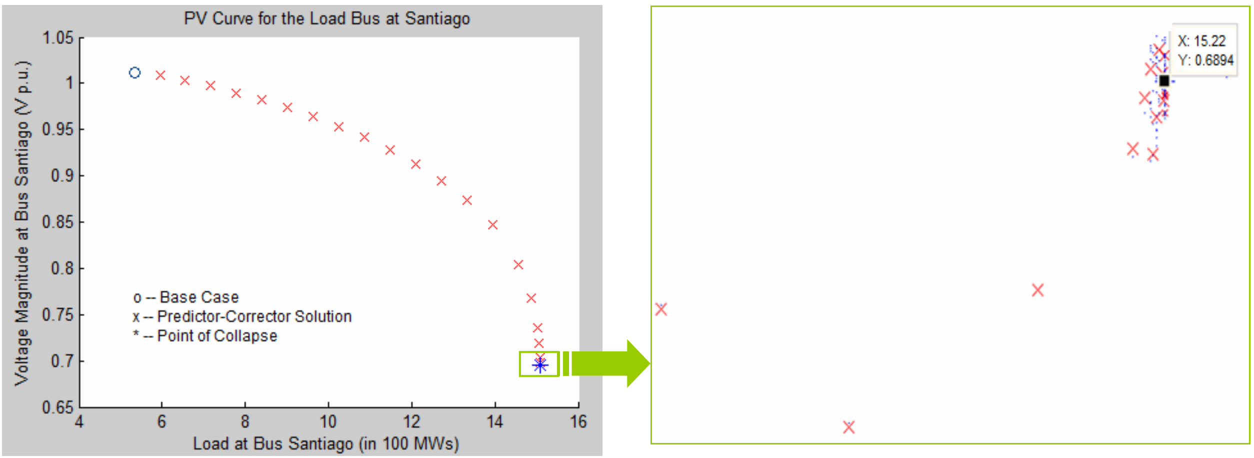


Figure 8: PoC Calculation by Predictor-Corrector Algorithm

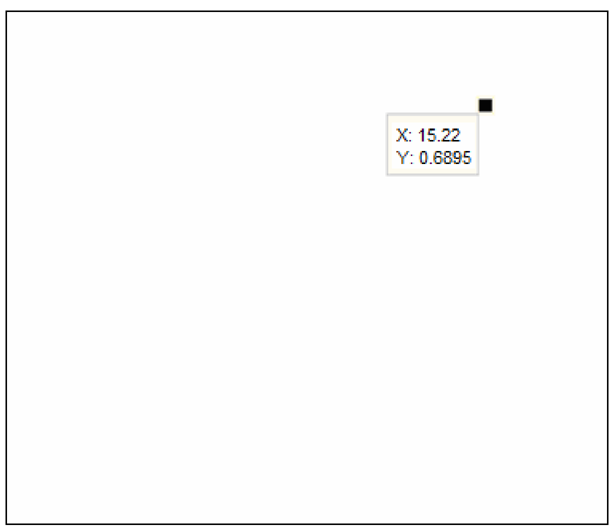


Figure 9: Direct Method's Accelerated PoC Calculation

3.6. Boundary Orbiting Method

After reaching the Point of Collapse (PoC) solution point using a combination of the Continuation Parameter and Direct Method for a specified stress direction, the challenge is to orbit a static voltage stability boundary without repeating the time-consuming Continuation

Parameter method along a selected slice. This problem is effectively solved by using the Boundary Orbiting Method algorithm instead, in order to change the stress direction and thus, trace the security region.

The Boundary Orbiting Method (BOM) may face divergence, for instance due to singularities at boundary edges, and hence, the continuation parameter method is repeated for a new stress direction predicted at the last iteration of the orbiting procedure. An example of a voltage security region for two loads in injection space has been shown below in Figure 10.

The slope of the boundary is determined by the sign of the eigenvalue corresponding to the load element in the left eigenvector. The positive slope illustrated in Figure 10 is due to the opposite signs of the eigenvalues of the two loads. Similarly, eigenvalues of the same sign results in a negative slope as shown in Figure 12.

