Wide-Area Measurement and Control Scheme Maintains Central America's Power System Stability

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Abstract—**The power system in Guatemala is part of the long, interconnected network in Central America that runs from the south of Mexico to Panama. This power system is connected to Mexico in the north and to El Salvador in the south. The power system in El Salvador is connected to the rest of the Central American countries in the south, all the way to Panama. The Guatemalan power system is a transmission corridor for power flowing from the abundant hydrogeneration resources in the southeast of Mexico, as well as a consumer of this power.**

The Guatemalan wide-area control scheme, called the wide-area supplementary control scheme (SCS), isolates the Guatemalan power system from the power system to the south of Guatemala when the scheme detects unstable operating conditions. This scheme is based on time-synchronized measurements of active power and modal analysis of the active power flow of the interconnection between Guatemala and El Salvador. Phasor measurement and control units (PMCUs) are installed at strategic buses in the Guatemalan power system. The strategic locations include the interconnections to Mexico and El Salvador. Operating modes in the power system that cause instability were identified based on operating experiences of the power system. The scheme detects unstable operating conditions and opens the interconnection with El Salvador to isolate the Guatemalan power system from the rest of Central America.

This paper discusses details of the Central American power system, the deployment of PMCUs, a modal analysis-based scheme, and the communications network of the scheme. It also presents events that show how the active power-based and modal analysis-based SCS avoided power system collapse.

I. INTRODUCTION

The power system in Guatemala, besides serving its local loads, also serves as the power corridor from Mexico to other Central American countries via its interconnection with El Salvador. The regional transmission network (RTN) interconnects Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama. Guatemala is the most northern country of the Central American RTN and links the Central American network to the Mexican power system.

The Mexican power system (50 GW) is significantly larger than the total interconnected Central American system (7 GW) and is a very strong system compared with the Central American system.

Fig. 1 illustrates the Central American Electrical Interconnection System, or SIEPAC (Sistema de Interconexión Eléctrica de los Países de América Central). The 230 kV transmission network wheels power among the members of this power system.

Fig. 1. Central American Electrical Interconnection System (or SIEPAC)

A 400 kV line from the Tapachula substation in Mexico to the Los Brillantes substation in Guatemala interconnects the two power systems. A power transformer steps down the voltage level to 230 kV, which is the SIEPAC transmission voltage level. The transmission system in Guatemala distributes the imported power to the local loads, but mostly wheels the power from Mexico to the SIEPAC system via the Ahuachapan substation in El Salvador.

Fig. 2 is a simplified diagram of the Guatemalan power system. The diagram shows the geographical location of the Tapachula, Los Brillantes, Guatemala Este, Moyuta, Aguacapa, and Ahuachapan substations. The transmission lines from Moyuta to Ahuachapan and from Aguacapa to Ahuachapan connect Guatemala to El Salvador.

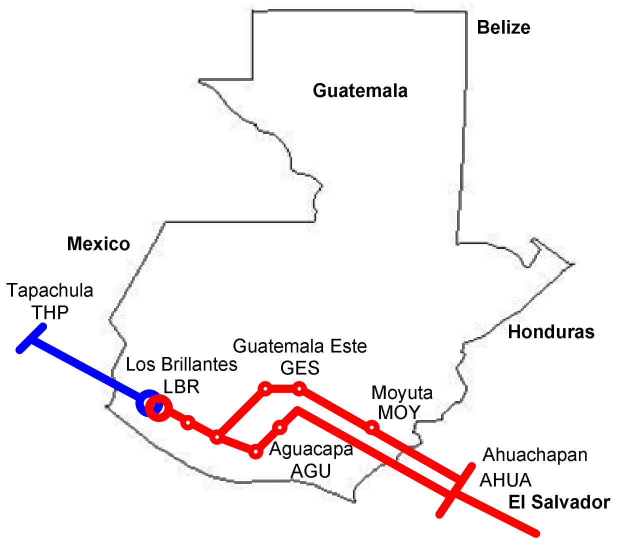


Fig. 2. The Guatemalan 230 kV network connects Mexico to the rest of Central America

II. Synchronized Measurement in Guatemala

In 2008, the wholesale electric market administrator Administrador del Mercado Mayorista (AMM) identified the benefits of using synchrophasor technology to operate the power system in Guatemala.

AMM coordinates the operation of power plants and transmission lines in Guatemala and the international interconnections with Mexico and the rest of Central America in order to optimize operating costs in an open-market environment. AMM also regulates short- and long-term prices in transactions of the power market. However, the most important function of AMM is to guarantee the delivery of reliable electrical energy to the loads in Guatemala.

