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System Interconnection Protection Scheme Prevent 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. ETESA-CND 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. Excess generation in the Panama system and overload condition in Central American interconnection could be steady state or transient conditions caused by uncontrolled and major loss of load due to fault induced slow voltage recovery (FIDVR), double ($N-2$) contingencies, load shedding schemes, or various other reasons.

This paper presents the challenges found during power system studies and the remedial action solutions implemented. Schemes require accurate and time synchronized measurements of the total power flow at the interconnection link composed by three transmission lines during transient conditions. Synchrophasors measurements (PMUs) and PMU high speed phasor 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. 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 slower 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 amount to shed and automatically changes selection both after dispatch changes, and after initial operation.

Keywords: System protection schemes,, interconnection protection, voltage stability, FIDVR, PDCs

1. 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. During recent years, both demand and generation have grown quickly while the development of transmission capacity, including lines and static volt-ampere reactive (VAR) compensation projects, has suffered delays. The Panama transmission system operates closer to its transfer limits, leading to reduced security margins or limited economic dispatch.

Panama's power system has unique geographical conditions that make system operation challenging. Fig. 1 shows Panama's transmission network. The biggest load centers, like Panama City, the Panama Canal, and other industrial zones, 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 is approximately 400 km of 230 kV lines that extend from west to east with typical longitudinal system problems, including transmission transfer limitations because of voltage stability issues [1].

Panama is at the southern end of the regional Central American system that also connects to Mexico and has no connection to South America. Fig. 2 shows the geographical location of each country and its corresponding relative size in terms of generation capacity

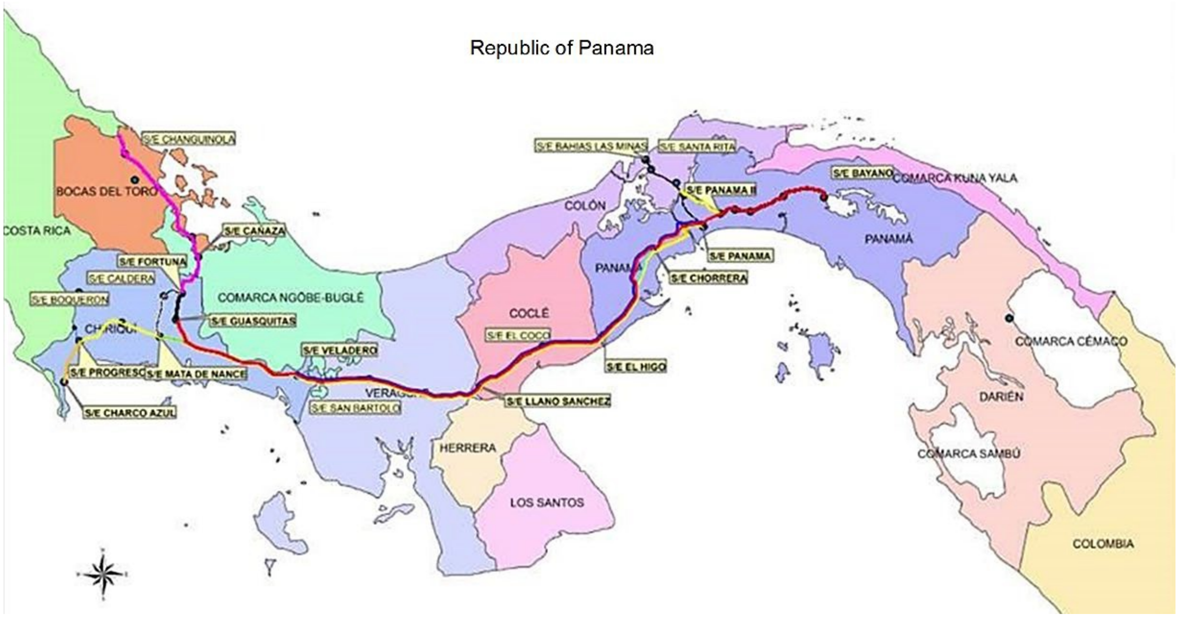


Fig. 1. Panama transmission lines, (geographical view).

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.

2. Fault-Induced Slow Voltage Recovery Concepts

Voltage stability is frequently presented as only power transfer limits related with PV or QV curves on steady state. It is dynamically related to generation or distribution voltage controls like automatic voltage regulators (AVRs) including overexcitation limiters (OEL) and transformer load tap changers (LTCs). The Panama system has power transfer limits from west to east related to the PV curves and active power transfer limits[1]. However, during Panama's past blackouts and other events, 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 phasor measurement units (PMUs)) and simulation results using a simple load model for operation studies. Present regulatory operation manuals for Panama require a modelling load of 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 may not lead to accurate results for voltage stability studies.

