Catch the Next Dynamic Wave: Overview and References of Wide Area Monitoring Systems and Remedial Action Scheme (RAS) Solutions

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CATCH THE NEXT DYNAMIC WAVE: OVERVIEW AND REFERENCES OF WIDE-AREA MONITORING SYSTEMS AND REMEDIAL ACTION SCHEME (RAS) SOLUTIONS

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***Summary*—The recent development of grid interconnections and the large and fast pace of changes that affects grid dynamics bring up many discussions about the importance of employing special protection schemes (SPSs), such as remedial action schemes (RASs) or SPSs to mitigate the associated challenges that have emerged along with those changes. This paper aims to provide a fresh look on this topic, starting with a discussion of the importance of wide-area control in general and remedial action schemes, specifically for modern power system grid operators. As the grid interconnectivities between countries and territories are increasing, more and more renewable energy power plants are being deployed and load and generation centers are geographically spreading, so grid operators are faced with serious challenges, from spreading oscillation across grid interconnections or stressed corridors to voltage profile control and difficult power flow control. The reactions to those challenges, which include static VAR compensators (SVCs) and phase-shifting transformers (PSTs), have brought consequences themselves, causing the power system operation and dynamic cycles to be more frequent and shorter, necessitating a fast dynamic situational awareness and remedial action solutions.**

The paper introduces various technologies, which includes synchrophasor technology, and how they can be applied to provide visibility and situational awareness. The discussion then introduces the RAS system, NERC's definition of it, and the candidate applications. Some reference case studies will be highlighted, focusing on the types of actions implemented to demonstrate the potential applications for various grid operators to address various challenges and meet certain objectives.

***Keywords*—RAS–Stability–Grid interconnection–Synchrophasor**

I. INTRODUCTION

A quick look at the electricity market over the past two decades shows without a doubt that an evolution is taking place in the electricity generation, transmission, and distribution systems. While many of the challenges have been successfully mitigated, the pace of changes has not seemed to slow down.

The interconnection between countries and territories is increasing, while the existing ones are expanding, forming many grids of grids. The power trading market, bilateral agreements, and bigger and bulkier power plants (including nuclear, solar, and wind) are introducing power flow control challenges as well as issues associated with stressed corridors (like voltage and voltage profile problems). Those problems are addressed by installing static VAR compensators (SVCs), phase-shifting transformers (PSTs), etc., which address some aspects of the problem and bring more ramifications, especially to the grid power system dynamics.

Furthermore, initiatives related to carbon reduction programs are pushing more renewables at an unprecedented pace and introduce a suite of challenges related to inverter-based resources, such as intermittence, weather vulnerability, inertia, and protection challenges. Again, solutions are introduced, such as batteries, which provide solutions—and many promises—to the planning and operation; and, again, this causes more ramifications, meaning that there is a lot that has to be done for power system protection, stability, and resilience.

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The newest practice in the electricity market is the introduction of hydrogen, and there are huge plans in the Middle East region for power-to-hydrogen projects [1] [2]. The hydrogen business formed a bridge between the electricity energy market and the hydrocarbon energy market (and is forming a market of its own). Even though sometimes the aim is solely hydrogen production, hydrogen introduced as energy storage—especially the big power-to-hydrogen projects—will have a considerable impact on the electric grid. What makes this more challenging is the fact that those projects are associated with a large renewable power plant, which is a big contributor to system stability, and it is a grid operator's responsibility to mitigate power generation and load (e.g., demand and is characteristic of the hydrogen electrolyzer).

With these new developments and challenges in mind, it is now crucial to have more situational awareness as well a faster and more effective control scheme that focuses on the power system dynamic.

This paper aims to provide as much background as possible for various solutions for wide-area monitoring and remedial action scheme (RAS) applications.

II. FUNCTIONALITY

A. *Synchrophasors*

Synchrophasors as a technology have received a decent amount of attention and discussion in the electrical engineering community, and there are many application data and publications that discuss the basics and applications of synchrophasors in accordance with the well-written and mature IEEE C37.118 standards. However, in the author's opinion, there are many applications yet to be discovered, and there is still a degree of confusion regarding how the synchrophasor system works as it is often compared with supervisory control and data acquisition (SCADA) and defined as high resolution or faster data, which is inaccurate.