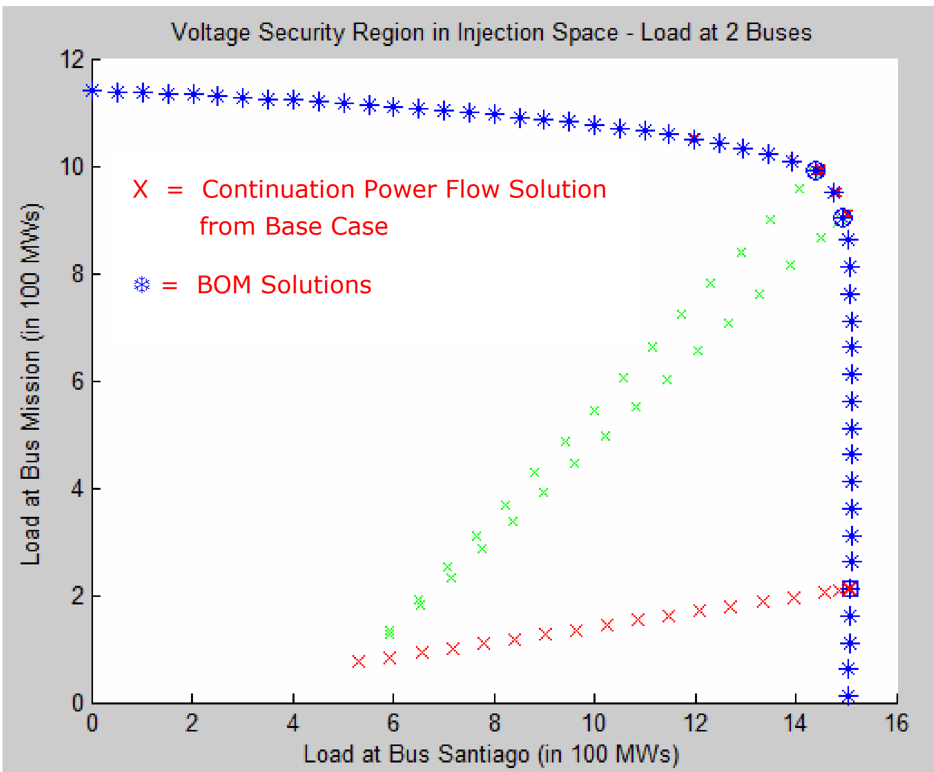


Figure 10: Security Region by Boundary Orbiting Method

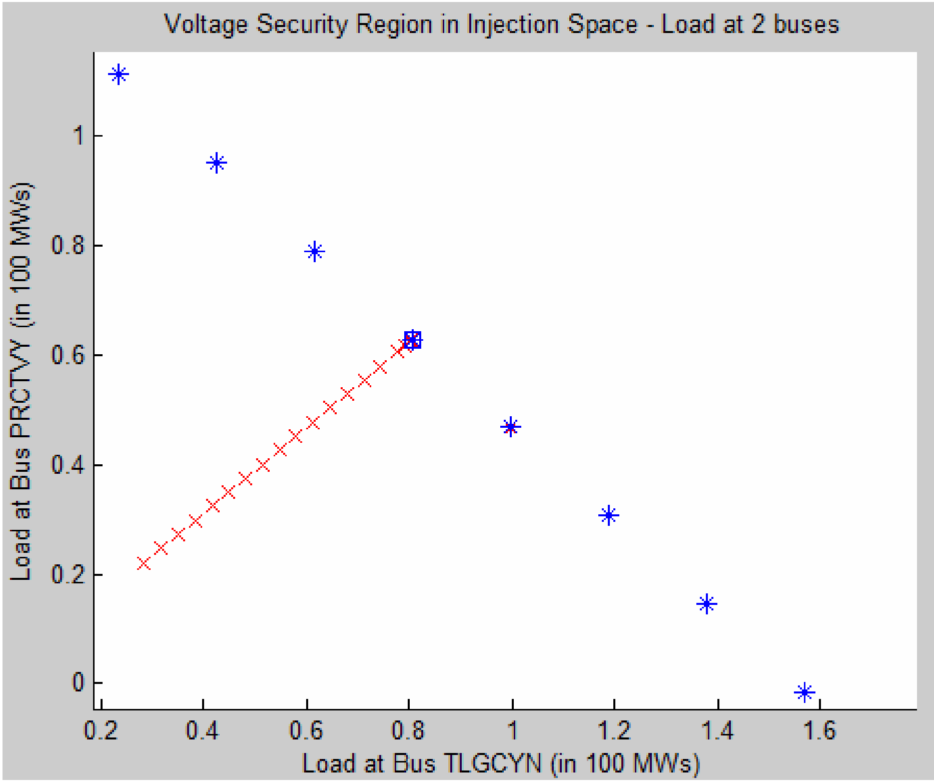


Figure 11: Security Region for Two Loads (For Eigenvalues with Same Signs)

To test the accuracy of the boundary points obtained by the orbiting procedure, the Continuation Parameter method, along with the Direct Method, was simulated for certain stress directions. A typical test result, as shown in Figure 13 below, reveals the precision of the Boundary Orbiting Method.

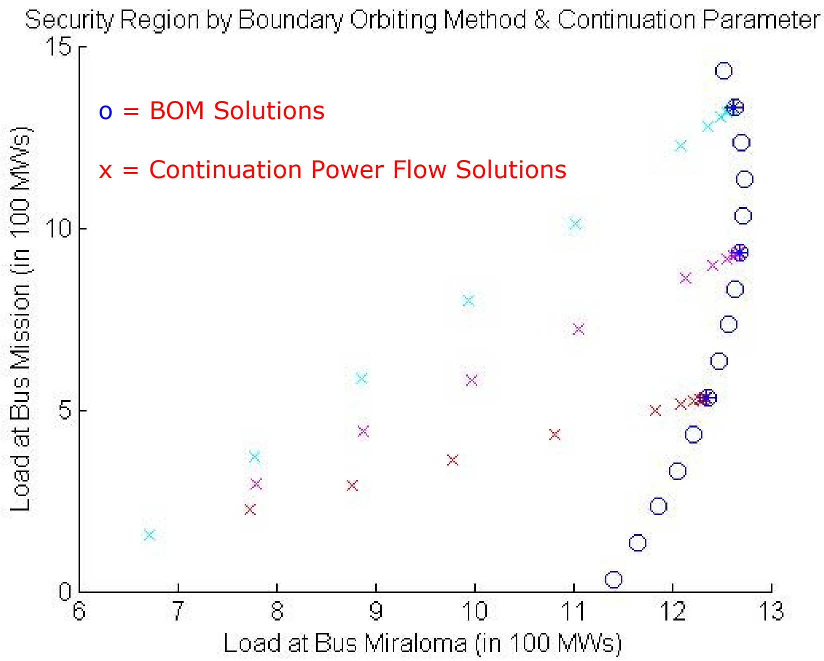


Figure 12: Testing the Precision of Boundary Orbiting Method

The original PSERC Predictor Corrector algorithm was designed to switch generator to load buses (i.e., PV to PQ buses) due to the nature of the one-dimensional stressing process. However, the RTVSA proposed two-dimensional security region calls for a more complex two way switching of the buses from type PV to PQ and back to a PV bus as and when required. Hence, the RTVSA tool was modified to accommodate the required algorithm for conveniently switching the buses, thus generating a precise and smooth security region as shown below:

