Case Study: Modern RAS Applied to Furnas 765 kV Transmission Corridor Improves Itaipu Power Plant and Brazilian Power System Stability

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Abstract—**Furnas, one of the largest generating and electrical transmission companies in Brazil, recently implemented an important remedial action scheme (RAS) to improve the reliability of the national interconnected power grid. A mission-critical RAS was deployed to replace an aging system for a 765 kV transmission corridor, which consists of 9 765 kV lines, 4 500 kV lines, 10 765/500 kV autotransformers, and 4 500/345 kV autotransformers.**

The paper discusses the problems the RAS solves, the design criteria and challenges, the deployment of such a system, and the wide-area communications system configuration and test results to accomplish a fast and reliable tunnel for the IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messages.

I. INTRODUCTION

A large interconnected system needs a set of coordinated control measures with high levels of complexity to plan and operate reliably and economically. Power systems have a stability limit, and the desired operating conditions may require special protective systems, known as remedial action schemes (RASs), to operate the system in a secure manner. Thus, RASs are essential to maintain the safety and integrity of the electrical system when it is subjected to phenomena that cause instability or cascade shutdowns.

RASs are applied to protect the electrical system against events that have a low probability of occurring but a high impact on stability when they do, such as multiple trips of transmission lines or loss of critical busbars or entire substations.

There is no doubt that the use of RASs plays a significant role in interconnected systems, serving to [1] [2]:

- Improve the operation of power systems by increasing safety margins, providing greater flexibility, and removing or minimizing operating restrictions.
- Operate power systems safely close to limits.
- Increase power and energy transfer limits while maintaining a level of safety.
- Find a temporary solution to compensate for delays in the construction program of works (operation outside the transfer limits) or situations of equipment shutdown.
- Increase the security of the system, particularly in regard to extreme or multiple contingencies that can lead the system to collapse.

RAS schemes can provide different types of remedial control actions, based on the problems created when major disturbances occur. Some schemes trip generator units, intentionally open transmission lines, perform load shedding in multiple locations, apply dynamic braking, rapidly change power transmitted through high-voltage direct current (HVDC) links, and create islanded systems at predetermined locations through controlled system separation. RAS schemes have common characteristics [1] [2]:

- They are dynamic security control systems designed to control power system stability in cases where an uncontrolled response is likely to be more damaging than a controlled response.
- They require offline power system studies and simulations to qualify and quantify contingencies and their impacts on power system stability and identify which actions are required to remediate their effects in the power system.
- They are armed for certain operating system conditions, for instance, when the power flow in a given transmission corridor is greater than a specified threshold.
- They provide one or more types of remedial actions that are designed to alleviate a certain observed system condition or take a predetermined action when a certain event or a combination of events occur whose resulting effects are deemed too serious to ignore.

In the Brazilian system, the RAS associated with the 765 kV transmission corridor from the Itaipu Power Plant (Itaipu) plays a key role in keeping the stability of the National Interconnected Power Grid (NIPG). The 765 kV transmission corridor can carry a high-power flow, up to approximately 6,600 MW. Thus, any contingency involving this transmission corridor presents great risks to the stability of the NIPG. So, a reliable and efficient RAS is required to maximize the electrical energy production at Itaipu and quickly react to contingencies that could jeopardize the overall reliability of the NIPG.

II. BACKGROUND

Furnas, one of the largest generating and electrical transmission companies in Brazil, recently implemented an important RAS to improve the reliability of the NIPG. A mission-critical RAS is deployed to replace an aging system for the 765 kV transmission corridor that connects the 60 Hz section of Itaipu to the Southern and Southeastern Electrical Transmission Systems.

Itaipu is a binational (Brazil and Paraguay) hydroelectric power plant with 20 generating units (GUs), 10 of which are operating at 60 Hz (connected directly to Brazil) and 10 at 50 Hz (connected to Paraguay), totaling 14,000 MW. From its 10 GUs, Paraguay only needs 3 GUs to supply loads nationally; the remaining generated energy, produced by 7 GUs, is transmitted to Brazil by bipolar 600 kV Furnas HVDC lines. Itaipu provides about 10.8 percent of the energy consumed in Brazil and 88.5 percent of the energy consumed in Paraguay. The Brazilian part of the energy produced in Itaipu is carried out over a 1,000 km ac transmission corridor, which consists of 9 765 kV circuits, 7 500 kV lines, 11 765/500 kV transformers, and 4 500/345 kV transformers. This system is known as the 765 kV system. Figure 1 shows the single-line diagram of the 765 kV transmission system and its components.

A contingency in this transmission system, depending on its operating states (like power flow values or line-out quantities), can lead to serious consequences for the NIPG. In extreme cases, it leads to system blackouts. To avoid such drastic situations, the new 765 kV RAS was designed considering reliability, speed, and selectivity as the utmost requirements. The RAS also allows the National System Operator (NSO) to operate the Brazilian NIPG with more reliability and optimization of water resources for all existing hydroelectric power plants. The main purpose of the RAS is to avoid, under certain operating conditions, the following situations in case of contingencies on autotransformers or lines from the 765 kV transmission corridor:

- Loss of synchronism between the Itaipu 60 Hz sector and the southern and southeastern power systems, see Fig. 1, leading to instability in the NIPG.
- Self-excitation in Itaipu 60 Hz GUs.
- Overvoltage of 765 kV and 500 kV systems.
- Overload of 765/500 kV and 765/345 kV autotransformers.
- Overload of 765 kV and 500 kV lines.
- Overfrequency with the consequent shutdown of thermal plants in the southern region.
- Voltage collapse in the 765 kV system.

The first RAS started operation with the second 765 kV circuit in 1989, maximizing the transmission of generated energy by the Itaipu 60 Hz sector. The RAS originally operated with auxiliary relays and control switches located at different points in the transmission system. The states of the control switches were changed by the operators according to operating conditions and the configuration of the transmission system at the time. Failures in the selection of proper position of these control switches led to numerous misoperations of the RAS during contingencies. Since the first version of the RAS proved not to be reliable, a second version of the RAS, based on programmable logic controllers (PLCs), was deployed in the second half of 1995, and it has performed satisfactorily for over 20 years.