The synchronized data measurement at the phasor measurement unit (PMU) side, time-stamped series transmission format, and the concept of time alignment at the receiving side (phasor data concentrator) allow for a synchronized auto- and cross-correlation of power system parameters and vector value calculations, enabling better situational awareness and analysis of power system dynamics to be performed for better judgment and a faster reaction by the grid operator. Fig. 1 is an example of a synchrophasor monitoring screen.

Synchrophasor technology has been used for the past two decades in many applications, including [3] [4]:

- Improving frequency and voltage monitoring (both limit and profile/contour).
- Detecting islanding and loss of generation.
- Eliminating black-start downtime during validation testing by comparing a generation-starting voltage recording with a system voltage recording.
- Identifying small signal issues and power system stabilizer tuning by having modal analysis data.

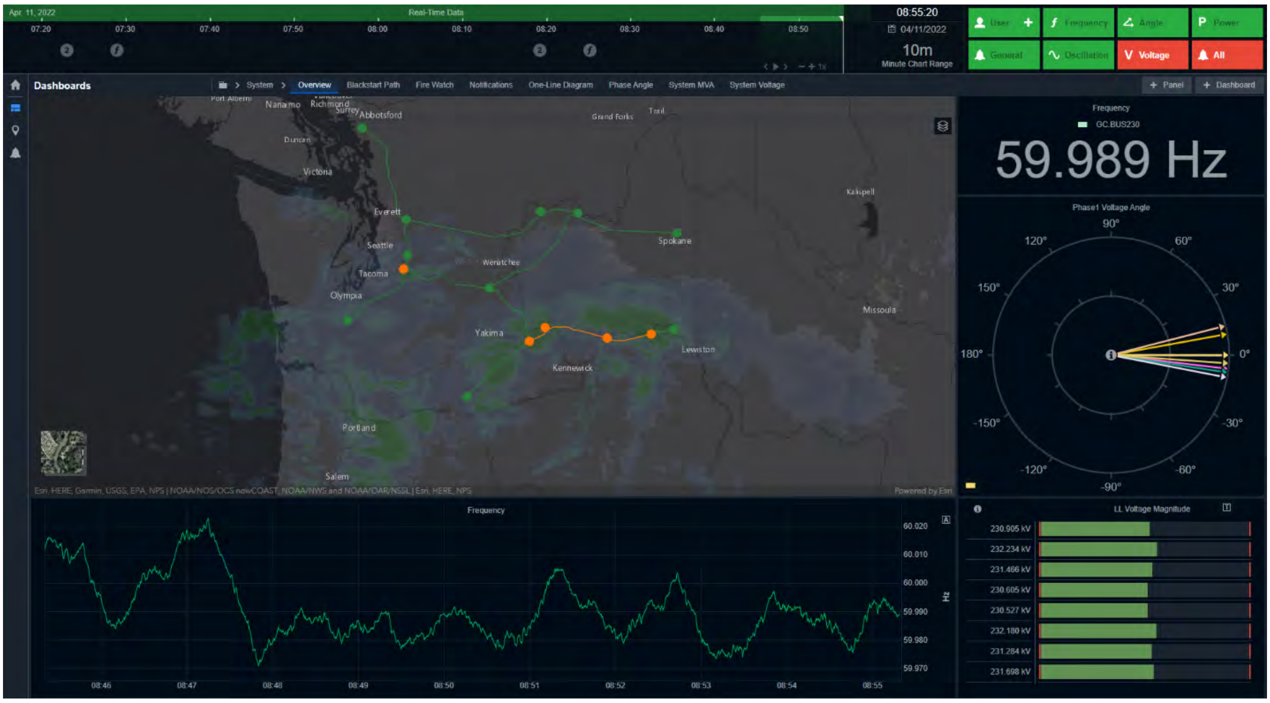

Fig. 1. Example of a synchrophasor's wide-area monitoring system.