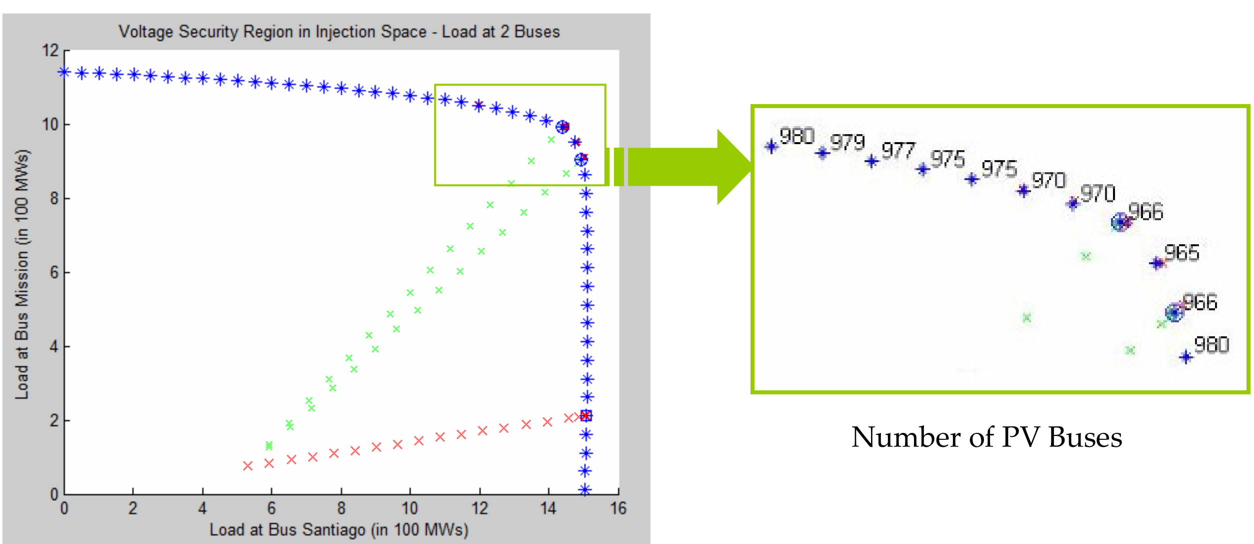


Figure 13: Switching of PV to PQ Buses and Vice-Versa

4.0 CERTS RTVSA Functional Specification

A functional specification document was developed for the Real-Time Voltage Security Assessment (RTVSA) tool that shall monitor voltage stability margin in real time, and will help the real time operators to manage this margin by controlling VAR resources, generation dispatch, and other resources on the transmission system. The application is expected to seamlessly integrate with the California ISO's real-time network analysis sequence (EMS) and run automatically after each successful state estimation process at every 5 minute intervals or on demand. The tool will help to identify the following:

1. Available voltage security margin
2. The most dangerous stresses in the system leading to voltage collapse
3. Worst-case contingencies resulting in voltage collapse and/or contingencies with insufficient voltage stability margin
4. Contingency ranking according to a severity index for voltage stability related system problems
5. Weakest elements within the grid and the regions most affected by potential voltage problems
6. Controls to increase the available stability margin and avoid instability
7. Information about voltage problems at the look-ahead operating conditions and for the worst-case contingencies (contingencies with large severity ranks) that may appear in the future
8. A real-time dispatcher's situational awareness-type wide area graphic and geographic displays.

This section summaries the key technical and functional requirements for the California ISO RTVSA tool.

4.1. On-Line RTVSA Functional Overview

The RTVSA application will be integrated with California ISO's real-time network analysis sequence and run automatically after each successful state estimation process at every 5 minute intervals or on demand. The application will use data from the California ISO state estimation fed in every 5 minutes. The State Estimator (SE) solution, present in a Dynamic CIM/XML format, and the Detailed Network Model, present in a Static CIM/XML format, are outputs of California ISO's ABB Ranger Energy Management System (EMS); whereas the *RTVSA Supplementary Files* are predefined set of flat files obtained from an external source. The above mentioned three files are required by the tool to perform a thorough voltage security assessment.

The RTVSA tool shall feature two dominant modes of operation:

1) *Real-Time Modes* - Real-time operations mode

Real-time look-ahead mode

Under the 'Real Time Operations Mode', the RTVSA tool would perform a real time assessment utilizing the most current state estimator snapshot. On the other hand, the 'Real Time Look-Ahead Mode' would be useful in performing a 2-hour "look-ahead" predictive assessment by applying planned outage information available within the EMS and load forecast over the next 2 hours to the current state estimator snapshot.

2) *Study Mode* - Study mode offers off-line analysis capabilities on either the real-time data or on modified version of real-time solved cases.

The two available modes described above serve different purposes for two separate user environments:

- Real-time modes for Operator Display Console users
- Study modes for Stand-Alone Console users

The associated functionality offered within these two modes of operation is summarized in Table 4.

	Real Time Modes		*Study Modes*
	Real Time	*Look-Ahead*	
Unidirectional Stressing			
– *contingency screening & ranking*	×	×	×
– *real time alarming*	×		
– *voltage profiles*	×	×	×
– *MW/MVAR reserves*	×	×	×
– *single line diagrams*	×	×	×
– *Loading margins*	×	×	×
– *margin sensitivities to reactive support*	×	×	×
– *ranking of corrective controls*	×	×	×
– *identification of weak elements*	×	×	×
Multidirectional Stressing			
– *2-D, 3-D or N-D Security Regions (Nomograms) developed Offline*			×
– *real time assessment of operating point including contingency ranking, margins*	×	×	×
– *real time ranking of controls to steer away from the boundary*	×	×	×

Table 4: Summary of RTVSA Capabilities

The RTVSA processor will simultaneously operate between the two given modes, i.e. the real-time performance of the RTVSA tool will not be compromised upon simulation of one or many study cases at any given instance. To meet the computing needs of RTVSA, this tool shall be deployed across a cluster of high performance distributed computing, supporting a scalable Server-Client architecture. The *RTVSA Central Server* will be responsible for the data management, algorithmic computation, automation, and handling of remote client requests.

4.2. System Architecture

The overall functionality of the RTVSA application can be subdivided into three interdependent modules, which are:

1. 1) Input Subsystems:
2. 2) Central Server:
3. 3) User Interfaces:

Figure 14 of the proposed system architecture illustrates the affiliations among the various modules, as well as the constitutive functionalities of each of the consoles.

There are three sources of data **input subsystems** (California ISO EMS, Data Input Module, and Flat Files Storage) to the Central Server vis-à-vis the RTVSA tool. Depending on the tool's mode of operation, data can be acquired from any of the sources.

