System Interconnection Protection Scheme Prevents Blackouts Due to FIDVR Effects at Panama's Transmission Systems

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***Abstract*—Panama's transmission system has geographical and infrastructure constraints that make it very susceptible to different contingencies. These contingencies have led to major blackouts that have affected loads in Panama and the Central American transmission system in recent years. CND (ETESA) developed a special protection scheme that takes remedial actions to increase reliability and power transfer limits of the Central American regional system to allow for the most economical operation. The uncontrolled and major loss of load due to fault-induced delayed voltage recovery (FIDVR), double (N-2) contingencies, load-shedding schemes, or various other reasons caused excess generation in the Panama system to flow into the Central American interconnection, driving the system to steady-state or transient overload conditions, which caused cascade events and blackouts before a new scheme was implemented.**

This paper presents the challenges found during power system studies and the remedial action solutions implemented to address these challenges. System protection schemes require accurate and time-synchronized measurements of the total power flow at the interconnection link, which consists of three transmission lines during transient conditions. Phasor measurements (PMUs) and high-speed phasor data concentration technologies (PDCs) are applied for synchronous measurement and used to make generation-shedding decisions. The implemented solution combines different schemes and logics to be effective for several different contingencies and operating conditions. Very fast generation-shedding actions are preferred, but pre-armed, contingency-based schemes cannot be applied for uncontrolled loss of load due to FIDVR, because there is no single location to detect contingency. Instead, the scheme needs to respond to power flow measurements after the event. Two response-based schemes are described, one uses the total power flow in the three interconnection lines to make tripping decisions during slow evolution events, while the other calculates the rate-of-change of power at the interconnection link to accelerate the protection. Generation-shedding algorithms perform a real-time selection among multiple generation plants to optimize the amount to shed and automatically changes selection both after dispatch changes, and after initial operation.

I. Introduction

Empresa de Trasmisión Eléctrica SA (ETESA) is the Panama state-owned company in charge of Panama's transmission system. Centro Nacional de Despacho (CND) is a subsidiary of ETESA that coordinates power system operations as well as national and regional market transactions in charge of the national control center. Panama's power system operates as an open market with several generation and distribution companies. Load demand and power generation have grown quickly while the development of transmission capacity has suffered delays. Therefore, the Panama transmission system operates closer to its transfer limits, leading to reduced security margins or limited economic dispatch. This paper builds upon [1].

Panama's power system has unique geographical conditions that make system operation challenging. Fig. 1 shows Panama's transmission network. The biggest load centers close to Panama City and Canal are in the eastern side of the country. Major hydroelectric generation capacity and interconnections to the regional Central America power system are on the western side of the country. The main transmission corridor consists of approximately 400 km of 230 kV lines from west to east with transmission transfer limitations because of voltage stability issues that are described in [2].

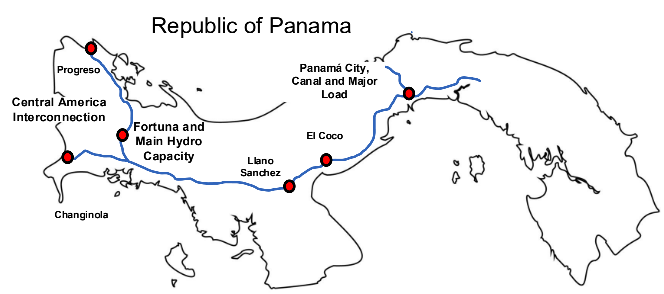

Fig. 1. Panama transmission lines, (geographical view).

Panama is at the southern end of the regional Central American system that connects with Mexico too. Fig. 2 shows the geographical location of each country and its corresponding relative size in terms of generation capacity connected to the system during the first phase of the project (2020).

Because of the large difference in power system sizes and inertias between the Mexico and Panama systems, every change of load or generation into the Panama system directly affects load flow from Mexico to Panama and all of the countries in between.

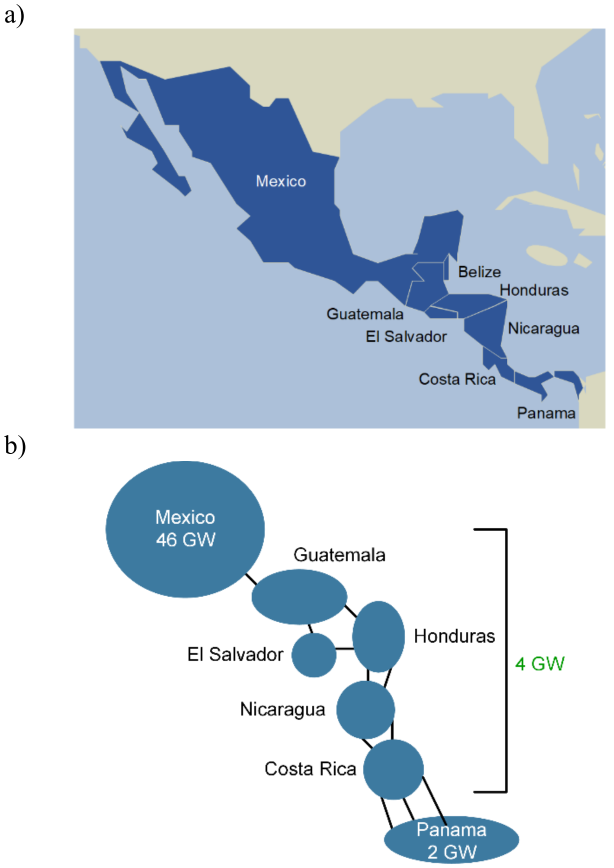

Fig. 2. (a) Geographical location of each country and their relative generation capacity connected, (b) relative size of interconnected power systems: Central America, Panama, and Mexico.

II. Fault-Induced Slow Voltage Recovery Concepts

Voltage stability is frequently presented as power transfer limits related with PV or QV curves on steady-state operating conditions. Generation or distribution voltage controls like automatic voltage regulators, overexcitation limiters (OEL) and transformer load tap changers (LTCs) must be considered for dynamic stability studies. The Panama system has power transfer limits from west to east related to the PV curves and active power transfer limits, as documented in [2]. However, during Panama's past blackouts, major and uncontrolled loss of voltage-sensitive loads was observed with power transfers very far from PV curve limits due to another effect known as fault-induced delayed voltage recovery (FIDVR). Fig. 3 shows the comparison of a real-world fault event on a transmission line close to the Panama load center (recorded with PMUs) and simulation results using a simple load model for operation studies. Present regulatory operation manuals for Panama require modeling load with 30 percent constant admittance and 70 percent constant current, which is a very commonly used combination that provides accurate results for angular transient stability but will not lead to accurate results for voltage stability studies.

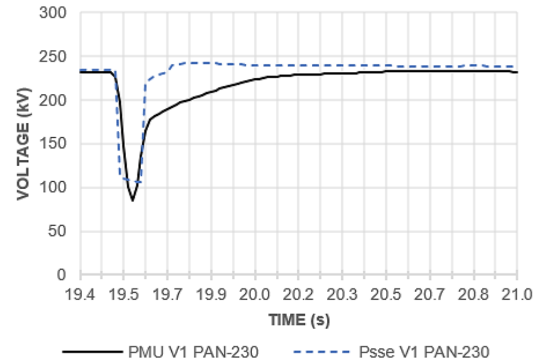

Fig. 3. FIDVR at a Panama's load center, simulation versus measurement.

