FINAL PROJECT REPORT

REAL TIME SYSTEM OPERATIONS
2006 — 2007

APPENDIX E

REAL-TIME VOLTAGE SECURITY ASSESSMENT FUNCTIONAL SPECIFICATIONS FOR COMMERCIAL GRADE APPLICATION

Prepared for CIEE By:

Lawrence Berkeley National Laboratory

CERTS
CONSORTIUM FOR ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

University of California
ciee

A CIEE Report

Consortium for

Electric

Reliability

Technology

Solutions

FUNCTIONAL SPECIFICATIONS
For Commercial Grade Application

Prepared For:
California Independent System Operator (CA ISO)

Prepared by:
Consortium for Electric Reliability Technology Solutions (CERTS)

Funded By:
California Public Interest Energy Research
Transmission Research Program

Date: April 09, 2007

CERTS
CONSORTIUM FOR ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

PREPARED FOR:

California Independent System Operator

PREPARED BY:

Electric Power Group
Manu Parashar, Ph.D. - Principal Investigator
Abhijeet Agarwal - Investigator

Pacific Northwest National Laboratory
Yuri Makarov, Ph.D. - Principal Consultant

University of Wisconsin, Madison
Ian Dobson, Ph.D. - Consultant

DATE:

April 2007

EXECUTIVE SUMMARY

Voltage stability is the ability of a power system to maintain acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition cause a progressive and uncontrollable decline in voltage. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power. *Voltage collapse* is the process or sequence of events accompanying voltage instability which leads to a low unacceptable voltage profile in a significant part of the system.

Objectives

Develop functional specifications for a Real-Time Voltage Security Assessment (RTVSA) tool that monitors voltage stability margin in real time, and help the real time dispatchers to manage this margin by controlling VAR resources, generation dispatch, and other resources on the transmission system. This application is expected to seamlessly integrate with the CA 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.

Approach

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 CA ISO test cases.

This document describes the design, functional and visualization requirements for a Real-Time Voltage Security Assessment (RTVSA) tool, as well as CA ISO's preferences on certain implementation and visualization techniques.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

Participants of the face-to-face interviews for their evaluation of the project and advice:

1. INTRODUCTION

California Independent System Operator's (CA ISO) intends to implement a Real-Time Voltage Security Assessment (RTVSA) tool as a part of the suite of advanced computational tools for monitoring and preventing system problems and congestion management in the California ISO Control Area. Modern voltage assessment methods include such advanced functions as identification of real/reactive loading margins under different stressing conditions and associated weak elements, advice on selection of remedial actions and automatic development of operating nomograms and security regions. Real-time production-grade Voltage Security Assessment tools are becoming increasingly available nowadays. These tools are integrated with EMS/SCADA systems and use results from the state estimator.

1.1 Background

A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable decline in voltage. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power. *Voltage stability* is the ability of a power system to maintain acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. *Voltage stability margin* is the distance to instability determined for a selected *loading* or *stress direction* in parameter space.

It is known that voltage magnitudes alone are poor indicators of voltage stability or security. Voltages can be near normal with generators, synchronous condensers, and Static VAR compensators (SVCs) near current limiting levels, thus resulting in a possible voltage collapse. However, as a security problem distinct from voltage collapse, it is also desirable that the system voltage magnitudes remain within limits, and some of the control actions to maintain voltage magnitudes may also be of benefit in avoiding voltage instability. Sufficient reactive power reserves at generators and SVCs contribute strongly to maintaining voltage stability, but do not measure the ability of the transmission system to transmit reactive power. Both voltage magnitudes and reactive load margins are useful indicators; however, the voltage stability margin is the more accurate and complete metric for the proximity to voltage collapse.

CA ISO system operators need to know how to more effectively manage the grid and its reactive resources, including coordination with other organizations (interconnected system operators, load-serving entities, and generators), within today's changed operational environment, particularly during periods of system stress. Today, generation operated by independent power producers as well as generation operated by utilities are not responding to system-operator-directed voltage-VAR requirements as reliably as they did prior to restructuring. This condition, which is compounded by the continued, large volumes of long distance energy transactions in the Western Electricity Coordination Council (WECC), is creating very unusual and dangerous voltage patterns that could jeopardize the reliability of both the CA ISO's grid and the Western Interconnection. Inadequate, region-wide coordination of VAR reserves was a contributor the 1996 west coast blackouts, leading WECC to adopt stricter voltage-VAR requirements.

The California Energy Commission has been sponsoring the ongoing research to review, and assess the state-of-art in voltage security assessment that is geared towards a real time environment. This work has been conducted by the Electric Power Group and Pacific Northwest National Laboratory (CERTS members) with an active participation of the leading

University professors (through PSERC). At the onset of the project, a questionnaire had been distributed among 60 leading specialists worldwide in order to collect a collective and incorporate their feedback and ideas on the state-of-the art approaches and technologies in the area. Based on the responses and feedback from this expert community, a multi-year project roadmap was developed which has guided the CERTS research on evaluating and demonstrating the recommended approaches on the CA ISO test cases. Leading utilities have also been interviewed in parallel on their implementation of a similar voltage security assessment tool within their operations or planning environment.

