Implementing a Country-Wide Modular Remedial Action Scheme in Uruguay

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***Abstract*—This paper presents a country-wide remedial action scheme (RAS) implemented in Usinas y Transmisiones Eléctricas (UTE) in Uruguay. When a single contingency or multiple closely timed contingencies occur, the RAS protects the power system from thermal damage to lines, voltage collapse, generation load unbalance, and overvoltage/undervoltage conditions. The RAS consists of six different schemes operating independently and, in certain cases, simultaneously to calculate power system states and define the remedial actions. Operator-defined gain constants and zone priorities are used to calculate the amount and location of load to shed respectively. Supplementary control modules such as the Brazil power exchange override are used to reduce the amount of load shed. The line-shed module prevents power oscillations on the Uruguay to Argentina interconnections. The post load-shed reactive power compensation module improves system voltage profile and eliminates possible overloads that could still be in the system.**

I. Background

A. Uruguayan Power System

The Uruguayan power system is connected to the Argentinian and Brazilian power grids at the northwest and northeast boarders. Usinas y Trasmisiones Eléctricas (UTE) is a government-owned company and regulates most of the generation and transmission in Uruguay. The transmission network consists of 500 kV and 150 kV transmission lines. The Uruguayan power system relies heavily on its 500 kV interconnection to the Argentinian power grid. The Uruguayan power system at 50 Hz is connected to the Brazilian power system at 60 Hz through two converter stations. Fig. 1 shows a map of the UTE power system, identifying 500 kV and 150 kV transmission lines and substations. The UTE power system is connected to Argentina at the Salto Grande and San Javier (500 kV) substations and to Brazil at the Rivera (230 kV) and Melo (500 kV) substations.

Peak demand of approximately 1,900 MW occurs typically during the winter months. To meet the increasingly higher demand during the drier years, Uruguay relies on power imported from Argentina. There has been a dramatic increase of dry years within the past decade. Building additional transmission lines and generation plants to meet the seasonal demand is expensive. UTE is hence required to operate the installed and existing equipment closer to their operating limits at high utilization levels. Such highly stressed power systems have an inherent problem of growing oscillations resulting from a single event, eventually leading to complete or partial system outages.

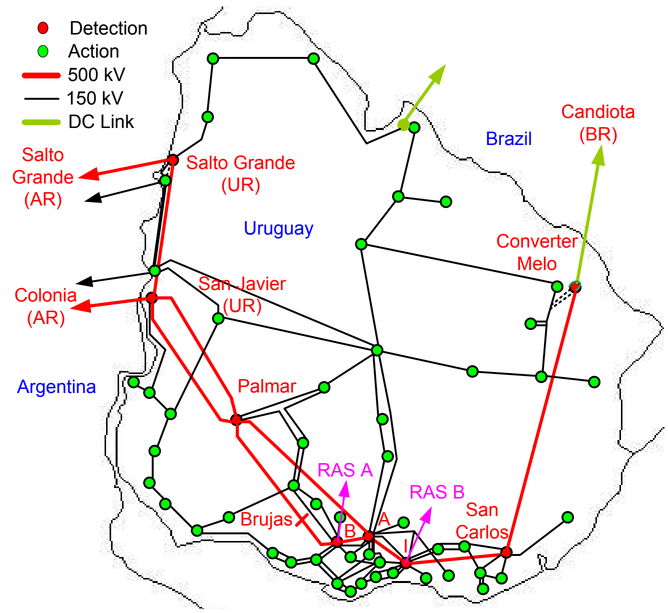

Fig. 1. The 500 kV/150 kV UTE Power System Grid

A contingency-based system-wide fast remedial action scheme (RAS) that can detect events and take remedial actions in milliseconds is required. Some key feature requirements included speed of operation, security, dependability, expandability, reliability, and ability for post-event analysis.

B. History

The RAS becomes a necessary and cost-effective solution when the power system by itself is not capable of recovering after a failure. Power transfer capacity in the western United States power grid has nearly doubled with a RAS in place [1]. The RAS remediates detrimental conditions on larger systems and protects power systems from additional problems that could surface.

Several remedial schemes to mitigate system outages were investigated by UTE. Existing schemes in the neighboring grids rely on generator shedding to mitigate loss of high-voltage assets. Shedding the limited available generation resource was not an option for UTE. With low damping strength of the UTE power system, any additional generator shedding as a remedial action, in most cases, worsens the system stability. The underfrequency-based load-shedding systems have slow response times and typically shed more load than required.

The RAS discussed relies on accurate load shedding to balance generation and load and to mitigate system overload and voltage collapse. The installed RAS replaces a slow-response, limited, and nonredundant load-shedding system. The old system was limited in the sense that its responses were contained to a small number of conditions and geographical zones. The area of influence of the old system did not match the growing system needs. The old system was not adaptive, and did not take into account the existing power system state and the power transfer between UTE and neighboring grids, which are both important factors in determining the level of remediation.

With the old system not being adaptive to changes in the power system configuration, small changes in the power system operations (e.g., taking a line out of service for maintenance or repair) demanded power flows across the monitored path to be drastically reduced. The old system did not include other remedial actions such as reactive power compensation and Brazilian intertie power demand override actions. Reliability, fast operation speeds, and system expandability were some of the features that the old system lacked.

The newly installed RAS can monitor a wide diversity of data from dispersed locations. The module selection and parameter definition feature of the RAS make it very flexible for future expansion. The RAS design allows easy modifications to accommodate new discoveries related to system stability response and operation. With a robust communications backbone in place, the RAS can rapidly consider changes to the power system state, continuously monitor the status of power exchange corridors, and make decisions that allow optimal use of the power system. The RAS also accounts for operator inputs such as load priorities, load-shed inhibits, and other system definitions like critical equipment selection, allowing routine maintenance of equipment without reducing the power flow levels across the monitored path. Post load-shed ancillary controls such as reactive compensation, voltage control, Brazil intertie power exchange override, and a backup underfrequency remedial system are some additional features of the RAS that the old system lacked. The new system is redundant in providing higher levels of availability.

II. RAS Requirements

A. Timing Requirements

The response time required by the RAS to prevent thermal overloading of equipment due to the outage of certain critical assets is in the order of minutes. Certain contingencies require remediation for voltage and frequency stability. The response times required for these contingencies are much faster.

When the typical fault detection time, communication time, field equipment response times, and other communications delays are excluded from the total time budget, the RAS is left with less than 20 milliseconds of operating time. The total throughput time shown in Table I is the total measured time from an input in the RAS input/output (I/O) module asserting to the front-end processor (FEP) sending control signals. Although the RAS has the capability to process the detection signals faster, the process is deliberately delayed to differentiate between single event and multiple event contingencies. Prior experience has shown that a single event contingency can evolve to a multiple event contingency while the RAS already responds to the first contingency. If the processing for the initial event is not delayed (in a few milliseconds), it could result in excessive load tripping.