Simulation results show that the voltage is depressed during the fault and that it recovers instantaneously after breakers clear the fault. However, records from the PMU show that the recovered voltage is below 80 percent of nominal voltage and takes more than 1 second to reach nominal levels after fault clearing.

Reference [3] explains in detail dynamic load modeling and FIDVR effects. The behavior of the load is affected by electronic loads, controls, and different types of motors. Fig. 4 shows these complex model components.

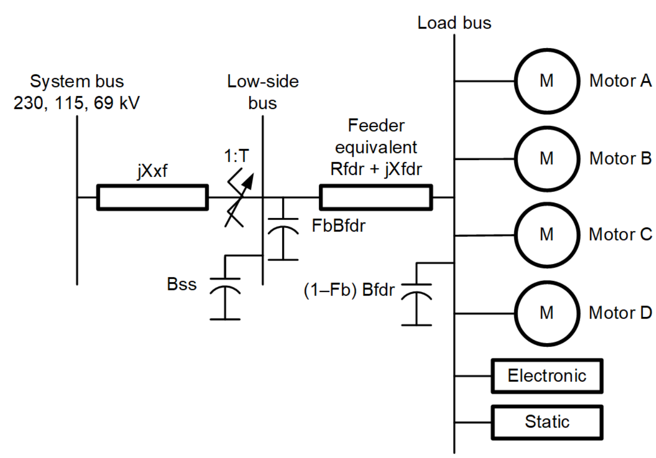

Fig. 4. Complex load model.

Some three-phase motor loads are lost because the contactor opens fast if there are low-voltage conditions that last between 20 to 100 ms. Some of these loads may trip before breakers clear the fault or during the slow voltage recovery period. The most notable effect comes from single-phase induction motors, which are common in residential air-conditioning systems. These motors tend to stall if a low-voltage condition affects the phase where they are connected. During a fault at the transmission level, a voltage sag affects several loads (red lines) and motors stall. Once the fault is cleared, the voltage recovers to values closer to nominal (blue lines), increasing both active and reactive power consumption by factors between 4 and 5 times the nominal value, as shown in Fig. 5.

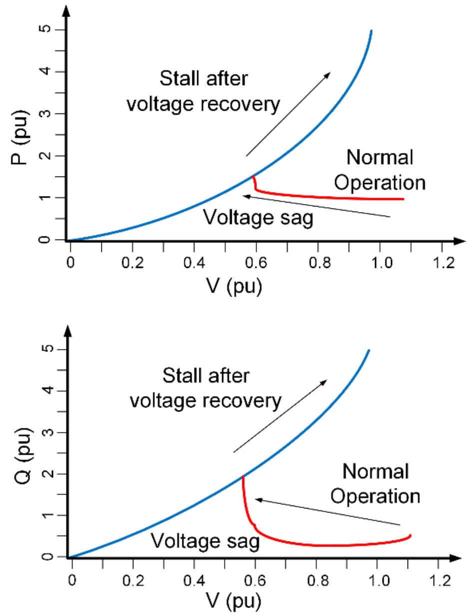

Fig. 5. Active and reactive power consumption of some air-conditioning motors.

This abnormally high reactive power consumption remains several cycles or even seconds after the fault is cleared and voltage partially recovers because the motors are already stalled. The motor protection takes a long time to trip because it normally consists of a MCCB low-voltage breaker or a similar type of thermal protection. When this type of load is a considerable amount of the total system load, the FIDVR effect has two system level consequences: active and reactive power consumption large grow, which leads to a sustained voltage sag condition in a large area, and part of the load is lost in an uncontrolled manner while the low-voltage breakers continue tripping. This loss of load contributes to voltage recovery. Fig. 6 shows a simulation of reactive power demand at the main urban load, at Panama City 230/115 kV transformers, using the complex load model for the same event shown on Fig. 3 and described with more detail in Section III (June 23, 2019). This sudden change in reactive power may be used to differentiate events related only to voltage collapse caused by transmission limitations from events related to voltage effects produced by FIDVR that cause large and sudden change in reactive power consumption. However, this approach using reactive power has not been implemented yet.

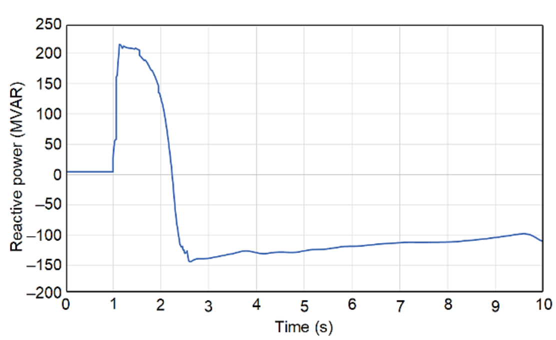

Fig. 6. Reactive power at Panama's load center during FIDVR event.

Other dynamic effects contribute to the complexity and accuracy of voltage stability simulations. Low-voltage ride-through (LVRT) on inverter-based generators is the ability of the generator to remain connected to the power system during low-voltage conditions. Dynamic models should also consider the LVRT characteristics because, during low-voltage events, generators may trip, increasing the power transfer on the affected corridor and reducing the generator's reactive power contribution.

The proper modeling of OELs, LTCs, capacitor bank controls, together with the LVRT characteristics, and load—especially complex motor load models—have a major impact on dynamic voltage stability study results. For large regional systems and open markets with different participants, it is challenging to get accurate models for all these components, increasing the uncertainty of the simulation results. System protection schemes should be flexible enough to prevent wide variations on the load loss during FIDVR events. Different models and simulations were used during Panama system contingency and schemes analysis, however general system load models could not be tuned to accurately reproduce all recorded events. Model tuning and scheme decisions are strongly based on observation and learning from previous events.

Lost of load caused by FIDVR on low-voltage motors is unavoidable once the motors stall. The only way to limit load losses is to clear the faults faster before the motors stall. The scheme proposed in this paper and described in Section V protects the system from other problems after a large amount of load is lost.

III. Regional Events Caused by FIDVR Before New Scheme Implementation

Several FIDVR-related events were recorded by CND (ETESA) wide-area monitoring system (WAMS) in recent years. We describe one of these events in this paper as an example of FIDVR behavior and effects.

Panama's simplified one-line diagram is shown in Fig. 7. There is a system protection scheme installed in the Costa Rica interconnection substations Cahuita (CAH) and Rio Claro (RCL). The scheme was designed to avoid overflows on the Costa Rica – Panama interconnection corridor during loss of load events in Panama. Costa Rica's scheme is based on overpower and overfrequency elements (32/81), with the logic shown in Fig. 8. The scheme remedial action is to trip the three lines on the link.