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 voltage recovered is below 80 percent of nominal voltage and takes more than a second to recover to nominal levels after fault clearing.

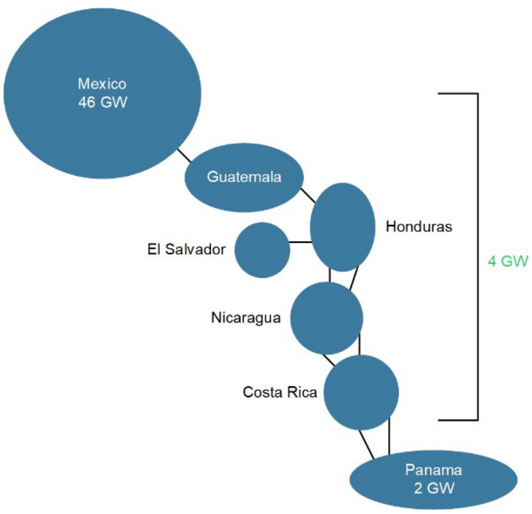
NERC's Dynamic Load Modelling Document[2] explains in detail dynamic load modelling and FIDVR effects. The behavior of the load is affected by electronic loads, controls, and different types of motors. Fig. 4 shows these complex model components.

Some three-phase motor loads will be tripped or lost because the contactor opens fast if there is low-voltage between 20 to 100 ms order. 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, common in residential air-conditioning systems. These motors tend to stall if a low voltage condition affects the phase where they are connected, increasing their reactive power consumption by factors between 4 and 5 times the nominal value. This reactive power consumption remains 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 considerable amount of the total system load, the FIDVR effect has two consequences: both active and reactive power consumption that can be very high at the system level which leads to a sustained voltage sag condition and part of the load is lost in an uncontrolled manner. This loss of load contributes to voltage recovery. Fig. 5 shows a simulation of reactive power demand at the main urban load, at Panama City 230/115 kV transformers using the complex load model. 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.

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.

Proper modelling of OELs, LTCs, capacitor bank controls, together with the LVRT characteristics, and load —especially complex motor load models— will 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 simulation results.

(a)



(b)

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

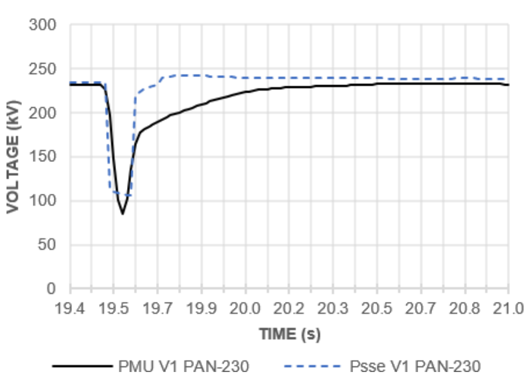


Fig. 3. FIDVR at a Panama's load center, simulation versus measurement.

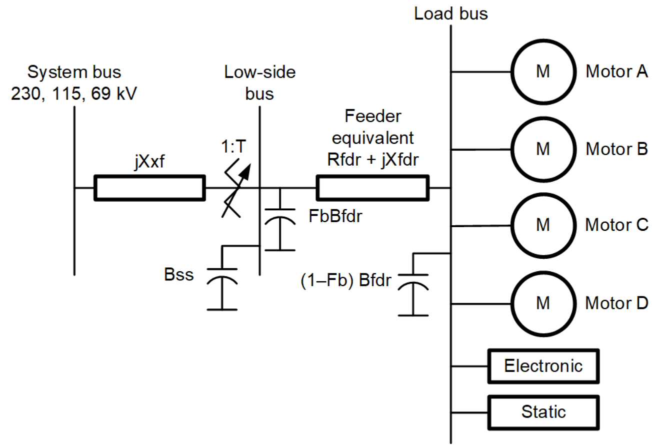


Fig. 4. Complex load model.

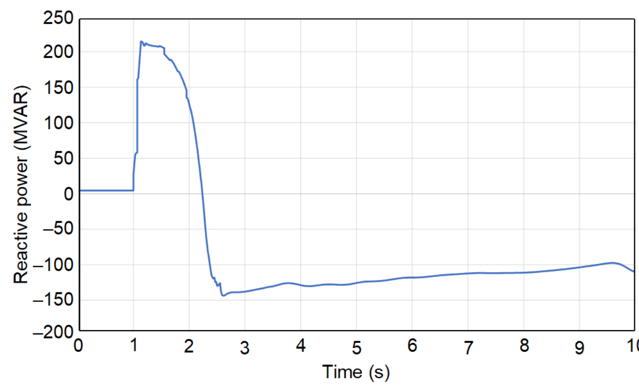


Fig. 5. Reactive power at Panama's load center during FIDVR event.