B. RASs

A RAS, also known as a special protection scheme (SPS), is a system designed for the purpose of providing protection-grade controls to mitigate certain power system conditions.

From the first name, the RAS system has the function of remediating the power system or taking actions to remediate certain conditions, while in the latter name, SPS refers to the special or nonconventional nature of the scheme this system is providing. Typically, the RAS is designed to take action that is critical in nature like load shedding or generation tripping. Moreover, the RAS functionality and design is often nonconventional in terms of its architecture, group of actions, interfaces, communication, etc., but at the same time, the RAS system uses standard protocols and technologies that are well-proven and field-proven devices and configurations.

While the name is not common in many regions around the world and is sometimes misleadingly referred to as a system that performs critical actions like underfrequency load shedding, the RAS system is well defined by NERC. It is a good starting point to consider the NERC definition for the RAS system as a common platform for the discussion of RAS.

C. NERC Definition

NERC defines a RAS as:

> *an automatic protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability. Such action may include changes in demand, generation (MW and MVAR), or system configuration to maintain system stability, acceptable voltage, or power flows. [A RAS] does not include (a) underfrequency or undervoltage load shedding or (b) fault conditions that must be isolated or (c) out-of-step relaying (not designed as an integral part of [a RAS]). Also called [Special Protection System] [5] [6].*

The first criterion in the definition is very important; RAS is a protection system. This means it is protection-grade and anything that is applicable for a protection system applies for RAS, from reliability and selectivity to simplicity, economics, or the speed of operation performance. This is also critical to differentiate it from control-grade (or SCADA-grade) solutions.

The definition then generalizes the objective of the RAS function and finally includes what the RAS is not (e.g., out-of-step, or local underfrequency and undervoltage load shedding).

The RAS's primary objectives are grid survivability and stability and maintaining grid operation limits, which can include:

- Preventing overloads and trips.
- Decoupling from an unstable grid.
- Preventing unacceptable or intolerable voltage dips.
- Preventing subsynchronous resonance.
- Allowing increased power transmission (a guaranteed fast response permits smaller safety margins) [7].
- Preventing high-voltage direct current (HVdc), a flexible ac transmission system (FACTS), and SVC controller overshoots, all of which limit power transfer during a severe disturbance.

Those objectives are achieved by implementing certain high-speed control actions that generally balance the power deficit or change the power system configuration. These actions include:

- Load shedding.
- Generation shedding.
- Reactor switch and control.
- Capacitor switch and control.
- HVdc/FACTS/SVC control.
- Battery energy storage system control.
- Intentional islanding control (decoupling).
- Runback or load ramp.

The actions will only be able to achieve the objectives if they are sufficient and effective, and the main factor here is speed, but it is also important to maintain the security, selectivity, and sensitivity requirements.

For example, the RAS system response time was 16 milliseconds in one implementation [8] and 12 milliseconds in another [7]. This includes input/output (I/O) module input debounce, I/O module to RAS processor communication delay, RAS processing time, and RAS to I/O communication delay. The RAS system has to respond in a deterministic manner to ensure system stability. Fig. 2 shows example timing for a RAS system compared with power cycles for different scenarios. Based on stability studies for the most severe fault case (a multiphase fault on a 345 kV line close to a power plant), the total time from the event to the resulting action must not exceed 5 cycles. Fig. 2 shows the time allocation for this case. Zone 1 faults (faults close to the power plant) are the most severe events; for these events, the overall reaction time is 3.7 cycles. When the typical fault detection, communications time, and unit breaker opening time are excluded from the total time budget, the RAS is left with 20 milliseconds of operating time [7].