Table I
RAS Timing Requirements

Item	Process Time (ms)
I/O module input debounce	2
I/O module to FEP communication	4
FEP to RAS central processing unit (CPU) communication	4
RAS processing time	2
RAS to FEP communication	4
Total time	**< 16**

The communications between the RAS substations and the remote substations are separated over several hundred kilometers, and the load breaker opening time adds additional latency. Dynamic simulation studies have shown that a total round-trip clearing time of less than 200 milliseconds from the contingency is required for maintaining power system stability. Since the level of load shed performed is adjusted based on the power transfer override capabilities on the Brazilian intertie, faster response times similar to initial load shedding are required for control signals to the convertor. Ancillary modules such as reactive power compensation and supplemental load shedding have typical response times in the order of a few seconds.

B. Contingency Detection and Remedial Actions

The status of 500 kV transmission lines and 500 kV substation transformers are monitored at high speed. Following the breaker status contacts (52a or 52b) for declaration of an open line requires several changes to the existing breaker wiring scheme. Moreover, the existing breaker auxiliary contacts are prone to mechanical failures. To avoid faulty detection, loss of a 500 kV transmission line is detected by an open line detection algorithm (OLDA) programmed in the peripheral controllers designated as detection equipment. The OLDA uses currents and voltages to monitor the status of the 500 kV line and declares an open line. With several inherent security checks, it also differentiates between the opening of the local end or the remote end of a line.

It is necessary to monitor the status of critical lines and/or other equipment to declare an event in the power system. Table II lists the 500 kV equipment monitored by the RAS and the associated event number.

TABLE II
RAS EVENTS

Event #	Description
E1	Palmar – Brujas Line
E2	Brujas – Montevideo B Line
E3	Palmar – Montevideo A Line
E4	San Javier – Palmar1 Line
E5	San Javier – Palmar2 Line
E6	San Javier – Colonia Elia Line
E7	San Javier – Salto Grande Line
E8	Salto Grande Uruguay – Salto Grande Argentina Line
E9	Montevideo A – Montevideo B Line
E10	Montevideo A – Montevideo I Line
E11	Montevideo I – San Carlos Line
E12	San Carlos – Melo Line
E13	Converter Station at Melo
E14	500 kV/150 kV Transformer at San Carlos

Any power system event for which a remedial action is required is defined as a contingency. A contingency can be a single event contingency like event E8 or can be a multiple event contingency such as events E2 and E3. The possible combinations of contingencies in the RAS are defined by the user as explained in Section IV.

The RAS responds to multiple closely timed and simultaneous contingencies. The RAS control actions are classified as the follows:

- Fast load shedding to prevent voltage collapse, eliminate the overload conditions on critical equipment, or correct the generation-load imbalance.
- Power transfer controls for run-back, increment or disconnection of 50 Hz/60 Hz power converter station to regulate the power flow to and from Brazil.
- Reactive power compensation to avoid overvoltage conditions after a fast load shed. The reactive power is reduced by disconnecting capacitor banks in certain substations.
- Slow load shedding to eliminate overloads that could remain in the system after fast load shedding due to undesired loss of generation or an action not executed.
- Automatic disconnection of certain 150 kV lines after a fast load shed for certain power system states to disconnect Uruguayan and Argentinian power systems.
- A backup decentralized underfrequency load-shedding system that has five levels, f0-df/dt, f1, f2, f3, and f4.

III. SYSTEM ARCHITECTURE

Fig. 2 shows the overall architecture of the RAS. RAS A and RAS B are dual primary systems, and both RAS controllers are running at all times. The communications backbone for the RAS system is based on a synchronous data hierarchy (SDH) network over a fiber-optic cable. SDH multiplexers are installed at the RAS substations, detection substations, and action substations. Ethernet over SDH is used as the interface for communications. Each RAS system (A and B) consists of remedial action controller (RAC), FEP, supervisory control and data acquisition (SCADA) gateway (GTS), human-machine interface (HMI) system, synchrophasor vector processors (SVPs), I/O modules, and managed Ethernet switches.

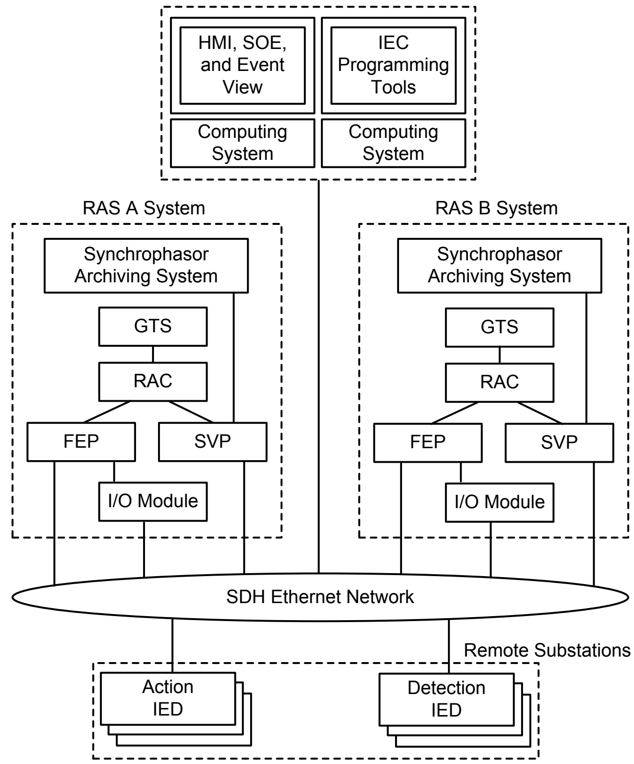

Fig. 2. RAS System Architecture Overview

The detection and action equipment in the field serve as phasor measurement units (PMUs), which transmit the data required by RAS to the SVP using C37.118 synchrophasor protocol. The SVP collects power system information such as analog data, breaker position, and out-of-service conditions and passes the data to the RAC for processing. The GTS acts as an Inter-Control Center Communications Protocol (ICCP IEC 60870-6/TASE.2) gateway link between the RAS and UTE dispatch control center. These gateways serve as a redundant, secondary source of data for the RAC. The RAS health status and other RAS diagnostic information are transmitted to the UTE SCADA via ICCP. All the high-speed data such as contingency detection and remedial actions are transmitted using IEC 61850 Generic Object-Oriented Substation Event (GOOSE) protocol. Within each RAS panel, a substation-hardened computer provides an HMI, Sequence of Events (SOE) viewing, and event report viewing (oscillographic) capability. All OSI layer 2 GOOSE and OSI layer 3 protocols (C37.118, ICCP, FTP, and Telnet) are communicated over the SDH network.

All synchrophasor measurement data are archived. The archiving allows UTE to investigate power system events and to analyze the power system behavior. The high sampling rate of the archived synchrophasor data also opens up possibilities of small signal analysis for monitoring system stability.