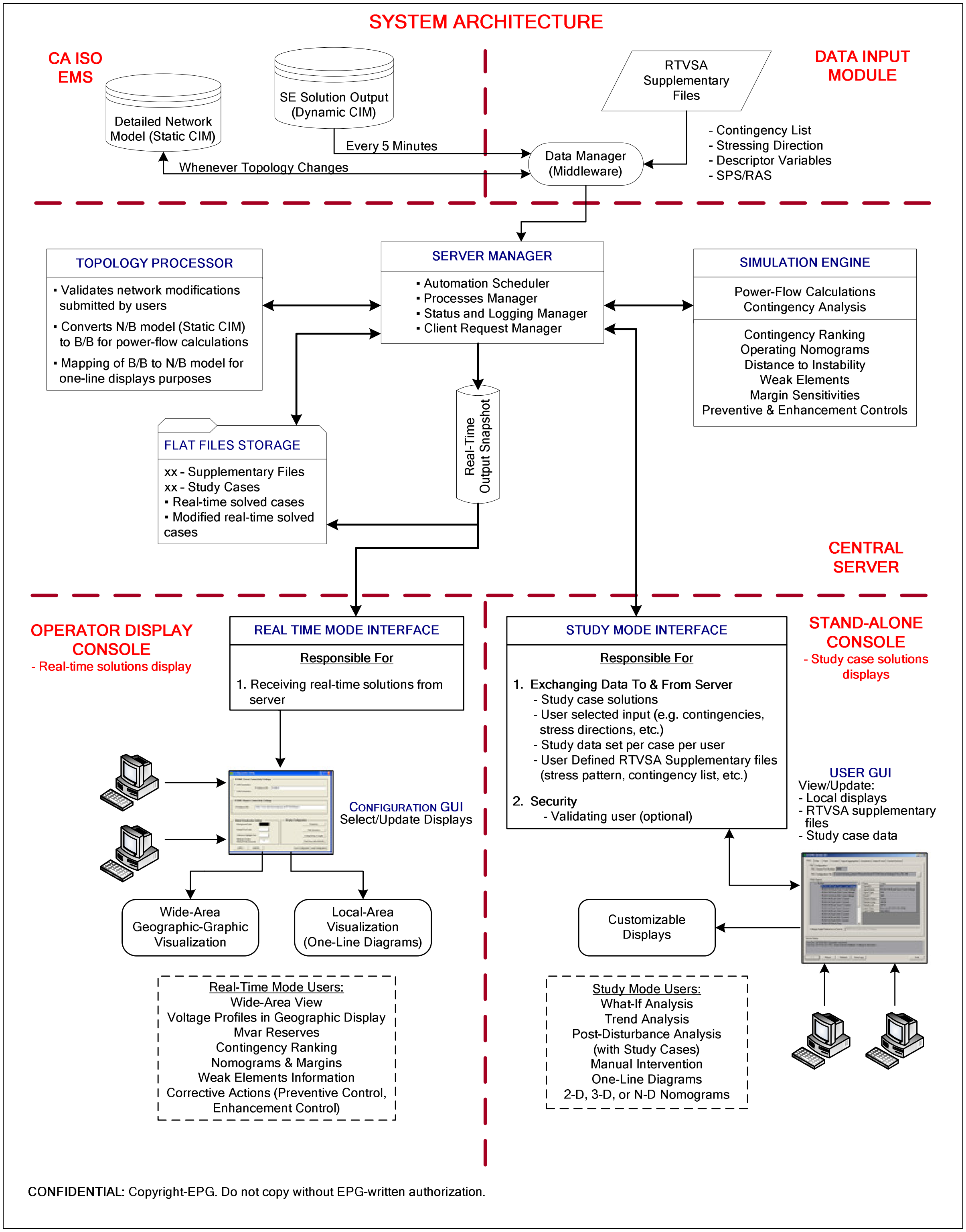


Figure 14: RTVSA System Architecture

As is shown in Figure 14, the California ISO's ABB-Ranger EMS generates Dynamic CIM/XML files at 5-minute intervals. This file in combination with the Static CIM (which contains network topology information) provides all the necessary data required to run a power flow. The *Data Input Module* primarily accounts for combining and managing the various files required by the RTVSA tool to perform power flow calculations and voltage security analysis during a real-time sequence. The *RTVSA Supplementary Files* are user predefined set of data that are essential while performing a complete voltage security assessment with the previously mentioned functionalities. These include Contingency List, Stressing Directions & Descriptor Variables, and Special Protection Schemes/Remedial Action Schemes.

The following are the data requirements for the RTVSA tool based on the operating modes:

Real-Time Modes:

- Data Source: California ISO EMS
  1. Valid State Estimator Solution
  2. Detailed Network Model
  3. System Component Status Information
  4. Available Power System Controls and their Priorities
  5. Limits (Voltage, Thermal, MVAR)
  6. Generator Model
  7. Distributed Slack Bus Information
  8. Low Voltage Load Models
  9. HVDC Models & Control Schemes
- Data Source: Data Input Module
  10. Contingency List
  11. Stressing Directions & Descriptor Variables
  12. Special Protection Schemes/Remedial Action Schemes

Study Modes:

- Data Source: Flat Files Storage
  1. Real-time solved case
  2. Modified real-time solved case
  3. RTVSA Supplementary Files

The minimum requirement for the data that is required to correctly describe the system equipments are Bus data with breaker information and status, transmission line data, transformers and tap control data, Generator data, Load data, Fixed Shunt data, Controllable shunt and static VAR devices (SVD) data, and HVDC controls data.

The **Central Server** houses the RTVSA application that performs simulations pertaining to voltage security assessment, processes network topology models as required by the system, a

Central Manager that streamlines the various processes, and a storage system for RTVSA application's study cases. The sub-modules that collectively define the functionality of the *Central Server* include Server Manager, Topology Processor, Flat Files Storage, and Simulation Engine

The *Simulation Engine* sub-module is the backbone of the system architecture. This unit is responsible for receiving data from the *Server Manager*, performing the various simulations, and sending the solution sets to the relevant users. It may run both in the real-time and study modes, simultaneously, while operating on a distributed computing platform.

The **User Interface** of the RTVSA application can be categorized under two domains of operation: 1) Operator Display Console for Real-time mode, which receives solution snapshots from the Central Server every time the RTVSA application runs on a set of real-time data. 2) The Stand-Alone Console caters to users of the RTVSA application under the study mode described earlier.

4.3. Visualization and User Interaction

The goal of the RTVSA application is to provide the real-time and study mode users with visualization capabilities that will assist them in making decisions. These capabilities can be classified under two broad domains: (1) Situational Awareness, and (2) Voltage Security Assessment.