The personnel at AMM are responsible for operating the system in the most efficient way, supervising the power system in real time, and managing electric energy transactions.

While AMM is not particularly responsible for the operation and maintenance of transmission lines, the main mandate for AMM is to secure the operation of the Guatemalan power system. Because of this challenge, AMM implements the emergency control systems required to meet this main purpose.

Based on their knowledge of the characteristics of SIEPAC interconnections and operating experiences with the Mexican power system, AMM conducted several power system stability and operational studies. Moreover, during the operation of the power system, occurrences of instability and blackouts provided information to propose a wide-area control scheme to aid in guaranteeing secure operation of the power system. The implementation of the AMM wide-area supplementary control scheme (SCS) started in 2011.

Since June 2010, SIEPAC has been experiencing large power oscillations. Fig. 3 shows the total active power exchange between Guatemala and El Salvador prior to a disconnection event on November 27, 2011. AMM coordinated with the transmission line operators and implemented control schemes in transmission line relays using the programmable logic capabilities of the relays. These schemes detected overloads in the interconnection lines and qualified their operation with time delay to open the corresponding interconnection.

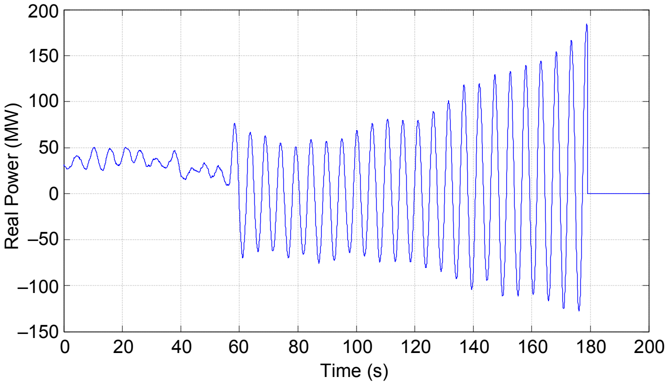


Fig. 3. Unstable active power oscillations between Guatemala and El Salvador on November 27, 2011

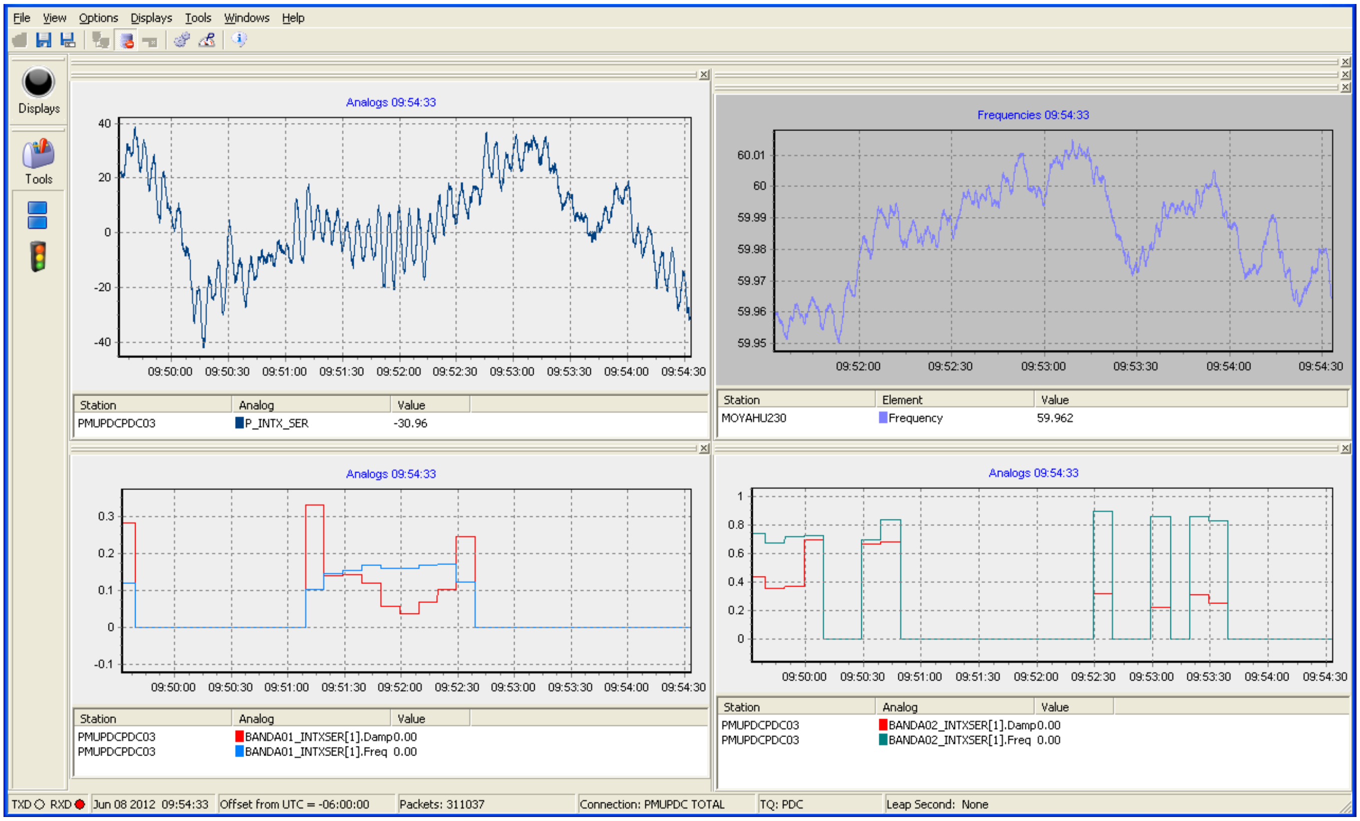
One of the challenges of operating the interconnected system is complying with the security requirements of the interconnection with Mexico. In the past, the link with Mexico was not allowed to operate during certain periods of the day when the system is more prone to instability. This operation limitation was not in the best interest of AMM because not having the link with Mexico can compromise the security of the Guatemalan power system. AMM also has economic reasons for this interconnection.