A. IED Communications Settings Management

The expansive RAS communications architecture includes up to 50 remote substations. Each substation has at least one action intelligent electronic device (IED) and one or more detection IEDs depending upon the location. Managing the settings and keeping them consistent for a critical application such as the RAS with approximately 200 action and detection IED can be challenging.

The implemented settings management philosophy addresses efficient and consistent substation IED settings. The settings management philosophy implemented in the RAS relies heavily on network address translation (NAT) and virtual local-area network (VLAN) translations. Depending upon the equipment type, all the IEDs at substations are configured with the same settings including internet protocol (IP) addressing.

For example, all action IEDs will always have a B.0.0.90/24 IP address and identical RAS settings irrespective of the substation location. The substation NAT is used by the RAS to differentiate devices in multiple substations. The substation firewalls keep the IED local IP address transparent and exposes the IED with the IP address A.B.SEID.90/24 to other RAS devices. A, B, and SEID represent the first, second, and third octets of IPV4 nomenclature.

Similarly, the IEDs in all substations will subscribe and publish IEC 61850 GOOSE messages over the same VLAN ID. Because of network congestion, multiple IEC 61850 GOOSE messages on a large network over the same VLAN are not recommended. VLAN tag translation by a managed Ethernet switch are used to efficiently manage internal substation and external SDH network VLAN tags. Using consistent subscription and publication settings over the same GOOSE VLAN allows use of consistent network management settings for the substation automation engineers. These translations streamline IED settings and provide enhanced network security. Table III shows the IP addressing that is used for RAS equipment in each substation, where SEID stands for the unique substation identification number.

TABLE III
TRANSMISSION SUBSTATION NAT SCHEME

Equipment Type	Local Address	WAN Address
Action IED	B.0.0.90	A.B.[SEID].90
Detection IED 1	B.0.0.91	A.B.[SEID].91
Detection IED 2	B.0.0.92	A.B.[SEID].92
Detection IED 3	B.0.0.93	A.B.[SEID].93
Detection IED 4	B.0.0.94	A.B.[SEID].94
Detection IED 5	B.0.0.95	A.B.[SEID].95

Fig. 3 represents the RAS VLAN translation scheme for two remote substations. On the Ethernet switch at the substation for VLAN mapping, the specified RAS PVID (3000 + SEID, 3500 + SEID) packets are mapped to the specified substation PVID (3901, 3902) when they enter the port. Symmetrical mapping back to the RAS PVID occurs when the packet exits the port.

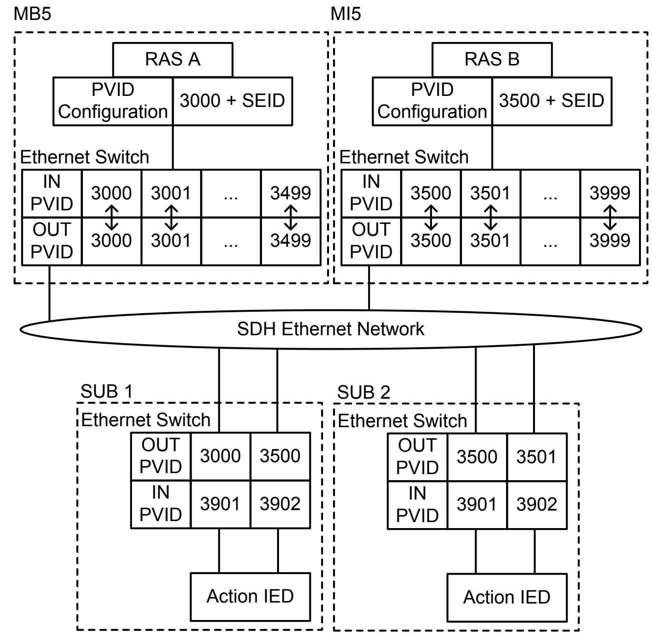

Fig. 3. VLAN Translation Scheme

B. Rugged RAS Design

All hardware devices shown in Fig. 3 are protective class substation-hardened equipment with extended temperature range, shock resistance, electromagnetic immunity, and static discharge capabilities. There is a small chance for equipment failure due to dust accumulation; therefore, there are no fans or spinning hard drives in any of the IEDs and controllers.

A dual primary UTE RAS system is a redundant system where both controllers gather I/O, performs calculations, and make decisions at all times. Other redundant architectures based on failover time between the primary and the secondary sources require a failover delay time between the two systems. The two RAS controllers are located in different 500 kV substations, MI5 and MB5. The redundant design is set up such that all critical controlling devices are duplicated at both main substations creating two systems that are capable of performing independently of each other. The RAS uses dual-Ethernet communications connections to eliminate all single points of failure in communication between the remote substations and the RAS substations. It would take two simultaneous hardware failures or two simultaneous process failures to disable and prevent operations [2]. Path diversity in the SDH network eliminates loss of communications due to a single point failure.

The main control algorithm resides on an embedded RAC. The algorithm is programmed using IEC 61131 programming language. Watchdog counters implemented on all programmable IEDs detect communications failures. All data used by the controllers are checked for out-of-range conditions. The RAS is set up to automatically reject bad data and reselect available good data or in certain cases default to a more conservative value.

IV. RAS Algorithm

The RAS algorithm designed for and specified by UTE dynamically calculates load to shed based on power system state and predefined set points. System definition parameters for the RAS are defined by the operating engineers. The data required for the operation of the RAS originate from the equipment in the field and from the UTE SCADA system. To make the RAS flexible, reliable, fast, and efficient, the RAS logic has four parts: module selection and parameter definition, data handling and acquisition, RAS algorithm calculations, and ancillary controls. Fig. 4 shows an overview of the RAS algorithm.

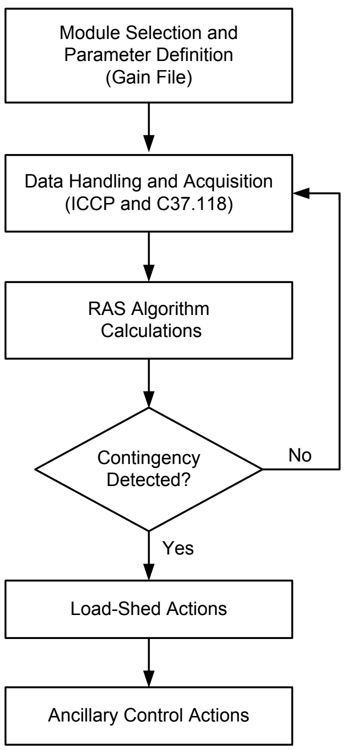

Fig. 4. RAS Algorithm Overview Flowchart

A. Module Selection and Parameter Definitions

The UTE RAS design allows the operator to define and control the type of remediation. Engineers at the dispatch control center can define the scope, geographical zone, and the level of the remedial actions. The definitions vary based on the day-to-day operation of the power system. However, the level of remediation required depends on the severity of the power system event and the present load demand. An event in the power system due to the loss of a 500 kV line or transformer is identified as an E event (Table II). Contingencies identified as C require remedial actions. The UTE RAS incorporates 32 events and allows definition for as many as 64 contingencies.