Situational awareness type of displays present to the viewers simplified wide-area real time metrics, detection, alarming, trace, and trend visualization solutions. Accompanying the real-time displays would be scenarios under the worst case contingency. These include Voltage profiles at various buses, real and reactive power reserves across the system, Interface/line flows across key transmission corridors/voltage levels, and one-line diagrams.

Voltage Security Assessment displays demonstrate results of the Voltage Security Assessment tool under the look-ahead scenario with respect to key stressing direction(s). Such scenarios may be based on current operating conditions or under the worst case contingency. These illustrate voltage security conditions and metrics that help users study voltage stability and take decisions to prevent adverse situations. These capabilities include Real and reactive loading margins, Contingency ranking based on severity index (voltage margin, loading margin, etc.), Operating nomograms, Distance to instability, Weak elements information, and Corrective actions (preventive control, enhancement control)

The RTVSA visuals are displayed to both user interfaces: real-time user interface located in California ISO's Operator Consoles, and study-mode interface located in Stand-Alone Consoles. Since the simulation results obtained under each of the modes are case dependant (study or real-time case), the visual displays and techniques are different for the two users.

The Operator Console users view real-time results of RTVSA simulations under Current system scenario (base case) and System conditions under the worst case contingency. Display capabilities and features required for the Operator Console users to include Wide area geographic view of the current system conditions with the capability to zoom-in on a desired local area, effective displays of priority based corrective controls information with rankings based on their effectiveness for each simulated stressing direction(s), and the capability to modify and customize display settings.

Study mode users shall interact with the system through a GUI in order to select the desired study case, make necessary modification to the same, and run simulations with preferred execution parameters (Supplementary Files) and controls. They would be able to study the reliability of the system with the help of various displays as well as by comparing multiple study cases. Display capabilities required for the stand-alone console users to include the ability to conveniently modify network topology, displays that indicate the available RTVSA execution control parameters and their current values, Emphasis on 'Voltage Security Assessment' type of displays, Capability to compare cases against each other, and Capability to plot simulation parameters and variables as a function of time.

5.0 Conclusion

The Real Time Voltage Security Assessment project was designed to be part of the suite of advanced computational tools for congestion management that is slated for practical applications in California in the next few years. The prototype application that was developed under this project is based on an extensive analysis of the existing VSA approaches, by surveying the leading power system experts' opinion worldwide, and also with feedback from industrial advisors. The mismatch between the core power system reliability needs and the availability of the VSA tools was a motivation to design the RTVSA prototype.

The robustness of the Parameter Continuation technique combines with the accuracy of the Direct Method and Boundary Orbiting Method makes the RTVSA prototype a preferred choice for an advanced VSA application.

The underlying concepts are applicable to the simple one-dimensional approach or the more complex multi-directional stressing to explore the entire voltage security region in the parameter space or in full P-Q injection space. The RTVSA algorithms are complex enough to handle system stress/relief by allowing the generator buses to switch to load buses and vice-versa.

The functional specification document prepared for the California ISO lays out the technical and functional requirements for a state-of-art Voltage Security Assessment tool that is designed to run in real time and is targeted towards real time operators to help them manage their reactive margin by controlling VAR resources, generation dispatch, and other resources on the transmission system. In particular, it allows operators to monitor system voltage conditions and provides real time reliability information related to reactive margin, abnormal nodal voltages, weak elements, contingency rankings, and recommended corrective actions. These functional specifications were used by the California ISO to select a vendor and to implement a commercial grade application to be in fully operation at the California ISO by summer 2008.

APPENDIX A – SURVEY 1 RESULTS TABLE

Reviewer	*VSA using Hyperplane Methods*
[1]	❑ Recommends hyperplane approach for VSA. Furthermore suggests online hyperplane computation if loading directions and generating unit dispatch vectors are known a priori. Needs only up to 10 load flow runs with to compute "weak" elements.
[2]	❑ Adopted similar direct methods for contingency ranking and also in hybrid system aimed to give a measure of angle as well as voltage stability. These experiences demonstrate the applicability of the proposed methodologies. ❑ Practical security boundary must account for grid topology changes (implying online security assessment).
[3]	❑ More information needed about the hyperplane approach to VSA.
[4]	❑ Has real potential – and it is not as unproven as some other concepts like interior point optimization.
[5]	❑ Seems to be ideally suited for voltage instability where the phenomena is more localized and ideally suited for decision based on measurements ❑ Not convinced that Practical Dynamic Security Region direct method has any particular computational advantage over other methods
[6]	❑ Experience has shown that secure operating space calculations done off line rarely match exact real time conditions, which may well be away from design conditions, implying online security assessment or adequate safety margins.
[7]	❑ Least squares approximation of hyper planes with load flow simulations is prone to error enhancement for bad state estimator measurements.
[8]	❑ Proposes New Electricity Transmission Software Solutions (NETSS) for voltage optimization, and the economic assessment of voltage support measurements (known as pilot points). ❑ It is important to determine the right locations to measure. Results depend on voltage dispatch strategies, loading conditions and system-specific equipment status.

Reviewer	*General comments on Tools and Methodologies Discussed in the Survey*
[9]	❑ Advises to use equations like J′(X) F(X) =0 to search for the closest points of the steady-state stability boundary. He also warns that the thermal constraints are often more limiting than stability constraints.
[10]	❑ Methods not yet been utilized by grid operators. ❑ Emphasizes mode meter and system stiffness. ❑ Refers to WACS paper by Carson Taylor.

[11]	Suggested the advantages of the following V&R products: ❑ For off-line computations the exact boundary of dynamic security region (security nomogram) is automatically constructed using V&R's Boundary of Operating Region (BOR) software. ❑ For on-line computations, sensitivity-based *n*-dimensional boundary of operating region can be computed using BOR. The approximated boundary may be computed using Direct methods.
[12]	❑ Visualization of voltage stability region in cut-set space has been implemented and a visualization system of dynamic security region in injection space to guarantee transient stability is in development for Henan Power System of CHINA ❑ It might be used in monitoring, assessment and optimization of security. "Up to now almost all research results of mine are about the dynamic security region in power injection space and the voltage stability region in cut-set power space. I think it might be used not only in security monitoring and control, but also in probabilistic security assessment."
[13]	❑ Submitted a Proceeding of IEEE paper on WACS accepted for publication in May 2005. This paper co-authored by Taylor describes an online demonstration of a new response based wide area control system with discontinuous actions for power system stabilization.
[14]	❑ Submitted a product overview of Energy Concepts International software "QuickStab".
[15]	❑ Submitted a company overview and product list of Bigwood systems. ❑ This included information that showed partnerships with ABB to install BCU-DSA at the EMS of three power companies. BCU method is the only method used in EPRI Direct 4.0 and BCU method has been implemented by Siemens, at the Northern Power Company.
[16]	❑ Provided areas of concern in the implementation of wide area monitoring such as: ❑ Validity of the system model to capture the phenomena of interest. ❑ Accuracy of angle measurements by PMUs. ❑ Accuracy of angle differences from PMUs of different vendors. ❑ Determining acceptable vs. unacceptable levels of angular separations among various pairs of PMU