The event shown in Fig. 3, as well as other occurrences that ended in blackouts, prompted AMM to find the proper tools to guarantee the stable operation of the power system. AMM realized the potential of time-synchronized phasor measurements (synchrophasors) to provide information and flexible tools to operate the power system in stable conditions.

A. Synchrophasor-Based Monitoring System

AMM now monitors the operation of the Guatemalan power system using supervisory control and data acquisition (SCADA) and synchrophasors. A traditional SCADA system is in operation supplying the pertinent data to the operators every 4 seconds.

AMM operators also have access to visualized, real-time synchrophasor data, which are updated 30 times per second. Fig. 4 illustrates a typical human-machine interface (HMI) used by the operators, showing power and voltage measurements in key nodes of the system. The faster rate allows the operator to view and recognize transients never seen in the SCADA system [1]. Preexisting but invisible phenomena are now visible and actionable due to low latency and the coherency of the information. This overcomes the infrequent and incoherent data collection associated with typical SCADA client-server communication. One example is the recovery of the power system after a transmission line fault. The operators can visualize the power oscillations, generation trips, and power flows in the interconnection lines.



Station	Analog	Value
PMUPDCPDC03	🟦P_INTX_SER	-30.96

Station	Element	Value
MOYAHU230	🟦Frequency	59.962

Station	Analog	Value
PMUPDCPDC03	🟥BANDA01_INTXSER[1].Damp	0.00
PMUPDCPDC03	🟦BANDA01_INTXSER[1].Freq	0.00

Station	Analog	Value
PMUPDCPDC03	🟥BANDA02_INTXSER[1].Damp	0.00
PMUPDCPDC03	🟩BANDA02_INTXSER[1].Freq	0.00

TXD ○ RXD ● Jun 08 2012 09:54:33 Offset from UTC = -06:00:00 Packets: 311037 Connection: PMUPDC TOTAL TQ: PDC Leap Second: None

Fig. 4. Synchrophasor data in the control center

AMM has found that synchrophasor data and the corresponding visualization tools greatly complement traditional SCADA systems in the control center. Fig. 5 is a picture of the displays available in the AMM control center, where synchrophasor data displays are used together with traditional SCADA information.