The UTE RAS allows engineers to define contingencies and the remedial action module to be executed for each contingency in a tabular format identified as a RAS file. The RAS file is a combination of multiple gain tables, maintained in comma-separated variable (CSV) format. The automatic error tracking tool in the RAS file prevents the user from entering erroneous values. The RAS file in CSV format is converted to a binary format and then loaded in the controller for further calculations. Contingencies requiring remedial actions are defined as single or multiple event contingencies in the gain table for contingency definition. Each UTE RAS module remediates a different type of stability issue in the power system and has different types of actions. The RAS algorithm modules for each contingency are defined in Table IV.

Table IV
Example of Module Selection

Module	Contingencies						
	C1	**C2**	**C3**	**C4**	**C5**	**…**	**C64**
Load Shed – Module 1	1	0	0	1	1	…	0
Load Shed – Module 2	0	1	0	0	0	…	0
Supplemental Load Shedding	0	0	1	1	0	…	0
Reactive Compensation Module 2	0	0	0	0	1	…	0
Brazil Power Override	1	1	0	1	0	…	1
Line Shed	0	0	0	1	1	…	1

B. Data Acquisition and Handling

Data required for the operation of the RAS are collected from the remote substations and the central SCADA system. These data can be classified into high-speed data and low-speed data. Contingency signals that trigger a remedial action are detected at high speeds. Metering information such as real power, reactive power, and voltage values required for calculating the level of remediation are not needed at high speeds. Collecting all data at high speeds would require wide communications bandwidth, demanding additional communications infrastructure. Moreover segregation of data into high and low speeds has been proven to yield better performance on both large scale and small scale schemes [3][4][5]. Both the high- and low-speed data are multiplexed at the remote substations and transmitted to the RAS through the SDH network.

1) High-Speed Data

The UTE RAS uses the teleprotection equipment for high-speed digital communication such as power system event detection. Contact transfer cards in the SDH network transfer the hardwired digital input signals to dataflow and transmit the event detection signals from the remote substations to the RAS substations.

These SDH data signals are converted to output signals and wired to I/O modules in the RAS panel. The communications between the contact transfer cards to the I/O modules are accomplished in less than 20 milliseconds. The IEC 61850 GOOSE protocol is used to transmit the contingency detection signals from the I/O modules to the RAS controllers. The same protocol is used to then transmit the action signals from the RAS controllers to the FEP. Other calculations such as output selection logic and communication required to initiate the remedial action signals are also accomplished in less than 8 milliseconds.

2) Low-Speed Data

Low-speed data includes information from the SCADA system and data collected using the C37.118 protocol. This data includes analog data like active and reactive power, capacitor bank status, and out-of-service conditions.

The C37.118 data are collected from the IEDs dedicated to the RAS at 50 times a second. The C37.118 data are archived in the RAS substations for future analysis. The SVP in the RAS panel then sends the data to the RAS controller every 100 milliseconds. Data are collected from the SCADA system at two different speeds. Data required for the operation of RAS are polled at a faster rate (200 milliseconds) and are configured for unsolicited reporting. Other noncritical data such as analogs and status information required for display on the HMI are polled every 2 seconds.

The RAS processes the low-speed data and calculates the actions for all contingencies every 100 milliseconds. These actions are then fed into the Crosspoint Switch (CPS) [4]. The high-speed detection inputs are cross multiplied with the CPS to issue remedial trips.

C. RAS Algorithm Calculations

This section discusses specific components of the RAS algorithm: data selection and validation, critical equipment and power system state, load shed − gain table technique, process of load selection, CPS − line trip versus substation trip, and multiple and closely timed contingencies.

1) Data Selection and Validation

All digital and analog data selected by the RAS for calculations are based on their speed and reliability. The RAS monitors the communications for failure at different levels of the network and selects the best data available. The final data used in the RAS algorithm are chosen based on data quality. The majority of the data are collected from both the SVP and the UTE SCADA system that act as a redundant data sources. Data validation is accomplished by comparing the two sets of data from both sources and ensuring that neither is outside a given threshold from one another. If the analog values from two different healthy sources are within 5 percent of each other, the average value of the two sources is used by the RAS. If a single value from the two equally healthy sources exceed a 5 percent difference, the larger value is chosen and used by the RAS.

2) Critical Equipment and System State

Critical equipment identified as *j* are important 500 kV/150 kV transmission lines and transformers in the UTE power system. The RAS currently monitors 64 critical equipment. During a contingency (C), certain critical equipment (*j*) are operating at a level beyond their normal operating limits until a remedial action is taken. With years of experience, UTE engineers use detailed power flow and dynamic simulation studies to select up to eight critical devices for each contingency. The selection of the critical equipment to monitor depends upon their geographical location and their pre- and post-contingency connectivity to the out-of-service equipment that triggered the contingency. The load-shed level for a contingency will depend on the total overload levels in the critical equipment selected for that contingency. The selection of critical equipment for each contingency is done using the critical equipment selection table in the RAS file.

The valid combination of in-service and out-of-service conditions of critical equipment converge to a system state S. In other words, the system state actually represents the present power system configuration in terms of critical equipment. With 64 critical equipment, a total of 2^{64} (1.8×10^{18} values) system states theoretically exist. Since all combinations are not possible or valid, the UTE RAS includes 1,000 system state definitions using the state table in the RAS file (e.g, the RAS system state S1 is defined as critical equipment J1 out-of-service and S235 is defined as J23 and J45 and J63 out-of-service, in the state table). The present system state S is very critical in determining the level of remediation.

UTE investigated several earlier RAS for system state calculations. The approach used in earlier RAS defines up to 1,000 fixed system states representing possible power system configurations, as recorded in the state table. The RAS compares the present critical equipment statuses from the field with the predefined combinations in the state table. With this approach at any point in time, a single system state is chosen for all contingencies. If the RAS comparison does not converge to a predefined system state, then a default system state is chosen. For example, if there are 32 possible system states defined by the combination of 9 critical equipment, the probability of finding the exact system state will be $32/(2^9) = 0.06$. Under this condition the RAS resolves to the default power system state. For certain contingencies, the difference in the load-shed calculations between the default system state from the state table, and the actual system state based on equipment status could lead to excessive load shedding. The UTE RAS uses a dynamic system-state calculation algorithm and calculates a system state for each contingency instead of selecting one system state for all contingencies. Based on its geographical location, every contingency has a few critical equipment's that are more relevant than the rest. By only considering the critical equipment relevant for that particular contingency, the probability of finding the exact system state increases. The relevant critical equipment for each contingency for state calculations are defined in the RAS file. The UTE RAS uses the following parameters to identify the gain constants to be used in the load-shed calculation for each contingency:

- Critical equipment selected for each contingency
- Calculated system state (S)

These gain factors are then applied along with the filtered analog and digital data from the field to calculate the amount of remediation (MW required to shed). The location of loads to shed is explained in detail in later sections.