2. ON-LINE RTVSA FUNCTIONAL OVERVIEW

The RTVSA application will be integrated with CA 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 CA 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.

2.1 Modes of Operation

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.

In general context, the real-time mode will provide the system operators up-to-date information on the security status of the system with respect to voltage stability, including real time contingency analysis to ensure security of the system in the event of occurrence of any of critical contingencies, and compute key indices such as real or reactive loading margins under different stressing scenarios that quantify the degree of stability or instability for each case. The application will also suggest appropriate controls to the operator for increasing these margins.

The real-time case results are automatically stored into a centrally located rolling *Flat File* archive for future retrieval. The size of this rolling buffer of RTVSA solved cases must be configurable and shall be determined by CA ISO depending on the storage space requirements.

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.

Under the study mode, the users of the stand-alone console would have the option and convenience to run the RTVSA simulation engine on a "study case". Such study cases are: (1) real time RTVSA solved cases archived overtime within the *Flat Files Storage* (under Central Server), (2) modified versions of the above mentioned real-time solved cases to study hypothetical scenarios. For instance, a study mode user may extract a previously archived RTVSA solved case from the *Flat Files Storage*, remove one or more transmission lines, manually specify stressing directions, resolve using the RTVSA simulation capabilities and perform a complete voltage security assessment, and export this as a new "study case" to the central server if so desired.

The RTVSA tool should restrict users from overwriting a real-time solved case. Any modifications made to these cases must be stored as a new study case. Although multiple

users would be allowed to simultaneously access the same file, the RTVSA tool should prevent everyone, except the first user of the case, from imposing changes to the same. This 'locking' feature of the tool would help in preventing certain possibly conflicts. However, all the users should have the option to perform simulations as well as to save the case (under a different name) in order to make the desired changes.

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 are described in details in the next section and summarized in Table 1.

2.2 RTVSA Capabilities

The RTVSA application shall offer the following categories of functional capabilities:

Real Time Voltage Stability Analysis under Unidirectional Stressing

1) *Contingency screening and ranking with respect to voltage limit violations or loading margins associated with known stressing direction* – The application should perform such contingency analysis under all N-1 conditions and some user defined N-2 conditions within each 5 minute real time cycle. A directional stressing, representative of the actual system loading conditions based on the real time dispatch schedule and load forecast, will be used for this analysis and the most binding contingency shall be identified.

2) *Wide area monitoring capabilities offering real time situational awareness to the operators on key indicators that are closely associated with voltage security* – These include voltage profiles at select buses, real or reactive reserves at key generators both under base case and the most binding contingency within geographic visualization. It also includes animated power flow visuals at the higher voltage levels (e.g. 500 kV, 230 kV, and 138 kV). The application will also have the capability of sending real time alarms to the end-users on voltage violations and insufficient real or reactive loading margins.

3) *Real time voltage stability analysis with known stressing direction* – The application shall present the loading margins (real or reactive) to the point of collapse under the base case and the most binding contingency, allowing for an additional 2.5% and 5% (user configurable) safety margins for N-1 and N-2 contingencies, respectively. (Note to CA ISO: Voltage margins between base case and Point of Collapse (POC) solution may be an optional voltage stability metric).

4) *Quantify the efficacy of reactive power support at the most effective buses in terms of their sensitivities* (Note to CA ISO: These sensitivities translate to a linear constraint and is representative of the voltage stability limit associated with the unidirectional stressing which can be incorporated into Security Constrained Unit Commitment (SCUC) and Security Constrained Economic Dispatch (SCED) applications in the future).

5) *Rank available corrective controls based on their effectiveness* – These actions may include enhancement controls that optimally increase the loading margin with respect to

the stressing direction, or remedial controls in the situation that a contingency may lead the system state into an insecure region.

6) *Identify the weak elements within the system associated with the one-dimensional stressing* – These are buses/regions with the grid that experience severe degradation in their voltage profile at the voltage collapse caused by the additional stressing. The proportions by which the voltage magnitudes will fall at these buses shall be presented.

<u>Comprehensive Voltage Security Assessment under Multi-Directional Stressing</u>

This is generalization of the above mentioned capabilities to a multi-directional stressing situation presenting the interaction and tradeoffs between different stressing directions, and the associated interpretation of the safe-operating region as a 2-D or 3-D (or higher dimensional) nomogram.   The application shall:

1) *Develop and update voltage security regions offline on demand based on a set of pre-defined stressing directions* – The boundaries of these regions shall be expressed as piece-wise linear approximations (i.e., hyperplanes) in coordinates of key descriptive parameters (such as MW transfers, total MW generation, total MW loading, etc) associated with the stressing directions. As with the unidirectional stressing case, these security region boundaries too shall be representative of the most binding contingency in the various stressing directions
(<u>Note to CA ISO</u>: These hyperplanes are representative of the voltage stability limits associated with various stressing scenarios which can ultimately be embedded into SCUC and SCED applications).