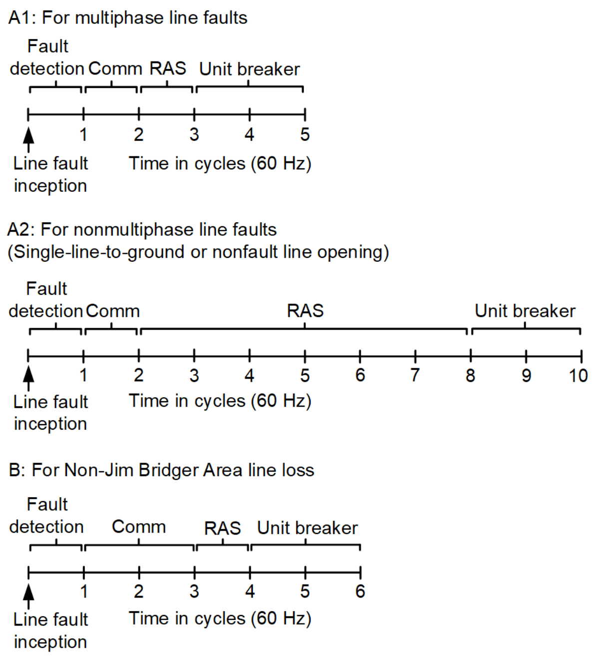

Fig. 2. Example of RAS operating time [9].

III. Enabling Technologies

From the previous discussion, it can be concluded that the RAS system design is a nontrivial task and it requires harnessing the capabilities of proper technologies. However, many devices and technologies used for protection applications provide an excellent platform to build a RAS system.

There are multiple case studies for projects that use different communication infrastructure, devices, architecture, and data communication protocols [3] [8] [10].

The key criterion for the communication technology to be adopted is to ensure suitability for the purpose. While IEC 61850 Manufacturing Message Specification, Distributed Network Protocol, and IEC 60870-5-104 are good protocols over Ethernet for data acquisition and reading of root-mean-square (rms) values, the IEEE C37.118 protocols provide time-stamped series enabling vector calculation. On the control command side, deterministic performance is the key criterion to select the communication protocol (although cybersecurity is equally important). Generic Object-Oriented Substation Event (GOOSE) messages are a good example of a protocol used for protection-grade communication over Ethernet, while Mirrored Bits® communications is an example of protection-grade serial communication. Both provide deterministic communication.

On the device side, discriminative processing is the key criterion where the device should process and respond to different data in different ways and at different speeds. This necessitates the use of modern real-time controllers to enable RAS to achieve its objective.

IV. Performance, Testing, and Validation

Considering the criticality of RAS, its impact, its nature of being connected over a wide area, and how it is related to the dynamics of the power system, it is crucial to ensure system reliability and have the implemented system tested and validated thoroughly.

RAS is designed for reliability, and normally, reliable metrics for various parts of the system are considered, ensuring high reliability. Reference [11] provides some details on designing a RAS system for reliability while considering IEC 61850 as well as other references for reliability measures like mean time between failures and mean time to repair.

The validation and testing of RAS systems are fundamental for a successful RAS implementation. While the distance between detection points and actuation points is a big challenge facing proper testing of the system, the fact that RAS system action mitigates power system oscillation represents the main challenge. The necessity of validating the convergence of a successful control reaction cannot be replaced by an offline simulation, which will typically involve a lot of assumptions.

For that, hardware-in-loop (HIL) testing represents the most accurate and practical means to test, verify, and validate the RAS performance.

A power system electromagnetic transience simulator with modeling data processing capability and I/O interfacing terminals enables near-real-life simulation of the power system. A typical HIL setup will connect the RAS system and the necessary IEDs or relays to the simulation system to enable a closed-loop testing environment to evaluate, verify, and validate the RAS performance, as shown in Fig. 3.

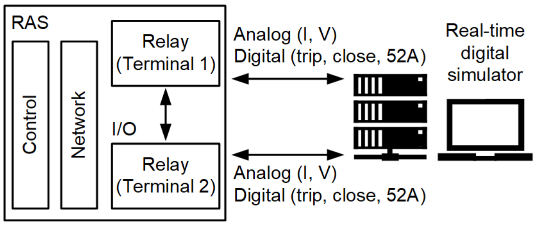

Fig. 3. HIL test setup.