3) Load Shed – Gain Table Technique

For each contingency, a combination of multiple control actions restricts the power system from not exceeding its limits. The polynomial equation used to calculate the amount of load to shed (MW) depends on the load-shed module chosen for the contingency in the module selection table of the RAS file. Load-shed module 1 is based on calculating load-shed levels to reduce the overload in critical equipment below its thermal limit after a contingency. The equation for load-shed module 1 is a function of critical equipment status, pre-event loading conditions of the 500 kV and 150 kV equipment, nominal rating of the critical equipment and gain constants that are used to control sensitivity. Load-shed module 2 is based on calculating the load-shed levels for an isolated grid (disconnection from Argentina). The load-shed levels calculated for module 2 focus on preventing generation-load imbalance, which if not corrected could lead to loss of additional assets and frequency fluctuations. The equation for load-shed module 2 is a function of pre-event loading conditions of 500 kV and 150 kV equipment and gain constants that are used to control sensitivity. The load-shed modules work independently of each other. The RAS controller executes the two load-shed modules simultaneously. However, only one load-shed module can be selected per contingency.

The load-shed level for each critical equipment for a predetermined contingency for module 1 is expressed as:

$$DAC_{0\_Ci}(j) = \left[\frac{DFV_{Ci}(j) \bullet \Phi_{500} - \left(NM_j - \Phi_j\right)}{AFV_{Ci}(j)}\right] \bullet S_j \quad (1)$$

$$DAC_{0\_Ci} = MAX\left[DAC_{0\_Ci}(1), \ldots, DAC_{0\_Ci}(8), 0\right] \quad (2)$$

where:

$DAC_{0\_Ci}(j)$ is the MW load to shed for each critical equipment.

j is the critical equipment for contingency Ci (j = 1 to 8).

$DFV_{Ci}(j)$ and $AFV_{Ci}(j)$ are the distribution factors and alleviation factors load gain constants for critical equipment *j* and contingency Ci.

NMj is the post contingency power flow desired in the critical equipment, typical thermal rating for 1 hour, voltage drop limitation, or stability limit.

Φ_{500} is the power flow in the lost 500 kV equipment that triggered the contingency.

Φj is the power flow in the critical equipment *j* before the contingency.

Sj is the status of critical equipment *j*.

DAC_{0_Ci} is the MW load to shed for contingency Ci.

The final load to shed is then adjusted based on the power transfer with Brazil through the convertor. The final load-shed level is expressed as:

$$DAC_{Ci} = MAX\left[DAC_{0\_Ci} - DAD_{Ci} \bullet R_{Ci}, 0\right] \quad (3)$$

$$R_{Ci} = \frac{AFC_{Ci}(j)}{AFV_{Ci}(j)} \quad (4)$$

where:

DAC_{Ci} is the final load-shed value for contingency Ci.

DAD_{Ci} is the calculated final power demand override through Brazil intertie.

R_{Ci} is the DAD adjustment factor.

$AFC_{Ci}(j)$ is the alleviation factor convertor gain constants for critical equipment *j*.

For the eight critical devices chosen for each contingency based on the calculated power system state, eight distribution factors, alleviation factor loads, and alleviation factor convertor gain constants are chosen. The gain constants (DFV j, AFV j, and AFC j) for each critical equipment are updated using the gain constant table. The dimension of each gain constant table is system state by contingency by critical equipment. The final dimension of the DFV gain table is 1,000 by 64 by 8 gain constants. This equates to a total of 512,000 gain constants not including matrices for other modules and several other gain constant matrices of smaller sizes. Fig. 5 shows the three dimensional DFV, AFV, and AFC gain table. For each contingency (C) and based on the power system state (S) calculated, the gain constants from the corresponding cells are chosen for up to eight critical equipment (*j*) and are used in the formula shown above for calculating the load shed. For example, G1 is the gain constant for C3, J3, and S1. Similarly, G2 is the gain constant for C45, J1, and S100. UTE engineers update the gain constants depending on the system load flow and detailed stability studies.

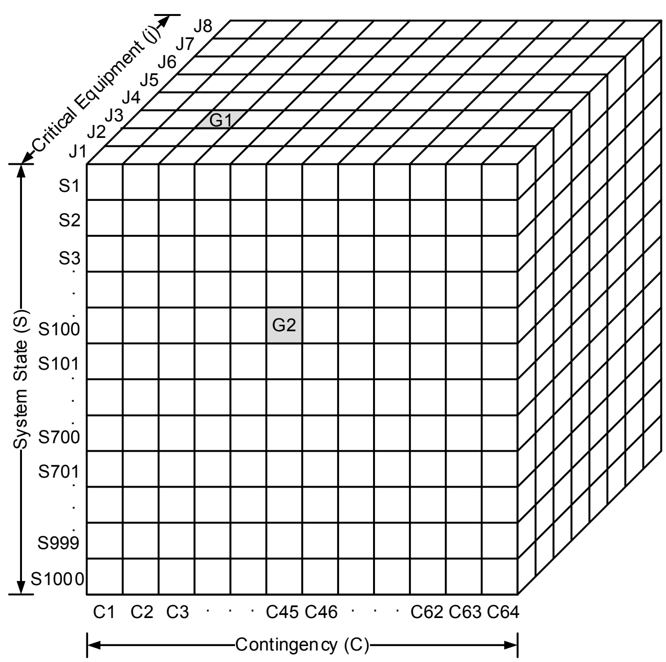

Fig. 5. Gain Constant Table for DFV, AFV, and AFC

Module 2 uses a different equation with a different set of gain constants. The gain constants however are defined in a similar fashion. The final load-shed value for module 2 is also adjusted based on the power flow through Brazil (DAD_{Ci}) explained in Section D ancillary controls.

4) Process of Load Selection

After calculating the load-shed value for each contingency, the RAS performs the process of load selection. The loads selected to be shed are located throughout Uruguay. The loads are grouped into geographical zones identified as Z. The RAS considers 128 loads and 32 zones for process of load selection (PLS) calculations.

The grouping and assignment of loads to a particular zone is done through the zone selection table in the RAS file. For each contingency, a unique priority number (Z_{PRTY}) is assigned for each geographical zone. Location of load to shed is determined by the assignment of loads and Z_{PRTY} to a particular zone. The same zone can have Z_{PRTY} for different contingencies. A zone threshold (Z_{THLD}) is defined for each zone. The Z_{THLD} are defined based on the reactive power generated by the susceptance of lines in the zone. Z_{PRTY} and Z_{THLD} are entered through the RAS file.