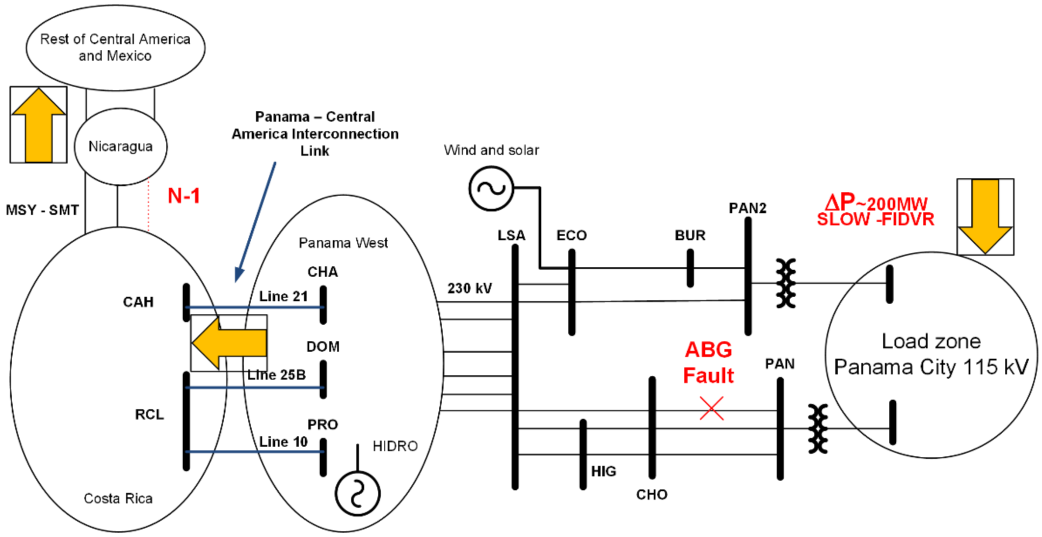

Fig. 7. Panama simplified one-line diagram during a blackout event on June 23, 2019.

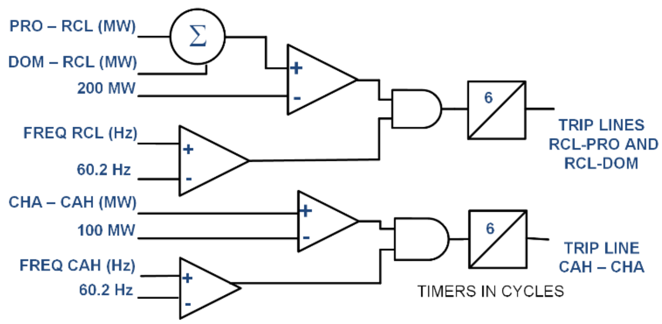

Fig. 8. Costa Rica interconnection link protection scheme.

Frequency supervision was included to operate the Costa Rica scheme only during sudden power change events caused by contingencies with fast loss of load previously observed. The amount of exported power from Costa Rica to Panama must be limited for these events because the other Central American links between Panama and Mexico, shown in Fig. 2, are weak and may not withstand sudden power flow changes.

Panama's system had a scheme on the same interconnection corridor at the Panama substations, CHA, DOM, and PRO, shown in Fig. 7. The goal of Panama's scheme was to shed generation at the Fortuna hydroelectric plant to reduce interconnection corridor power flow and avoid being disconnected by Costa Rica's scheme. Panama's scheme logic was similar to Costa Rica's side scheme, but with more sensitive thresholds, including frequency supervision at 60.1 Hz and corridor total power threshold 200 MW.

On June 23, 2019, a phase-to-ground (ABG) fault on the Panama – Chorrera 230 kV line shown in Fig 7. (PAN – CHO, Line 230-3A) was cleared by the primary line relays in 66 ms including the breaker operation time. During the fault and after fault clearing, 200 MW of load were lost, and Panama's excess generation had to flow through Costa Rica overloading line MSY – SMT North at Nicaragua's system while a parallel line was undergoing maintenance. Fig. 3 shows voltage behavior during this event confirming FIDVR. The west to east transfer limit was well below the PV curve limits, confirming the voltage decrement was not caused by transmission transfer limits. Fig. 9 and Fig. 10, from the regional operator report, shows how active power grew from 30 MW to more than 200 MW, above the scheme power threshold. However, Costa Rica's and Panama's interconnection schemes did not operate because the frequency oscillated without exceeding the 60.1 Hz supervision during the first part of the event. Uncontrolled loss of load due to FIDVR was not so fast and power flow continued growing for 6.6 seconds until the line MSY – SMT at Nicaragua tripped because of the distance element's backup protection.

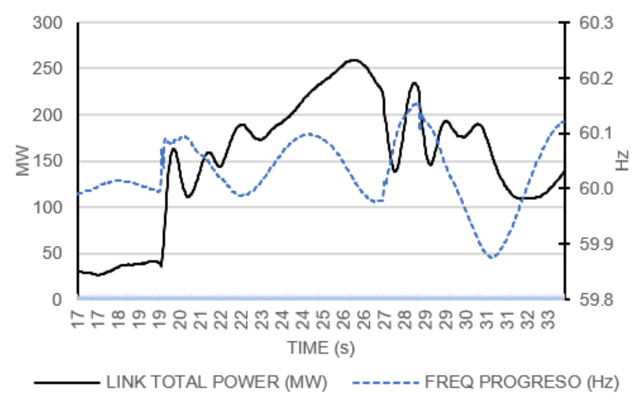

Fig. 9. Regional Operator Report June 23, 2019, event. Panama to Costa Rica power flow and frequency first 7 seconds.

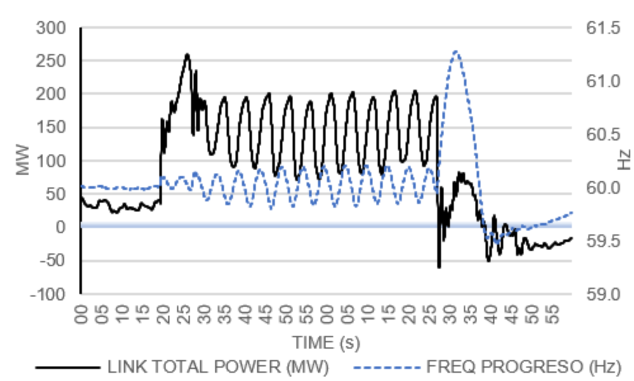

Fig. 10. Regional Operator Report June 23, 2019, event. Interarea oscillations for 56 seconds.

Network topology between Costa Rica and Nicaragua was modified by the MSY – SMT line trip in a way that caused most of the flow to remain in a single long line that led to interarea oscillations. The oscillation lasted for 56 seconds until additional lines were disconnected, isolating all Central America from Mexico, and splitting Central America into two islands. Total load loss was close to 500 MW in six countries.

Previous schemes were not effective because the frequency threshold was not reached. Several simulations with different operation scenarios show that it is very difficult to set this threshold because FIDVR's slow evolution does not always produce a sudden change of frequency. Remedial actions for FIDVR should not depend on frequency threshold, or at least the threshold level should be reviewed for the slower evolving events with smaller frequency changes. The scheme should use sudden changes of reactive power at the load center instead of frequency supervision to identify FIDVR events, however such improvement has not been implemented yet on the scheme.

IV. Other Contingencies That Lead to Fast Power Changes on the Central American Interconnection

The analysis of other events shows more weaknesses of the previous schemes.