APPENDIX B – SURVEY 2 RESULTS TABLE

Survey Bullets	BCTC	NE - ISO	Idaho Power	Midwest ISO	American Electric Power	PJM
• Tool Name	Currently: In-house RTVSA Future: VSAT & Areva product	Power World	POM Real Time	VSAT & Areva product	Currently: In-house Voltage Contingency Analysis (VCA) *Note: Its not an assessment tool*	Real Time Voltage Stability Analysis and Control
• Solution Provider	PowerTech and Areva	Power World	V & R Energy Systems Research	PowerTech and Areva	AEP	Siemens, Bigwood Systems, PJM
• Contacts	Greg Dwernychuk, Djordje Atanackovic Vankayala, Vidya Vidya.Vankayala@bctc.com 604-293-5851	Xiaochuan Luo (413) 540-4236	--	Dede Subakti dsubakti@midwestiso.org 651-632-8472	Scott Lockwood; Kalle Chan splockwood@aep.com; kchan@aep 614-716-6671; 614-716-6623	Jianzhong Tong tongj@pjm.com 610-666-4621
• Interfacing Capabilities						
- Tool type	EMS/SCADA Application	Stand Alone Tool	Stand Alone Tool	EMS/SCADA Application	EMS/SCADA Application	EMS/SCADA Application
- Data source	State Estimator Data	Areva State Estimator Data	State Estimator Data	State Estimator Data	State Estimator Data	State Estimator Data
- External data input formats	CIM	PowerWorld AUX file	.epc, .raw, CIM/XML	.raw	--	.raw
- External data output formats	CIM	.raw	--	.raw	--	--
- Internal data formats	--	PowerWorld AUX file	POM format	--	Proprietary ABB database	database
- Input data model	Node Breaker	Node Breaker	Node Breaker, Bus Branch	Node Breaker, Bus Branch	Bus Branch	Node Breaker, Bus Branch
- Data integration specifics	Flat text files	Habitat, PI, Flat text files (AUX files)	Relational DB, Flat text files	eDNA, Flat text files (.raw files)	ABB database	real-time DB, Flat text files (.raw files)
- Comments/Recommendations	• The current file-transfer interface between EMS & VSAT is being replaced by JMS (Java Messaging Service) under the SOA (Service Oriented Architecture) environment - both at input & output of the tool. • JMS is very useful when using structured data • Historical files are stored in a 'history folder' for purposes of post-disturbance or trend analysis - separate from EMS database. • Clustered computing, centralized processing • Separation of planning and real-time environment	• EMS is generating PowerWorld network model and contingency list after each State Estimation run. • An in-house Java code converts the State Estimator output along with the network information (acquired from EMS) into AUX files for PowerWorld. • State Estimator [real-time data] is stored in PI (which does not contain the network information). Power World has the capability to process historical data acquired from PI. • A configuration file maps PI tags to objects in AUX files • A topology processor exists within Power World application	A real-time tool should be capable of monitoring system constraints such as: thermal overloads, voltage deviation, voltage stability & dynamic security	Our tools utilize Areva EMS node breaker model and Areva convert the files to ".raw format to be used by Powertech VSAT analysis. The result is fed back to Areva EMS for our operator display	• VCA performs approx. 400 contingency analysis on the modified operator's load flow, and displays results to operators/dispatchers • AEP is considering installing Powertech's VSAT and Areva's EMS system	• There are 8 files that are transferred from EMS to VSAC (i.e. Network model, SE solution, contingencies, transfer interface definition, source/sink definition, facility limits, capability curve, load model). • The interface between EMS & VSAC is being replaced by Enterprise Messaging Bus technology. • The real-time DB, which is present in the EMS, acts as the data source to VSAC • The input data [to the tool] can be stored as "compressed files" for 60 days (which is open to customization) for trend analysis.

• Processing Capabilities

- Available simulations:	BCTC Y/N	BCTC RT?	BCTC Freq	NE - ISO Y/N	NE - ISO RT?	NE - ISO Freq	Idaho Power Y/N	Idaho Power RT?	Idaho Power Freq	Midwest ISO Y/N	Midwest ISO RT?	Midwest ISO Freq	American Electric Power Y/N	American Electric Power RT?	American Electric Power Freq	PJM Y/N	PJM RT?	PJM Freq
Power Flow (PF)	√	√	5 mins	√	√	na	√	√	5 mins	√	√	na	√	√	30 mins	√	√	na
PF uses full model?	√			√			√			√			√			√		
Contingency analysis	√	√	5 mins	√	√	na	√	√	5 mins	√	√	5 mins	√	√	30 mins	√	√	5 mins
Distance to instability	√	√	5 mins	√	√	na	√	√	5 mins	x	x	x	x	x	x	√	√	5 mins
Most dangerous stress direction	√	√	5 mins	x	x	x	√	√	5 mins	√	√	na	x	x	x	√	√	5 mins
Weak elements	√	√	Manual	√	√	na	√	√	5 mins	x	x	x	x	x	x	√	√	5 mins
Margin sensitivities	√	√	Manual	√	√	na	√	√	5 mins	x	x	x	x	x	x	√	√	5 mins
Corrective actions	√	√	Manual	x	x	x	√	√	5 mins	x	x	x	x	x	x	√	√	5 mins
Operating nomograms	√	√	5 mins	x	x	x	√	√	5 mins	√	x	x	x	x	x	x	x	x
Multidimensional?		2-D			--			Can handle 3-D			2-D transfers			No			No	