Loads are generally shed by disconnecting transformers in the substation. The RAS operator has the ability to inhibit a load from tripping. If the sum of loads available (noninhibited loads) to be tripped is greater than the threshold value for the zone, then the RAS trips the entire zone through its interconnecting lines followed by the substations in the next zone until the DAC_{Ci} number is satisfied. Lines are tripped by opening breakers on both ends of the line.

Table V shows an example of the PLS for a contingency with DAC_{Ci}=700 MW. The RAS sorts the substation in descending order of MW within each zone and arranges each zone in ascending order of zone priority. The PLS selects Zones 3 and 2 to be tripped by lines and substations MVE and PAN in Zone 4 are selected to be tripped individually. The total load shed for this contingency will be 140 + 350 + 148.1 + 66 = 704.1 MW. The PLS discards Substations NOR and MVC in Zone 4, because there are smaller substations available that can satisfy the required DAC_{Ci}.

TABLE V
EXAMPLE OF PROCESS OF LOAD SELECTION

Zone #	Z_{PRTY}	Z_{THLD}	PLS Substation List	Load (MW)	Zone Load (MW)	Trip by Lines	Trip by Substation
3	1	80	MAL	48.0	140	✓	
			BIF	35.2			
			PES	21.1			
			SCA	14.0			
			ROC	11.0			
			PAZ	10.3			
2	2	90	MVF	98.3	350	✓	
			MVJ	98.1			
			MVH	92.6			
			MVR	36.7			
			MVG	34.0			
4	3	0	MVE	148.1	533		✓
			NOR	109.6			
			MVC	76.3			
			PAN	66.0			✓
			MVL	45.7			
			MVK	45.1			
			PIE	42.5			
			Laisa	0.0			
			MVM	0.0			
1	4	0	ROS	32.7	83		
			FLO	26.4			
			DUR	14.1			
			TRI	9.7			

5) CPS – Line Trip Versus Substation Trip

The RAS dynamically calculates the load shed value and location for each contingency. The RAS mitigates overload conditions and reduces generation load imbalance for up to 64 contingencies, using the gain table technique [6]. The process of load selection provides a more flexible use of system assets and prevents over-remediation. All system definitions and load selection parameters are entered and managed by the dispatch engineers using the RAS file.

The output of the RAS algorithm is the CPS. The results from the load-shed level calculation and the process of load selection are used to populate the CPS. It is a two-dimensional array that shows contingencies (C) and actions. Each cell of the array displays the zone number where the action is taken. The CPS also indicates whether the loads will be shed by tripping individual substations or entire zones will be shed by tripping lines. The CPS results are updated every 100 milliseconds by the RAS. As soon as a contingency is detected, the RAS triggers the actions as represented by the CPS. Fig. 6 shows a UTE RAS CPS. The CPS also identifies if a substation is inhibited by the operator from tripping.

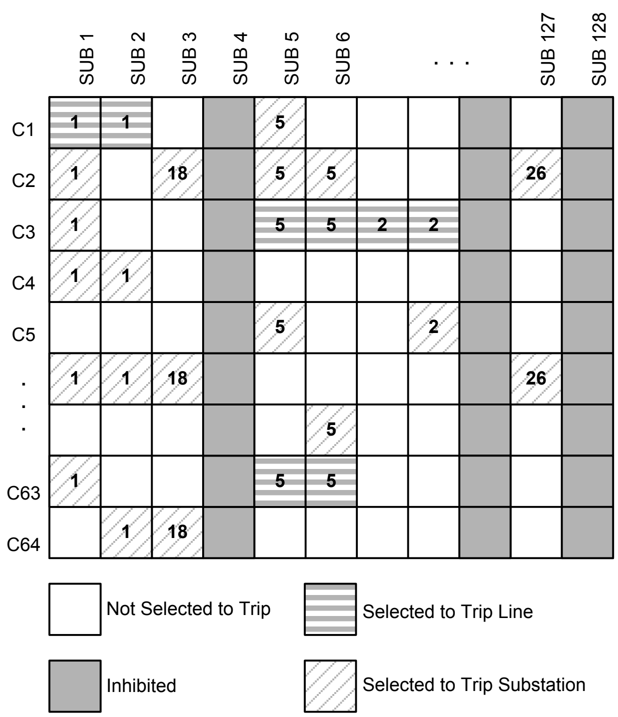

Fig. 6. CPS Action Table

6) Multiple, Closely Timed Contingencies

When remedial actions are taken for multiple closely timed contingencies, additional care and checks are performed by the UTE RAS to avoid poor decisions. Any contingency that happens in the system creates a disturbance. These power disturbances could cause the gathered analog data to fluctuate before the power system settles to a new steady-state level. To prevent these disturbances from affecting the RAS decisions for closely timed contingencies, all values representing the pre-event power system are frozen for a certain period.

If a second contingency happens during this time, the freeze timer is reset and data are frozen until the new timer is elapsed. However, not all contingencies in the UTE power system produce strong enough oscillations to cause the analog data to fluctuate. A freeze flag associated with each contingency is updated using the freeze flag table in the RAS file. Data are frozen only if a freeze flag is active for the contingency.

There are several logic timers and counters used in the RAS logic. The total number of consecutive RAS actions allowed within a freeze window is limited by counter value NB. When the power system reaches a state when more than a predetermined number of 500 kV equipment are out-of-service, defined by counter value NT, the RAS disables automatically. No further actions are taken until the number of out-of-service 500 kV equipment falls below NT value. System studies and prior operator experience have shown that power system state calculations for an NT value greater than 4 does not represent the system accurately.

D. Ancillary Controls

Besides the initial high-priority load-shed actions, additional control actions may be required for certain contingencies. These ancillary controls are required for power exchange override with Brazil, stabilizing voltage, reactive power compensation, and post load-shed power flow control. The following ancillary control modules are implemented based on the module selection for each contingency.

1) Brazilian Power Exchange Override

The Brazilian power exchange override module (BPOM) can be implemented for contingencies by choosing in the module selection table (Table IV). Since the level of load shed is adjusted based on the calculations in this module it is executed simultaneous with the load-shed module. The main function of the BPOM is to reduce the total amount of load shed. The theoretical goal for the RAS is to calculate a required power exchange value with Brazil ($DAD\Delta_{Ci}$) that achieves zero MW of load shed ($DAD\Delta_{Ci} - DAC0_{Ci} = 0$ MW). This is done by controlling the power exchange through the convertor at the 500 kV Melo substation. Table VI summarizes the required convertor power exchange actions after a contingency.

TABLE VI
POWER EXCHANGE WITH BRAZIL

Convertor Power Exchange	Required Exchange Action
Import	Increase import
Export	Decrease export and start import, if required

The theoretical goal $DAD\Delta_{Ci}$ is limited by two factors:

- Import and export limits set by Brazil and Uruguay power authorities. The operator enters this value in the RAS.
- Convertor power demand override (PDO) set points defining the converter capabilities and limits.