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 of the recorded events. Model tuning and scheme decisions are strongly based on observation and learning from previous events.

3. Regional Events Caused by FIDVR Before New Scheme Implementation

Several FIDVR-related events were recorded by ETESA-CND 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. 6. There is a 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 over frequency elements (32/81), with the logic described in Fig. 7. The schemes remedial action is to trip the three lines on the link.

Frequency supervision is included to operate the scheme only during sudden events caused by contingencies with fast loss of load observed previously. Power 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.

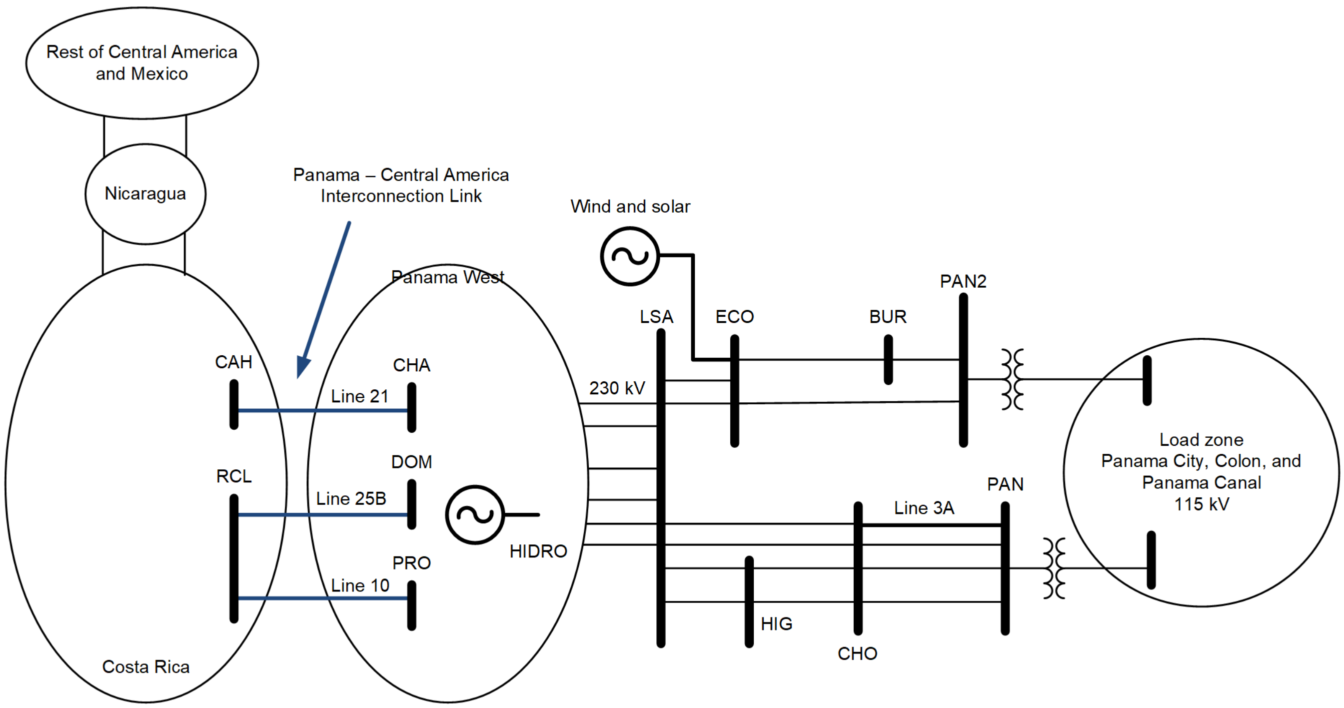


Fig. 6. Panama simplified one-line diagram.

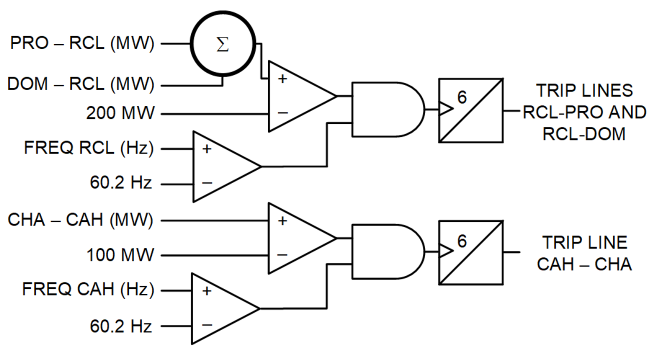


Fig. 7. Costa Rica interconnection link protection scheme.