V. Design and Application Positioning

The design of a RAS system is a flexible, distributed design with measuring devices or input controllers, a central processing controller, and actuation output controllers. The systems can ideally be located anywhere as long as reliable, deterministic communication is available. A RAS system is composed of integrated devices that are hundreds of kilometers away. This distance is essential for the nature of the problem it is supposed to solve, which involves information and measurements from locations across a wide area, a trigger (contingency) in one substation location that requires an action in another substation location, and central logic or an algorithm that is independent from the trigger, action location detection, and action location, as illustrated in Fig. 4 and Table I.

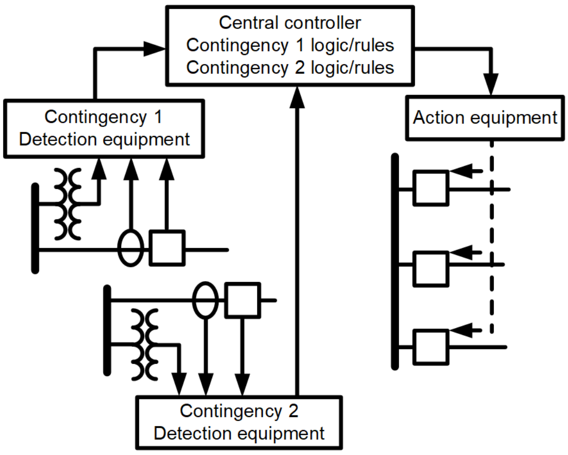

Fig. 4. Example of RAS deployment architecture.

TABLE I
EXAMPLE OF RAS COMPONENT LOCATION

Substation	Detection	Logic	Action
A	X	X	X
B	X		X
C	X		X
D	X		X
E	X		
F	X		X
G			X
H	X		X
J			X

Another aspect of the design is the resiliency of the system. There are multiple ways to design a RAS with high availability. A redundant system is a common design, while in very critical systems, dual triple modular redundancy has been implemented for maximum availability and system maintenance [12].

Some RAS designs consider distributed versus central schemes to ensure system resiliency and enable partial scheme operation upon failure—or absence of measurement—of parts of the system [13].

A. Where Does RAS Fit, and How Can It Be Classified?

The RAS system is often misrepresented—and accordingly misperceived—as an extension to a SCADA system or protection system and sometimes, as an added function to the synchrophasor monitoring and analysis systems (wide-area monitoring systems [WAMS]).

Fig. 5 shows the spectrum of the applications. It vertically shows the states of the power system and typical solutions to address control at each area, which primarily corresponds to the response time. The growing triangle also refers to the size of the data; as the applications move toward steady state, the volume of data increases.

It is important to highlight that a synchrophasor software-based solution or a WAMS extension (often referred to as wide-area monitoring, protection, automation, and control) can be used to address some of the dynamic problems but in many situations are not sufficient to address some very fast dynamic incidents. While RAS is the solution for all dynamic problems and it is technology- and protocol-agnostic, there are several references for the usage of synchrophasor protocols IEEE C37.118 and PMUs as part of the RAS, which can include other protocols as well [3] [8].

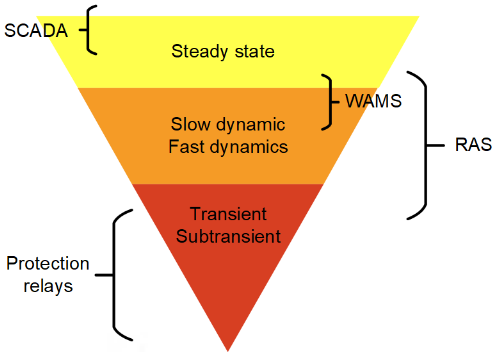

Fig. 5. Power system-related control system performance requirement comparison.

The RAS system, from another perspective, must be an integral part of the overall power system operation, protection, control, and management. Therefore, functionally and performance-wise, it should work in tandem with lower-tier systems and schemes and higher-level systems and schemes.

For example, it shall respond to contingencies and finish its action before the protection relay thresholds (e.g., underfrequency, out-of-step) kick in and initiate trip. Also, while the load dispatch center (LDC) systems (e.g., automatic generation controller and voltage controllers) work and respond to load and system state variation, the RAS system should respond and take action in coordination with the automatic generation controller of the LDC as well as take into consideration unit controller expected performance (e.g., generator droop characteristics and HVdc/FACTS/SVC controller). Fig. 6 illustrates the concept of tier coordination.