The RAS adjusts the $DAD\Delta_{Ci}$ based on the power exchange limits. The adjusted power exchange value, $DAD\Delta 1_{Ci}$, is further adjusted based on the PDO selection process. Based on the current operating status of the convertor, six different PDOs are entered by the operator. Each PDO corresponds to a target exchange of power that can be achieved by the convertor. The RAS uses the threshold values defined for each contingency to choose a final PDO when the calculated $DAD\Delta 1_{Ci}$ is between two PDO set points. A PDO set point that is closest to the adjusted $DAD\Delta 1_{Ci}$ is chosen as the final power exchange.

The BPOM module of the RAS continuously calculates the final DAD_{Ci} for each contingency and reduces the final load shed (DAC_{Ci}) required. When a contingency is detected, control signals are sent to the convertor simultaneously with the load-shed signals. The maximum convertor ramping rate is 1,500 MW per second.

2) Supplemental Load Shed

The RAS implements the supplemental load-shed module after an initial load shed and the Brazilian convertor controls are exercised. A very accurate load-shed action is required for certain contingencies involving the loss of 500 kV lines connecting the north and south of the country. Supplemental load shedding may be required to achieve this accuracy. Small discrepancies such as load breaker failure, improper measurement of analog quantities by certain field equipment, and even undesired generation loss can lead to DAC_{Ci} variations of up to ±100 MW. This leads to undervoltage and overvoltage conditions in the 500 kV Montevideo bus that serves the majority of the electrical load or overloads in the 150 kV system.

Supplemental load shedding is triggered by monitoring the voltage and power flow of critical equipment. Individual substation loads are shed after a small time delay (until the voltage and loading of the critical equipment are operating at acceptable levels). Block close signals are sent to prevent static compensation capacitors from turning on during the supplemental load shedding. Turning on the static compensation capacitors leads to an increase in power flow through the critical equipment for which supplemental load shedding is being performed. Parameters required for the operation of this module, like the critical equipment to monitor for voltage and power flow, the number of supplemental load-shed actions, and the trigger levels for each contingency are updated using the supplemental load-shed table of the RAS file.

3) Reactive Power Compensation

The reactive power compensation module monitors the pre-event reactive power flow (Q) in the 500 kV equipment lost during the contingency. This module attempts to normalize the reactive compensation in the power system after a remedial action. For contingencies involving events E4 and E5 for example, excessive reactive power compensation may be present after a load shed. The RAS achieves this by tripping capacitor banks located in the three 500 kV substations to prevent overvoltage conditions. The RAS calculates the correct amount of capacitors to trip. Excessive capacitor tripping could lead to severe undervoltage conditions. The RAS allows supplemental load-shedding and reactive power compensation ancillary controls to be chosen for the same contingency.

The amount of reactive power compensation required is expressed as:

$$Q_{Ci} = X_{Ci} \bullet DAC_{Ci} + Y_{Ci} + \left(Z_{Ci} \bullet \Phi_{500q}\right) \tag{5}$$

where:

Q_{Ci} is the calculated reactive power compensation for contingency Ci (Mvar).

X_{Ci}, Y_{Ci}, and Z_{Ci} are the reactive gain constants for contingency Ci.

Φ_{500q} is the reactive power flow (Mvar) in the lost 500 kV equipment that triggered the contingency.

The RAS has the capacity to trip up to 32 capacitor banks. The operator assigns a unique priority number for each capacitor bank. The RAS sorts and trips the capacitor banks in ascending order of their assigned priority until the calculated reactive compensation is satisfied for the contingency.

4) Line Tripping

The line tripping module is implemented simultaneously with the initial load shed. However, for certain contingencies, it is implemented following an operator-entered time delay. Line shedding is performed for the following two reasons.

First, for certain contingency combinations that lead to loss of Argentinian and Uruguayan 500 kV interconnection, a supplemental 150 kV line shed is required. There are inter area oscillations in the Uruguayan power system, following a large DAC_{Ci} load-shed action, The RAS controller disconnects the 150 kV lines interconnecting Argentina and Uruguay to prevent these undamped oscillations.

Second, line tripping is required as a remedial action to force the power system state (*S*) to a desired value, by forcing certain lines out of service. Moreover, the lines tripped in this process are carrying limited or no load, because of a prior load-shed action. Selection of gain constants based on an inaccurate power system state can lead to insufficient or excessive load shedding. Forcing certain lines out of service increases the probability of an accurate *S*. An accurate *S*, in turn, allows a more definitive gain constant definition, assuming these lines are not in service.

V. RAS HMI

The RAS HMI is launched from a substation-hardened computer. It is used for setting changes and monitoring purposes only. The RAS functionality is not affected by a failure of the RAS HMI. Some key screens of the HMI include:

- Status display of live power system data used in the RAS calculations.
- Real-time view of the CPS.
- Communication of diagnostics and alarming.
- SOEs and oscillographic event viewing.
- RAS file settings — definition and status screens.
- Backup underfrequency load-shed settings and status.

The RAS file includes a large number of tables. Edits made to any single table are detected by the RAS by comparing the date and time stamp of the gain files. The operators use the RAS HMI to load the new files to the controllers.

A backup underfrequency load-shed system serves a backup of the primary contingency-based system. Underfrequency threshold levels are monitored at the 31.5 kV substation IEDs that trigger load-shed signals. The settings and operations of underfrequency-based load shedding (UFLS) are centrally managed and operated from the RAS HMI. At the RAS operator's request, these settings are then transferred to all the underfrequency action IEDs in the 31.5 kV substations.

The RAS HMI has three tiers of UFLS screens. The Level 1 screen is used to define up to five levels (f0−df/dt, f1, f2, f3, and f4) of underfrequency thresholds (Th) and the corresponding time delays for pickup. Thresholds defined on Level 1 screens are enabled and disabled for each substation using the UFLS Level 2 screen. The UFLS Level 3 screen is used to apply the selections from UFLS Level 1 and Level 2 to individual outputs of action IEDs. The Level 3 screen for each substation allows selection of threshold levels for each output. For example, Level 3 UFLS screen selection can be set up to operate OUT301−305 for f1, OUT306−309 for f3, and OUT310−OUT312 for f4. Note that each output sheds a load in the substation. HMI is also used to inhibit individual outputs from operating, irrespective of the threshold selections. The three levels of UFLS screens in the RAS HMI provide RAS operators with a wide range of options and higher selectivity for the UFLS settings. Fig. 7 shows the simplified IED logic for the backup underfrequency load-shed system supervised by set points and selected from the RAS HMI. These options are set up and updated based on the current operating conditions.