Panama's system had a scheme on the same link at the Panama substations, CHA, DOM, and PRO, shown in Fig. 6. The goal of Panama's scheme was to shed generation at the Fortuna hydroelectric plant to reduce interconnection link 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 link total power threshold 200 MW.

On June 23, 2019, a phase-to-phase to ground (ABG) fault on the Panama–Chorrera 230 kV line (PAN–CHO, line 230-3A) was cleared by primary line relays in 66 ms including breaker operation. 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. 8 and Fig. 9, from the regional operator report, shows how active power grew from 0 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.

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 it is very difficult to set this threshold because FIDVR's

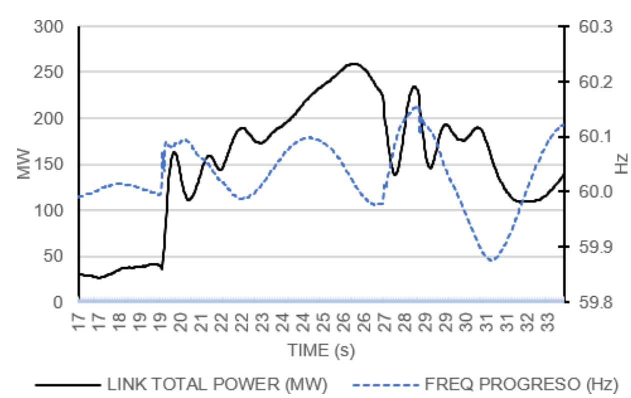


Fig. 8. Regional Operator Report June 23, 2019, event. Panama to Costa Rica power flow and frequency first 7 seconds.

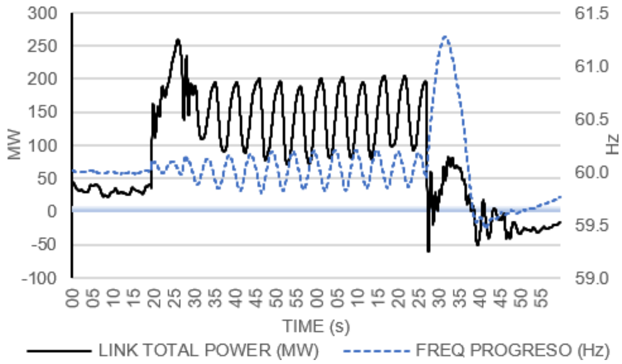


Fig. 9. Regional Operator Report June 23, 2019, event. Interarea oscillations for 56 seconds.

slow evolution does not always produce a sudden change of frequency. Remedial actions 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.

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

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 was low voltage on a 115 kV network, and the existing low-voltage scheme operated correctly, shedding $\sim$ 60 MW. However, because the complex load includes several motors, uncontrolled load loss was close to 250 MW, greatly exceeding the 60 MW on the low-voltage scheme. This behavior shows that undervoltage load shedding schemes are not effective to prevent FIDVR effects and for this type of case make the power flow change worst. Panama's previous interconnection link 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 for other low- voltage conditions, not only short circuit faults. It also shows that a generation-shedding scheme should not depend on a single power plant, it should be able to dynamically change generator selection between different power plants.

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 and inrush effects. According to WAMS records, the disconnected load was 141 MW. Fig. 10 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 in 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.

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.

5. New Interconnection Protection Scheme Implementation

5.1. 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 32/81 scheme was also implemented and provided significant improvements over previous scheme:

1) The new scheme uses PMU synchronized measurements to calculate total link power providing accurate measurements during changing power flow conditions. The previous schemes did not use synchronized signals and were inaccurate during transient conditions.
2) The new scheme operation time is below 80ms. The previous scheme did not have adjustable intentional delay and, due to technical limitations, operation time was 500 ms, which is not fast enough for some fast- evolving events.

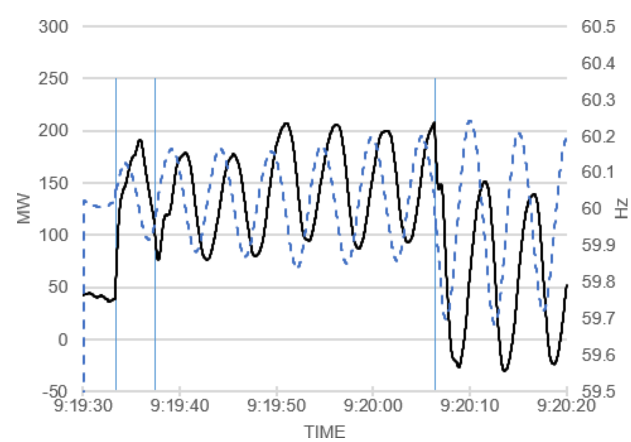


Fig. 10. WAMS records from the Panama – Costa Rica interconnection link July 13, 2019 event.