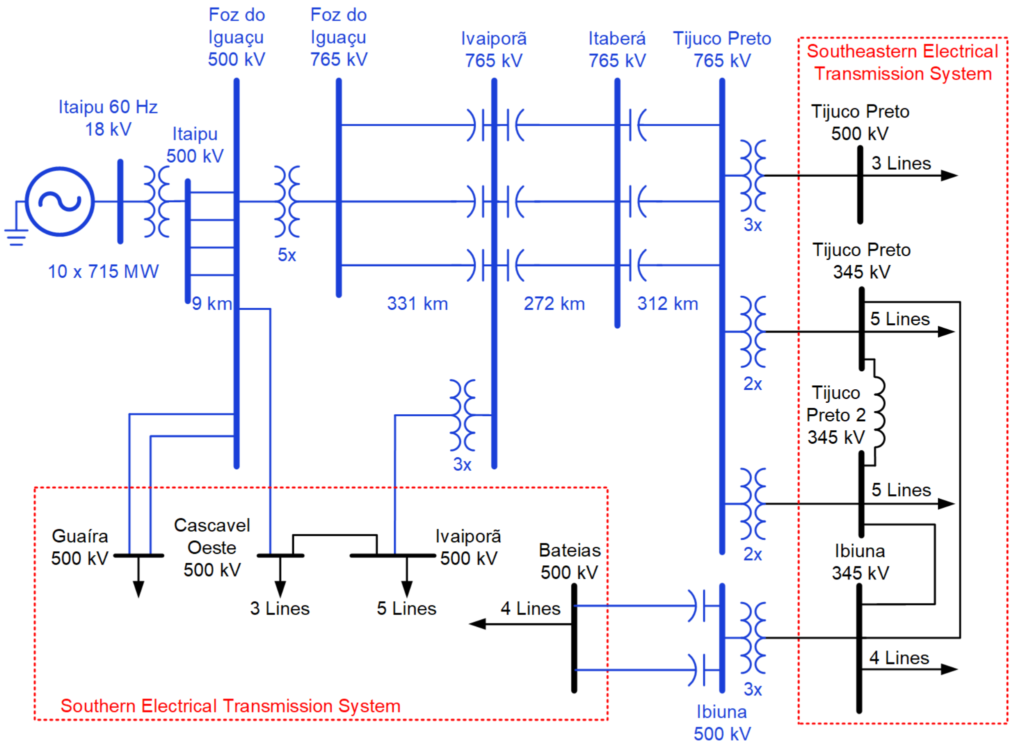

Fig. 1. Single-line diagram of the 765 kV transmission corridor. The system components covered by the 765 kV RAS are outside the dotted, red borders.

In 2011, the 500 kV Foz do Iguaçu—Cascavel do Oeste transmission line was commissioned and energized. This transmission line is composed of a 115 km single circuit and has created a connection between the Itaipu 60 Hz sector and the southern system, see Fig. 1. The connection of this transmission line has allowed the full transmission of Itaipu 60 Hz generation, making it necessary to reevaluate the logic and references of the second-version RAS.

Considering the need to maximize the energy exchange between the subsystems, the PLCs obsolescence of the second version of the RAS, the impossibility of the second version of the RAS hardware to meet the new implementation demands, and the expected transmission system expansion, it was decided to carry out a technological update of the RAS and the consequent reevaluation of the logic and their references. This third version of the RAS will be called the 765 kV RAS for the rest of this technical paper.

The 765 kV RAS covers the generation and transmission assets in blue (outside of the red, dotted borders) in Fig. 1. For each of these substations, new devices were installed to monitor circuit-breaker and disconnector statuses, load flow in the lines and transformers, and status of the series compensation, etc., and then send the data to the redundant controllers in Itaipu, as discussed in the next sections.

Most of the logic of the 765 kV RAS operates by shutting down a certain number of GUs at Itaipu for contingencies occurring in the power system, based on the precontingency power flow in the transmission lines.

Considering the total distance of the 765 kV transmission system from the Tijuco Preto substation to Itaipu and the number of substations, transmission line circuits, autotransformers, series capacitors, and generators in the system, the design, implementation, and operation of this protection system is a great challenge to all engineers involved in this project. These characteristics make this project a unique implementation. Furthermore, for the correct operation as designed and acceptable reliability in day-to-day operations, the implementation of a large communications infrastructure, system redundancy, and optimized configuration of communication channels are necessary. Added to that, the 765 kV RAS has a large amount of data that are exchanged among different components of the system.

III. 765 KV RAS REQUIREMENTS

For the new 765 kV RAS, the NSO performed a comprehensive power system stability study and prepared a report describing the contingencies and remedial actions required to ensure secure operation of the power system. The same report defined the performance and redundancy requirements for the RAS. The total response time requirement for the scheme is 200 milliseconds, from the inception of the contingency until the circuit breaker opens.

The 765 kV RAS is based on data acquisition and control units (DACUs) installed at the four substations of the 765 kV transmission system, Foz do Iguaçu, Ivaiporã, Itaberá, and Tijuco Preto at Itaipu, and the Ibiuna 500 kV substation. The local DACU is responsible for acquiring the substation binary data—such as the status of transmission line shunt reactors (open or closed), series capacitor banks, circuit breakers, and disconnecting switches—acquiring the analog data—such as the magnitudes of voltages, currents, active power, and reactive powers—and checking the consistency of the acquired data. Each local DACU sends all these data to the master controllers (MCs), physically located at Itaipu, through the IEC 61850 Generic Object-Oriented Substation Event (GOOSE) communication protocol. The MC receives these data and runs the RAS algorithm and, depending on the contingency and the system state at the moment, sends command signals to Itaipu with the number of GUs to be shut down, or the power generation reduction at Itaipu, or the lines to be tripped at the 500 kV or 345 kV busbars at Tijuco Preto substation.

The RAS topology is totally redundant with Systems A and B working in a dual principle. Each substation has at least two DACUs, which send the data to the two MCs through communication tunnels configured in redundant, multiplexed communication systems. One of them is based on a multiplexed fiber synchronous digital hierarchy (SDH) and the other on a microwave radio system, which provides redundant and independent communication links to Systems A and B. See Fig. 2.