2) *Real time voltage security assessment with respect to the multidirectional stressing* – The voltage stability margins between the most current base case operating condition and the security region boundaries shall be evaluated within each 5 minute real time cycle.

3) *Suggest appropriate controls to enhance margin to the boundary* – While the current operating point is within the security region, the application should also suggest appropriate control actions to optimally steer away from the closest boundary.

	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 1 - Summary of RTVSA capabilities

(Note to CA ISO: The above mentioned unidirectional and multidirectional stressing analysis could be implemented through a 'staged approach' whereby the more straightforward unidirectional capabilities could be requested from the vendor over the short-term and successfully demonstrated at the CA ISO, and this capability could by enhanced at a follow-on stage and transformed to handle the broader multidirectional stressing for a more comprehensive security assessment.

2.3 System Hardware Performance Requirements

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.

At any given time, the CA ISO anticipates that there will be XX real-time and YY off study mode users of the application. Under these conditions, the vendor will be asked to recommend appropriate hardware requirements to ensure that the CPU usage at the *RTVSA Central Server* not exceed 50% over any extended periods of time.

3. SYSTEM ARCHITECTURE

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

1) Input Subsystems

- CA ISO EMS

- Data Input Module

- Flat Files Storage

2) Central Server

- Server Manager

- Topology Processor

- Flat Files Storage

- Simulation Engine

3) User Interfaces

- Operator Display Console (Real-Time Mode Interface)

- Stand-Alone Console (Study Mode Interface)

The following figure of the proposed system architecture illustrates the affiliations among the various modules, as well as the constitutive functionalities of each of the consoles.

SYSTEM ARCHITECTURE

CA ISO EMS

Detailed Network Model (Static CIM)

SE Solution Output (Dynamic CIM)

DATA INPUT MODULE

RTVSA Supplementary Files

- Contingency List
- Stressing Direction
- Descriptor Variables
- SPS/RAS

Every 5 Minutes

Whenever Topology Changes

Data Manager (Middleware)

TOPOLOGY PROCESSOR

- Validates network modifications submitted by users
- Converts N/B model (Static CIM) to B/B for power-flow calculations
- Mapping of B/B to N/B model for one-line displays purposes

SERVER MANAGER

- Automation Scheduler
- Processes Manager
- Status and Logging Manager
- Client Request Manager

SIMULATION ENGINE

Power-Flow Calculations
Contingency Analysis

Contingency Ranking
Operating Nomograms
Distance to Instability
Weak Elements
Margin Sensitivities
Preventive & Enhancement Controls

Real-Time Output Snapshot

FLAT FILES STORAGE

xx – Supplementary Files
xx – Study Cases
- Real-time solved cases
- Modified real-time solved cases

CENTRAL SERVER

OPERATOR DISPLAY CONSOLE
- Real-time solutions display

REAL TIME MODE INTERFACE

Responsible For

1. Receiving real-time solutions from server

STUDY MODE INTERFACE

Responsible For

1. Exchanging Data To & From Server
   - Study case solutions
   - User selected input (e.g. contingencies, stress directions, etc.)
   - Study data set per case per user
   - User Defined RTVSA Supplementary files (stress pattern, contingency list, etc.)

2. Security
   - Validating user (optional)

STAND-ALONE CONSOLE
– Study case solutions displays

CONFIGURATION GUI
Select/Update Displays

Wide-Area Geographic-Graphic Visualization

Local-Area Visualization (One-Line Diagrams)

USER GUI
View/Update:
- Local displays
- RTVSA supplementary files
- Study case data

Customizable Displays

Real-Time Mode Users:
Wide-Area View
Voltage Profiles in Geographic Display
Mvar Reserves
Contingency Ranking
Nomograms & Margins
Weak Elements Information
Corrective Actions (Preventive Control, Enhancement Control)