3) The new scheme uses real-time power measurement information from each generator, and it can select generators at several different power plants. 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.

New scheme logic is shown in Fig. 11.

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.

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 any of them decide, the other is blocked for 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 time equidistant samples are required to enable rate-of-change over time calculations. It also requires 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. Fig. 12 shows the PDC/Logic engine concept.

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, ETESA- CND looked for other solutions that can rely on just Panama's system, available signals, and infrastructure. Our approach is to limit sudden changes on the Panama – Central America link to a set 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 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 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 has with 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 EMS and generator controls are not fast enough to avoid the consequences of the growing flow using closed feedback loop control, the wide-area protection 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 $|DeltaP$ for external systems. HVDC systems may provide excellent solutions for these challenges because its continuous and fast control of active power, however investment is difficult to be justified for this amount of energy interchange. Future improvements may consider fast controls over inverter-based resources (IBR) 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.

1. *Generation Selection Logic*

The generation amount required to shed is defined by the operator in the HMI. Later this 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 provide inhibit inputs for the generator shedding logic. The HMI identifies 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 inhibits the corresponding generator from shedding automatically.

Table 1 shows all generation stations involved in the generation-shedding scheme.

If a generator was shed by an RAS scheme action, then it is automatically blocked for the following operations until the operator enables them again. This 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. 13.

Table 1. 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

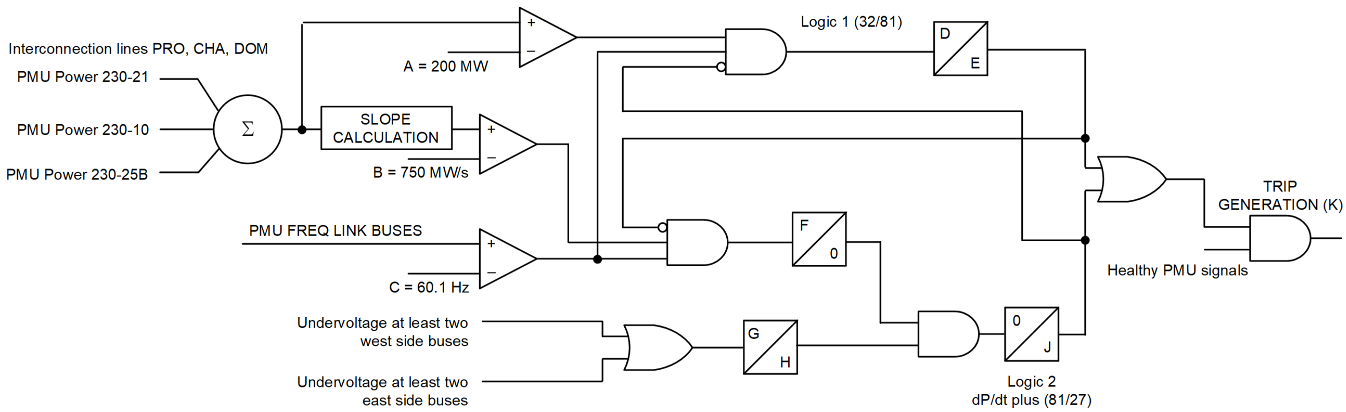


Fig. 11. New scheme logic based on PMU measurements.

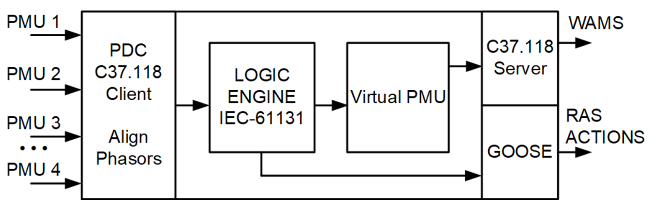


Fig. 12. PDC/Logic engine concept.

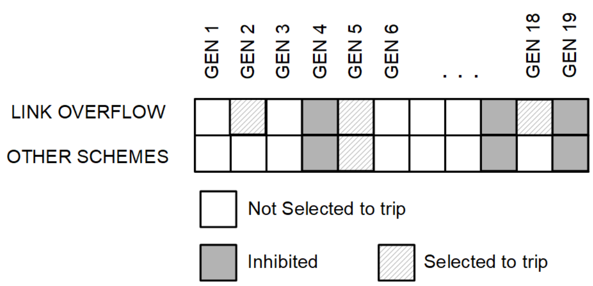


Fig. 13. Generator selection matrix.

5.2. *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 operations. 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 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 WAN 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 communication-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 by Castillo *et al.* [1] Fig. 14 shows general RAS architecture. Actual schemes include more than 50 IEDs at different facilities.