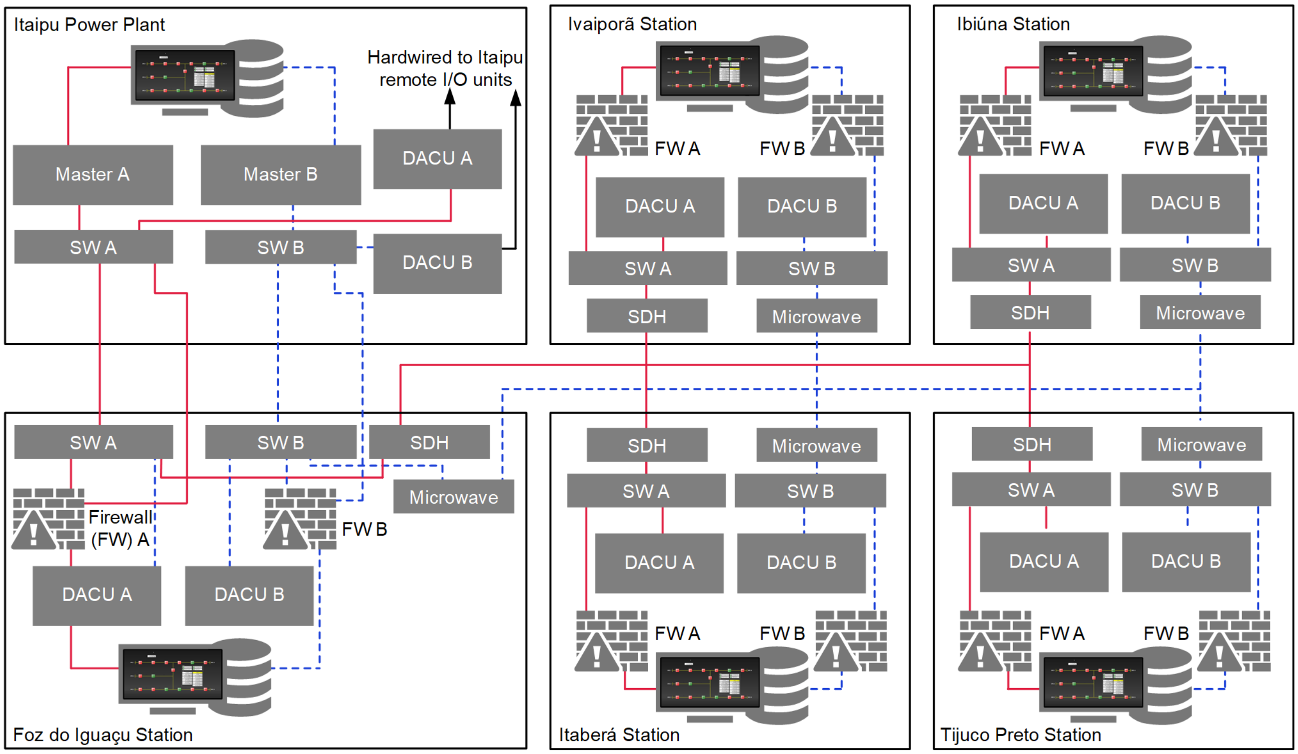

Fig. 2. Simplified network architecture. Solid, red lines are System A communications and dotted, blue lines are System B communications.

IV. 765 kV RAS ALGORITHM

In each substation, the DACUs collect the following information: the statuses of circuit breakers and disconnectors and the quantities of current and voltage in the transmission lines. Additionally, the actions on the electrical system are performed through the digital outputs of the DACUs. In addition to acquiring data, the DACUs locally process the logic for data consolidation, such as the consistency of circuit breakers and disconnectors, as well as analog quantities. This consolidation is important to validate the data and guarantee the correct operation of the system. In case of inconsistencies, the logics perform the appropriate actions to block the operation and inform the operator.

In the following items, the algorithms of the implemented logic are presented, from the consolidation of measurements, through the detection of contingencies and selection of the remedial action, to the operation of the special protection system.

A. Power Flow Measurements

The measurements of the analog quantities, currents, and voltages for the calculations of the system power flow are taken in duplicate, that is, in two different substations, and a selection logic is implemented to decide which value should be used in the RAS logic. This selection logic considers local DACU alarms, voltage transformer failure supervision, circuit-breaker alarms, and the ratio between zero-sequence and positive-sequence quantities to detect failures in the current transformers. Therefore, the power measurement switches from one terminal to another in the event of any failure detected for the terminal currently being measured, as shown in Fig. 3, generating an alarm to the supervisory control and data acquisition (SCADA) system. In Fig. 3, the terms GIPU and FSE are the active power flows between the Itaipu 500 kV bus and Foz do Iguaçu 500 kV bus and the Ivaiporã 765 kV bus and Itaberá 765 kV bus, respectively, and are used to arm some of the RAS logic.

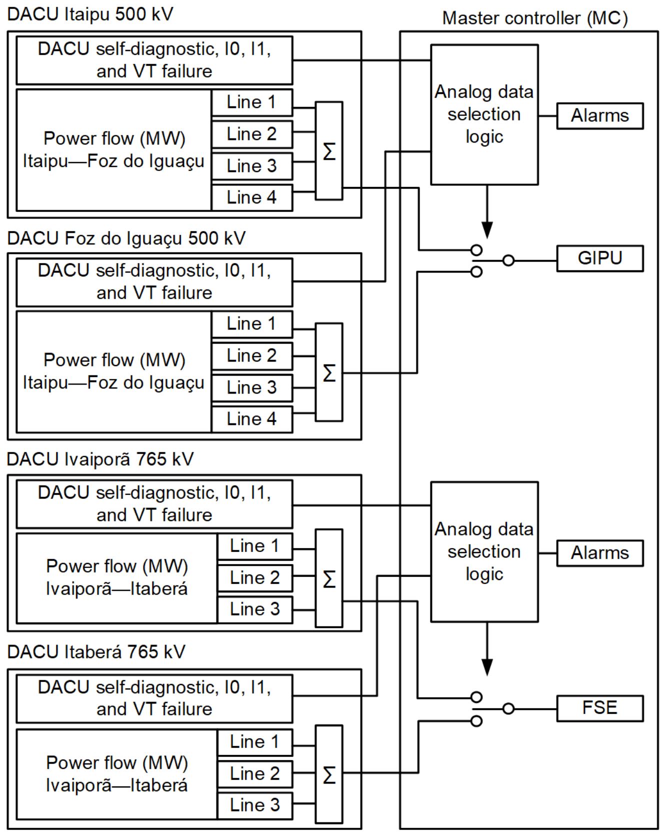

Fig. 3. Analog data selection for the arming logic.

B. Contingency Detection

The main possible contingencies for the system are:

- Line opening
- Transformer overload
- Line overload

In cases of an overload, the local DACU identifies a magnitude above the nominal value for a certain period of time and sends a signal to the MC to command the reduction of generation before the transformer or the line overload protection trips, thus avoiding the unavailability of the equipment.

The open-line detection logic, shown in Fig. 4, adopts an approach more focused on dependability, trying to ensure the operation of the RAS to preserve the system; this logic does not use the current or voltage measurement, for example, and does not wait for confirmation from the remote terminal. The equipment's open and closed signals are verified to check their consistency; however, the simple opening of a terminal triggers the contingency. Another characteristic determined by the implementation report is that the inconsistency of the open or closed position must declare the equipment as open. However, series capacitor banks must be considered out of service in case of failure in the indication of the status of their circuit breakers or disconnecting switches.

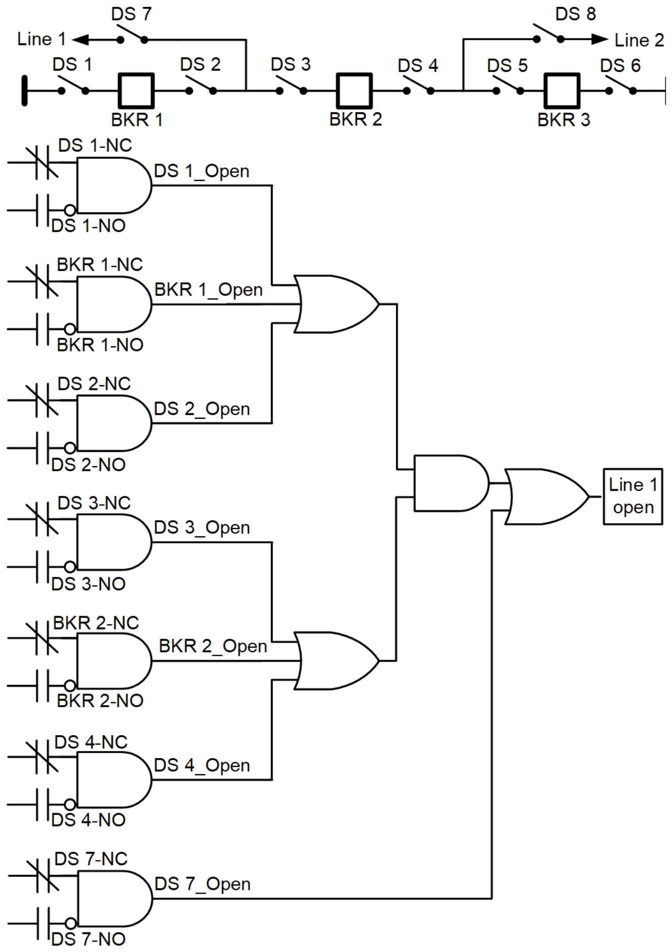

Fig. 4. Open-line detection logic.