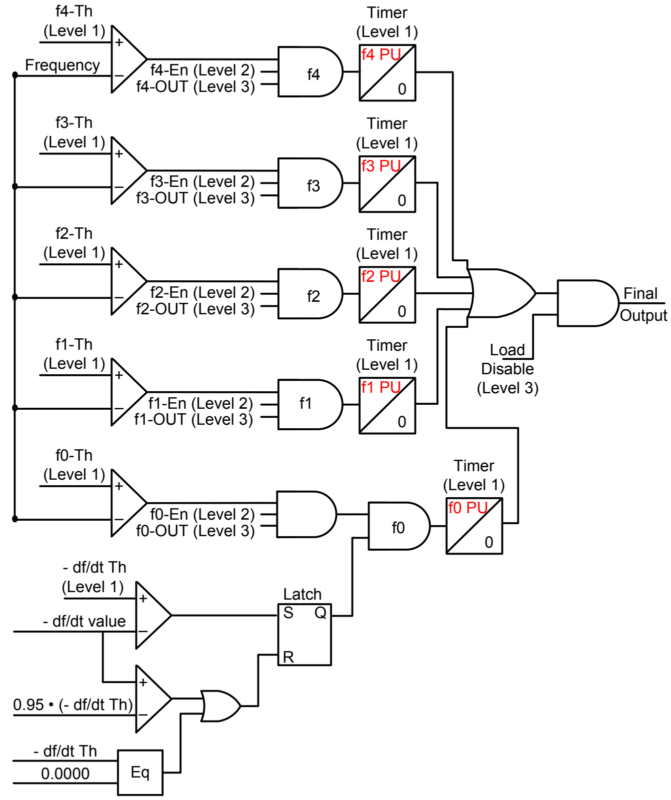

Fig. 7. Simplified Backup Underfrequency Logic Diagram

VI. Supervisory System

Differences in analog values or communications loss can result in the dual RAS controller making different remedial decisions. Different decisions in the controllers can lead to excessive load shedding. A quality index generated in each RAS based on the operational and communications status of all RAS and field devices are used to address the discrepancies in the CPS calculation. All field devices communicating to the RAS controller are given a different quality number that correlates with information it's providing to the RAS controller. For example, an action equipment is given a smaller quality rating than an FEP or an SVP, since the loss of one FEP or an SVP may constitute loss of communication with several equipment in a remote substation. A single quality index (QI) number is generated based on the weighted average of the individual device quality numbers. The QI number is used to supervise and decide which RAS has better data availability. The controller with better data quality supervises the actions of the other controller. The QI number generated at the RAS controller is compared every processing cycle between the two RAS systems.

VII. Testing Simulator

The dual primary architecture of the system gives the flexibility to disable either RAS for testing or maintenance and keep at least one RAS available at all times. The modular RAS has many features and set points that an operator can enable and disable to change the nature and magnitude of actions. Approximately six million gain constants are used for the primary load shedding and the ancillary control logic calculations. A thorough testing of the applied changes are required to verify and validate the results compared to the desired outcomes before applying the changes in the live RAS system. Fig. 8 shows the simulator communicating with the RAC using Network Global Variable List protocol.

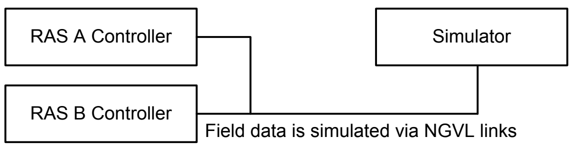

Fig. 8. Simulator Panel Connections

The test simulator for the RAS simulates all inputs, including digital statuses, analog data, PMU data, and data from the ICCP SCADA system. The simulator is built using the same hardware platform used for the RAS controllers. The simulator provides two options for testing; static simulation and playback simulation.

The static simulation method uses a CSV file to simulate the field data in the controller and to create event(s) to observe controller actions. The CSV file provides the operator an ability to drive each analog and digital input quantity to a desired value. It is also extremely useful for testing all I/O points and creating any desired power system state for RAS controllers. Communications failures can also be simulated to test the supervisory logic.

In the playback simulation mode, the simulator is used to replay event report files generated by RAS controllers. The RAS allows replay of actual events, which is very helpful in understanding the behavior of the control system and fine tune gain constants. The simulator playback mode provides a valuable method during factory acceptance testing because playback files generated by UTE for historical events could be played back with no risk to the actual power system.

Although the test simulator is an excellent tool for the RAS algorithm validation, a closed-loop power system test for validating the post load-shed ancillary controls was required. An equivalent Uruguayan power system and the interconnections with Argentina and Brazil are modeled using the Real Time Digital Simulator (RTDS®). RTDS equipment allows dynamic modeling of the Uruguayan power system with a simulated small time step to test all closed-loop controls [7]. Modeling the system inertia, governor response times, and generator exciter controls provide dynamic stability validation of the Uruguayan power system after a remedial action.

VIII. Conclusion

A portion of the RAS was successfully commissioned in July 2015, which included a select few contingencies and limited loads. Including the open line detection time, communications time and the field equipment response times, and other communications delays, the RAS performed remedial load shedding within 200 milliseconds from the actual contingency. Commissioning a system of this magnitude involved many groups in UTE and the supplier. A thorough factory acceptance testing procedure prior to field commissioning greatly reduced the commissioning time. Several test cases including the most probabilistic combinations of closely timed contingencies, device communication failures, different gain constants, and different levels of power demand were tested to validate the RAS.

The RAS is designed to allow future expansion with little interruption to the performance. The dynamic module selection feature of the RAS allows the operating engineers to control the power system based on the current operating scenarios and power system state. Synchrophasor data archived from the field PMUs are used by UTE for detailed analysis of the power system that was not possible earlier. This information coupled with the post-event analysis tool of the RAS helps UTE fine tune the system performance and define more accurate gain constants.

Time alignment of PMU synchrophasor data in the SVP coupled with efficient data processing techniques can be used for model analysis and synchrophasor-based controls in the future. Interfacing the RAS with the dynamic simulation tool, which calculates the gain constants and other parameters critical for the operation of RAS, will be investigated in the future. This direct interface will make the RAS more dynamic and eliminate the requirement of maintaining a RAS file.

A close working relationship between UTE engineers and the supplier engineers was crucial for the execution of the project. Site-specific experience brought by UTE engineers and special protection system experience brought by the supplier engineers were critical in replacing the old system with the RAS.

IX. Acknowledgment

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XI. Biographies

Julián Malcón graduated in electrical engineering from Universidad de la República, Uruguay, in 1984. He joined Usinas y Trasmisiones Eléctricas in 1983. Since 1984, he has worked as a protection engineer, assistant manager in maintenance in protection systems, manager in protection system, and since 2014 is the manager in protection, automation, and control. He leads projects in protection, automation, synchronization, and control for the 500 kV and 150 kV network in Uruguay, including the remedial action scheme.

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Rameez Syed is an automation engineer for the engineering services division of Schweitzer Engineering Laboratories, Inc. (SEL). He received a Bachelor of Applied Science in electrical engineering from the University of Windsor, Ontario, Canada. Rameez has been employed with SEL since 2008 and has experience in designing and implementing control systems for utility and industrial customers.

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