6. 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; this is 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 adjustment to them before the commissioning work. This also reduces the commissioning time on site due to most of the possible improvements being done in the lab. 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 are critical for success of the interconnection link RAS scheme described on this paper to validate dynamic performance.

7. 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 operations are described in this section.

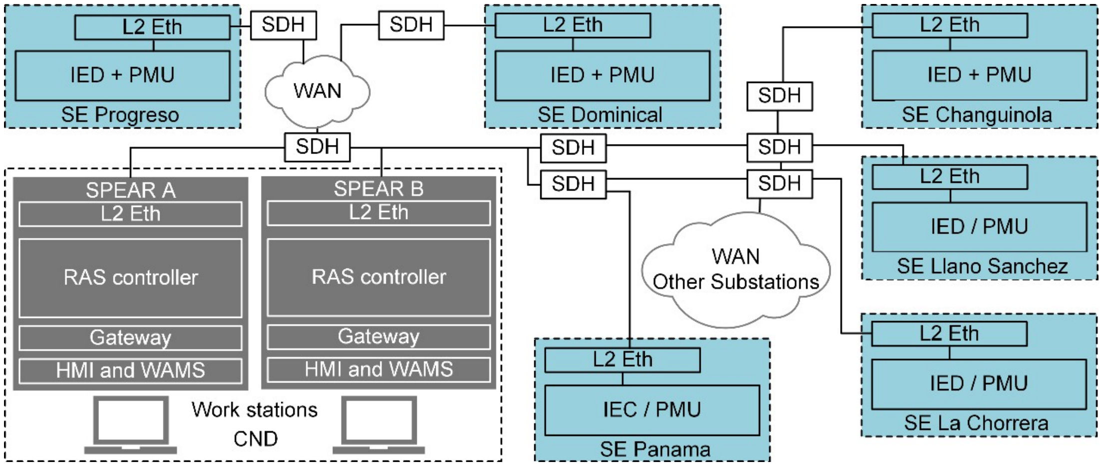


Fig. 14. General RAS architecture.

On April 22, 2022, there was a fault at one 34.5 kV distribution feeder close to the Chorrera substation 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 1 minute and 40 seconds the distribution operator closed breaker to test the faulted feeder. The test was negative because the permanent fault cleared after 238 ms. Even if 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. 15 shows voltage at Chorrera 230 kV (CHO) close to that of the feeder fault and it also shows Panama 115 kV (PAN) voltage measurement at the load center.

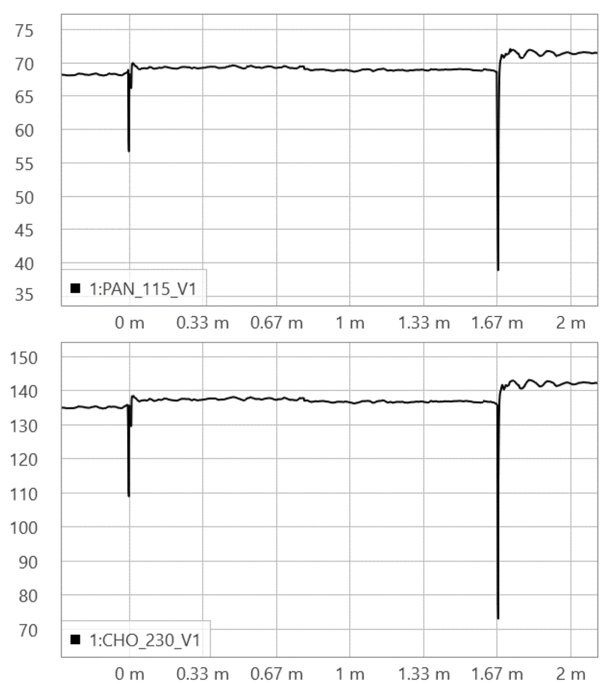


Fig. 15. Positive sequence voltages at CHO 230 kV and PAN 115 kV during CHO distribution feeder faults.