In addition to detecting a single contingency, just one line tripped, for instance, the RAS algorithm has provision to respond properly to multiple contingencies, two or three lines tripped close in time, for instance. For multiple contingencies detection, a 5-second window is opened from the first contingency trigger, and the power flow values are frozen for calculating the reduction of generation. Any new event occurring in the 5-second window is added to the previous event, and multiple contingencies are considered by the logic. Any event occurring out of the 5-second window is considered a new single contingency event. If any event occurs that leads to a multiple loss of circuits in different sections, the number of Itaipu GUs to be shutdown must be decided by the logic that commands the largest cut, limiting the total cut to a maximum of four GUs. This approach aims to avoid the risk of self-excitation in the GUs at Itaipu, which can be caused by the large reactive power produced in the transmission corridor when operated in a degraded state [3].

After identifying a contingency, the 765 kV RAS algorithm sends a required command from the MCs to the DACUs to accomplish the proper remedial action to preserve system stability. The DACUs, in turn, physically act on the power system through their digital output contacts. If the required remedial action leads to the opening of a transmission line or the shutdown of a transformer, the outputs directly command the opening of the circuit breaker associated with that primary equipment. In the case of actions that lead to a reduction in generation, the commands of the DACUs are directed to Itaipu. These remedial actions, directed to Itaipu, take into account a special logic based on a rotating-priority queue, developed to select the GUs to be shut down in an optimized way and avoid tripping more GUs than required. This logic is described in a later section.

C. *Examples of RAS Logic*

This section describes some examples of the remedial actions logic that are triggered due to contingencies in the 765 kV system. Figure 5 shows the logic of detecting line-open contingencies between the substations Foz do Iguaçu 765 kV and Ivaiporã (FI–IV). The logic detects how many circuits are open and declares single, double, or triple contingencies in the FI–IV section. The line-open condition is detected in each terminal by the DACUs and sent to the MCs, which defines the number of contingencies, as shown in Fig. 5.

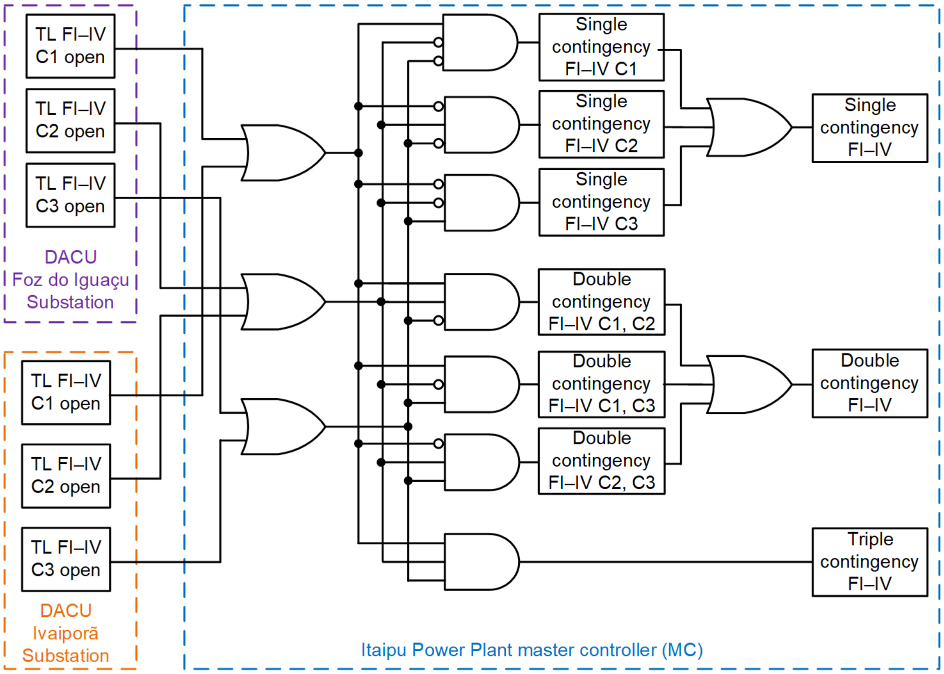

Fig. 5. Logic to detect the number of contingencies between the Foz do Iguaçu and Ivaiporã substations (FI–IV).

Figure 6 shows an example of remedial actions that must be taken to preserve power system security. Based on the pre-event power flow (GIPU) between the Itaipu 500kV and Foz do Iguaçu 500 kV buses and the number of contingencies detected for the section between substations Foz do Iguaçu and Ivaiporã, a certain number of GUs must be shed at Itaipu. Figure 6 shows an example of a double contingency, i.e., two lines between substations Foz do Iguaçu and Ivaiporã tripped.

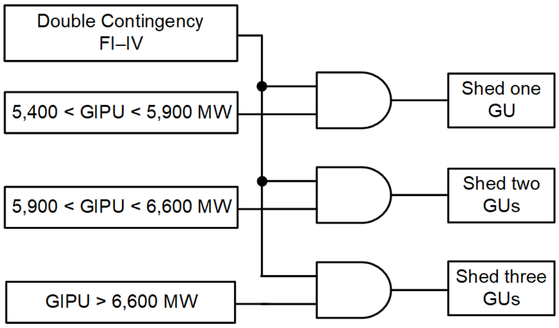

Fig. 6. Remedial action logic for a double contingency between the Foz do Iguaçu and Ivaiporã (FI–IV) substations.

Figure 7 shows another example of remedial actions to avoid tripping the 765/500 kV autotransformers at the Tijuco Preto substation due to an overload condition. The DACUs monitor the load in each of the three autotransformers and send a signal to the MCs if the load is greater than 150 percent of the rated autotransformer capacity. In the case of an overload, the MCs send a command to trip a 500 kV transmission line connected to the Tijuco Preto substation. If the autotransformer overload persists, commands to shed GUs at Itaipu in intervals of six seconds are sent, as shown in Fig. 7.