On October 30, 2019, one bus in Panama City was lost, the network topology changed, and some 115 kV lines were overloaded until one of them tripped. There were low-voltage operating conditions in the 115 kV network, and the existing low-voltage scheme operated correctly, shedding ~60 MW. However, because the complex load includes several motors, the uncontrolled load loss was close to 250 MW, greatly exceeding the 60 MW shed by the low-voltage scheme. This behavior shows that undervoltage load-shedding schemes are not effective to prevent FIDVR effects. In this type of case, the undervoltage load-shedding scheme makes the power flow change worse. Panama's previous interconnection corridor scheme correctly detected power flow above the threshold and frequency above 60.1 Hz. However, that day the Fortuna hydroelectric plant was out of service and there was no generation available to shed. Costa Rica's scheme disconnected from Panama after 6 seconds and lost Panama's power contribution, which was then compensated for by Mexico's system, overloading the Mexico to Guatemala link. Then Mexico's link disconnected, and load was shed in all the six countries by underfrequency schemes. Event analysis shows complex load models should be used when making power system studies for other low-voltage conditions, not only short-circuit faults. It also shows that a generation-shedding scheme that protect a transmission corridor with flow coming from several power plants should not depend on a single power plant, it should be able to dynamically change generator selection between different power plants, covering as many different operation scenarios as possible.

On July 13, 2019, a large mining company load was lost because of sustained low voltage on their main 34.5 kV bus during a large transformer energization with significant inrush effects. According to WAMS records, the disconnected load was 141 MW. Fig. 11 shows the power flow on the three Panama – Costa Rica interconnection lines. Power did not reach the 200 MW limit during the first oscillation. The overload was not enough to trigger interarea oscillations or line protection operations under normal conditions. However, due to a maintenance condition on a line in Nicaragua, together with the excess on power flowing from south to north from Panama, the Amayo – Liberia line (not shown in the one-line diagram) internal to Nicaragua was overloaded, and line protection operated triggering interarea oscillations. Oscillations were detected in Mexico's link scheme, then the Central American system was disconnected, and the low-frequency scheme operated and shed load at Guatemala, Salvador, and Honduras. This event was not related at all to FIDVR; however, the effect on the interconnection link is the same, and the scheme needs to cover other types of large loss of load.

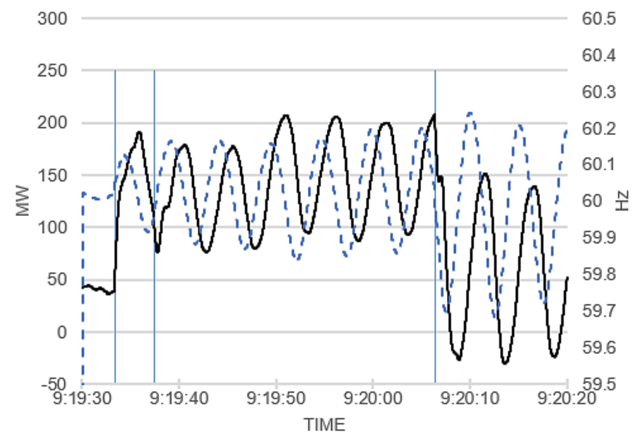

Fig. 11. WAMS records from the Panama – Costa Rica interconnection link July 13, 2019, event.

One approach would be to have regional schemes coordinated between the six countries that adapt thresholds to prevent double contingencies such as when a loss of load event happens in Panama with a maintenance condition on lines in other countries north on the link, known as N-1-1 contingencies. Implementation of such a scheme would present several challenges including:

1. Studies to determine limiting contingencies for all N 1-1 contingencies in all possible operation scenarios are complex and require analysis of hundreds of combinations.
2. Implementation responsibilities across different operators, transmission companies, and national regulators.
3. Communication channels available for fast and reliable wide-area protection.

Such a scheme has not been implemented because of these challenges. Solution needs to limit the size of sudden changes on power flow on the interconnection link using information available into Panama and ETESA system.

V. New Interconnection Protection Scheme Implementation

A. Generation-Shedding Logic

A new remedial action scheme (RAS) uses a rate-of-change of power detector to act faster than previous schemes and anticipate operation of fast-evolving events. This scheme also needs to protect the interconnection link under the previous assumptions made for slower evolving power flow increments and coordinated to operate before the Costa Rica interconnection scheme using the same variables. A conventional power/overfrequency 32/81 scheme was also implemented, which includes significant improvements over the previous scheme, including:

1. PMU synchronized measurements to calculate total link power providing accurate measurements over the three interconnection lines during changing power flow conditions. The previous schemes did not use tie synchronized signals and were inaccurate during transient conditions.
2. Operation time below 80 ms. The previous scheme did not have adjustable intentional delay and, due to technical limitations, the operation time was 500 ms, which is not fast enough for some fast-evolving events.
4. Real-time power measurement information from each generator. It can select generators at several different power plants dynamically and reach optimal amount of generation to shed. The new scheme can also select new generators for consecutive operation when needed a few milliseconds after the first generation-shedding action is completed. The previous scheme only shed generation at the Fortuna hydroelectric plant.

The new scheme logic is shown in Fig. 12.

1) *Logic 1*

1. The power entering the interlink is detected to be greater than an operator-defined threshold (A).
2. The interlink frequency is detected to be greater than the operator-defined threshold (C).
3. Logic 2 has not yet been satisfied.

2) *Logic 2*

1. Rate-of-change of power entering the interlink is greater than an operator-defined threshold (B).
2. The interlink frequency is detected to be greater than the operator-defined threshold (C).
3. There are more than two undervoltage (27) triggers asserted from the Panama west or east side selected buses.
4. Logic 1 has not yet been satisfied.

Logic 1 and Logic 2 have cross blocking; once a decision is made by any of them, the other is blocked for a short period of time. Once the generation-shedding action happens, the logic is ready for new operation after few milliseconds.

A rate-of-change of power scheme must be implemented using PMU measurements to ensure accurate total power calculations during dynamic conditions, and because constant time among samples is required to enable rate-of-change over time calculations. It also requires a fast PDC/Logic Engine processor capable of obtaining PMU signals using IEEE C37.118 standard protocol from three remote locations, aligning them, and delivering them to the logic engine. The logic engine then processes the calculations and logic every 4 ms to take fast actions sent by Generic Object-Oriented Substation Event (GOOSE) messaging to power plants previously selected. Even if new PMU data arrive every cycle (16 ms), the faster task cycle at the logic engine processes the

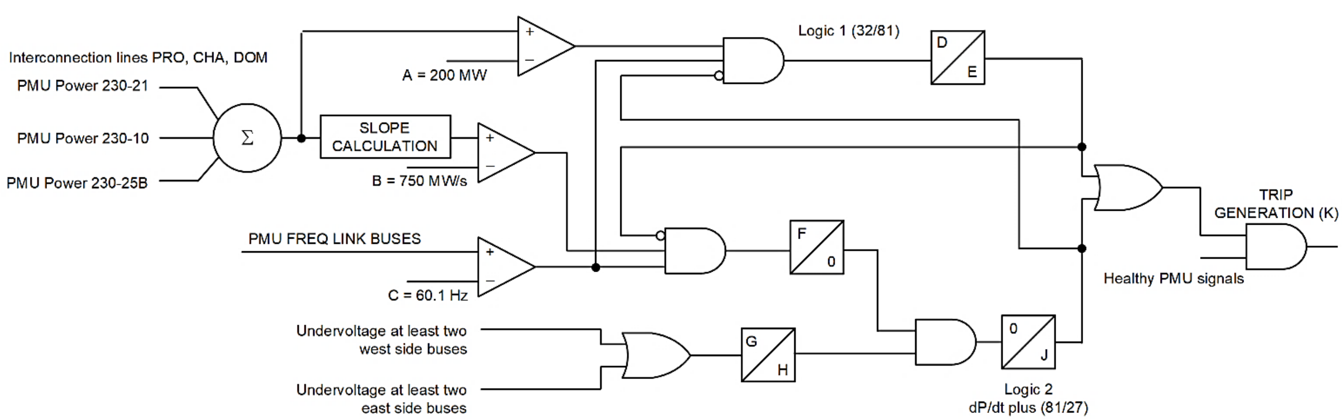

Fig. 12. New scheme logic based on PMU measurements.

received signals and logic to generate outputs by GOOSE faster. Fig. 13 shows the PDC/Logic engine concept.

