The Largest RAS in Brazil Increases Power Transfer While Preserving System Stability

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Presented at the
51st Annual Western Protective Relay Conference
Spokane, Washington
October 22–24, 2024

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Abstract—**In recent years, the installation of wind farms, mainly in the Northeast region of Brazil, has shown strong growth, requiring the expansion of the transmission system along with the implementation of a new remedial action scheme (RAS), which involves 15 different transmission companies. This paper discusses the difficult operating scenarios that this new RAS solves in the Brazilian power system, 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, as well as how the cybersecurity requirements were fulfilled.**

I. Introduction

Countrywide interconnected electrical power systems require a set of coordinated control measures with high levels of complexity to plan and operate reliably and economically. Maximizing the utilization of the power system capabilities may not be achievable safely without jeopardizing system stability or imposing limitations on generation, which could increase operational costs. To keep power systems operating securely, remedial action schemes (RASs) may be required. Thus, RASs play an important role to maintain the safety and integrity of a power system when it is subjected to phenomena that cause instability or cascading shutdowns. The typical steps that a RAS follows during a disturbance are disturbance identification, disturbance classification, application of initial corrective actions, and application of supplementary corrective actions, if necessary.

In Brazil, significant reinforcements have been made to the transmission system in recent years, aiming to facilitate the flow of hydroelectric generation from the North and wind generation from the Northeast to other regions of the national grid. However, these reinforcements demanded a reevaluation of the system dynamics and stability limits. In response, Operador Nacional do Sistema Elétrico (ONS), the independent system operator in Brazil, identified the need to modernize and expand the existing RAS within the interconnection transmission system linking the North, Northeast, and Southeast regions.

The primary objective of the new RAS is to conclude remedial actions in less than 150 ms from the inception of contingencies, thereby preventing line overloads and loss of synchronism between regions while maintaining voltage within operational limits.

II. Brazilian Power System Overview

Brazil's electricity production and transmission system is a large hydro-thermal-wind-solar system, with a predominance of hydroelectric plants, composed of multiple asset owners. The National Interconnected System (NIS) is made up of four subsystems:

- South
- Southeast/Central-West
- Northeast
- North

The NIS-installed generation capacity is mainly made up of hydroelectric plants distributed across 16 river basins in different regions of the country. In recent years, the installation of wind farms, mainly in the Northeast and South regions, has shown strong growth, increasing the importance of this generation in serving the market. Thermal plants, generally located close to the main load centers, play a relevant strategic role, as they contribute to the security of the NIS. These plants are dispatched depending on the current hydrological conditions, allowing the management of water stocks stored in the reservoirs of the hydroelectric plants to ensure future service. Transmission systems integrate different sources of energy production and enable supply to the consumer market.

At the time of the writing of this technical paper, the installed generation capacity in Brazil is as per Table I [1].

TABLE I
NIS-Installed Generation Capacity

Source	Power (MW)	%
Hydro	108,092	48.1
Wind	30,843	13.7
Mini- and microgrid	30,244	13.5
Gas	17,022	7.6
Biomass	15,990	7.1
Solar	13,869	6.2
Oil	3,429	1.5
Coal	2,900	1.3
Nuclear	1,990	0.9
Others	116	0.1

The basic transmission power grid in the Brazilian NIS is generally defined by a voltage level of 230 kV and above and is composed of several transmission companies (TCs). However, the operation of the NIS is centralized and coordinated by only one operator, ONS. At the time of the writing of this technical paper, the transmission line network in the NIS is as per Table II [1].

TABLE II
NIS TRANSMISSION NETWORK

Voltage level (kV)	Extension (km)
230	64,265
345	10,597
440	7,061
500/525	69,247
600 (HVdc)	9,544
750	1,722
800 (HVdc)	9,204
TOTAL	171,640

One of the particularities of the NIS is that a transmission substation may be shared among multiple TCs. Fig. 1 shows the simplified single-line diagram of a 500 kV substation from the Brazilian NIS. The substation is owned by transmission company TC3. However, the ownership of the transmission assets is as follows:

- TC1, highlighted with the green background, owns one transmission line bay.
- TC2, highlighted with the blue background, owns two series-compensated transmission line bays, two transmission line bays, and one bus shunt reactor bay.
- TC3, highlighted with the red background, owns two series-compensated transmission line bays, one bus shunt reactor bay, and two busbars.
- TC4, highlighted with the yellow background, owns one series-compensated transmission line bay.

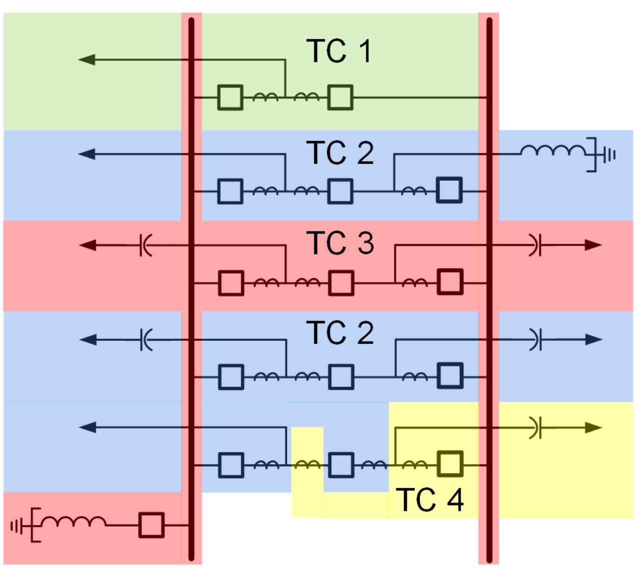

Fig. 1. Example of a multicompany shared substation.

III. RAS

The Brazilian NIS presents several operational complexities. One factor that contributed to the increase in the operational complexity of the NIS was the strict restrictions imposed by environmental regulation. These restrictions made it unfeasible to build new hydroelectric plants with large reservoirs and difficult to obtain environmental licenses for constructing transmission lines.

With this scenario, the Brazilian electricity sector experienced an exponential growth of renewable sources, such as wind and solar plants, including rooftop solar units. This increase in renewable sources has brought important changes to the Brazilian energy matrix. Wind and solar plants cannot generate power continuously; hence, they must have their energy dispatched whenever available. The problem with dispatching energy from these sources lies in the capacity of the transmission system combined with their intermittent behavior, their lack of inertia, and the short circuit contribution that wind and solar plants make compared to the synchronous machines of conventional sources. Delays in transmission line projects bring more complexity for dispatching all energy generated by renewable sources and meeting the stability requirements of the power system.

The planning of the Brazilian system is based on the most traditional reliability criterion of the power system, the n–1 scenario; that is, the system must be able to withstand the loss of any single element without interruption of supply. This means that for any simple contingency, the system must be able to continue operating without interruption of the power supply, loss of stability, or violation of electrical standards (frequency or voltage) and without reaching the overload limits of equipment and installations. In the operation of the NIS, the n–1 reliability criterion is generally adopted, but for some specific points of the system, especially for the main transmission interconnections, a more restrictive reliability criterion is adopted, involving the loss of two or more components. As a result, the implementation of the RAS has grown considerably, aiming to fully exploit the existing sources in the Brazilian electrical power sector without compromising operational security. Whether the planning criterion is n–1 or probabilistic in nature, the RAS plays a key role. In many cases, the electroenergetic restrictions imposed by the criterion of supporting the simplest worst-case contingency or the more restrictive reliability criterion, involving the loss of two or more components, have a higher cost than the RAS over time.

The RAS is an automatic control and protection system designed to enhance the use of the transmission and generation system, increase its reliability, and provide greater operational security for the interconnected electrical power system. The RAS is responsible for detecting adverse conditions and taking the necessary corrective actions in a timely manner to contain the extent of disturbances. The actions of the RAS prevent consequences that can lead the system to the loss of angular or voltage stability, avoiding potential large blackouts in the electrical power system as well as providing continuous operation outside normal electrical parameters, such as overload or overvoltage.

In a large, interconnected power system with numerous transmission lines and generation sources, it is necessary for the RAS to monitor and supervise a large amount of equipment spread throughout the substations and power plants so that its actions are effective. Due to this characteristic, integrating these monitoring and supervision systems through a wide-area network (WAN) can make the RAS more effective.

On the other hand, the actions of the RAS become very constrained when it is applied in an isolated way. Without integration through a WAN, its monitoring and action are restricted to the equipment from a single substation, reducing its effectiveness at increasing the reliability and safety of the operation of interconnected electrical power systems.

IV. North/Northeast/Southeast RAS

In Brazil, significant reinforcements were deployed for the ac transmission system of the North, Northeast, and Southeast (N/NE/SE) interconnections to enable the transfer of the large amount of energy produced by the hydropower plants of the North region and the wind farms of the Northeast region, as shown in Fig. 2.

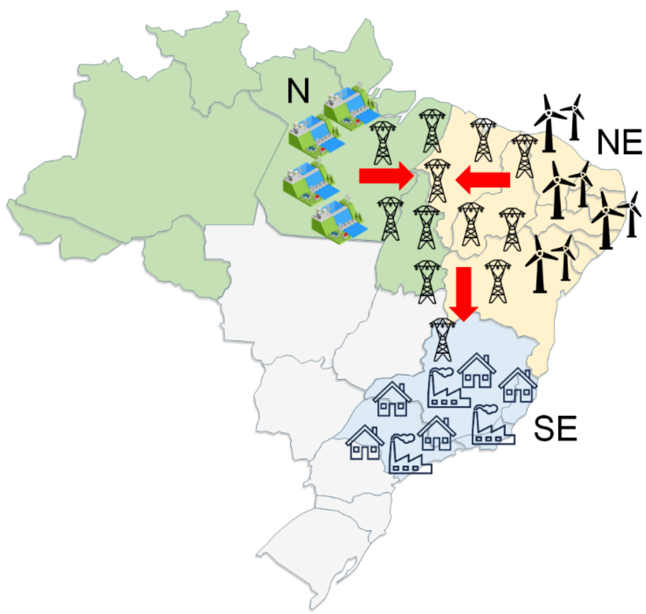

Fig. 2. N/NE/SE interconnections.