Study Mode Users:
What-If Analysis
Trend Analysis
Post-Disturbance Analysis
(with Study Cases)
Manual Intervention
One-Line Diagrams
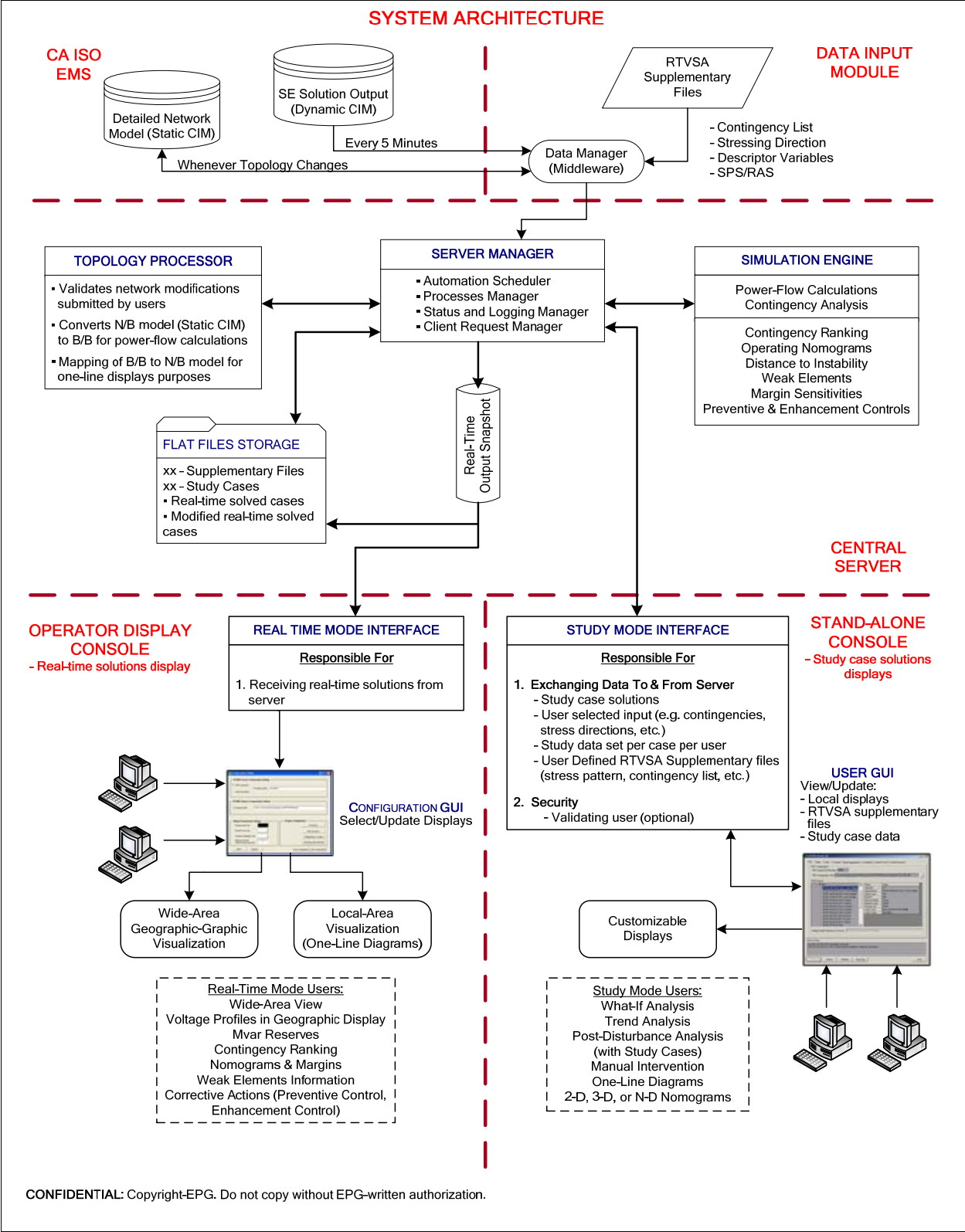2-D, 3-D, or N-D Nomograms

Figure 1 - RTVSA System Architecture

3.1 Input Subsystems

There are three sources of data input to the *Central Server* vis-à-vis the RTVSA tool:

1) CA ISO EMS
2) Data Input Module
3) Flat Files Storage

Depending on the tool's mode of operation, data can be acquired from any of the above mentioned sources.

3.1.1 CA ISO EMS

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. These files are available to the *Data Input Module* for purposes of combining them with the *RTVSA Supplementary Files*. The SE solution is passed on at a frequency set by the RTVSA *Central Server*. The Detailed Network Model file is not required frequently unless the network topology undergoes modifications.

(Note to CA ISO: The CA ISO EMS also houses a historian which stores the dispatcher's load flow saved cases for 7 days (subject to expansion). This database may be used for fetching files under the study mode, for purposes such as trending and post-disturbance assessment. Since both the Static and Dynamic CIM files are stored, the RTVSA tool should be equipped to match the timestamp on both the files during the retrieval process).

3.1.2 Data Input Module

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. With the help of a *Data Manager*, the Static and Dynamic CIM files, as well as the RTVSA Supplementary Files are combined into a single file to be transferred to the *Server Manager* within the *Central Server* module. This manager shall check for any missing or poorly transmitted data and take necessary actions.

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
- Special Protection Schemes/Remedial Action Schemes

These files are fetched for each real-time simulation sequence, and a copy of these files is stored in *Flat Files Storage* since they are needed during offline studies. The tool shall offer a convenient way (e.g. GUI) to edit the above mentioned supplementary files.

3.1.3 Flat Files Storage

Please refer to page 15 for details.

3.2 Data Requirements

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

Real-Time Modes:
- Data Source: CA 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

The RTVSA tool running in real-time modes would require all the above mentioned data to be present in the *Central Server*.

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

While running the RTVSA tool under a study mode, the user has the option to choose between the two study cases – real-time solved case or the modified solved case. RTVSA Supplementary Files would also be required here for a complete voltage security assessment with the previously mentioned functionalities.

3.2.1 Data Description

The following are details on the required list of data:

1. Valid SE solution
Contains Nodal voltage magnitudes and phase angles, and is the solved load flow solution obtained from the EMS that guarantees convergence.