Fig. 16 shows a closer look into PAN 115 kV positive sequence voltage. The voltage dip was 58 percent of nominal phase-to-ground voltage. Low voltage remains around 500 ms before recovering to a stable condition, confirming 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 shows the performance and impact of PMU and PDC use 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 836 MW/seg, 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

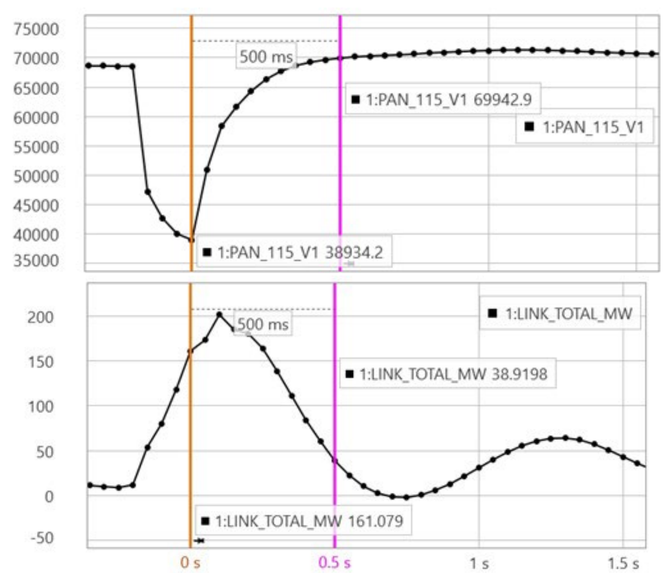


Fig. 16. Positive sequence voltages at PAN115 and total Central American link power, Apr 22.

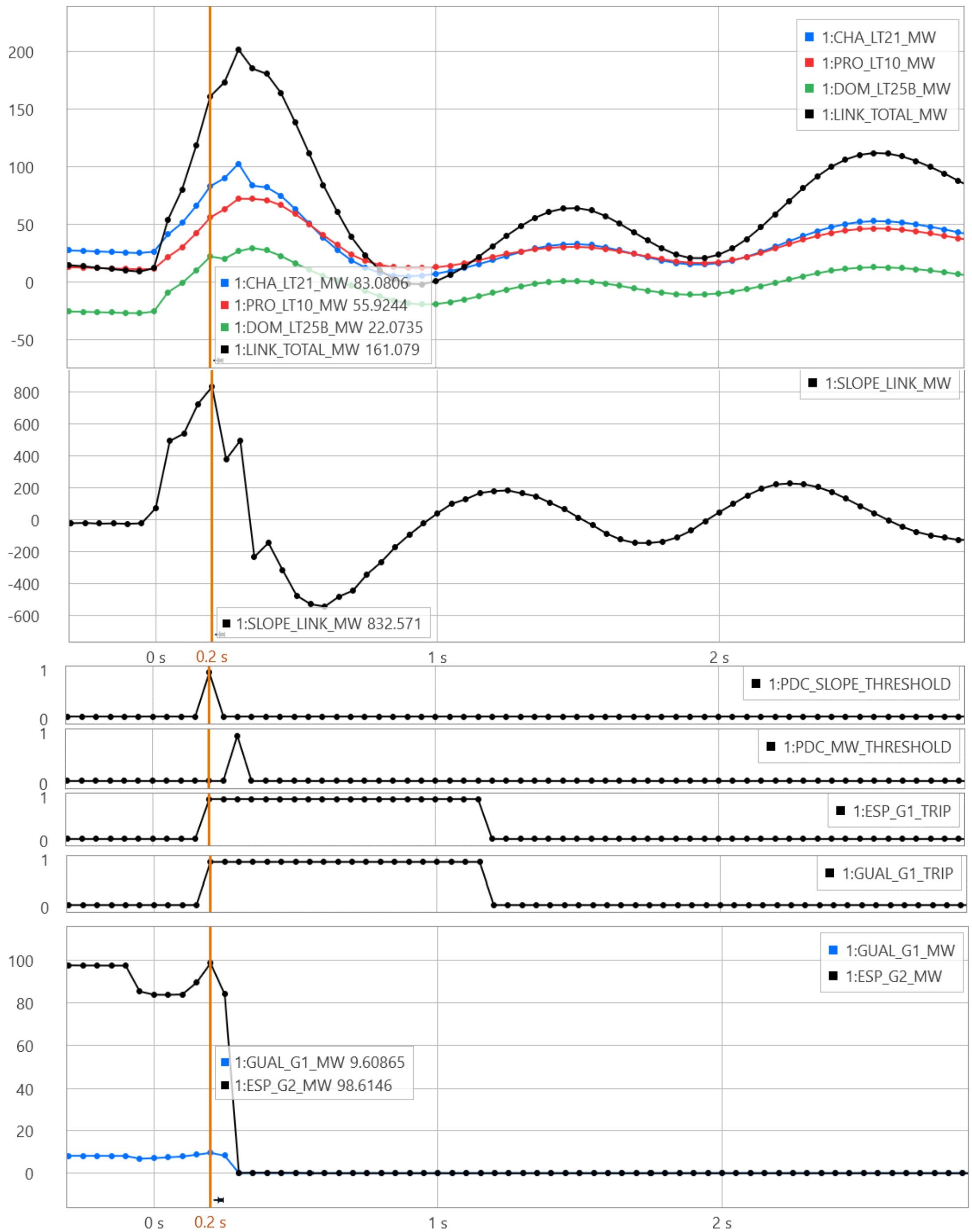


Fig. 17. Total and individual lines power, rate-of-change of power, generation-shedding, and digital signals related to RAS operation Apr 22.