The RAS currently installed at the North-Southeast interconnection is based on outdated programmable logic controllers (PLCs), since its implementation started in 1998. Considering the need to maximize the energy exchange between the transmission subsystems of the North, Northeast, and Southeast regions, the obsolescence of the existing version of the RAS, the impossibility of the PLC 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 all logic schemes and their references. Therefore, in 2021 ONS started an effort to coordinate with the TCs to design and implement a new RAS to replace the existing one. This new version of the RAS will be called the N/NE/SE RAS for the rest of this technical paper.

The coverage area of the N/NE/SE RAS is about 750,000 km^2, extending 1,600 km from south to north, as shown in Fig. 3.

Fig. 3. N/NE/SE RAS coverage area.

The N/NE/SE RAS involves 15 TCs, identified throughout this technical paper as TCn, where $n = 1$ to 15, plus the national operator, ONS. It is composed of thirteen transmission substations, five hydro power plants, thirty-three 500 kV lines, and two 800 kV HVdc bipoles. The most challenging aspect of this RAS is not its large geographic area, but rather the data integration associated with the assets from many TCs, which requires a robust and cybersecure communications architecture to collect real-time data and send remedial action controls to the different assets.

The N/NE/SE RAS aims to monitor certain transmission lines in the area of coverage and send commands of runup or runback to 800 kV HVdc controllers and/or shut down to the generators in the power plants involved in the scheme. Such actions aim to eliminate overloads (loads exceeding the short-term emergency limit of the transmission lines) or avoid loss of synchronism between the North, Northeast, Southeast-Central, and South subsystems in the event of multiple contingencies in transmission lines monitored by the scheme. Additionally, the scheme will be responsible for carrying out voltage control actions in certain regions of the coverage area, like tripping shunt capacitor banks, which may be needed because of such contingencies.

The architecture of the N/NE/SE RAS is based on redundant data acquisition and control units (DACUs), which transmit required data to implement the logic schemes to the redundant central controllers (CCs) running the RAS algorithms. Fig. 4 illustrates the general concept of the N/NE/SE RAS.

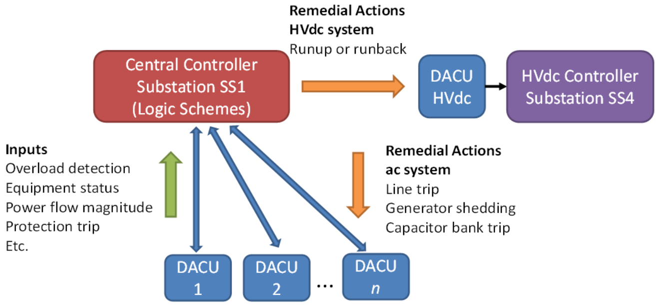

Fig. 4. The general concept of the N/NE/SE RAS.

As previously mentioned, the N/NE/SE RAS involves 15 different TCs, and a single transmission substation may be shared among several TCs. ONS appointed the TC with the largest number of monitored transmission lines to be responsible for the CCs, which is the transmission company TC2 in this technical paper.

Fig. 5 shows the transmission system covered by the N/NE/SE RAS along with the location of the monitoring and control panels (MCPs), which have the DACUs, and the CC. Fig. 5 does not show additional transmission lines and subsystems from the other regions.

The two 800 kV HVdc bipoles, shown in Fig. 5, are among the longest transmission lines in the world. One of the HVdc bipoles spans 2,543 km, and the other HVdc bipole is 2,092 km long. These 800 kV HVdc lines operate in parallel with a 500 kV ac system, allowing greater flexibility in controlling the flow of energy between the North and Southeast regions of Brazil, a configuration that presents unique characteristics and operational challenges. These HVdc bipoles play a critical role in stabilizing and optimizing the electrical grid in Brazil, ensuring that energy generated in the North can be efficiently transmitted to the Southeast and South regions, where the largest load centers are located.

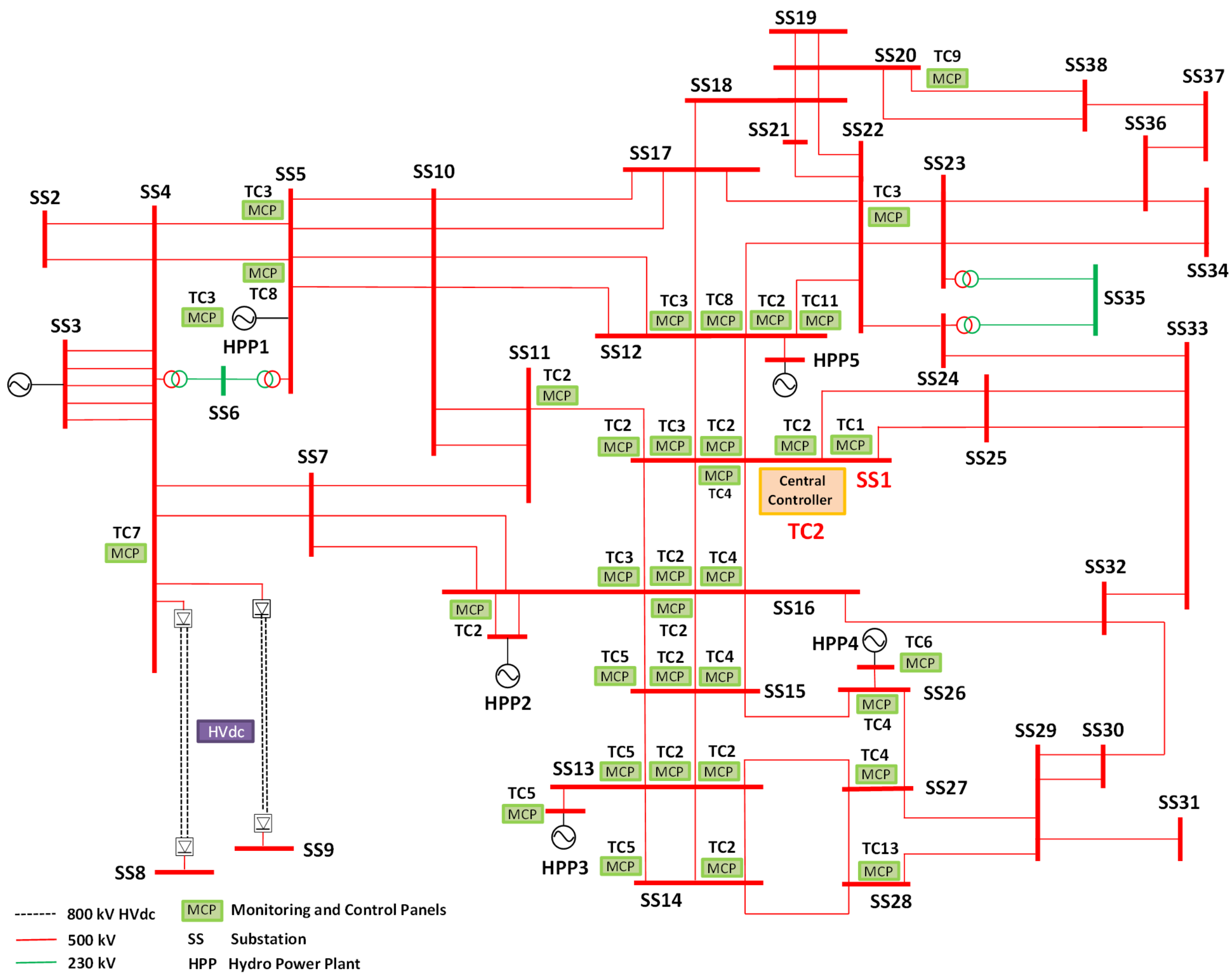

Fig. 5. Transmission system covered by the N/NE/SE RAS with the location of the DACUs and CC, not showing redundancy.

V. Stability Studies and Contingencies

The remedial actions from the N/NE/SE RAS avoid the implementation of complex algorithms in the national supervisory system to monitor power flow limits and control overloads in the transmission network, which could cause higher operating costs due to nonoptimal operating states from an electroenergetic point of view. Furthermore, the implementation of the N/NE/SE RAS is especially beneficial to the system in the event of maintenance interventions in the interconnection transmission lines. In these degraded network situations, overloads are more prone to occur and double contingencies may lead to loss of stability between the subsystems.

The N/NE/SE RAS philosophy considered in the stability study works as follows: once an overload condition above the emergency limits of the interconnection transmission lines or instability conditions are detected, a runup or runback action is commanded in the HVdc controllers located at Substation 4 (SS4). The amount of power related to the runup or runback is not predefined and depends on the systemic conditions at the moment of the contingency. So the HVdc bipole controllers receive a command that is a pulse with variable duration, which is defined by the algorithm in the CC. With this, it is possible to implement a more selective and assertive RAS, which is less dependent on simulations and is capable of taking the best action even with the evolution of the electrical power system.