2. Detailed Network Model
Contains information in a volume sufficient for detailed power flow simulations, under the CA ISO standards, i.e., branch information (connectivity data, line impedance), breaker status, etc

3. System Component Status Information
Includes the current status of generators, transmission circuits, transformers, switching devices, and other system components

4. Available Power System Controls and their priorities[1]

The available controls and their priorities must be provided to support the control advisory function of the RTVSA application. Examples are:
- Tap Changers
- Static VAR Compensator (SVC)
- Fixed and Controllable Shunt
- Generator Redispatch, etc.

5. Limits (Voltage, Thermal, MVar, Others)[2]

Consists of operational limits of system facilities/components that are to be specified in appropriate units, e.g. transformer limits in MVA, line limits in Amps, etc

6. Generator Model

Required information for generator modeling, such as:
- MVA ratings
- Q_{max}, Q_{min} values
- Leading and lagging power factor

7. Distributed Slack Bus Information

Required for governor power flow simulations

8. Low Voltage Load Models

These models (static characteristics) should cover the low voltage load behavior and voltage collapse situations. Any load model switching for low voltage cases should be clearly described by the vendor.

9. HVDC Models & Control Schemes[1]

Note: Vendors are requested to provide details on HVDC modeling and control schemes their RTVSA tool would feature.

10. Contingency List

Consists of:
- All (N-1) and some (N-2) contingencies, *or*
- User specified contingency list
- Any Remedial Action Schemes (RASs) associated with these contingencies

11. Stressing Directions & Descriptor Variables

Contains:
- Generator dispatch sequence & pattern
  (Should be capable of factoring in CA ISO's Unit Commitment Operating Procedures)
- Load stress pattern
  (Should feature the capability to assign participation factors to loads on an individual, area or zonal basis)

Descriptor variables are parameters that influence the voltage stability margin in certain parts of the system (voltage stability problem areas). Examples of descriptor variables are: total area load, power flows in certain transmission paths, total area generation, and so on. The operating engineers' should be able to define/modify these variables for the known voltage problem areas in the course of offline studies.

---

[1] The study mode users should have the capability to turn off the power system controls for simulation purposes.
[2] The study mode users should be able to turn off the operational limits for study purposes.

12. Special Protection Schemes/Remedial Action Schemes

During the system stressing process (mentioned in 'Data Description #11' above) and contingency analysis, it is required for the RTVSA tool to automatically trigger Remedial Action Schemes (RAS) or Special Protection Schemes (SPS) to provide realistic voltage stability margins.

3.2.2 Modeling Details

Accurate modeling of voltage stability conditions and parameters that influence them is a must for the RTVSA application. This includes the following requirements:

(1) Voltage stability conditions simulated using full power flow Jacobian singularity conditions.

(2) The algorithms used must converge accurately to the power system equilibrium in all cases in which that equilibrium exists, including cases at and nearly at voltage collapse.

(3) Low voltage/voltage stability load models including the models reflecting the OLTC action (e.g., constant active and reactive power for the OLTC regulation range), static characteristics representing load behavior outside the regulation range of the OLTC, and static characteristics approximately reflecting load behavior at the low voltage conditions

(4) Special Protection Schemes (SPS), Under-Voltage Protection schemes, and Remedial actions schemes (including remote RAS)

(5) Consistent treatment of the discrete event sequences, for example, the switching sequence of capacitors (non-uniqueness of these sequences for a given stressing path is not acceptable)

(6) Distributed slack bus/post-transient power flow (governor) model

(7) Generation dispatch options reflecting California ISO models and practices (e.g. generators maximum and minimum active power output, reliability must-run units, emission-induced constraints, etc)

(8) Multi-area power flow

(9) Adequate modeling of the reduced (equivalent) parts of the system, especially, voltage and governor responses of the reduced part of the system.

The RTVSA tool should be capable of handling CIM/XML file format at both the input and output ends. The minimum requirement for the data that is required to correctly describe the system equipments have been briefly mentioned here.

1. Bus data
   - Consisting of all bus types: swing/slack, PQ, PV, HVDC
   - Representation with breaker information and status

2. Transmission line data
   - Consisting of: out-of-service, in-service, bypassed, and HVDC lines
   - Representation with lossy model

3. Transformers and tap control data
   - Model types: 2 & 3 winding transformers
   - Control types: Fixed impedance with no control, voltage, MW, and MVAR control

4. Generator data
   - Generator remote regulation
   - Reactive power limits as Q_{min}/Q_{max}

5. Load data
   - Static model as described under Modeling Details (3) above

6. Fixed Shunt data

7. Controllable shunt and static VAR devices (SVD) data
   - SVD control types: locked, stepwise control, continuous control, stepwise control with deadband, on/off control with deadband
   - Models any controllable capacitive/inductive devices, such as:
     o Static VAR compensators (SVC)
     o Mechanically Switched Capacitors (MSC)
     o Synchronous Condensers

8. HVDC controls
   - The vendor is requested to provide details on the control modes featured by their tool.

Note: *The vendor is asked to provide model parameterization details for their tool, as well as any additional modeling details beyond the above mentioned set of minimum requirements.*