Survey Bullets	BCTC	NE - ISO	Idaho Power	Midwest ISO	American Electric Power	PJM
- Max # of buses supported	5,000 (open for expansion)	100,000	No limit	80,000	No limit	13,500
- PF simulation speed (6000 bus)	1,200 powerflows < 3 mins	seconds	45,000 buses = 0.5 seconds	powerflow takes 3-5 seconds	3 minutes	n/a
- How does it work in an 'on-line' real-time environment?	The RT-VSA is part of the real-time sequence and is triggered by the state estimator for every valid SE solution. The SE solution is sent by file transfer and real-time VSA results are sent back to EMS by file transfer as well - an in-house script.	• We are still working on the implementation. PowerWorld simulator shall take the AUX file generated from the EMS, then the PV tool shall calculate the voltage limits. • The automation server is available as an add-on component	It uses dynamic created cases by SE every 5 minutes	Our tools utilize Areva EMS node breaker model and Areva convert the files to ".raw format to be used by Powertech VSAT analysis. The result is fed back to Areva EMS for our operator display	• It is embedded in AEP's EMS system • The SE output is stored in ABB's internal database in binary format, and VCA automatically picks it up for every valid SE solution	Application takes SE solution with network model and SA contingencies to perform calculation of the margins (distance to instability) for each transfer interfaces, margin sensitivities, identifying weak elements, preventive and corrective controls.
- Recommended simulations *(for a real-time tool)*	--	--	Monitor dynamics of the system by using phasor measurement data	--	--	--
- Comments	Powertech's VSAT only displays worst contingencies, operating nomograms, and remedial actions (since these were the only requirements of the utility).	--	--	--	--	• It utilizes 10 dual-core clustered machines (Windows 2003 server) and performs power flow on 14000 buses, along with 3000 contingencies and 1 or 2 stressing directions, within 3 minutes

Survey Bullets	BCTC	NE - ISO	Idaho Power	Midwest ISO	American Electric Power	PJM
• **Visualization Capabilities**						
- Results' display options:	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No
One-line diagrams	x	√	√	x	√	x
Geographical	x	√	√	x	√	x
Tabular	x	√	√	√	√	√
Graphical	√	√	√	√	x	√
Security Regions	√	√	√	√	x	x
Summary Dashboard	√	x	x	x	x	√
- Most useful visualization method	A two dimensional graph with the x and y axis being two separate generation sources. Operating point is displayed as well as generation limits and import/export limits	Graphical - (1) GIS based contours (Nodal LMP and Voltage), and (2) Bubble diagram (internal interface & wide area monitor)	Something that is easy to understand	–	• One-line diagrams - in node-breaker format • Tabular - (1) Contingency results in delta-V, (2) voltage profile at buses • Geographical - Voltage contour plots (color coded) • Power flow on interfaces and transmission lines	–
- Recommended visuals *(for a real-time tool)*	What we have is adequate to meet our objectives	Alarm capability	Graphical Secure Operating Regions	Bar charts	--	–
- Comments	• In addition to providing voltage stability results it has proven very useful for state estimator maintenance and evaluation of quality of state estimator results. • Visualization schemes is provided by EMS itself (Areva's eterra platform)	• The future displays include: (1) 3D MVAR reserve, (2) Island display, and (3) Advanced displays as per operators' request	–	–	• Areva and Power World are helping AEP with visualization techniques • AEP utilizes 32 50" LCD screens as their display medium (by Aydin Displays, INC) • Node-breaker form of display is liked by the operators/dispatchers	–
• **General Comments**	• RT-VSA was place on line Mar 2006 and has been executing with an availability of 97%. When the AREVA EMS goes into service in fall 2008, the intention is to integrate Powertech's VSAT as the primary voltage stability analysis tool. • This tool is to be used by the planning group	This is a follow-up to our control room visualization project. We have used PowerWorld as a visualization tool in control room and have established a real time synchronization between PowerWorld and EMS model. Naturally we plan to use the PV tool of PowerWorld simulator to calculate voltage limits. We may also consider other tools integrated with EMS to assess voltage security such as VSAT.	–	–	--	PJM RT VSA&C has real time mode and study mode. The study mode provides a very comprehensive tool to operation engineers and dispatchers to perform any kinds of study.

Notes:
PF = Power Flow
Y/N = Yes/No
RT = Real Time
Freq. = Frequency of simulation

Survey Bullets	Bigwood Systems	V&R Energy	Powertech Labs	ABB	Energy Consulting Intl.
• **Tool Name**	SecureSuite On-Line Voltage Stability Analysis and Enhancement - Real-Time Mode & Study Mode	Physical and Operational Margins (POM) Suite of Applications	VSAT (Voltage Security Assessment Tool)	Voltage Security Assessment (VSA) - Real Time and Study	QuickStab Professional and WeakLinks Professional
• **Contacts**	Pat Causgrove 607-257-0915 pat@bigwood-systems.com	Marianna Vaiman 310-979-5966 marvaiman@vrenergy.com	Hamid Hamadani 604-590-7476 hamid.hamadani@powertechlabs.com	Mani Subramanian 281 274 5045 mani.subramanian@us.abb.com	Savu C. Savulescu (212)913-9154 scs@eciqs.com
• **Interfacing Capabilities**					
- Tool type	Stand Alone Tool	Stand Alone Tool	Stand Alone Tool	EMS/SCADA Application	EMS/SCADA Application
- Data source	State Estimator, EMS database	State Estimator	State Estimator	SCADA, SE, Contingency cases	SE, dispatcher's PF, off line PF
- External data input formats	pss/e all recent up to v30	epc, raw, CIM/XML	epc, raw, CIM/XML	--	epc, raw, IEEE
- External data output formats	pss/e	epc, raw, CIM/XML	epc, raw, CIM/XML	CIM/XML	CSV and ASCII flat files
- Internal data formats	common information technology data structures	--	proprietary binary format	ABB Data Base Management System	ASCII flat files
- Input data model	Node/Breaker, Bus/Branch	Bus/Branch	Bus/Branch	Node/Breaker	Bus/Branch
- Data integration specifics	Flat Text Files	Access, ACII, Excel files	Flat Text Files	ABB Relational Database	Flat Text Files
- Comments	The tool is an application in our customers' EMS, but stand-alone vis-a-vis the vendor EMS	--	For existing VSAT users, Powertech has worked with EMS vendor to establish an effective and efficient data exchange (flat files) between EMS and VSAT. The same can be done for CAISO.	--	QuickStab has been seamlessly integrated, and is currently being used, in real-time, but is also available, and has been used for a long time, as a stand-alone off-line application