If the transmission line contingency happens in a scenario that risks the network angular stability, the runup or runback command issued to the HVdc bipoles will remain active until the power flow on the interconnections, measured by the RAS, is restored to predisturbance levels. In such cases, ensuring the speed of the RAS is imperative to make this mitigating measure effective. Conversely, if the contingency only causes an overload on the remaining transmission lines, similar signals will be sent to the HVdc Master Controller and will remain active until the ac power flow decreases sufficiently to eliminate the overload. The simulations demonstrated that runup actions promoted by the N/NE/SE RAS must be carried out at a rate of at least 4,000 MW/s to avoid the loss of synchronism between the North and Northeast subsystems in the event of triple contingencies (or double contingencies when elements are unavailable) on the 500 kV interconnection of the North and Southeast subsystems.

In addition, the N/NE/SE RAS commands generation shedding at the five hydro power plants involved in the scheme, in case of a lack of regulation margins in the 800 kV HVdc bipoles or when it is not possible to use them due to operational limitations.

In addition to the runup and runback control actions on the 800 kV HVdc bipoles and shutting down generation, voltage control measures are also necessary to guarantee the effectiveness of remedial actions. Specifically in the North and Southeast subsystem exporting scenarios, the N/NE/SE RAS commands the trip of certain 345 kV capacitor banks in certain substations of the power system, due to overvoltages that may occur after certain contingencies.

Double contingencies (or simple contingencies with the unavailability of another transmission element) and triple contingencies (or double contingencies with the unavailability of another transmission element) were analyzed in the 500 kV transmission system shown in Fig. 5 with different load and power flow scenarios, evaluating aspects of electromechanical stability, line loading, and voltage control. Sixty double contingencies and 48 triple contingencies were assessed for four different scenarios shown in Table III.

Table III
Stability Study Scenarios

Scenario	Description
1	North subsystem exporting power, mainly to the Southeast subsystem (Fig. 6)
2	North subsystem exporting power, mainly to the Northeast subsystem (Fig. 7)
3	Northeast subsystem exporting power (Fig. 8)
4	Southeast subsystem exporting power, mainly to the Northeast subsystem (Fig. 9)

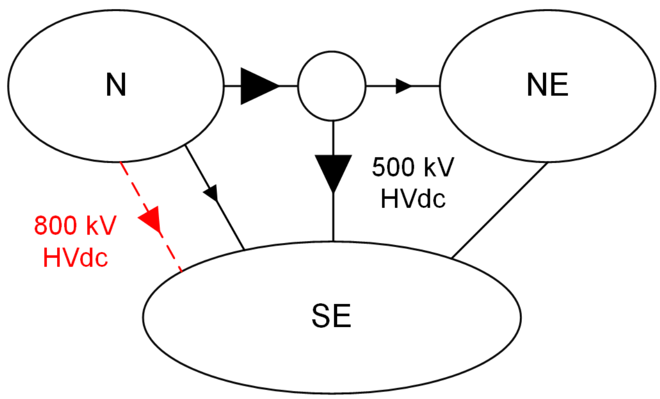

Fig. 6. North subsystem exporting power, mainly to the Southeast subsystem.

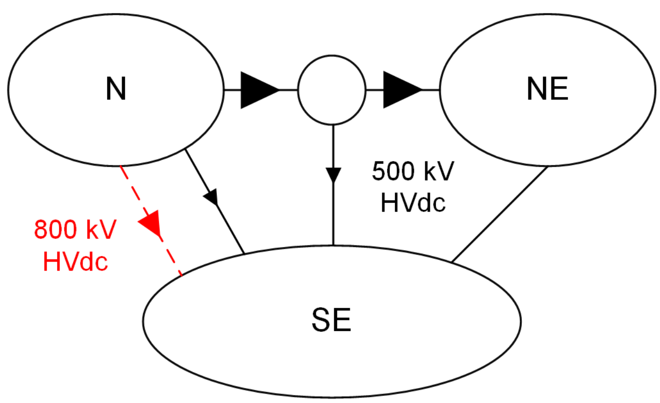

Fig. 7. North subsystem exporting power, mainly to the Northeast subsystem.

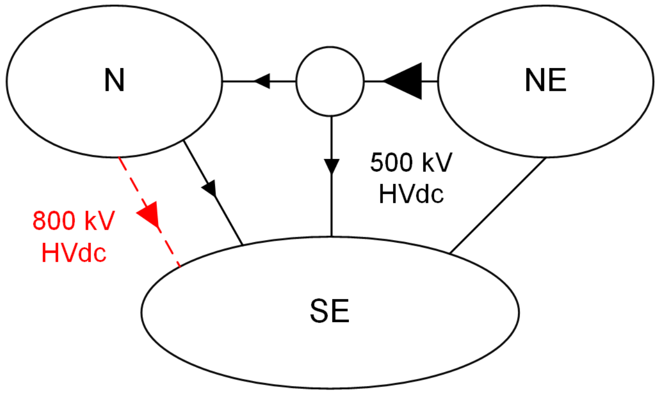

Fig. 8. Northeast subsystem exporting power.

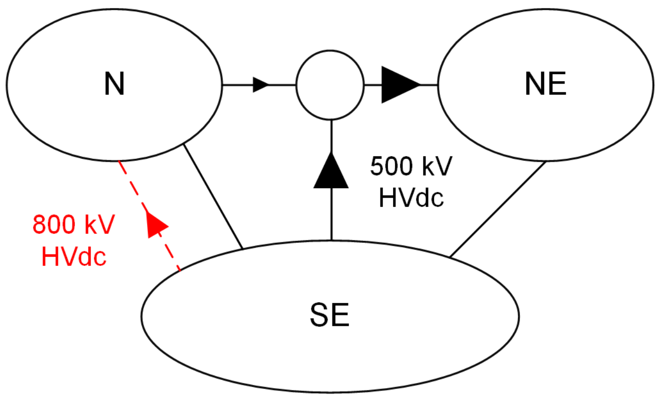

Fig. 9. Southeast subsystem exporting power, mainly to the Northeast subsystem.

There are too many scenarios to be discussed in this paper about how the N/NE/SE RAS helps maximize power transfer while keeping power system stability, so a single case is discussed here. The following situation could lead the system to an unstable operation:

1. The system is operating in Scenario 1 or 2 (North subsystem exporting), see Fig. 6 or Fig. 7, AND
2. The sum of the power flows from the North subsystem to the South and Northeast subsystems is greater than 2,500 MW, AND
3. The 500 kV transmission line between SS27 and SS26 is out of service, see Fig. 5, AND
4. A double contingency occurs between SS15 and SS27, see Fig. 5.

Hence, this is an example of a scenario in which the N/NE/SE RAS allows the power exchange between the North subsystem and the rest of the system to be more than 2,500 MW.

VI. N/NE/SE RAS Requirements

Although the ownership of the DACUs and WAN communications that compose the N/NE/SE RAS is spread among 15 different companies, this RAS is treated as a unified system. Therefore, ONS defined that the technical solution for this RAS should be developed by a single manufacturer, as this is considered the best solution for the implementation process.

Additionally, all processes related to the implementation of the N/NE/SE RAS technical solution, including field services, must have the direct involvement of the selected manufacturer, since the responsibility for meeting the ONS technical requirements lies with the selected manufacturer.

The main benefits, as evaluated by ONS, for the implementation process in adherence to the requested technical solution are as follows:

- Greater assurance of meeting the total operating time requirement for RAS in stability logics.
- Standardization of the RAS architecture, avoiding integration issues between equipment.
- Increased speed in RAS implementation.
- Integrated factory acceptance testing (FAT) with all equipment before field tests.
- Flexibility in implementing the architecture of a testing platform.
- Easier implementation of the centralized RAS monitoring system.

ONS defined that each TC is responsible for executing the project of developing the required infrastructure related to the transmission asset and WAN communications under its ownership, for procuring the necessary equipment, and for carrying out FATs, field installation, and commissioning. The TCs were also responsible for developing and making available all the design documentation as built and the commissioning test reports to ONS. Additionally, the TCs are responsible for implementing a monitoring system, a RAS monitoring network called RASMNET, which will send monitoring data to the central human-machine interface (HMI), located in the same substation of the CC, allowing the acquisition of monitoring data and sequences of events related to the operation of the N/NE/SE RAS. All the data required to run the logic schemes associated with the N/NE/SE RAS are transmitted through a logically segregated, but not necessarily physically segregated, network from the RASMNET, a RAS protection network called RASPNET.

The following requirements were considered for the implementation of the N/NE/SE RAS.

1. Redundancy shall be planned for all equipment associated with the RAS infrastructure, including communications routes and two segregated systems, called System A and System B, working in a hot-hot configuration. The information traffic of the DACUs associated with the System A chain must use a completely independent communications route from the information traffic of the DACUs associated with the System B chain, and vice versa.
2. Two CCs shall be implemented, considering redundancy, to process all logic schemes related to the N/NE/SE RAS, which must be sized to receive and process all information sent by the DACUs to comply with the operating time required for the scheme to maintain power system stability. The CCs shall be located at the Master Controller Substation, under the responsibility of TC2.
3. The WAN communications shall use physically independent telecommunication equipment and media for each route to avoid common-mode failures, and

solutions that share the same transmission line structure are not allowed.