3.3 Input Subsystems Interface Requirements

As described above, the RTVSA processor may operate, though simultaneously, under the two mentioned modes. The files required under each of the modes have also been described in details. The question that yet remains to be answered is how should data be transferred from one module to another? Specifically:

▪ Data flow along *Interface 1* (refer to Figure 2 below)
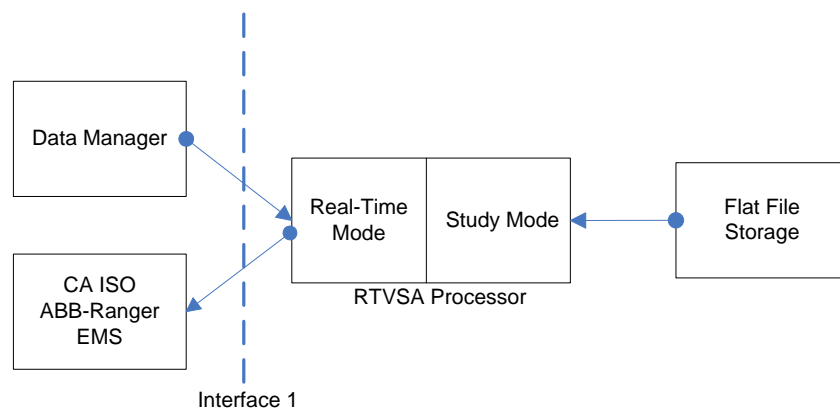
Figure 2 - Input Subsystems Interface

The approach that will be used to transfer data along Interface 1 should result in the seamless integration of the RTVSA tool with CA ISO's EMS, thus minimizing time lag and enabling the tool to run in "real-time". Industry standard technologies such as, messaging queue, web services, COM/DCOM, etc shall be used for this data transfer. Vendors are requested to suggest feasible options for this data exchange between RTVSA and CA ISO's ABB-Ranger EMS. Implementation details will be worked out in close consultation between CA ISO IT/Network Applications experts and the chosen vendor.

Note: *The vendor is requested to recommend supported interface options in their responses.*

3.4 Central Server

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.

This module is capable of simultaneously handling both real-time and study mode data processing based on the State Estimator solutions and study cases, respectively. The real-time data set solution outputs are displayed to the real-time mode interface users, whereas the study case results are demonstrated to the study mode interface users. Both these results are also stored in *Flat Files Storage* for trending purposes, post-disturbance analysis and future retrieval. The *Central Server* allows customization to server settings such as alarms, threshold levels, and simulation frequency.

The sub-modules that collectively define the functionality of the *Central Server* include:

1) Server Manager

2) Topology Processor

3) Flat Files Storage

4) Simulation Engine

The tasks of each of the sub-modules will now be discussed in details.

3.4.1 Server Manager

This sub-module is responsible for the following four tasks:

1) *Automation Scheduler* – automates the process of retrieving the real-time data at regular intervals (every 5 minutes for instance); these files are the SE snapshot, RTVSA Supplementary Files and the Detailed Network Model (when needed).

2) *Processes Manager* – manages the various sub-modules contained within the Central Server (i.e. topology processor, simulation engine, and flat files storage) under both the real-time and study mode environments. It procures either real-time data or study cases, performs the relevant topology processing with the help of the *Topology Processor*, executes the voltage security assessment application via the *Simulation Engine*, and stores the solutions (depending on server settings) in *Flat Files Storage*. These solution files are also sent to the relevant users upon certain processing of its network topology.

3) *Status and Logging Manager* – is responsible for displaying the current server status relevant to users, such as the details of the data set the Simulation Engine is currently working upon, time at which the process started, and the number of contingencies it has already simulated to name a few. It also maintains solution logs, and time & name stamps for every solved/modified case. This helps in identifying appropriate solved cases while retrieving them from the storage module.

4) *Client Request Manager* – identifies and pursues requests that originate from the Stand-Alone Console. These requests can be in the form of:

- Retrieval of study cases from Flat Files Storage

- Modification request to RTVSA Supplementary Files present in the storage

- Submission of study cases for simulations

The Client Request Manager should restrict users from overwriting a real-time solved case. Although the Manager may allow multiple users to simultaneously access the same file, it should prevent everyone, except the first user of the case, from imposing changes to the same. This 'locking' feature prevents from overwriting of study cases or causing system deadlocks and bottlenecks. However, all the users should have the option to perform simulations as well as to save the case (under a different name) in order to make the desired changes.

3.4.2 Topology Processor

The topology processor sub-module, as the name suggests, deals in either converting node/breaker model to bus/branch format and vice-versa or validating network modifications submitted by Stand-Alone Console users. For instance, it checks for and eliminates any islands (or hanging buses) that have been created due to the removal of transmission line(s) in study cases submitted by users.

The Detailed Network model, which the Server Manager receives as a real-time data in node/breaker model format, is converted to bus/branch format as required by power flow algorithms. Additionally, the Simulation Engine solutions are mapped back to the node/breaker model for one-line diagram displays to users.