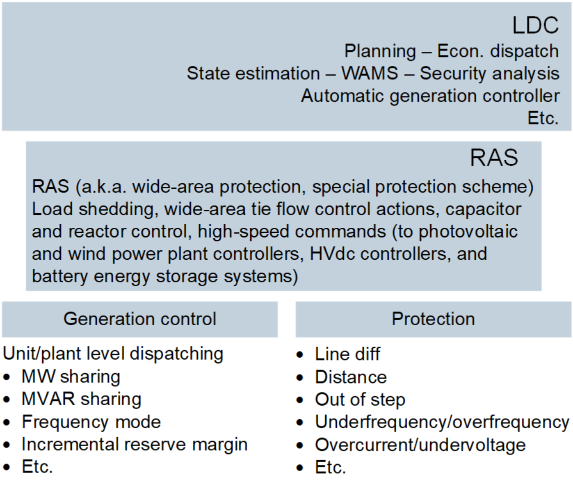

Fig. 6. RAS coordination with upstream and downstream systems and devices.

B. *Digitization*

The RAS system must also be interfaced and integrated with systems, devices, and subsystems at all tiers and for different applications. Some examples include:

- Intelligent electronic devices (IEDs) (relays, bay control units, meters, and PMUs). This integration allows RAS to acquire status, rms data, vector-ready measurement (time-stamped series), etc.
- LDC: Typically, IEC 60870-5-101 or IEC 60870-5-104 but can be an Inter-Control Center Communications Protocol or other protocols.
- WAMS and distribution management system: IEEE C37.118.
- Distributed control system: Open Platform Communications (OPC) and Modbus.
- Security Information and Event Manager: Syslog and other protocols.
- Enterprise resource planning: Application programming interface, OPC, and others.

VI. CASE STUDIES

The following case studies summarize different variants of RAS implementations around the world.

A. *Case 1*

A RAS implemented to react to excessive angle differences between the synchronized voltage measurements of two nodes that are 400 kilometers apart to disconnect loads and maintain the stability of a country's power system. The RAS was required for the safe operation of the power system because of the recent expansion of large industrial loads (mining) in a concentrated region of the country. The study was performed with power system stability software, and it identified six contingencies that could jeopardize the operation of the industrial, concentrated part of the power system. It was determined that the best indicator of a problem was the voltage angle difference between substations and that the remedial action would be to disconnect some of the large mining loads.

The RAS architecture uses PMUs installed in the substations of the country's 500 kV corridor that leads to the industrial, concentrated region. These PMUs supply synchronized measurements to redundant RAS controllers. Decision-making logic is applied by the RAS processors, and trip commands are sent to the large industrial loads according to certain selection criteria. The RAS operation takes place within 52 milliseconds after the angle threshold is satisfied. The implemented system has allowed industries with large load installations to connect to the grid while complying with power system stability regulations and reliability requirements [3].

B. *Case 2*

In this case, RAS implemented two algorithms in one system at a transmission substation. The substation is the terminus of three 345 kV, one 230 kV, and one 500 kV transmission circuit. This substation transports power from power plants in a central location to load centers hundreds of kilometers away. When one or more of the high-voltage circuits is lost, overloading can occur on the remaining lines across the path. The primary function of this RAS is to protect lines against thermal damage, while helping optimize the transfer across critical corridors. The secondary function of the RAS is to dynamically predict power flow scheduling limits on critical transmission lines and corridors. A power company decided to build a RAS that can trip generation units, bypass series capacitors, insert shunt capacitors at remote substations, or take any combination of these actions to ensure continuation of power flow and avoid any line overloads, subsynchronous resonance, or other problems [7].

C. *Case 3*

A grid operator implemented a RAS to maintain power system stability in a country's power system. This RAS was based on customized operating principles devised specifically for this country's power system. The scheme involves more than 30 distributed controllers in all of the main 500 kV substations.