4. To avoid the risks involved in sharing control and current signals between relay and control rooms of different TCs in the same substation, dedicated DACUs shall be provided for each TC to acquire the necessary signals, having exclusive communications ports to transmit the data required to implement the logic schemes associated with the N/NE/SE RAS.
5. All stability, overload, and overvoltage logic schemes that lead to remedial actions shall be implemented only in the CCs. The logic schemes implemented in the DACUs shall be limited to monitoring overload, overvoltage, and open-line terminal conditions and sending the results to the CCs.
6. The open terminal detection logic implemented locally in the DACUs at each terminal of the line, which is composed of the monitoring of the status associated with the circuit breakers and disconnect switches, shall be sent directly to the CCs. The CCs, with the information of the status of both terminals of the line, shall determine the open-line status.
7. The stability logic schemes shall have a total operating time of up to 150 ms for remedial actions. To guarantee this total operating time, the time from the detection of the contingency to the time the runup or rundown is received by the HVdc controller must be no longer than 100 ms, considering the HVdc controller may take up to 50 ms to command the converters.
8. The implementation of a maintenance mode for the N/NE/SE RAS shall be considered. When the maintenance mode is active, all output contacts related to the remedial actions shall be blocked and not allowed to be closed for all the DACUs of the system chain that is put in maintenance mode. The maintenance mode shall be implemented independently on System A and System B chains.

General communications requirements established by ONS for the local-area network (LAN) and WAN include the following.

1. The communications protocols used by the RAS shall comply with the IEC 61850 standard, ensuring interoperability among all equipment, including the integration of future equipment associated with possible expansions.
2. The analog and digital data necessary for the implementation of the logic schemes shall be transmitted exclusively via IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messages over RASPNET.
3. RASPNET shall implement network segmentation using resources such as virtual LANs (VLANs) and the prioritization of GOOSE messages, ensuring the isolation and quality of service for these messages.
4. In the RASPNET, each local DACU shall communicate strictly with the CCs, via GOOSE messages, composing a star topology. DACUs from different TCs shall not communicate with each other. This requirement aims to facilitate future logic revisions, as well as enhance cybersecurity.
5. To ensure the cybersecurity requirements of each TC involved in the system, communications between the DACUs and the local supervisory system of the TC shall be protected by a firewall. This applies to remote engineering access as well, ensuring that only the expected data traffic from the DACUs reaches the TC local supervisory servers.
6. To prevent access to and from the TC corporate networks via the DACUs, the use of at least two communications cards per DACU with different IPs shall be implemented. One card must be exclusively for the communications network between the local DACU and the remote CC (RASPNET), and the other for monitoring, engineering, and supervisory access (RASMNET). This interface shall incorporate all necessary cybersecurity tools.

The minimum requirements in terms of monitoring functionalities established by ONS are as follows:

1. The RASMNET infrastructure shall be distributed and hierarchical, where the N/NE/SE RAS devices are monitored by the local TCs. It collects monitoring data and transfers them up to a delivery location where the data can be retrieved by TC2, which is in charge of the CCs.
2. The N/NE/SE RAS equipment must be monitored via Simple Network Management Protocol (SNMP) and IEC 61850 Manufacturing Message Specification (MMS) protocol. The communications port connected to the monitoring network, through which SNMP and IEC 61850 MMS traffic flow, shall be distinct from the communications port dedicated to the RASPNET, through which GOOSE traffic flows.
3. The monitoring data collected by the local TC shall be provided to the central monitoring system, which TC2 is in charge of, including information related to the LAN and WAN equipment, as well as cybersecurity equipment and DACUs.
4. The central monitoring system shall have an HMI to provide a graphical visualization of the system architecture, allowing for the supervision of all equipment or communications failures on the network in real time and any other necessary management and historical information.

It was also a requirement that TC2, which is responsible for the CCs, acquires a testing platform, called a simulator, that simulates all equipment associated with the N/NE/SE RAS and includes a replica of the CC. This platform allows the reproduction of occurrences, in a controlled way, by configuring the initial scenario with all digital and analog data. This platform is supposed to be used as a tool for the FAT and for testing future logic schemes or configuration modifications prior to field implementation.

VII. Planning and Bidding Phases

To start planning the N/NE/SE RAS with all 15 TCs involved in the project, ONS organized a presentation with the general philosophy for the scheme. After the initial presentation, several meetings were held between ONS and the TCs to consolidate a proposal for the architecture of the N/NE/SE RAS.

After several discussions, ONS appointed TC2 responsible for the implementation and operation of the CCs and the central monitoring system, since it is the TC that holds the most equipment associated with the N/NE/SE RAS.

With the agreement of the TCs on the initial proposal for the new RAS, ONS issued the N/NE/SE RAS Implementation Report, which aimed to detail the infrastructure, logic schemes, and basic requirements for the new RAS.

The N/NE/SE RAS was split into two scopes, one related to the protection, control, and supervision system (PCSS) and the LAN and the other scope related to the WAN that interconnects the substations through communications links. TC2, as the owner of the CCs, was responsible for discussing with multiple vendors the possible solutions to implement the PCSS & LAN, since all equipment associated with the N/NE/SE RAS would be integrated with the CCs.

After prospecting the possible solutions for the PCSS & LAN and WAN and with the intention to harmonize the technical requirements of the N/NE/SE RAS among the 15 TCs, ONS issued the document "Minimum Requirements for the LAN and WAN." The document's development was led by TC2, with the contribution of all utilities involved in the RAS and ONS. The document took seven months to draft, requiring several meetings for technical alignment.

The document allowed all TCs to carry out the basic project for the implementation of the N/NE/SE RAS, defining the location of installation of the MCPs, as well as the necessary infrastructure for electrical interconnections, such as equipment status and analog quantities, to the DACUs and interconnections of the RAS LAN communications. Each TC oversaw procuring, installing, and testing the MCPs under their responsibility.

An important aspect of such a large project involving multiple companies is to harmonize the schedules of all the TCs. Consequently, TC2 started, alongside the basic project of the N/NE/SE RAS, the bidding process to select the manufacturer with the best solution for the PCSS & LAN. This approach ensured that by the end of the bidding process, when choosing the manufacturer to supply the PCSS & LAN, the other utilities would have their basic projects completed and could start contacting the chosen manufacturer to supply the PCSS & LAN network for their transmission assets involved in the N/NE/SE RAS.

One of the most challenging aspects of the PCSS & LAN was establishing technical requirements that would allow the interconnection among local DACUs from multiple TCs in the same substation and the CCs to exchange data through high-speed protocols, while keeping the necessary cybersecurity and the required very-low operating time for the N/NE/SE RAS. To accomplish these requirements, the security equipment (SEC) was defined. This equipment handles protection-class high-speed traffic and GOOSE messages and can provide the required cybersecurity by isolating the local RASPNET from each TC, as well as allowing only the necessary Ethernet traffic for the RAS without introducing significant delay to the communications. The minimum requirements defined for the SEC were:

- To allow only the Ethernet traffic related to GOOSE messages pertaining to the RAS. Any other traffic is considered prohibited and must be dropped.
- To filter and throttle RASPNET traffic.
- To filter traffic at Layer 2. In the case of an Ethernet switch being used, it must be able to disable dynamic media access control (MAC) address learning and make an access-control list.
- To provide filtering for at least source and destination MAC addresses, EtherType, and VLAN.
- To have a mechanism to limit the bandwidth for each network flow. This mechanism aims to limit the effects of a possible denial-of-service attack through an allowed flow within the RASPNET or RASMNET.

Fig. 10 shows a typical communications network architecture, with four TCs in the same substation, defined during the planning phase as a result of the discussions with all the TCs and ONS. Each piece of WAN communications equipment is interconnected to the SEC, which is owned by the same TC that owns the WAN equipment. It should be noted that the configuration and administration of the SEC is the responsibility of the TC that owns the WAN equipment, with no shared administration. Each piece of SEC is connected to the DACUs in the substation, respecting the requirements of independence between System A and System B. The DACUs, SEC, and WAN equipment are also connected to the local network of each TC through a firewall for supervision and monitoring.

To ensure that the solution proposed by the vendors complied with the requirements already defined, TC2 requested that the vendors perform a proof of concept (POC). The system shown in the Fig. 10 plus the CC were set up on a bench in the laboratory, and several tests were performed to prove that the proposed solution worked as required. The POC was described as a technical requirement in the specification and served as evidence of compliance with the predefined requirements for all the TCs involved in the process.