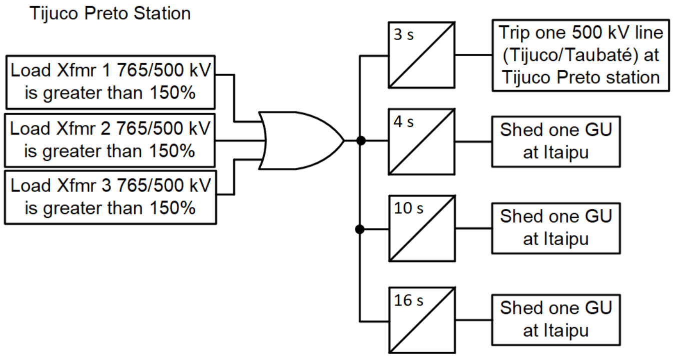

Fig. 7. Remedial action logic for an overload contingency on the 765/500 kV autotransformers at Tijuco Preto substation.

D. Rotating-Priority Queue

The RAS 765 kV logic defines the number of GUs to be shed but does not define which GUs to be tripped. Itaipu has defined a logic to rotate the GUs in a rotating-priority queue to optimize the maintenance schedule of the machines and avoid overshedding.

The shed queue must be formed so that the GUs that have been operating for the longest time occupy the first positions in the queue for shutdown. When a GU is shut down, it is removed from the queue, and when one is synchronized, it is added to the end of the queue, forming a rotation of the GUs, as shown in Fig. 8.

The Itaipu SCADA system includes a logic switch for each GU that allows it to be intentionally placed at the end of the rotating-priority queue, the middle, blue box ("GUs out of the rotation queue") in Fig. 8, thus inhibiting its participation in the rotation of the GUs.

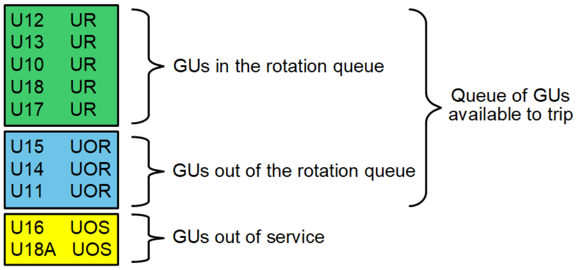

Fig. 8. Example of a generator rotating-priority queue.

Due to the breaker-and-a-half arrangement for the 500 kV 60 Hz busbar at Itaipu, see Fig. 9, the queue logic must also take into account the state of the circuit breakers associated with the GUs. If the bus circuit breaker of a GU is open and the two GUs of the span are synchronized, the GU that shares the span must be allocated to the end of the shutdown queue, to occupy a later position in the queue with respect to the GU that has the circuit breaker open and to avoid shutting down two GUs when only one needs to be turned off.

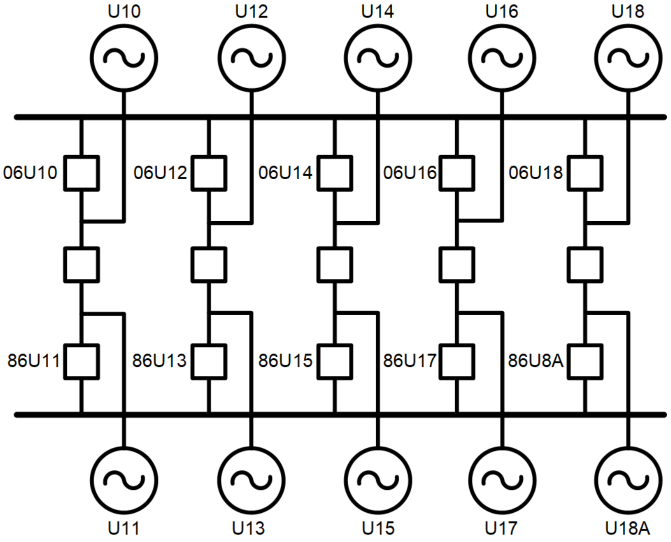

Fig. 9. Busbar and circuit-breaker configuration in the 60 Hz section of Itaipu.

Figure 10 exemplifies how the GU shedding queue is dynamically formed. Refer to Fig. 9 for the GUs and circuit breakers identification. For instance, if Circuit Breaker 06U14 is open for any reason, Generators U14 and U15 are connected to the same bus through a single breaker (86U15), so shedding Generator U15 will also shed U14. For this reason, U15 is put in the last place in the rotation queue. Now suppose Circuit Breaker 06U10 is open. With this configuration, Generators U10 and U11 are connected to the same bus through a single circuit breaker. As Generator U10 is out of the rotation queue for a given reason, Generator U11 is also pulled out from the rotation queue because tripping U11 will also trip U10.

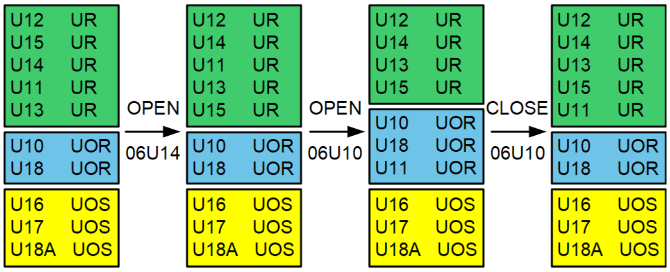

Fig. 10. Example of the logic sequence for the rotating-priority queue.

V. NETWORK ARCHITECTURE

The data acquired and consolidated by DACUs are sent to the MCs via the IEC 61850 GOOSE protocol. This protocol was chosen mainly due to the speed required for sending and updating information to guarantee the shortest possible total operating time of the RAS system. If a contingency occurs, the MCs process the logic then send the remedial action commands to the DACUs through the same IEC 61850 GOOSE protocol. Finally, actions on the equipment are performed through the DACUs output contacts.

The communications between the DACUs, local human-machine interface (HMI), and remote SCADA are carried out via the IEC 61850 Manufacturing Message Specification (MMS) protocol. Through the HMI, it is possible to visualize the local data processed by DACUs as well as information about diagnosis, alarms, or faults. Likewise, the MCs also make the data available for the SCADA systems of Furnas and Itaipu. The HMIs play an important role in monitoring and supervising the 765 kV RAS system. This system also represents a major advance compared to those previously implemented, allowing more visibility, better diagnosis, and more comprehensive controls for the operation of the RAS.

A. Physical Topology

The communications interconnection between the substations involved in the 765 KV transmission lines is made through two routes, see Fig. 11. The main route is composed of fiber-optic links in the optical ground wire (OPGW) cable of the transmission lines, while the secondary route is composed of microwave radio links.

The fiber-optic route is about 967 kilometers long and involves five substations and three repeaters, which are responsible for signal regeneration due to the large distances involved. Its data transmission capacity is STM-16, 2.5 gigabits per second (Gbps), which is sufficient for data transmission in corporate, operational, and telephony networks.

The microwave radio route, in turn, involves 15 repeaters for signal regeneration and has a capacity of STM-1, 155 megabits per second (Mbps), which is sufficient for redundancy of critical channels of operational and telephony networks.