3.4.3 Flat Files Storage

The storage space provided in the Central Server stores the following information:

- Real-time solved cases - solution outputs from Simulation Engine for each real-time data set

- Modified real-time solved cases - modifications to real-time solved cases submitted by users and/or the simulation solutions thereto

- Original or modified versions of RTVSA Supplementary Files

Every modified case has a name tag that identifies the user responsible for making the change(s). While a user is working upon a study case, the system (specifically the Client Request Manager) prevents another user from using the same case for modification purposes.

3.4.4 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.

All the data that is delivered to the *Central Server* is rendered to the Engine for simulation purposes. Moreover, the *Detailed Network Model* file (received from the EMS in a Node/Breaker format) is converted into a Bus/Branch model (by the *Topology Processor*) as required by power flow algorithms.

Perhaps one of the most important aspects of this document is the simulation capabilities offered by the RTVSA application. Apart from calculating the power flows and determining the nodal voltages and angles, the tool should feature the following mentioned simulation capabilities for given stressing direction(s):

1) Contingency Analysis & Ranking

2) Distance to Instability

3) Corrective Actions

     a. Enhancement Control

     b. Preventive Remedial Control

4) Weak Elements Information

In the case that multiple stressing directions have been defined, the application shall create 2-D, 3-D or N-D operating nomograms in coordinates of key descriptive parameters (such as MW transfers, total MW generation, total MW loading, etc).

1) Contingency Analysis

Contingency analysis is to be performed for all (N–1) and some (N–2) contingencies that may occur in the system. This process shall be repeated for every 5 minute real-time sequence. The contingency analysis simulations should:

- Perform full AC power flow computations for each stressing direction(s). Generation re-dispatch may be involved if the corresponding contingency includes forced generator unit outages.

- Trigger any Remedial Actions Schemes (RASs) associated with such contingencies.

- Rank contingencies based on voltage violations and/or loading margins.

Note: *If the RTVSA tool utilizes a screening process for contingency simulation, the vendor is requested to provide detailed description of this process.*

2) Distance to Instability

This simulation capability is particularly useful in providing users with useful margin indices, such as voltage margin, real & reactive load margin, etc. Distance to instability, or to voltage collapse, is to be calculated for both the base case scenario and under the worst case contingency for each stressing direction(s).

During the process of system stress, it is required for the RTVSA tool to automatically trigger Remedial Action Schemes (RASs) to provide realistic distance to instability.

Note: *Vendors are requested to provide details on the computation technique used to calculate distance to instability.*

3) Corrective Actions

Corrective controls provide users with the ability to increase the stability margin, or steer away from the region of instability should certain critical contingency(s) occur. These controls shall be ranked based on their effectiveness for each simulated stressing direction(s).

Enhancement control capabilities shall allow users to increase the stability margin by specifying an amount (in %) of improvement desired under both the base case and worst-

case contingency. This capability includes controlling of the phase shifters, ULTCs, static VAR devices, controllable shunts, etc for improving the current system state.

Preventive remedial controls provide the ability for users to secure the system from critical (or insecure) contingencies by suggesting priority-based control actions to improve margin indices. For instance, if the current base case scenario indicates sufficient load margin, whereas the occurrence of a certain contingency(s) places the system in the insecure operating region, the tool would determine 'preventive' controls to retract into a safe operating region.

4) Weak Elements Information
This simulation capability shall provide voltage sensitivity information with respect to stressing direction(s). This may be at various buses/regions that experience severe degradation in their voltage profile under additional stressing representative of voltage collapse patterns.

5) Operating Nomograms
The boundaries of the 2-D, 3-D or N-D operating nomograms shall be expressed as piece-wise linear approximations (i.e., hyperplanes) in coordinates of key descriptive parameters (such as MW transfers, total MW generation, total MW loading, etc.) associated with the stressing directions.

3.5 User Interfaces
The users of the RTVSA application can be categorized under two domains of operation:

1) Real-time mode users *or* users of the Operator Display Console
2) Study mode users *or* users of the Stand-Alone Console

3.5.1 Operator Display Console
Operator Display Console receives solution snapshots from the Central Server every time the RTVSA application runs on a set of real-time data. The users of this console, called real-time mode users, view results to RTVSA tool's simulations (consisting of the ones mentioned in Section 3.4.4) in the two mentioned modes, namely: real-time operations mode and real-time look-ahead mode.

The *Real-Time Mode Interface* facilitates exchange of unidirectional data from the *Server Manager* located within the *Central Server*. It receives only the real-time solutions data for display purposes, and restricts users from interacting with the Central Server. The interaction capabilities of these users are limited to the post processing of solution data. These include customization of display settings, such as, assigning a value (say 5%) to the reactive load margin on top of the most binding contingency – a criteria mandated by Western Electric Coordinating Council (WECC).

A Configuration Graphical User Interface (GUI) allows users to switch between the various display options, as well as update and modify the current display methodology. The users have the capability to look at the system from a bird's eye view (wide-area visualization), and subsequently zoom into the area of interest (local area view and/or one-line diagrams).