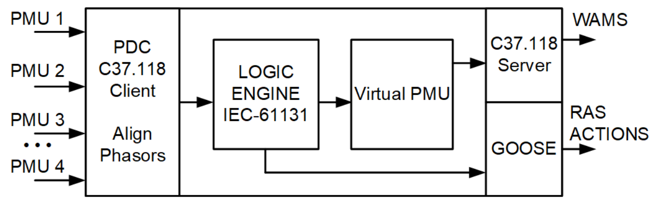

Fig. 13. PDC/Logic engine concept.

The PDC implements a virtual PMU that can add all the input phasors to the PMU server. The virtual PMU can also add any other signal available on the logic engine, such as data from other protocol sources or calculations executed on logic engine such as total link power or rate of change of power for this scheme.

Rate-of-change of power is designed to act faster for events with higher power system acceleration. Those events are identified by studies as FIDVR conditions on the east side of the system, close to the Panama load center, or phase-to-phase or three-phase faults with longer clearing times at the west side of the system close to the hydroelectric generation. Logic 2 is supervised by undervoltage at either of those two zones to provide additional security.

Because regional schemes detecting maintenance conditions N-1-1 and double N-2 contingencies are challenging and not implemented, CND (ETESA) looked for other solutions that can rely on just Panama's system, available signals, and infrastructure. Our approach is to limit sudden power changes on the Panama – Central America link to a user-defined amount, allowing the other operators to incorporate this potential change in power flow (ΔP) into their maintenance planning. The scheme needs to shed a moderate amount of generation to limit the power flow change as quickly as needed to avoid operation of the Costa Rica scheme and disconnection of the Panama system. However, this scheme needs to be fast enough to select and shed additional generation in case the power flow continues growing on the link after the initial operation because loss of load can last for several seconds, as it happened during prior FIDVR events. An ideal hypothetical control would be a closed loop continuous control fast enough to keep the link on the planned interchange. Because the existing energy management system and generator controls are not fast enough to avoid the consequences of the growing power flow using the closed feedback loop control, the wide-area protection scheme needs to shed generation, but the consecutive operations approach with relatively small steps accomplishes a similar goal. Generation to be shed is fixed on steps of 100 MW for simplicity and provides a reference for maximum ΔP for external systems. HVDC systems may provide excellent solutions for these challenges because of its continuous and fast control of active power; however, it requires investment that is difficult to be justified for this amount of energy exchange. Future improvements may consider fast controls over inverter-based resources, like solar or wind generators instead of generation shedding. Such controls have been implemented on other facilities keeping the reactive power support while reducing active power output.

B. Generation Selection Logic

The generation amount required to shed is defined by the operator in the human-machine interface (HMI). Later, this amount can be modified if required by new operation planning studies. The generators are sorted in descending order and selected based on the total generation amount required to shed. There is a total of 19 generators available for shedding. The RAS HMI includes a parameter for an ETESA operator to activate inhibit inputs for the generator shedding logic. The HMI displays which generators are online and can be inhibited from the shedding logic. The status and the MW value of each generator comes from IEDs installed at each generation plant. In case of loss of communication with the generator IED, the RAS also automatically inhibits the corresponding generator from shedding. Table I shows all generation stations involved in the generation-shedding scheme.

TABLE I
GENERATION STATIONS INTO SHEDDING SCHEME

Generation Station	Number of Generators	Individual Generator Capacity (MW)
Fortuna	3	100
Gualaca	2	12
Lorena	2	18
Prudencia	2	28
AES Estí	2	60
AES Changuinola	2	106
El Alto	3	22
Monte Lirio	3	16

If a generator was shed by an RAS scheme action, then it is automatically blocked for the following operations until the operator enables it again. This approach distributes operations throughout all power plants. The logic keeps at least one generator per power plant to keep auxiliary services and provide local active and reactive power support. To provide the operator with visibility of the real-time status of the selection logic, the HMI shows a selection matrix, as shown in Fig.14.

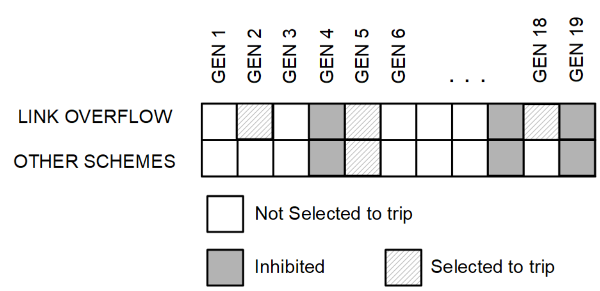

Fig. 14. Generator selection matrix.

C. Architecture and Infrastructure

Operating speed and dependability are critical aspects of the RAS controller to ensure power system stability. The proposed RAS system architecture and technology guarantees very fast remediation actions. To achieve this dependability, the Panama RAS scheme is a dual primary system. A dual primary system is a redundant system in which two controllers (RAS-A and RAS-B) make decisions simultaneously. Each RAS controller collects information from the power system and performs calculations to decide if an action is necessary.

To make decisions based on specific contingencies, the RAS controllers receive measurements and status from equipment installed across the Panama power system in multiple substations. Equipment in remote substations report the data at both slow and high speeds to the controllers using DNP3 and GOOSE protocols. Additionally, PMU data are collected from all equipment for monitoring and dynamic disturbance recording purposes and for synchronized measurement and rate-of-change schemes. All the equipment at the substations communicates to the RAS controllers using a Synchronous Digital Hierarchy (SDH) network over a fiber-optic wide-area network backbone. Layer 2 communications is preferred to avoid additional delays, points of failure and management complexity related to routers or firewalls between facilities. SDH multiplexors provide direct Ethernet ports and point-to-point L2 communication paths. Channel requirements like speed and reliability should be like those of any pilot or communications-based line protection scheme. The RAS controller also gets individual generator data directly from RAS IEDs and load data from two distribution companies through the ETESA supervisory control and the data acquisition (SCADA) system to confirm the load per feeder in real time and optimize the load to shed described in [2]. Fig. 15 shows the RAS general architecture. Actual schemes include more than 50 IEDs at different facilities.

VI. System Validation

An important part of developing RASs is the system validation test. The designed and developed RAS system (controllers and all the equipment involved) must be tested before commissioning in the field. The validation is done using a real-time digital simulator. Real-time simulations allow external equipment to be connected to the simulation and exchange information between them; these are known as hardware-in-the-loop (HIL) tests. HIL tests consist of developing several real-time simulations on a reduced power system model of Panama and Central America systems. One contingency could be simulated multiple times under different scenarios and conditions to validate the correct response of the controller and the entire RAS system for each test.