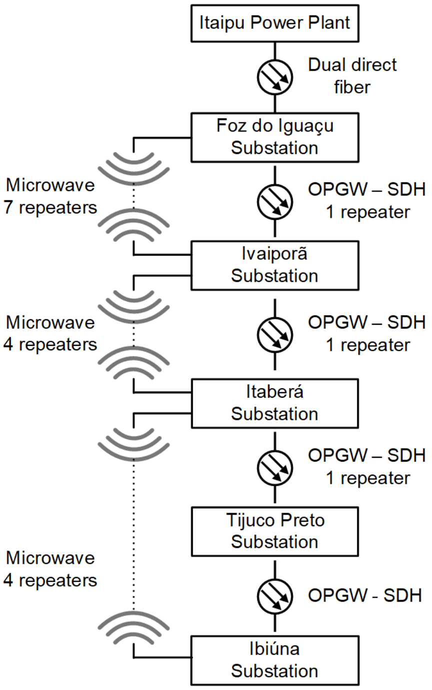

Fig. 11. Multiplexed fiber (SDH) and microwave radio communication systems.

Services are multiplexed into deterministic channels and different hierarchies according to traffic volume and criticality. For the 765 kV RAS traffic, exclusive 2 Mbps (E1) pipes between the Foz do Iguaçu substation and the other substations were created in the multiplex equipment of the fiber-optic and radio systems. These pipes are completely separate from operational and corporate traffic. To determine the bandwidth of the pipes, a detailed study was carried out to certify that the size of the messages would not exceed the transmission capacity of the channels.

B. Logical Topology

The data transport systems involved in the 765 kV RAS communications are interconnected to redundant switches in the substations, which are exclusive to the special protection system. These switches are connected to DACUs, the local HMI, and the remote SCADA system. An important aspect of such a major project is the optimization and reliable use of communications systems. In other words, it is important to avoid saturation in communications channels during the occurrence of an event, especially due to the repeatability (burst) in sending GOOSE messages when an event occurs. For this purpose, virtual local-area networks (VLANs) are used to segregate message traffic only for devices that should receive such information. Therefore, 20 different VLANs are configured on the switches, allowing the correct segmentation of GOOSE and MMS traffic. In this way, it is possible to guarantee that there is no interference in the traffic between the two protocols, allowing only the transport of GOOSE packets between substations. Additionally, the use of VLANs is necessary to limit the broadcasting of GOOSE messages.

As said, for transporting the GOOSE messages, each DACU transmits to the MCs using a distinct and unique VLAN. In the Foz do Iguaçu substation, all GOOSE communications from other substations end in a specific transport Ethernet switch with high-capacity packet routing.

For the transport between the Foz do Iguaçu substation and Itaipu, two pairs of dedicated fiber optics are made available. The first pair allows redundant GOOSE communications from the substations, which are multiplexed in the transport Ethernet switch to the Master unit. The second pair of fiber optics also allows redundant MMS communications between the devices installed at Itaipu and the Furnas SCADA system. In this way, the total separation between GOOSE and MMS messages is maintained.

C. *Network Cybersecurity*

At this point, it is important to emphasize that the 765 kV RAS is implemented in two different companies, Furnas and Itaipu. Naturally, both companies value the security of their information.

Additionally, four DACUs belonging to Furnas are installed in Itaipu. Therefore, it is necessary to adopt network cybersecurity policies for both companies. It is known that firewalls may add undesired latency to the traffic; thus, it is not possible to apply them in the network topology that involves the traffic of GOOSE messages.

Therefore, it is necessary to consider all GOOSE communications as unreliable traffic and introduce firewalls in all Furnas sites between switches and the SCADA system, as shown in Fig. 2. This allows the proper security practices to be adopted without causing an increase in latency to GOOSE packets.

Another possible solution would be the use of software-defined networking (SDN) technology, which, in addition to ensuring security in the interconnection of the networks, also brings a gain to the RAS final operation time since there is no need for interconnection between the Itaipu and Furnas DACUs through physical input/output (I/O) (digital inputs and output contacts). Using SDN, the MCs can send a GOOSE message directly to the Itaipu DACU. The SDN switches make it possible to physically interconnect the networks of the two companies while maintaining complete logical separation. SDN switches are deny-by-default, ensuring that only the allowed GOOSE messages are able to travel between the two networks. SDN is a very suitable technology for RAS systems, especially when the RAS involves multiple power companies.

VI. MONITORING

The DACUs inform the local HMI and the remote SCADA system via the IEC 61850 MMS protocol of any abnormality that may occur, such as internal errors in the DACU hardware or software, status inconsistencies in circuit breakers and disconnecting switches, and failures of analog measurement. The MCs inform the same systems in which the logic operated, which contingencies occurred and which analog quantities are being measured or calculated, such as GIPU and FSE. See Fig. 3.

In addition to the supervisory points being reported to the supervisory system, DACUs have an internal Sequence of Events (SOE). To keep the events synchronized, the DACUs have their internal clock synchronized through a GPS satellite clock via Inter-Range Instrumentation Group time code B (IRIG-B). Besides SOE, a special function is also implemented to record oscillographs of the entire system in the occurrence of events. When a contingency triggers a remedial action logic, the MCs send GOOSE messages to all DACUs installed in the substations to trigger event recording, so that they generate synchronized oscillographs from local analog channels. These oscillographs can be analyzed to evaluate the behavior and response of the entire 765 kV RAS system; however, they also provide a complete view of the system under large disturbances, providing important data for postanalysis and decision making.

As the system is distributed, it is also important to monitor the entire communications system. Communication is essential for the reliable operation of the 765 kV RAS. For this purpose, real-time monitoring of any communication failure was implemented. In addition to monitoring, points of failure are also used in the logics for decision making; for example, a communication failure of the GOOSE links in a specific network causes the block of the failed system and any remedial action will be performed by the healthy system without any additional delay.

VII. SIMULATOR

The simulator is designed to allow the logic to be tested before being effectively implemented in the field. For this, a rack was assembled with replicas of the DACUs of each substation involved and a replica of the MC.

The DACUs from the simulator are identical to the units installed in the substations, except that they do not have analog and digital I/O modules. This is due to the fact that a data generation controller produces all analog and digital information and sends them to the DACUs via IEC 61850 MMS and GOOSE protocols for emulating the static scenarios. Figure 12 shows the simulator schematic diagram.

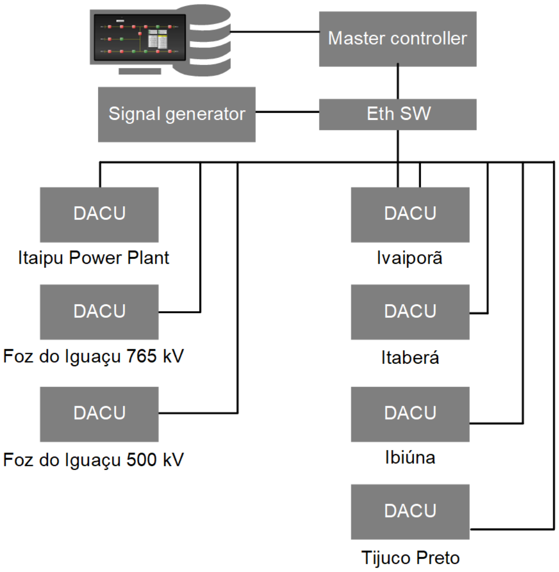

Fig. 12. A schematic diagram of the simulator.