3.5.2 Stand-Alone Console

The Stand-Alone Console caters to users of the RTVSA application under the study mode described earlier. The users have the option to choose from any of the following two study cases:

1) RTVSA tool's real-time solved case
2) User modified real-time solved case

After selecting the appropriate case, the user may modify solution parameters and network topology, and with the help of certain required Supplementary Files, perform simulations to study hypothetical scenarios.

The *Study Mode Interface* sub-module is responsible for exchanging data to and from the Central Server. The *Client Request Manager*, which is a part of the Server Manager, manages various requests originating from the Stand-Alone Console users. The users shall have the capability to request files from the Flat Files Storage (i.e., study cases) to conduct studies. The Simulation Engine performs the desired calculations and returns the results to the Server Manager. Subsequently, the Server Manager [optionally] saves results in Flat Files Storage (along with the appropriate time and name stamps), as well as passes on the solutions to the Study Mode Interface for display purposes.

The study-mode console is to be equipped with an effective and user-friendly graphic user interface with point and click features, and pull-down menus. Modern graphics shall be used for the quick assessment of complex situations.

The study-mode RTVSA environment must be easy to understand and manipulate. The following is the summary of the features that shall be available to users:

1. Ability to request study cases and save modification and simulation results thereto.

2. Ability to adjust certain system parameters and to compute the sensitivity of the results to changes in parameters: this may apply to selection of fewer or more contingencies, together with the ability to construct system scenarios for study purposes.

3. Capability to perform 'what-if' and post-disturbance analysis on desired case(s)

4. Ability to visualize simulation results through appropriate graphical means. The capability to plot simulation parameters and variables as a function of time (trend analysis) is also desirable.

5. Ability to compare simulation results obtained from multiple cases.

4. VISUALIZATION & 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

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, but are not limited to:

- ✓ Voltage profiles at various buses
- ✓ Real and reactive power reserves across the system
- ✓ Interface/line flows across key transmission corridors/voltage levels
- ✓ One-line diagrams

Voltage Security Assessment

The display capabilities under this category 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, but are not limited to:

- ✓ Real and reactive loading margins
    - o Margin at base case to point of collapse (POC)
    - o Margin under worst case contingency base case to POC
- ✓ Contingency ranking based on severity index (voltage margin, loading margin, etc.)
- ✓ Operating nomograms
- ✓ Distance to instability
- ✓ Weak elements information
- ✓ Corrective actions (preventive control, enhancement control)

4.1 Recommended Visualization Techniques

Based on discussions held with CA ISO operators and operating engineers/planners, the following are some of the preferred visualization techniques mentioned:

- ▪ "Situational Awareness" type wide area geographic color-coded contour plots displaying information for both the base case and under the worst-case contingency about:
    - o Nodal voltages
    - o Real & Reactive reserves

o   Interface/line flows with respect to flow limits

- The color coding legend on contour plots shall accommodate different 'normal' operating ranges for the different substations. For example, a particular 500 kV bus at a substation may normally operate at 525 kV and this should be appropriately indicated by the 'normal' color used within the legend.

- For each of the operating modes, the users would like to be able to view the loading margins as bar graphs under the base case and the most binding contingency.

- Additionally, for the real time modes, and under the most binding contingency, the line flows should also be shown within a geographic display at least at the higher voltage levels. The more detailed flows under these situations should be visible on one-line diagrams within CA ISO's Operator Display Consoles.

- The ability to filter and view information by regional buses and by voltage levels

- The tools should support alarming capabilities when voltage profiles and/or margins drop below pre-defined operating limits. These limits should be configurable.

4.2 User Interaction

The RTVSA visuals are displayed to both user interfaces: real-time user interface located in CA 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 four system scenarios:

(1) Current system scenario (base case)

(2) System conditions under the worst case contingency

(3) 2 hour look-ahead condition under base case

(4) 2 hour look-ahead conditions under the worst case contingency

Although presenting multiple plots may sound intimidating to users, a clever layout of the visuals may reduce the involved complexities. For instance, the "current mode" tab would display plots (1) & (2), and by simply clicking on the "look-ahead" tab, the displays would switch to plots (3) & (4) – thereby replacing the old values with new one while keeping the display pattern (or technique) unchanged.

Here are some of the display capabilities and features required for the Operator Console users:

- Wide area geographic view of the current system conditions with the capability to zoom-in on a desired local area

- 'Situational Awareness' and 'Voltage Security Assessment' type displays for the above mentioned four system scenarios

- Effective displays of priority based corrective controls information with rankings based on their effectiveness for each simulated stressing direction(s).

- 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. The following are some of the display capabilities required for the stand-alone console users:

- The ability to conveniently modify network topology through means such as one-line diagrams, tabular displays, etc. The same applies for the various user-defined RTVSA supplementary files.

- 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 through appropriate graphical means which focus on the key parameters associated with various comparisons (e.g. indices, margins, sensitivities and trends). For example, it would be desirable to be able to assess the sensitivity of results to any parameter of a component via clicking on that component in the GUI.

- Capability to plot simulation parameters and variables as a function of time.

5. SUMMARY TABLE

The RTVSA feature set and functional capabilities are summarized in the table below:

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.

Table 2 - RTVSA Summary Table