Developing this kind of test makes it possible to find conditions that were not considered in the initial design, and it allows modification to them if needed before the commissioning work starts. This also reduces the onsite commissioning time because most of the possible improvements are made in the laboratory. These findings could include mistakes in the system logic or end user network models. At the end of these validation tests, the result is an RAS system with high quality and a much easier field commissioning process. Real-time digital simulation and HIL testing were critical for the success of the interconnection link RAS scheme described in this paper to validate the dynamic performance of the scheme.

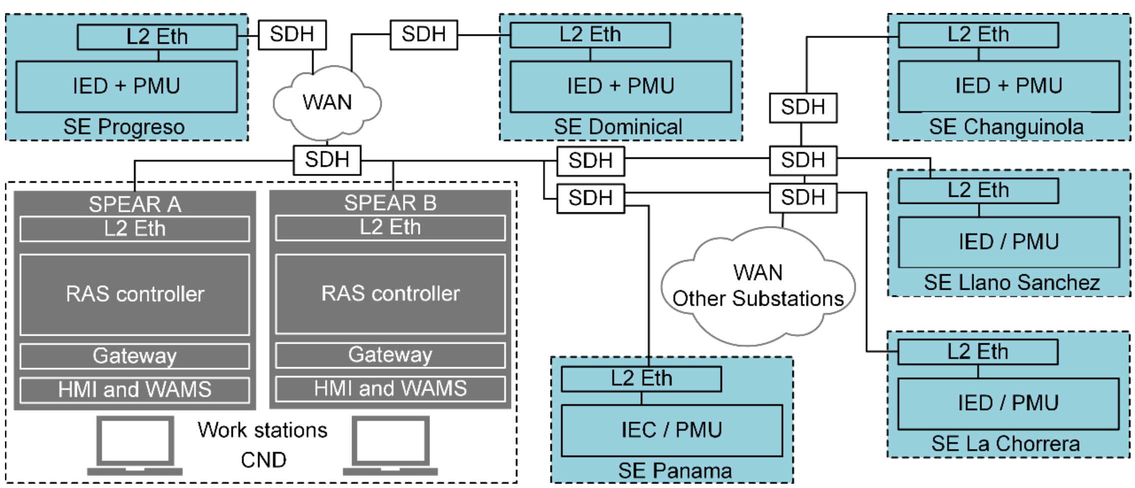

Fig. 15. General RAS architecture.

VII. Field Results

The RAS interconnection link scheme was commissioned in March 2021. It has successfully operated 14 times since then, preventing Panama from being disconnected from Costa Rica and reducing the impact of all other countries in the regional system. Two examples of this scheme's operations are described in this section.

On April 22, 2022, there was a fault at one 34.5 kV distribution feeder close to the Chorrera substation (CHO) that cleared after 240 ms followed by another distribution feeder fault from the same substation 450 ms later that cleared after 440 ms. Power flow on the interconnection link started close to zero; after these two initial events stabilized, power flow was at 54 MW, which should be close to the lost load because of the distribution feeders' faults. After 100 seconds, the distribution operator closed the feeder breaker to test the faulted feeder. The test was negative because the permanent fault was cleared after 238 ms. Even though the clearing time was normal for medium voltage feeder protection, this event caused a deeper voltage depression than previous faults and led to a FIDVR effect. Fig. 16 shows the 230 kV voltage at Chorrera (CHO) substation close to that of the feeder fault. Fig. 16 also shows the 115 kV (PAN) voltage measurement in Panama, closer to the load center.

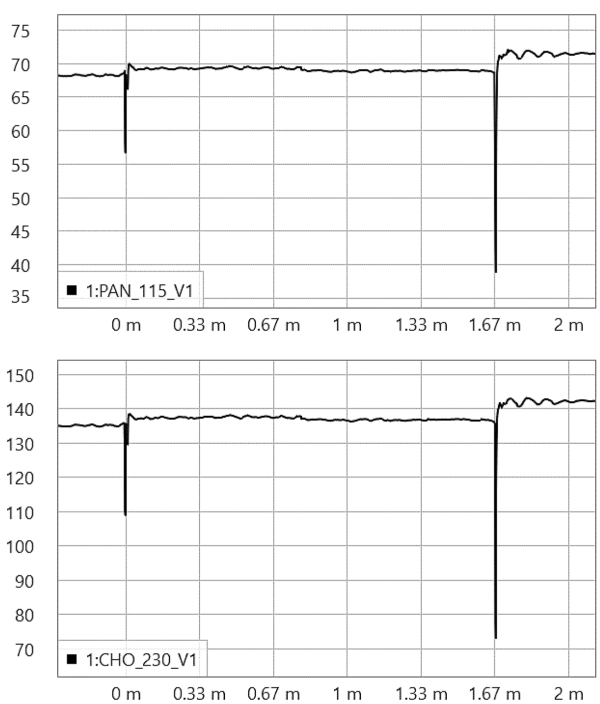

Fig. 16. Positive sequence voltages at CHO 230 kV and PAN 115 kV during CHO distribution feeder faults.

Fig. 17 shows a closer look into PAN 115 kV positive sequence voltage at the voltage sag moment. The voltage dip was 58 percent of nominal phase-to-ground voltage. The low-voltage conditions remain for approximately 500 ms before recovering to a stable condition, confirming the FIDVR effect. Total interconnection link power grew during the same period because of two different effects; the short-circuit fault accelerated Panama's generators and the loss of load because of FIDVR, until the RAS shed generation.

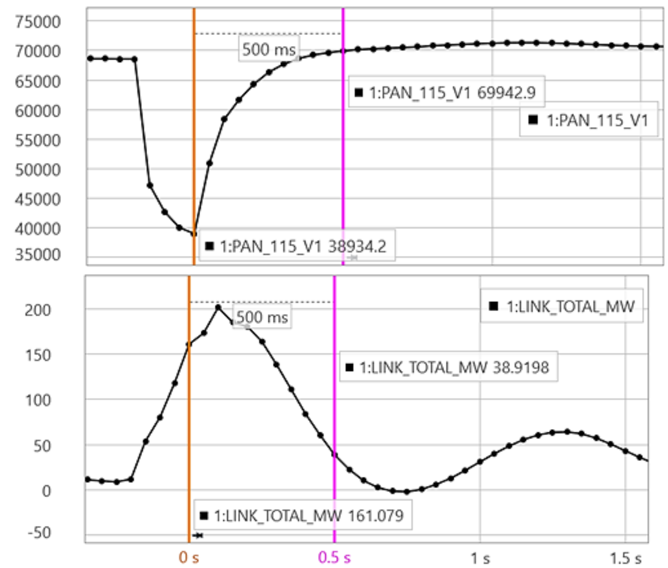

Fig. 17. Positive sequence voltages at PAN115 and total Central American link power, April 22.

Fig. 18 shows the performance and impact of using PMU and PDC for RAS schemes. The first graph shows synchronized PMU power samples from each transmission line on the interconnection link and the total power as calculated by the PDC logic engine. The second graph shows the total power rate-of-change or slope calculated by PDC logic engine, with a peak value of 833 MW/second, which is enough to trigger generation-shedding action. The rate-of-change acted 100 ms earlier than the total power could reach the 200 MW threshold, reducing the possibility of adverse effect on northern links and oscillations in this event.