The simulator has four static stages with configurable timing to switch from the current to the previous one, like in a state sequencer, which can be preprogrammed to simulate scenarios with multiple contingencies within a 5-second window. These stages are previously configured and then it is possible to run the simulation, verifying through the HMI system and the monitoring functions if the remedial action logic worked and performed as expected. Figure 13 shows the overall single-line diagram from the simulator HMI.

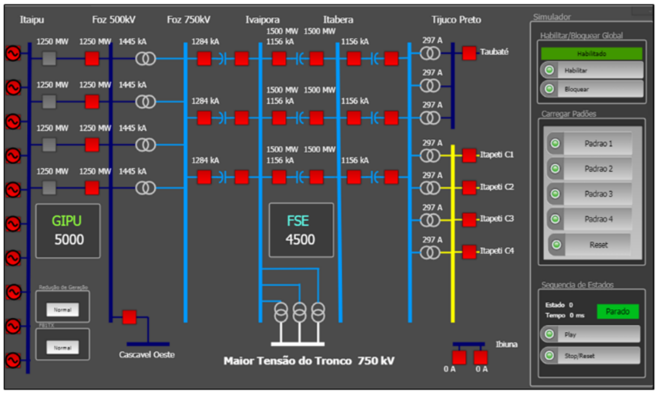

Fig. 13. HMI single-line diagram of the overall system.

This solution allows the remedial actions logic for all contingencies to be tested exhaustively during the factory acceptance test before the deployment and commissioning of the system. The simulator is also very important to test and validate any additions or changes to the logic after commissioning the 765 kV RAS.

Due to the static characteristic of the simulator, Furnas started a project to integrate the simulator with a real-time digital simulator (RTDS). This project aims to replace the previously mentioned data generation controller with an RTDS, which generates all analog and digital values and reports this information to the DACUs via IEC 61850 MMS and GOOSE protocols, see Fig. 14.

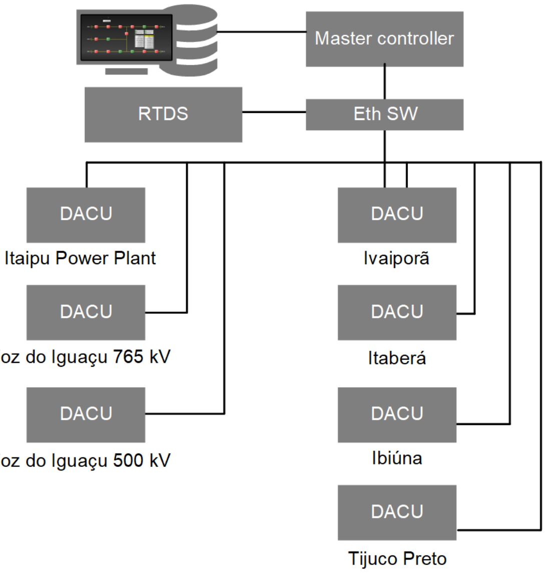

Fig. 14. A schematic diagram of the simulator integrated with an RTDS.

The most important difference of the simulator integrated with the RTDS is to allow analysis and configuration of all RAS logic in a hardware-in-the-loop simulation environment, allowing dynamic simulations and considerably increasing the capacity of the tests performed. Additionally, it is possible to simulate events out of the 765 kV transmission corridor to check the effects in the 765 kV RAS algorithm.

This project involves a real-time simulation of approximately 100 analog quantities and 370 digital quantities that are sent to the DACUs via MMS and GOOSE messages. The RTDS itself subscribes to the GOOSE messages generated by the MCs and checks if the remedial actions are correct.

VIII. FIELD TESTS AND COMMISSIONING

Tests are an extremely important phase for the implementation of such an RAS system. It is necessary to safely and reliably guarantee that the logic, actions, and performance of the system are within the required specifications. For this purpose, several tests were performed with specific methodologies and objectives to meet these requirements. Some of these tests are described in the following sections.

A. *Initial Tests for Validation of Communications Network*

At the beginning of the project, it was necessary to evaluate the transmission time of IEC 61850 GOOSE messages through the two communication systems, multiplexed fiber optics and microwave radio, for validating the possibility of the 765 kV RAS using such protocol to exchange high-speed data among substations. The Tijuco Preto substation was selected for this test, as it is the farthest substation, about 1,000 km from the Foz de Iguaçu Substation and Itaipu.

For these tests, a "ping-pong" approach was used. The received GOOSE messages from System A and B DACUs in Tijuco Preto were configured in loopback at the MCs in Foz do Iguaçu. That is, the DACU was configured to publish GOOSE messages and the MCs to subscribe to these messages and send them back to the DACU. See Fig. 15. For measuring the round-trip time of the messages, the SOE of the DACU was used. The total round-trip time was measured as the difference between the time of the transmission and the reception of messages. The one-way transmission time, which is the communication channel latency, is approximated as half of the measured time. The tests were performed with different traffic loading in the communication network.

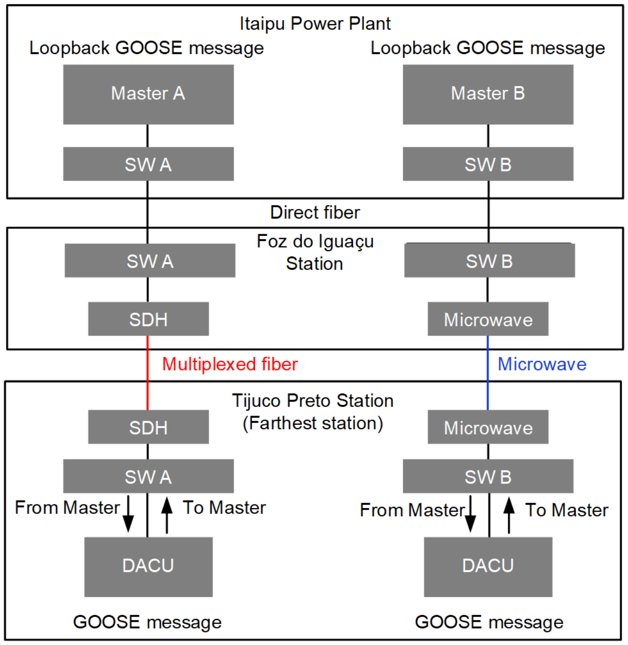

Fig. 15. Staged test to measure communication channel latency.

The results of the network performance tests are shown in Table I.