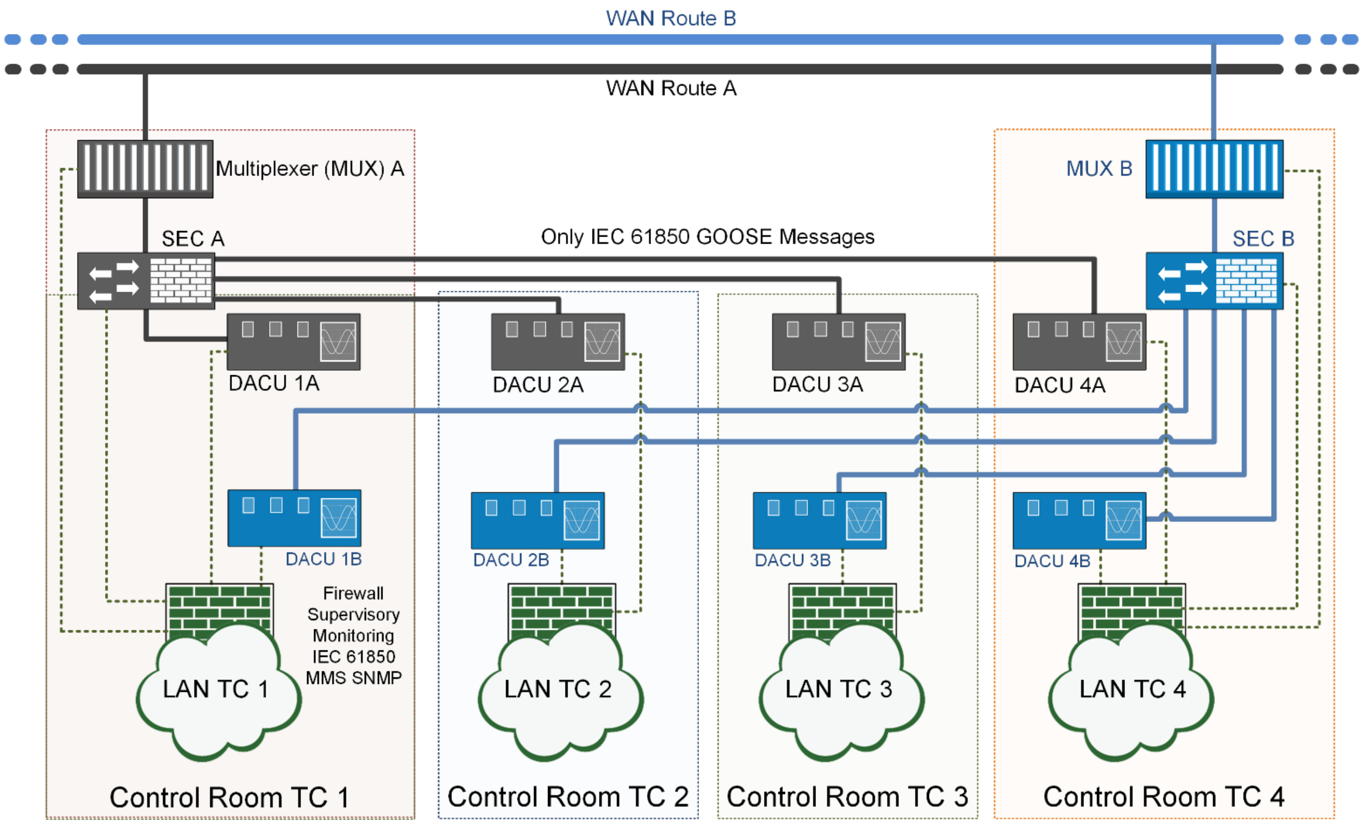

Fig. 10. Typical communications network architecture of a substation with multiple TCs.

VIII. WAN Communications

Due to the critical importance of the N/NE/SE RAS for the security and optimized operation of the NIS, ONS required that redundant communications routes must use independent physical media for communications, running through distinct transmission lines and towers, to eliminate the possibility of common failure. Based on this requirement, communications routes were created, considering the available optical ground wire cables and WAN infrastructure from seven TCs.

It is not in the scope of this technical paper to discuss in depth the WAN communications configuration to transport the required data for the proper operation of the N/NE/SE RAS.

Fig. 11 shows the proposed redundant communications routes for Systems A and B. The route for System A is represented by the solid black lines and for System B by the dashed red lines. It is interesting to note that there is no need for communications between DACUs from different substations; however, it is imperative that all DACUs have access to the network to communicate with the CCs located at the Master Controller Substation.

The WAN is based on Multiprotocol Label Switching Transport Profile (MPLS-TP). MPLS-TP is a variant of the MPLS technology simplified for transport-type networks providing predefined tunnels between service access points. It is an adaptation of MPLS to support traditional transport network requirements such as high availability and quality of service support, presently fulfilled by Synchronous Digital Hierarchy and synchronous optical network (SONET) transport technologies [2].

In the N/NE/SE RAS, all GOOSE messages, which are Ethernet Layer 2 frames, are transported through the WAN with configured and dedicated tunnels between the multiplexers (MUXs). This setup ensures that there is no bandwidth competition between GOOSE messages and other services. This makes MPLS-TP quasi-deterministic, which helps to fulfill the operating time requirement for the RAS.

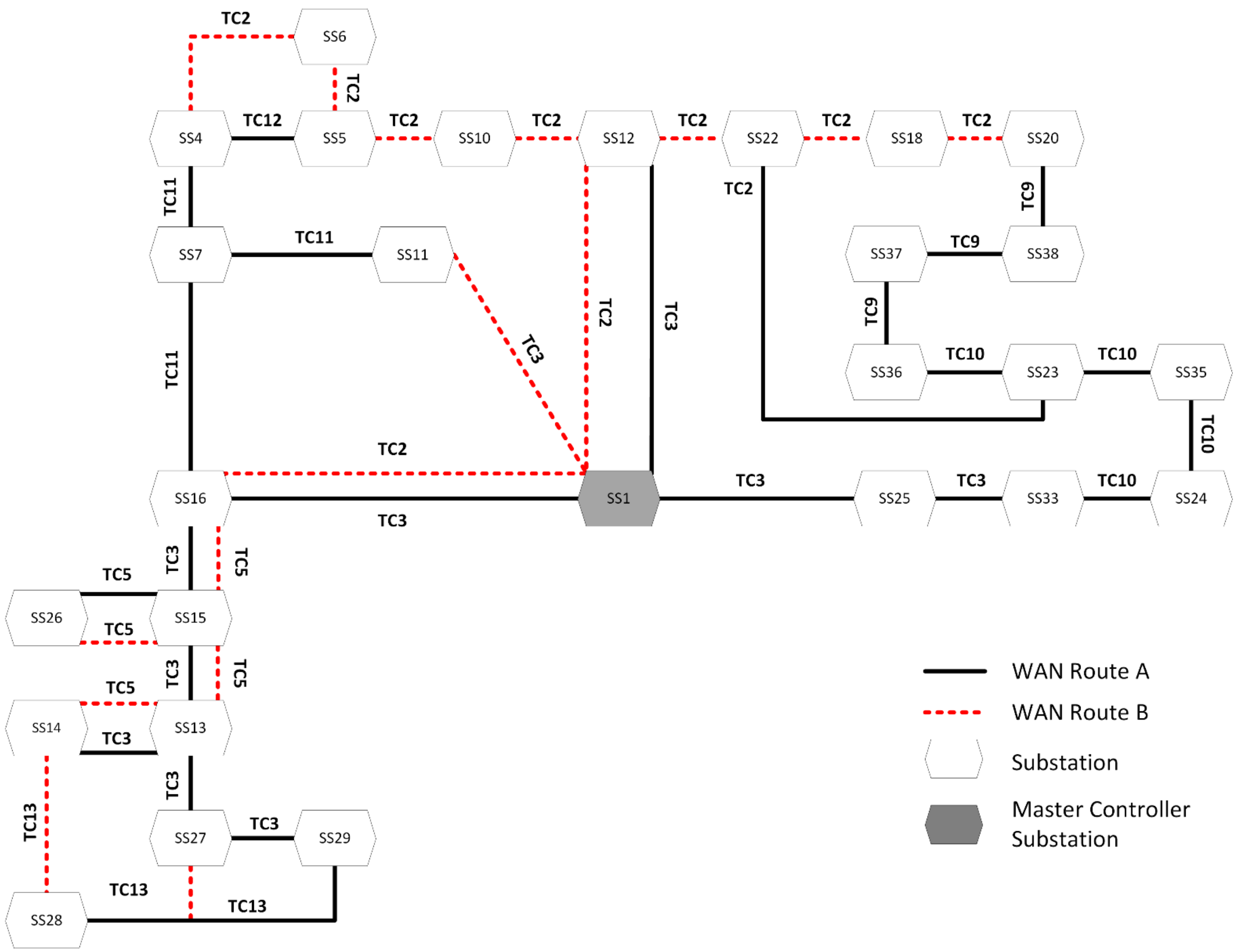

Fig. 11. Redundant and independent WAN communications routes.

No single TC is in charge of an entire WAN route. The WAN Routes A and B are composed of equipment from multiple TCs, as shown in Fig. 11. So in certain points, it is necessary to interconnect the MUXs from different TCs, which may be from different vendors. For example, WAN Route A from SS5 to SS4 (top left-hand side of the figure) is owned by TC12. However, the segment from SS4 to SS7 is owned by TC11. Thus, an interconnection between the WANs of these two different TCs is required at SS4, the shared substation.

During the POC tests mentioned in Section VII, certain issues related to the interoperability between MUXs from different MPLS-TP vendors were identified. To avoid problems in WAN communications, it was decided to interconnect the MUXs from different vendors through 1 GB Ethernet access ports, as shown in Fig. 12.

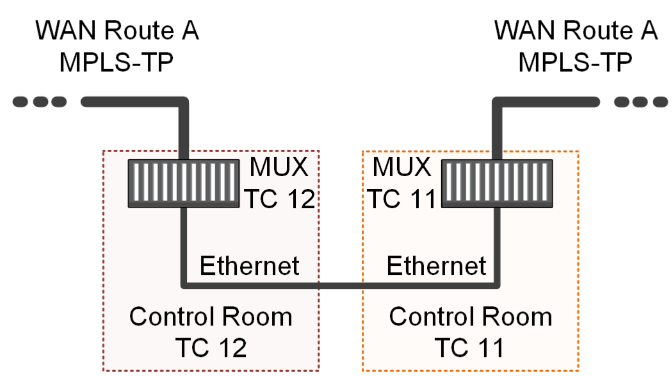

Fig. 12. Interconnection of MPLS-TP MUXs from different vendors.

IX. N/NE/SE RAS Architecture and Topology

This section provides an overview of the actual solution implemented for the N/NE/SE RAS.

A. N/NE/SE RAS LAN Network Challenges

To enable high-speed communications, the GOOSE messages travel in Layer 2, using a multicast mechanism. Several Layer 2 protocols are present in conventional LAN networks, such as Link Layer Discovery Protocol, Address Resolution Protocol, and Spanning Tree Protocol. The first challenge is how to create such a broad network formed by interconnecting the network of multiple TCs, as shown in Fig. 10, without mixing the Layer 2 multicast and broadcast messages from these different networks.