The grid operator ensures electric power transmission throughout the entire country. The operator is responsible for operations, management, and dispatching within the power system and has responsibility for the operation of the 500 kV, 220 kV, 110 kV, and 35 kV transmission facilities while maintaining power system stability. The system comprises 3,000 kilometers of transmission lines (500 kV, 220 kV, 110 kV, and 35 kV) and 89 substations in the country. A central hydropower plant in a distant region from the load centers generates the power that is delivered to the capital load region via the 500 kV dual lines (L1 and L2). The flow in the

220 kV system to the capital region is considered secondary compared with the 500 kV backbone. There is also an HVdc link with a neighboring country to import part of the required power.

If either the L1 or L2 line is lost, the power system can be effectively divided into two electrical islands (considering only the 500 kV system), and as a consequence, the 220 kV system can be overloaded. The capital load region will lack generation, and the main power plant region will have a power surplus; therefore, the two electrical islands will be unstable. In the capital load region, loads should be shed to mitigate the generation deficit. At the power plant, the excess generation needs to be reduced by shedding the appropriate number of generators. The present implementation of the RAS covers all of the 500 kV lines in the country as well as autotransformers, HVdc converters, and generators in the country's main and largest hydropower plant. Its actions are based on the magnitude and direction of the real power flows and the statuses of certain remote lines. There are 35 IEDs for monitoring, contingency detection, and action implementation that compose the RAS [13].

D. *Case 4*

A transmission system in a country with severe geographical and infrastructure constraints makes the system susceptible to different contingencies that have led to major blackouts affecting loads in the country's power system and in the regional cross-countries interconnection transmission system in recent years. The interconnection authority and the country's grid operator developed an SPS that takes remedial actions to increase reliability while keeping or increasing power transfer limits to allow for the most economical operation. Most hydroelectric power and cross-country connections are in the west of the country, and the largest loads, like the capital's loads or major critical, large industrial or business loads, are in the east. Power flows from west to east, reaching voltage stability transfer limits when there is high hydroelectric generation. The load center operates too close to the power-voltage curve limit. The system cannot withstand some single-line, double-line, or generation contingencies without the remedial actions or without limiting hydroelectric generation and increasing generation cost.

The remedial action solutions are implemented using modern technologies and wide-area, high-speed communications. For this power system and its operating conditions, there is no time to evaluate voltage stability indices or develop power-voltage curves in real time to take preventive actions. Some contingencies would lead to instantaneous voltage collapse or fault-induced delayed voltage recovery and may shed load in an uncontrolled manner. Very fast load-shedding actions are needed, so a contingency-based scheme is proposed and implemented. Load shedding needs to be adaptive and optimize the amount of load to be shed to maintain system stability. The load-shedding design adapts the amount of load to shed depending on the main transmission corridor power flow for line contingencies. The scheme additionally adapts to changes in local generation for generation contingencies, and the load-shedding amount is limited to avoid other consequences on the Central American interconnection link. Extensive real-time, HIL digital simulations were conducted to validate the implementation [14].

VII. CONCLUSIONS AND RECOMMENDATIONS

Amid the unprecedented development in the power system and the evolution of the power system structure, paying more attention to abnormal scenarios and operational challenges is crucial. RAS comes with a lot of answers, capabilities, and promises to mitigate a majority of the challenges related to power system dynamics. There are many case studies and many lessons learned from those projects, which demonstrate the effectiveness of RAS to mitigate serious problems.

The RAS system is an enabler; it allows safety margins to be relaxed, ensures safety and stability in several cases, and helps overcome many constructional and operational constraints.

It is recommended to consider the RAS system for any grid interconnection, grids with distant load and generation centers, and in general, any power system that is prone to severe sudden power unbalance between generation and consumption.

The RAS system harnesses and uses a lot of modern technologies and development, and it is important to understand the context and use of the technology within the system design.

It is a must to perform HIL testing to ensure accurate and meaningful validation of the RAS implementation. The HIL helps when testing corner cases that would be catastrophic if they happened in real life. Offline dynamic simulations do not have the same capabilities as HIL test setups, and they do not verify the same scenarios with the same details.

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X. BIOGRAPHY

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