TABLE I
MEASURED ROUND-TRIP TIME FOR IEC 61850 GOOSE MESSAGES

Communications system	Round-trip time (ms)	Observations
Multiplexed fiber (SDH)	25	Minimum
	31	Average
	39	Maximum
Microwave	39	Minimum
	40	Average
	50	Maximum

For the tests, the GOOSE messages were carefully configured, based on the expected size for the project, to simulate the loading of the communication channels. The test results were satisfactory, indicating the possibility of continuing to use the IEC 61850 GOOSE protocol for exchanging information and sending remedial action commands.

B. *Integrated Tests*

After installing the DACUs at their respective substations and the MCs at Itaipu, an integrated test procedure was developed to validate the operation and performance of the new 765 kV RAS system. The staged tests had the purpose of validating the communications infrastructure and the integration of DACUs with the MCs in the real system, since the RAS algorithm had already been exhaustively tested through the simulator during the factory acceptance tests.

The procedure had a total of 51 tests: 49 simulated tests, e.g., forcing the line contingency in the DACUs via software, and 2 real tests, the actual opening of the line and command to open a GU at Itaipu.

The tests basically consist of contingency simulations, verification of the information traveling through the telecommunications network, validation of the correct performance of the logic in the MCs, and verification of the commands for shedding the GUs and transmission lines in the SCADA alarms and SOEs of the MCs and DACUs.

The two real, staged tests consisted of opening one of the 765 kV transmission lines between the Itaberá and Tijuco Preto substations. The expected remedial action is to open one GU at Itaipu, to evaluate the total response time of the RAS. This section of the 765 kV transmission corridor system was chosen since it is the farthest from Itaipu. The implementation team was interested to check the longest RAS response time, measured from the instant that the local DACU detects the contingency and the GU at Itaipu is tripped.

The two real, staged tests were performed three times for each RAS system, A and B. The total response time, which includes the circuit-breaker time, for each test is shown in Table II.

TABLE II
TOTAL RAS RESPONSE TIME

Communications system	Staged test (GU tripped)	*Total response time (ms)
Multiplexed fiber (SDH)	First test (GU 15)	111
	Second test (GU 15)	112
	Third test (GU 15)	98
Microwave	First test (GU 18A)	164**
	Second test (GU 14)	133
	Third test (GU 14)	135

*Total response time includes circuit-breaker time.

**The response time for this configuration was expected to be the longest of the tests because it is referred to the B chain and the UG 18A, which has a longer circuit-breaker opening time.

The total response time average, from the open-line detection in the Tijuco Preto substation to the opening of the circuit breaker in Itaipu, was 144 milliseconds for the microwave and 107 milliseconds for the fiber-optic communication systems. Both total response times and the performance of the system were considered excellent since the requirement was for the system to respond within 200 milliseconds. That is, the performance of the system was better than the required by the studies developed by the NSO.

IX. CONCLUSION

The 765 kV transmission corridor is very important for the Brazilian NIPG, because the RAS allows Itaipu to maximize energy production while maintaining the security of the NIPG.

Multicast IEC 61850 GOOSE messages, containing binary and analog data, together with message quality supervision, are considered an effective solution for the 765 KV RAS to receive information and to send remedial action commands and monitor the health and performance of the scheme. The communications network was tested and traffic-engineered to ensure proper operation of the RAS.

The 765 kV RAS was tested and validated using a static simulator and a real-time power system model. A staged field test was used to validate the installation of the system.

Including the open-line detection time, communications time, the circuit-breaker response times, and other communications delays, the RAS performed the remedial action of tripping GUs at Itaipu in less than the required 200 milliseconds from the actual contingency.

The project involved several stakeholders, so a close working relationship among all the engineers involved in the project was crucial for the execution and successful deployment of the 765 kV RAS project.

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XI. BIOGRAPHIES

Paulo Max Maciel Portugal received his BSEE degree in electrical engineering (emphasis on power systems) from Rio de Janeiro State University, Brazil, in 2002, and his master's degree (power systems) and doctoral degree (power electronics) from Federal University of Rio de Janeiro, in 2007 and 2015, respectively. In 2002, he joined Furnas as a transmission planning studies engineer. In 2003, he joined Eletrobras as a transmission planning studies engineer. In 2015, he joined Furnas again as an operation planning studies engineer. He has expertise in line-commutated converter (LCC) and voltage-sourced converter (VSC)-HVDC transmission systems, self-excitation of synchronous generators, electromechanical stability studies, and special protection systems for transmission systems and synchronous generators. He is a CIGRE Member of the SC B4 (HVDC and power electronics) and C2 (system operation and control).

Renato Weingartner Pernas is an electrical engineer graduated from Fluminense Federal University (UFF), Brazil, in 2009. He has an MBA in project management and information technology. He worked for ten years in production and development of the information system at Caixa Econômica Federal Bank. Since 2015, Renato has been with Furnas Centrais Elétricas, working in the areas of supervision and protection of electrical systems.

Lucas Vernot Amaral is a telecommunications engineer graduated from Fluminense Federal University (UFF), Brazil, in 2006. He has an MBA in digital transformation and another in private equity and venture capital. He worked for ten years in telecom operator companies. Since 2015, Lucas has been with Furnas Centrais Elétricas, working in the areas of telecommunications and automation of electrical power systems.

Renata Ribeiro Silva is an electrical engineer graduated from Federal University of Rio de Janeiro (UFRJ), Brazil, in 2008. In 2009, she joined the National Electric System Operator, Brazil (ONS, in Portuguese) participating in several activities including recomposition and stability studies. In 2011, she received her master´s degree in electrical engineering from COPPE/UFRJ, working on PSS adjustment and commissioning of a system in an area which had been recently connected to the National Interconnected Power Grid. In 2013, Renata joined Furnas, performing activities related to power system regulation as well as operation studies.

Ricardo Abboud received his BSEE degree in electrical engineering from Federal University of Uberlândia, Brazil, in 1992. In 1993, he joined CPFL Energia as a protection engineer. In 2000, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as a field application engineer in Brazil, assisting customers in substation protection and automation. In 2005, he became a field engineering manager, and in 2014 he became an engineering services manager. In 2016, he transferred to SEL headquarters in Pullman as an international technical manager. In 2019 Ricardo joined SEL University as a professor. Currently he is a fellow engineer with SEL Engineering Services, Inc. (SEL ES). He is a senior member of IEEE.

Rafael Cernev received his BSEE degree in electrical engineering from Federal University of Paraná, Brazil, in 2005. In 2006, he joined Schneider Electric as an application engineer. In 2009, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as an application engineer, assisting customers in electric power system automation. In 2015, he became an automation engineer coordinator. In 2019, he took the position as engineering and services manager for Brazil. Rafael also has taken two specialization courses, the first one in project management (2010) and the second in electric power automation (2013).

Marcos Cabral received his BS in electrical engineering from the State University of Campinas (UNICAMP) in 2008. He began working at General Electric as an automation engineer in 2008 and has been with Schweitzer Engineering Laboratories, Inc. (SEL) since 2010, when he was responsible for training and customer support, configuration, factory testing, and commissioning. Marcos has taken a specialization course in automation of electric power systems at the National Institute of Telecommunications (INATEL) in 2014. Marcos is presently the special protection system leader at SEL Brazil.

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