Another inherent difficulty arising from the interconnection of the LAN networks of different TCs is related to cybersecurity aspects. Interconnecting multiple networks without a security mechanism could create a significant vulnerability, allowing issues from one TC network to potentially spread to the networks of other TCs.

The challenges, therefore, are to guarantee cybersecurity and communications speed, and filter and forward only GOOSE messages from the respective TCs to the CCs, located at the Master Controller Substation, and still meet the RAS speed requirements. The SEC discussed in Section VII and shown in Fig. 10 has this purpose.

B. Software-Defined Networking (SDN)

To interconnect the LAN network of multiple TCs involved in this RAS securely, SDN was applied to the SEC. SDN switches allow secure interconnection of networks to exchange GOOSE messages from different substations. With SDN switches, it is possible to physically interconnect the TC communications networks, while maintaining them as logically separate. This logical separation is achieved by allowing only Ethernet packets with preconfigured flows to be forwarded. In the case of the N/NE/SE RAS, this means allowing only predefined GOOSE messages to be forwarded to the network, and not allowing any other type of Ethernet packet to flow from one TC network into another [3] [4]. Those are the reasons the Ethernet SDN switches are applied as the SEC in the N/NE/SE RAS project.

SDN switches use deny-by-default security, in which all packets without a predefined, authorized path are rejected. Each communications path and packet type must be authorized in advance, which prevents unwanted or malicious traffic on the network [4]. This feature of packet inspection or filtering rules guarantees a logical separation of the networks of each TC involved in the RAS.

When a packet enters the switch, the various segments of the Ethernet frame are inspected, from the physical layer to the transport layer. If the field corresponds to a valid flow rule, then the corresponding action is performed, such as forwarding this packet to a certain switch port.

Fig. 13 illustrates a rule, which is similar to one of the various rules used in the N/NE/SE RAS, that can be configured in the SDN switch to identify a very specific GOOSE message entering Port B1 with multicast destination address 01:0c:cd:01:00:01 and forward it to Port B2. In other words, if the switch were configured with only this rule, only GOOSE messages with this multicast destination address would be forwarded from Port B1 to Port B2; all other messages would be discarded or forwarded to an intrusion detection system.

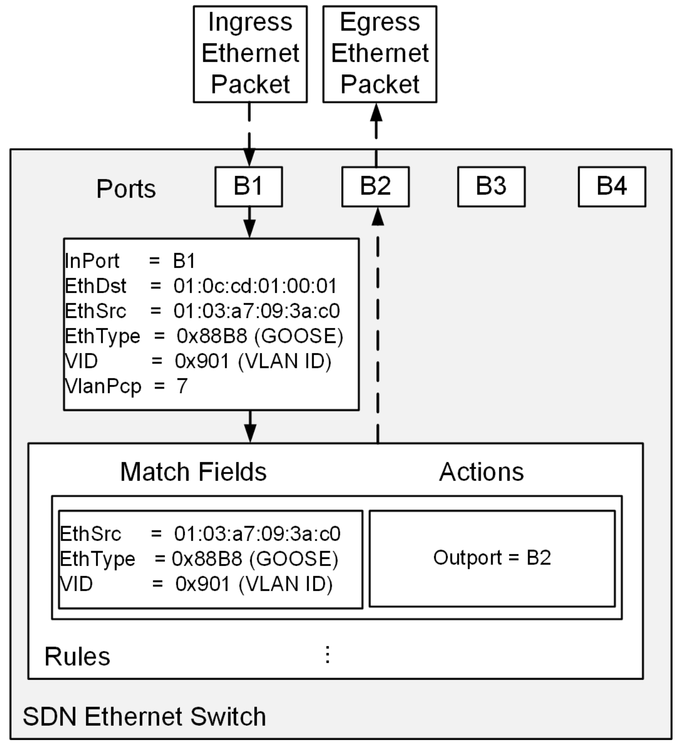

Fig. 13. The general concept of SDN switch flow rules.

C. Network Topology and Architecture

Fig. 14 shows the general N/NE/SE RAS architecture and its main components, which are as follows:

- Front-end processors (FEPs) make the interface between all DACUs and the CCs. They consolidate the multiple GOOSE messages received from the DACUs and pass them as a single message stream to the CCs. This reduces the processing burden in the CCs and makes the RAS operating speed faster. They also guarantee greater scalability and flexibility to the system. The CCs do not need to be reconfigured when any GOOSE messaging is modified; all work is done in the FEPs. The FEPs also monitor the communications channel delay through GOOSE messages that carry time stamps, as explained later.
- CCs are the house for all logic schemes related to the N/NE/SE RAS. They receive all binary and analog data, some of them consolidated in the DACUs or FEPs, to make decisions about remedial actions that need to be taken upon the occurrence of contingencies. They also send out commands through GOOSE messages to the DACUs to maintain the stability of the Brazilian electrical system.

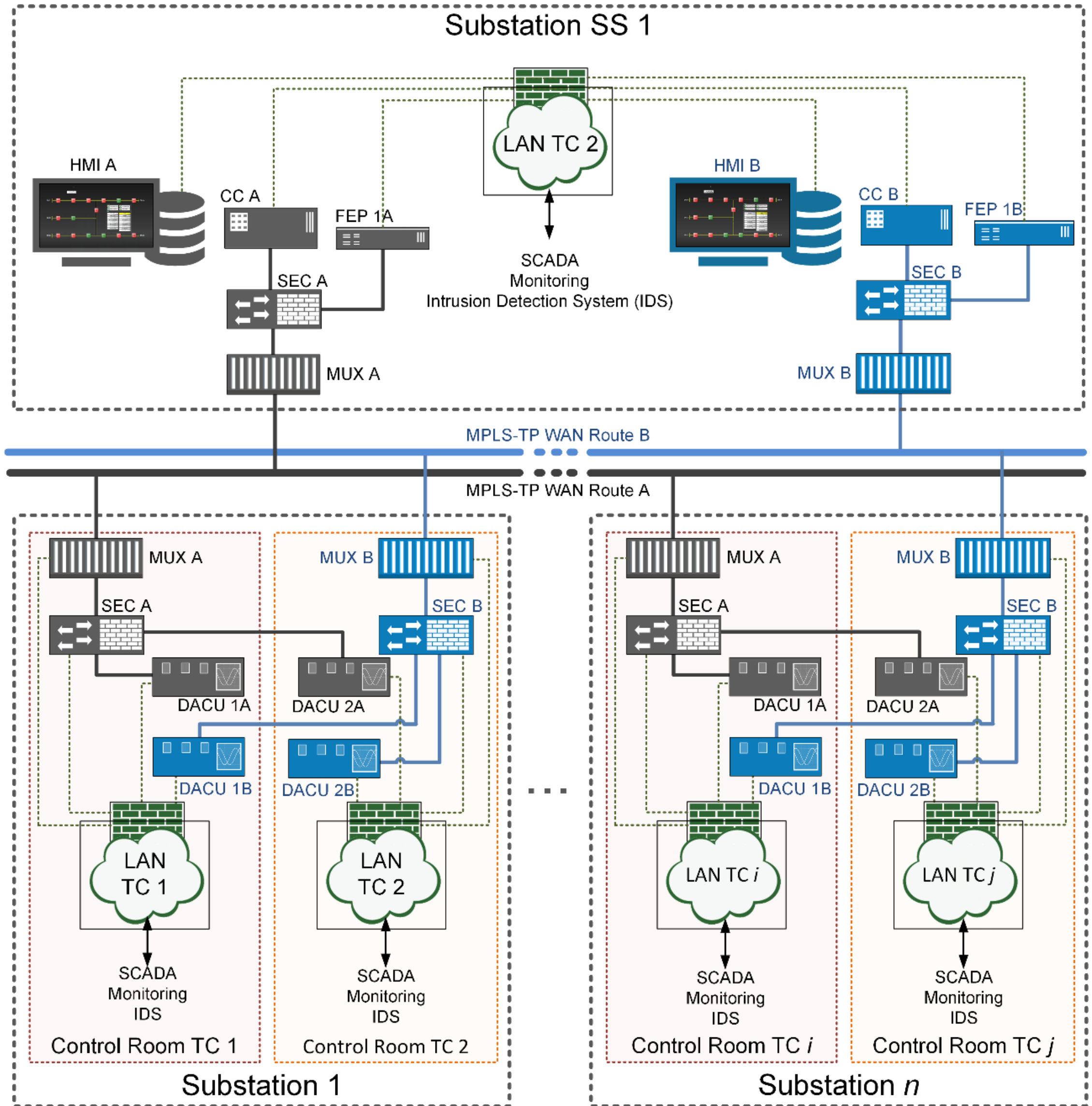

Fig. 14. General N/NE/SE RAS architecture and main components.

- DACUs are responsible for acquiring field data, such as equipment status (disconnectors and circuit breakers), power measurements, current and/or voltage measurements (to detect line overload or overvoltage), as well as detecting errors, such as inconsistencies in the equipment status and analog quantities, and sending these data to the CCs.
- SEC is made up of SDN Ethernet switches, which are network elements responsible for ensuring security in the interconnection of Ethernet networks of different TCs and for filtering and controlling GOOSE messages in the RAS network.
- MPLS-TP devices are intended to transport GOOSE messages across the WAN network that interconnects the various substations.

The system is fully redundant to ensure high availability of the RAS. The CCs are located in the Master Controller Substation and operate in a dual scheme, also known as hot-hot. For maintenance purposes, one of the CCs can be disabled while the other remains active.