• **Processing Capabilities**

- Available simulations:	Bigwood Y/N	Bigwood RT?	Bigwood Freq	V&R Y/N	V&R RT?	V&R Freq	Powertech Y/N	Powertech RT?	Powertech Freq	ABB Y/N	ABB RT?	ABB Freq	ECI Y/N	ECI RT?	ECI Freq
Power Flow (PF)	√	√	5 mins	√	√	5 mins	√	√	5 mins	√	√	15 mins	√	x	x
PF uses full model?	√			√			√			√			√		
Contingency analysis	√	√	5 mins	√	√	5 mins	√	√	5 mins	√	√	15 mins	√	√	5 mins
Distance to instability	√	√	5 mins	√	√	5 mins	√	√	5 mins	√	√	15 mins	√	√	5 mins
Most dangerous stress direction	√	√	5 mins	√	√	5 mins	x	x	x	x	x	x	√	x	manual
Weak elements	√	√	5 mins	√	√	5 mins	x	x	x	√	√	15 mins	√	x	manual
Margin sensitivities	√	√	5 mins	√	√	5 mins	√	√	manual	x	x	x	√	x	manual
Corrective actions	√	√	5 mins	√	√	5 mins	√	√	manual	x	x	x	√	x	manual
Operating nomograms	√	√	5 mins	√	√	5 mins	√	√	5 mins	x	x	x	x	x	x
Multidimensional?		2-D			computes n-D; 2-D & 3-D displays			1-D, 2-D			na			na	

	Bigwood Systems	V&R Energy	Powertech Labs	ABB	Energy Consulting Intl.
- Max # of buses supported	50,000 buses	none	100,000	none	35000 = input load-flow
- PF simulation speed (6000 bus)	0.1 sec	0.5 sec for 45000 bus system	0.07 sec	30-45 sec = base case + 10 conting.	1 sec for 3800 bus system
- How does it work in an 'on-line' real-time environment?	See attachment	See attachment	See attachment	See attachment	See attachment
- Comments	See attachment	See attachment	See attachment	See attachment	See attachment

Survey Bullets	Bigwood Systems	V&R Energy	Powertech Labs	ABB	Energy Consulting Intl.
• **Visualization Capabilities**					
- Results' display options:	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No
One-line diagrams	x	√	x	x	x
Geographical	x	√	x	x	x
Tabular	√	√	√	√	√
Graphical	√	√	√	√	√
Security Regions	x	√	√	x	x
Summary Dashboard	√	x	x	x	x
Others	na	na	Bar charts of transfer limits	na	SCADA trending charts; bar charts; speedometer charts; PV curves
- Most useful visualization method	Primary interest is on defined Interfaces (flow gates), the limiting contingency and margins.	--	Bar charts of transfer limts, 2-D plots of secure regions	PV plots	SCADA trending charts which allow the operator to follow minute-by-minute the evolution of the distance to instability
- Comments	VSA&E implements a Real-Time Mode appplication and On-line Study mode application	--	Customized displays can be developed based on user requirements	The results are available for each solution point for all buses. Can be displayed using visualization tools (eg.contours). Weak buses can be color coded.	QuickStab's speedometer charts are also quite unique in the industry and have received great acceptance from the users
• **Customer Information**					
- Participating utilities	PJM Inteconnection, Tennessee Valley Authority, Taiwan Power Company	25 utilities in US, Asia and South America	20 major utilities are currently using or implementing VSAT in the control center.	CFE (Mexico), ComEd, ITC	See attachment
- Is the tool used by operators and/or dispatchers?	Yes	Yes	Yes	Operators (to some extent) and Mostly Dispatchers	Yes
• **General Comments**	See attachment	--	See attachment	See attachment	See attachment

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PF = Power Flow
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APPENDIX C – RTVSA FUNCTIONAL SPECIFICATION SUMMARY TABLE

I	***Input Data Specifications***
A	Valid state estimation solution snapshots available every 5 minutes in dynamic CIM format.
B	Detailed network model with node-breaker details in the static CIM format.
C	Contingency list containing all N-1 and some user-specified N-2 contingencies with the associated RASs
D	Stressing directions including generator dispatch sequence and load patterns, and associated RASs.
II	***Modes of Operation***
A	'Real time operations mode' presenting real time voltage stability analysis using the current state estimator snapshot.
B	'Real time look-ahead mode' providing predictive voltage stability analysis using a priori knowledge of planned outages and load forecast.
C	'Study mode' offering offline 'what-if' capabilities on the real time study cases.
III	***Functional Capabilities***
A	Contingency analysis and ranking based on voltage violations or loading margins for each stressing directions.
B	Voltage profiles, powerflow patterns, real/reactive reserves and loading margins to PoC under base case and most binding contingency.
C	Margin sensitivities to reactive support for each stressing direction.
D	Suggest and rank Enhancement Controls to increase reactive load margins and Preventive Remedial Controls to retract to a secure region.
E	Identify weak elements and their voltage sensitivities to reactive load margins.
F	Construct 2-D, 3-D or N-D security regions (nomograms) offline for a set of pre-defined stressing directions and descriptor variables.
G	Evaluate current state estimator snapshot within N-dimensional security regions.

H	Real-time alarming on voltage violations and low real/reactive load margins.
IV	***System Architecture & User Environments***
A	Central-server/multi-client architecture
B	Simulation engine performing the various simulations and analysis.
C	Topology processor to convert the node/breaker to bus/branch for analysis and vise-versa for presenting simulation results.
D	Flat file storage housing the most current real time solved cases and modified study cases.
E	Real time information presented within Operator Display consoles.
F	Study mode capabilities within stand-alone user consoles.
G	User interface to enable/disable automated controls, and modify simulation parameters, supplementary files (e.g. Stressing directions, contingency list, RASs).
V	***Visualization Capabilities***
A	Voltage profiles, real & reactive reserves at key stations, and power flows at the higher voltage levels within wide within wide area geographic displays.
B	Real and reactive loading margins as bar graphs.
C	One-line diagrams within Operator Displays.