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 GOOSE after the rate-of-change of power was detected, changing their power output to 0 MW before 100 ms.

As a virtual PMU is configured at PDC to serve analogue and digital signals calculated by the PDC engine using IEEE C37.118 and not only the phasor data, we are able to analyze not only the power system behavior, but also the PDC's and logic engine's calculations and performance.

Fig. 18 shows that even if the voltage recovered after 1 second and generation shed 108 MW, 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 system remains stable.

On September 9, 2022, a 34.5 kV distribution feeder fault at Llano Sanchez (LSA) caused a sustained voltage dip because of

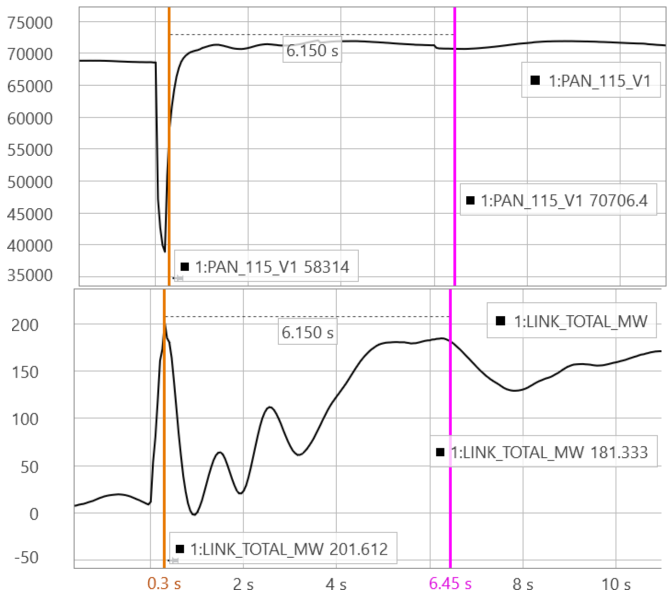


Fig. 18. Positive sequence voltages at PAN115 and total Central American link power, Apr 22.

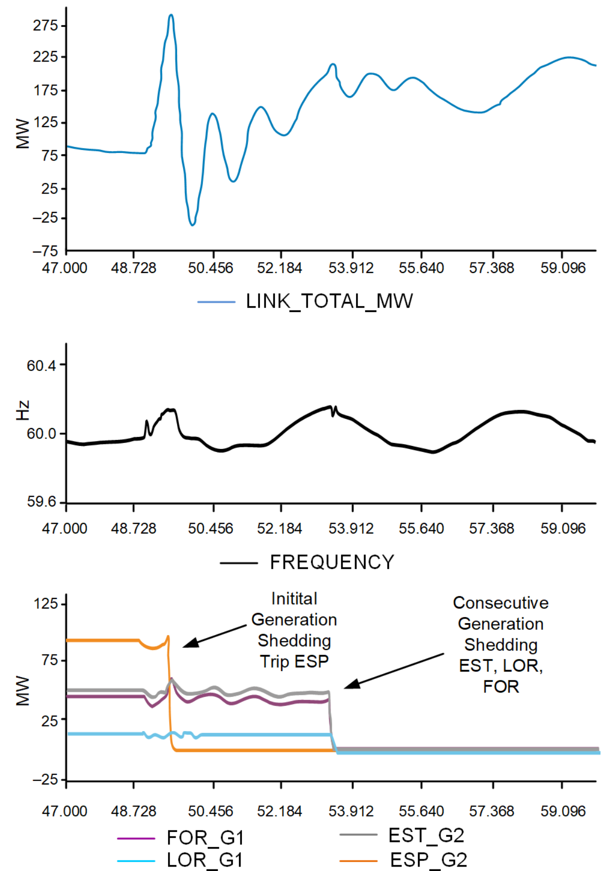


Fig. 19. Total power, frequency, and generation shed during two consecutive RAS scheme actions September 9, 2022.

incorrect protection operation. A phase-to-phase fault evolved to a three-phase fault and lasted more than 8 cycles. 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 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 event.

8. Conclusions

Implementation of an interconnection link 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 of several previous events to learn from past system performance.
3) FIDVR effects simulations and accurate complex load models are very challenging. Studies require proper modelling, 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 for use of a reliable wide-area communications infrastructure.

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

Solutions presented include generation shedding 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.

ETESA-CND 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 plant and individual generation information gathered in real time.

9. References

References

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