DACUs are responsible for receiving commands from the CCs to perform remedial actions, which include the shutdown of a generating unit in a different power plant, tripping of shunt capacitor banks, or runup or rundown commands on the 800 kV HVdc bipoles at a rate of 4,000 MW/s.

The architecture also implements RASMNET. This network is completely isolated from the RAS network, RASPNET, and is dedicated to monitoring all equipment via IEC 61850 MMS and SNMP protocols. As there is no time requirement for these protocols, conventional switches and firewalls were used to create this network.

The TCs can monitor locally in each substation, through their local HMI, the status of equipment and transmission lines, power flow values, device failure alarms, equipment status inconsistency alarms, communications failures, and bad performance. They also obtain performance reports, Sequence of Events, etc.

The system also incorporates the continuous measurement of the application time, which is the time between when an internal variable in the DACU changes state and the moment a GOOSE message is delivered to the CC. This time includes the processing time in the DACU, the time to transmit a GOOSE message in the WAN, and the processing time in the FEP. To monitor the application time, a dedicated GOOSE message is sent out from the DACU together with a time stamp generated in the DACU logic. As all DACUs, FEPs, and CCs are time synchronized through a global reference, it is possible to compare the time stamp from the DACU GOOSE message with the time it is received at the FEPs, obtaining the application time. The opposite routes, from the CCs to the DACUs that receive remedial action commands, are also monitored. The monitoring screen from the HMI then presents the statistical data related to the application time monitoring for each GOOSE subscription. If the monitored application time becomes too long, which means a long delay in the communications and in the GOOSE message processing, an alarm to the operator is triggered. For the time synchronization of all devices, Precision Time Protocol or IRIG-B protocols are used, depending on the requirements and availability in each TC. Fig. 15 shows the screen capture of the time monitoring application for one of the GOOSE subscriptions from the local HMI.

Using the application's time monitoring feature, it is possible to measure the delay from the moment a DACU detects the contingency to the moment a GOOSE message is received by the FEPs.

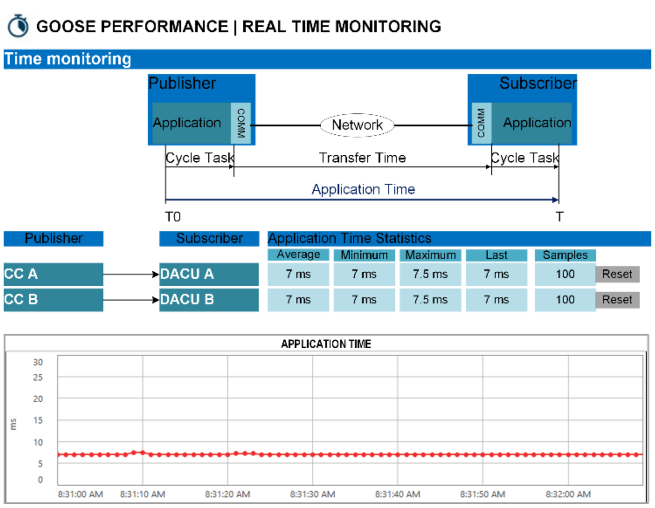

Fig. 15. GOOSE message application time monitoring screen.

At the Master Controller Substation, the redundant HMI provides visualization and a means to control the systems. From the central HMI, it is possible to execute some commands, such as activate the maintenance mode, block each of the logic schemes individually, and force safe analog values if there is a discrepancy in the reading of analog values.

SNMP proxies were installed at each substation to monitor communications network equipment, and there is an SNMP server at the Master Controller Substation responsible for receiving information from proxies in the monitoring network of other TCs. SNMP is used to monitor points such as health status, link up and link down interfaces, packets sent and received, CPU, and bad packets.

X. N/NE/SE RAS Auxiliary Logic Schemes

In the substations, 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.

The logic scheme implemented in the DACUs to detect an open-line condition in each terminal is shown in Fig. 16. In this example, a series-compensated line is depicted. In case of inconsistencies of circuit breaker or disconnecting switch status, the logic scheme will alarm and consider them closed, as this is a secure method to avoid false operation of the RAS, and the line-open detection will rely on the remote terminal status.

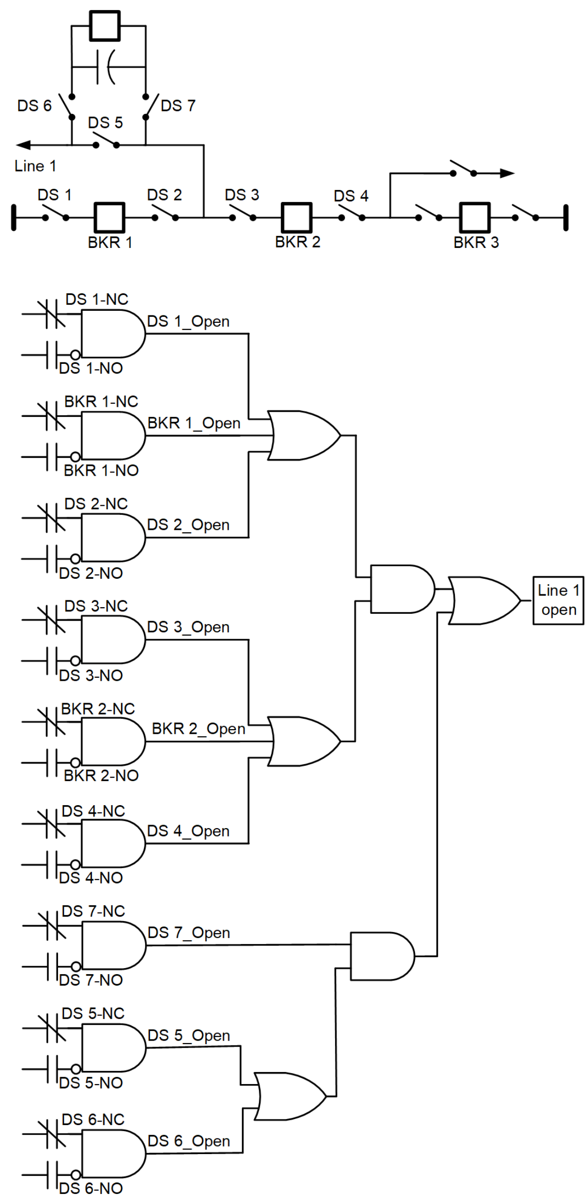

Fig. 16. Open-line detection logic scheme.

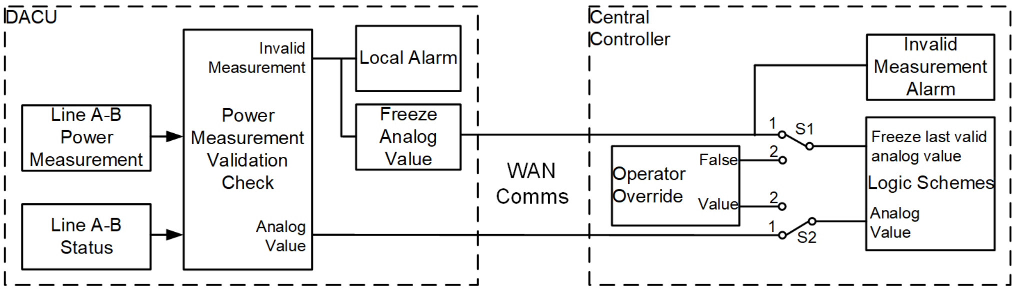

Fig. 17. Power measurement consistency check.

A logic scheme for validating analog measurements was implemented in the local DACUs to ensure consistency in the monitored power flows. As shown in Fig. 17, the transmission line terminal status is compared against the measured power. In addition, the sequence components are used to detect failure in the voltage and current measurements. If inconsistencies in the measurements are identified, an alarm is sent to the operator and the logic schemes associated with the failed measurement use the last valid measurement, and subsequently, the operator has the option to override the analog quantity value.

XI. Simulator

The simulator was developed with the aim of allowing the N/NE/SE RAS logic schemes to be tested and validated before being implemented in the field and training personnel. For this purpose, two racks were assembled. The first is a replica that contains the same equipment as the CC panel plus an automation controller capable of simulating all field signals acquired by the CCs. The second rack contains four DACUs.

Fig. 18 shows the simulator schematic with the composition of each rack and connections. The simulator is composed of the RASMNET, shown in dashed green lines, and the RASPNET, in solid red, which is dedicated to GOOSE message exchanging.

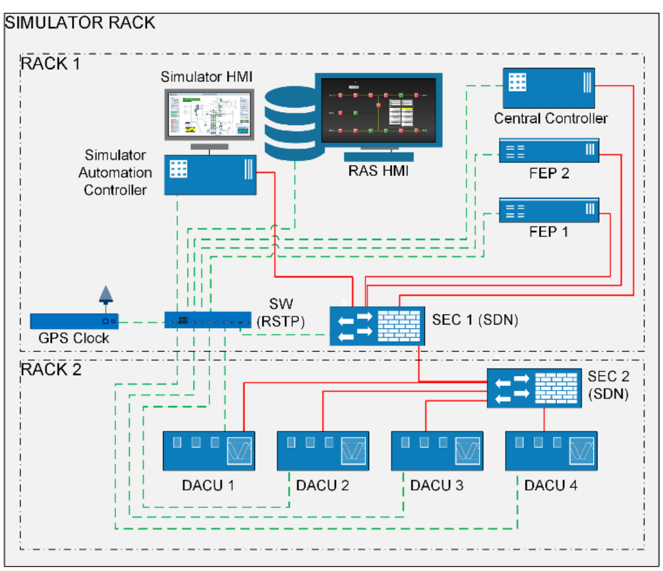

Fig. 18. Simulator rack architecture.