The third graph shows digital signals corresponding to the total power threshold, the rate-of-change threshold, and the trip signals sent to GUAL and ESP power plants.

The fourth graph shows the active power at Changuinola (ESP) generator Unit 2 (98 MW) and at Gualaca (GUAL) generator Unit 1 (9 MW) before the RAS action, meeting the criteria to shed at least 100 MW. These generators were preselected by the RAS scheme, then a trip signal was sent immediately by a GOOSE message after the rate-of-change of power was detected, changing their power output to 0 MW before 100 ms.

A virtual PMU is configured at PDC to serve analog and digital signals calculated by the PDC engine using IEEE C37.118 and not only the phasor data. With this information, we can analyze not only the power system behavior, but also the PDC's and logic engine's calculations and performance.

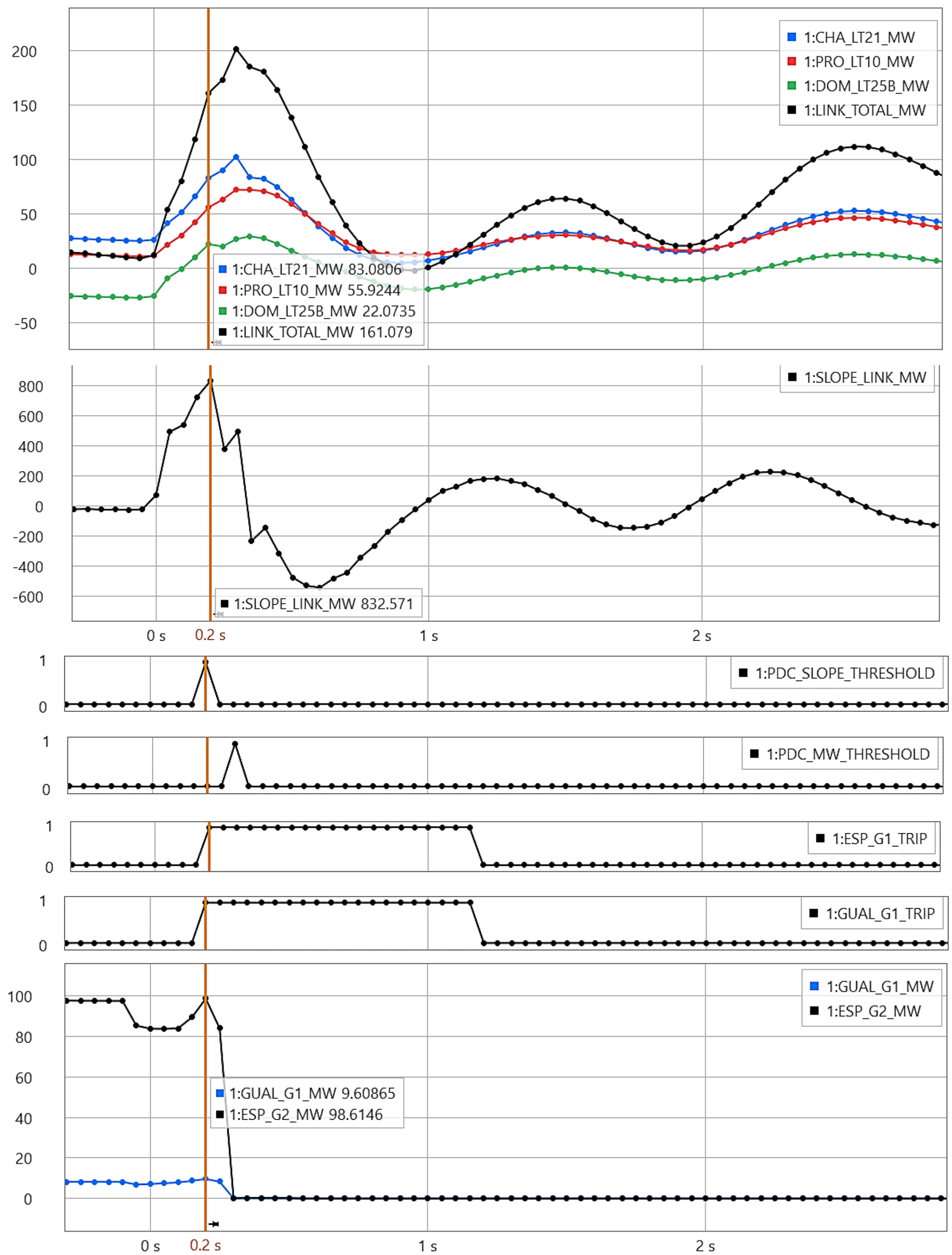

Fig. 18. Total and individual lines power, rate-of-change of power, generation-shedding, and digital signals related to RAS operation, April 22.

Fig. 19 shows that even if the voltage recovered after 1 second and 108 MW of generation shed, total power flow on the interconnection link continued growing up to 184 MW during 6 seconds because of additional uncontrolled loss of load caused by FIDVR. No additional action was required because total power never reached 200 MW or the rate-of-change thresholds, and the system remained stable.

On September 9, 2022, a 34.5 kV distribution feeder fault at Llano Sanchez (LSA) caused a sustained voltage dip because of incorrect protection operation. A phase-to-phase fault evolved to a three-phase fault and lasted more than 8 cycles. The RAS scheme reached the total power and frequency threshold for logic 1, shedding 104 MW. However, the FIDVR effect caused additional uncontrolled loss of load during the following 4 seconds and triggered interarea oscillations. The RAS scheme resets its trip condition 600 ms after the first operation and preselected more generators. Once the total power reached 200 MW again with the overfrequency condition, an additional 110 MW were shed.

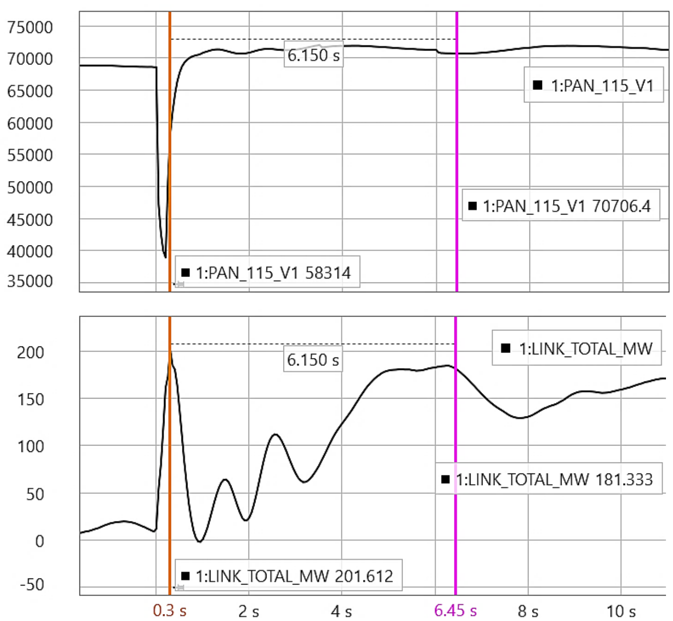

Fig. 19. Positive sequence voltages at PAN115 and total Central American link power, April 22, 2022.

Fig. 20 is a graph from the CND report showing the total power on the interconnection link, the frequency, and power on each generator shed during two consecutive operations of the September 9, 2022, event.

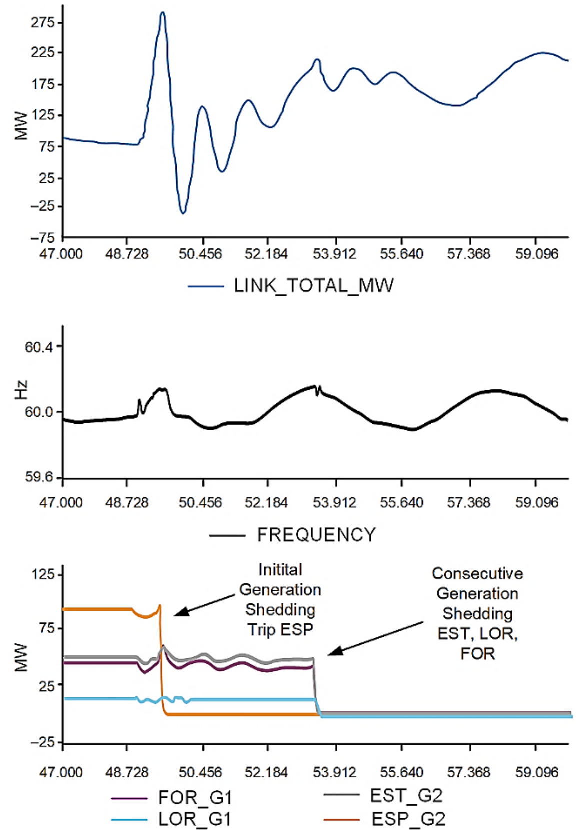

Fig. 20. Total power, frequency, and generation shed during two consecutive RAS scheme actions September 9, 2022.

VIII. Conclusions

Implementation of an interconnection link system protection scheme or RAS scheme presents several challenges, including:

1. The need for extensive simulation to account for different scenarios and power system conditions.
2. The need to review several previous events to learn from past system performance.
3. FIDVR effects simulations and accurate complex load models are very challenging. Studies require proper modeling, when possible, and good criteria for assumptions where there is not enough data. Availability of more PMU measurements closer to the load at the distribution levels will help to improve complex load models.
4. The need for detailed engineering and interphase design to be coordinated between different stakeholders such as transmission, generation, and distribution companies; control centers; and those with different specialties, like protection, automation, and communication engineers.
5. The need to use a reliable wide-area communications infrastructure.

This paper explained FIDVR effects and showed simulation and measurement examples to illustrate how uncontrolled loss of load happen in the Panama system. FIDVR and other possible uncontrolled loss of load contingencies produce interconnection link power overflows because excess generation flows to the biggest inertia system.

Solutions presented include a generation-shedding scheme that detects overflow conditions on the Panama to Central America interconnection link, and that automatically selects and sheds generators when needed to prevent regional events that lead to major load shedding or blackouts in Panama and other countries before scheme implementation.

The new RAS scheme uses PMU signals and a powerful PDC with real-time logic engine capabilities to accurately calculate total power from three different substations and lines that form the interconnection link during dynamic conditions; enabling the scheme to calculate the rate-of-change of power and act in less than 80 ms.

The system includes HMIs that allow visualization of generation to shed. The schemes include several features to increase reliability such as redundancy, channel supervision, and robust contingency detection supervision.

Field results confirmed the efficiency and reliability of the scheme with 14 successful operations since 2021. Two examples are shown in this paper; including one where the rate-of-change of power accelerated shedding decisions and another where two consecutive operations stopped interarea oscillations before they led to regional blackout.

CND (ETESA) received the following benefits after scheme implementation.

1. Power transfer limit increase.
2. Improved system reliability that greatly reduces the possibility of system blackouts.
3. Optimized generation shedding because of the incorporation of different power plants and individual generation information gathered in real time.

IX. References

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X. Biographies

Alonso Castillo is the manager of technical support for the National Dispatch Center. He graduated from the Universidad Católica Santa María la Antigua as an electronic engineer, and he graduated from the Interamerican University of Panama with a master's in business administration with an emphasis in strategic management. He joined the Institute of Hydraulic Resources and Electrification in 1986 in the communications department in the area of microwave communications infrastructure and PABX voice service. Since 1989, Alonso has been part of the National Dispatch Center with assignments and responsibilities for hardware in supervisory control and data acquisition (SCADA). He works with hardware that structures and implements the wide-area monitoring system (WAMS) and quickly integrates it with SCADA, and he also works on power line carriers (PLCs) intercommunicating with fiber-optic multiplexed channels to form a supplementary protection scheme for the international interconnection. Alonso participates as a leader in implementing a special protection scheme (SPS) for the National Interconnected System of Panama: Special Protection System With Remedial Actions (SPEAR).

Javier Echeverría Moreno is the engineering manager in special protection systems (automation and control) group for Schweitzer Engineering Laboratories (SEL) in Mexico. He graduated as electronic engineer from the Universidad Técnica Federico Santa María (UTFSM) in 2011 in Valparaíso, Chile. In 2014 he obtained a master's degree in electronic engineering sciences at UTFSM, focusing his work on power electronics. He joined SEL in 2015 as an automation design engineer for electrical substations and since 2018 he has served as control engineer for power systems and wide-area protection schemes. He has led several remedial action scheme projects, working on its design, development, implementation, testing and commissioning.

Aaron Esparza is the project engineer in the special protection systems department for Schweitzer Engineering Laboratories (SEL) in Mexico. He received ME and PhD degrees in electrical engineering from Autonomous University of San Luis Potosí, San Luis Potosí, Mexico, in 2013 and 2018, respectively. His research interests are power system models and simulations, wide-area protection, and control applications.

Ulises Torres is the group manager in special protection systems for Schweitzer Engineering Laboratories (SEL) in Mexico. He graduated as an electrical engineer from the National Polytechnic Institute of Mexico in 2011 and is currently studying for a master's degree in electrical power systems at the Autonomous University of San Luis Potosí. In 2012, he joined SEL, where he has served as a factory acceptance test engineer, field service engineer, and power system studies engineer. He has led multiple protection and control projects. In 2016 he joined the area of special protection systems, participating in the creation, development, and implementation of multiple remedial action schemes. He has participated in the stability studies for the Panamanian electrical system (CND [ETESA]) and lead the development and implementation of the remedial action scheme of Panama.

Jean León Eternod is the technology director for Schweitzer Engineering Laboratories (SEL) in Mexico. Prior to joining SEL in 1998, he worked for the Comisión Federal de Electricidad (CFE) power systems studies office in protection and control corporate management. While he was at CFE from 1991 to 1998, he worked with wide-area network protection schemes, single-pole trip and reclose studies, and database validation for short-circuit, load flow, and dynamic simulation, including generator and control model validation for most CFE generators. He received his BSEE from the National Autonomous University of Mexico (UNAM), where he also completed postgraduate course work in power systems. He received training in power system simulation from Power Technologies, Inc. He has authored numerous technical papers on the topics of power system protection, simulation, and wide-area protection and control applications.

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