The DACUs, CCs, FEPs, HMI, and GPS clock have the exact same configuration files applied as the actual N/NE/SE RAS system.

The simulator has a dedicated HMI, which can be accessed locally through the rack monitor, keyboard, and mouse, or remotely through the web interface. This interface is used to configure simulation scenarios and cases. It also allows real-time monitoring of scenario changes as the simulation progresses and the CCs respond to the contingencies being tested.

The simulator can inject system signals in two ways: in real time or through predefined scenarios with multiple states. In real time, field signals are sent instantly to the CCs as the variables are changed on the screen by the user. In the case of predefined multistate scenarios, the analogs and equipment status are defined for up to 25 states, with the duration defined individually for each state. At the user's command, the multiple states will run sequentially.

The multiple states can be configured through the simulator's HMI or preconfigured in a spreadsheet and loaded into the simulator.

The simulator allows the tests to be conducted in three different modes, as shown in Fig. 19 and as follows:

1. Using only DACUs: In this mode, only the DACUs send data to the CC, which sends back commands to the DACUs, providing a simulation closer to the actual response found in the field, with the configuration replicated in the test rack.
2. Using only the simulator automation controller: In this mode, only the simulator automation controller generates the data to send to the CC and receives responses from the CC. This mode focuses more on testing the CC and the logic schemes in this device. It simplifies the interconnection schemes and allows for more controlled and repeatable tests with a larger amount of field data, allowing for a more detailed analysis and documentation of the CC behavior and the RAS logic schemes.
3. Using them combined: In this mode, DACUs generate part of the data and the simulator automation controller generates the remaining required data to test the scheme, taking advantage of the real parameters of the DACUs along with the flexibility of generating complex scenarios.

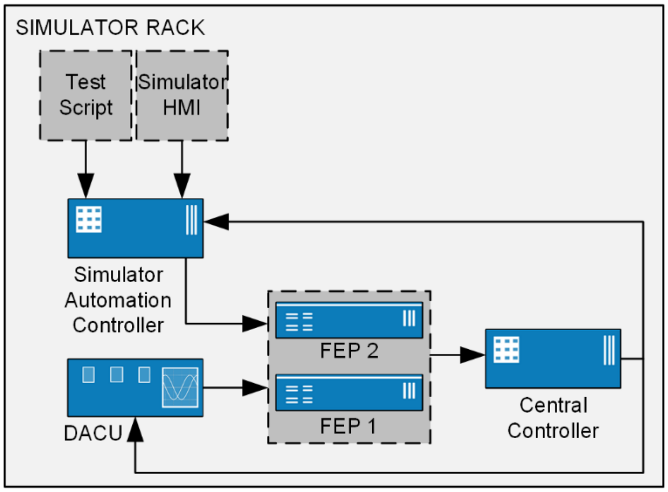

Fig. 19. Simulator data flow.

XII. FAT

As previously mentioned, each TC was responsible for procuring, installing, and testing the MCPs under their scope. During the FAT, with the support of the simulator rack, it was possible to test, at different times, the MCPs of each TC, the CC panels, and all the logic schemes involved in the N/NE/SE RAS.

The FAT of the MCPs was carried out in two phases. First, isolated tests of the panel were conducted, including physical inspection, functional tests, and tests related to local functionalities, which do not depend on communications with the CCs. In the second phase, the MCP was integrated into the simulator rack and the combined mode, as explained in the previous section, was used to validate the communications and data sent to and received from the CCs.

XIII. Commissioning

At the time of this technical paper, commissioning activities were underway. However, 51 field tests have already been concluded, allowing us to measure the performance of the scheme. The average response time obtained from the tests of logic schemes that depend only on the status changes of binary signals is 20 ms, with a maximum value of 22 ms. The logic schemes that involve binary status and analog measurement changes were performed with time-synchronized test sets, considering the farthest SSs from the CC, which involve the longest latencies in the communications. These tests had an average response time of 40 ms, with a maximum value of 42 ms. This performance is well within the required 100 ms response time.

XIV. Conclusion

The expansion of the transmission network and generation in the North and Northeast regions was crucial for the Brazilian NIS. The N/NE/SE RAS allows ONS to operate the system with the required flexibility needed to maintain optimal performance while ensuring its security.

Given the extensive MPLS-TP communications network implemented, the installation of DACUs at various strategic 500 kV substations, and the flexibility provided by using IEC 61850 GOOSE messages for signal exchange with the CC, ONS envisions the possibility of leveraging this RAS to address future system expansion needs. This includes potential integration with the future ±800 kV HVdc bipole that will connect the Northeast and Central-West regions in parallel with the ac network. This project is expected to be operational by 2030.

The N/NE/SE RAS extends approximately 750,000 km^2. However, the most challenging aspect of this RAS is not its large geographic area, but rather the data integration associated with assets from 15 different TCs, requiring a robust and cybersecure communications architecture to collect real-time data and send remedial action controls to the different assets. This was achieved by using SDN switches, which comply with the project cybersecurity requirements while granting individual TCs total control of Ethernet traffic within their local networks, without compromising RAS operating time.

Multicast IEC 61850 GOOSE messages containing binary and analog data, along with monitoring functionalities such as transmission delays and quality, are considered an effective solution for the RAS to receive information and to send remedial action commands through an MPLS-TP WAN. This setup also allows for monitoring the health and performance of the scheme.

The communications networks were traffic-engineered and tested to guarantee an operating time of less than 100 ms, aiming to achieve a total operating time under 150 ms, considering the operating times of the HVdc controllers and circuit breakers. This ensures the N/NE/SE RAS is effective at maintaining system stability.

The project involved several stakeholders, so a dedicated and coherent leadership and close working relationships among all the TCs involved in the project were crucial for the execution and successful deployment of the RAS project.

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XVI. Biographies

Igor de Siqueira Cardoso is an electrical engineer who graduated from the Federal Center for Technological Education of Rio de Janeiro (CEFET-RJ) in 2017 and is currently pursuing a master's degree at the Military Institute of Engineering (IME). He has been working at Brazil's independent system operator, ONS, since 2018, where he serves as an engineer in the Protection and Control Engineering division, working with disturbance analysis and implementation of remedial action schemes.

Edson Ferreira de Oliveira received his BS degree in electrical engineering from the Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Brazil, in 2006. He began working at Electricity Concessionaire Rio de Janeiro – LIGHT in 1998 with project analysis, configuration of protection and control systems, analysis of protection system performance for disturbances in transmission systems, analysis of control systems for failure or delay on remote commands or supervision, and site acceptance tests of new systems. Edson has taken a specialization course in protection of electric power systems at the Federal University of Itajubá, Minas Gerais (UNIFEI – MG) in 2018. He has been working at Brazil's independent system operator, ONS, since 2012, where he serves as an engineer in the Protection and Control Engineering division, working with implementation of remedial action schemes.

Bruno Pestana received his BS degree in electrical engineering from the Federal University of Rio de Janeiro (UFRJ), Brazil, in 2020. He has been working at ONS, Brazil's independent system operator, since 2020 as an electrical studies engineer in the Special Studies division, carrying out preoperational studies and transient stability studies, and defining remedial action schemes and systemic protections.

Thales Quintino received his BS degree in electrical engineering from Fluminense Federal University, Brazil, in 2021. In 2018, he started his career as an intern at TAESA, and as soon as he graduated in 2021, he became a protection and control engineer, working with project analysis, configuration of protection and control systems, analysis of protection system performance for disturbances in transmission systems, analysis of control systems for failure or delay on remote commands or supervision, and site acceptance tests of new systems.

Ricardo Abboud received his BS degree in electrical engineering from Uberlândia Federal University, Brazil, in 1992. In 1993, he joined CPFL Energia as a protection engineer. His responsibilities included maintenance, commissioning, specification studies, and relay settings for power system protection. In 2000, he joined Schweitzer Engineering Laboratories, Inc., (SEL), as a field application engineer in Brazil, assisting customers in substation protection and automation efforts related to generation, transmission, distribution, and industrial areas. In 2005, he became a field engineering manager, and in 2014, he became an engineering services manager and was in charge of the SEL engineering services branch in Brazil. In 2016, he transferred to the SEL headquarters in Pullman, WA, as an international technical manager. In 2019, he joined SEL University as a professor, and he is currently a fellow engineer in the Sales and Customer Service division.

Ronald Jogaib received his BS degree in electrical engineering from Rio de Janeiro State University, Brazil, in 2011. In 2011, he joined TAESA as an associate engineer, working on acceptance tests and inspection of extra-high voltage substation equipment. In 2013, he took a new role as a protection engineer, working on the analysis of the protection system performance for disturbances in the transmission systems, performing studies of coordination, selectivity, and configuration of protection systems, and completing site acceptance tests of new protection systems. In 2017, he became a protection specialist engineer responsible for providing training to the protection team. He received his MSc in electrical engineering from Fluminense Federal University, Brazil, in 2022. In 2024, he joined Schweitzer Engineering Laboratories, Inc., (SEL), as an application engineer in Australia, assisting customers in substation protection and automation.

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 customer support and training, configuration, factory acceptance testing, and commissioning. Marcos completed 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.

João Picheli graduated from the Federal University of Itajubá (UNIFEI) in 2022. He started his career at Schweitzer Engineering Laboratories, Inc., (SEL), in January 2022 as a technical support intern in Brazil. In November 2022, he became a field service engineer and is responsible for training, configuration, factory testing, and commissioning.

20240925 • TP7178-01