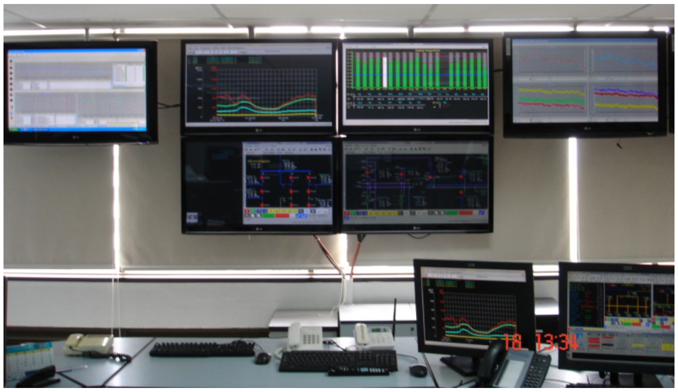


Fig. 5. Synchrophasor data complement traditional SCADA

B. Control Using Synchrophasor Data

Synchrophasor data can be used to take control actions [2] [3]. AMM identified this technology and implemented several schemes as part of its wide-area SCS based on synchronized measurements refreshed 30 times per second. This refresh rate allows for fast control applications with operating times of less than 100 milliseconds, which is not possible with the slower refresh rate (once every 4 seconds) of traditional SCADA.

The coherent nature of the synchrophasor measurements allows the implementation of both simple and sophisticated algorithms. A simple algorithm, for example, is the sum of two active power quantities measured from different nodes on the network. With traditional SCADA measurements that are not synchronized, arithmetic operations using noncoherent measurements are questionable. AMM also uses modal analysis techniques on the sum of two time-synchronized power measurements. The wide-area SCS sums the active power flowing in the two interconnection lines to El Salvador and applies modal analysis to the derived quantity.

Angle differences are also available for control. AMM will evaluate the use of angle difference data when more phasor measurement and control units (PMCUs) are in service.

III. Wide-Area SCS Details

AMM evaluated available synchronized measurement technologies and decided to use PMCUs to implement control algorithms instead of phasor measurement units (PMUs). AMM uses a leased communications network for this application. A synchrophasor processing unit (SPU) with phasor data concentrator (PDC) capability installed at the control center concentrates synchrophasor data from the PMCUs located at different substations. The SPU includes programmable logic and has the capability to send control commands to the PMCUs. A second, software-based PDC with archiving and publishing capabilities was deployed to provide visualization of the synchrophasor data to the power system operators.

A. Phasor Measurement and Control Units

The PMCUs used in this application have accurate synchronized measurement capabilities and receive control commands from the SPU where the control logic has been implemented. The PMCUs report measurements at 30 messages per second, and they have the capability to report up to six single-phase voltages and six single-phase currents. The wide-area SCS collects three-phase voltages and three-phase currents at each monitoring node on the transmission line terminals.

The PMCUs have programmable logic where schemes based on local information can be implemented. In addition to synchrophasor data, the PMCUs have the capability of sending 16 analog and 64 binary bits in the IEEE C37.118 data stream.

Some of the programmed local functions in the PMCU calculate the derivative of the power and the derivative of the voltage with respect to time, which are monitored at the control center.

The total number of PMCU devices to be installed in the power system is 22, with 16 installed at the time of this writing.

B. Communications Infrastructure

AMM does not own a wide-area communications network. Fortunately, the substations in Guatemala can be accessed via a communications service provider. Fig. 6 shows the AMM communications network based on Ethernet.

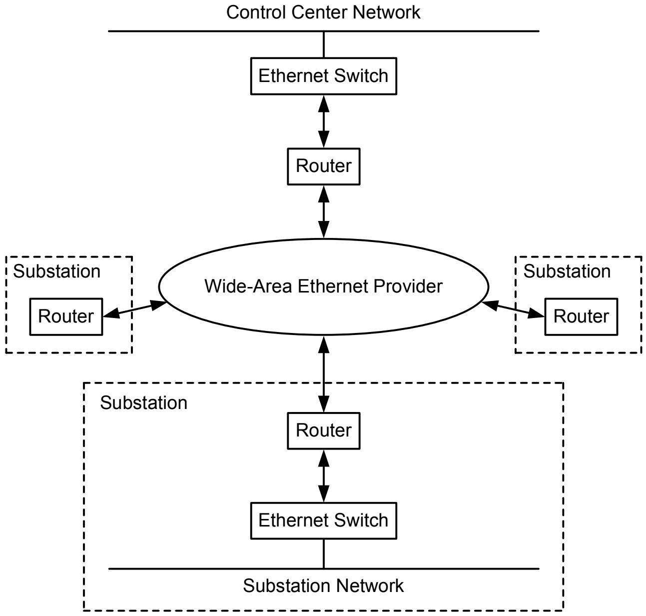


Fig. 6. Simplified AMM communications network

From the point of view of AMM, having a router at each substation and at the control center creates the necessary links to form an Ethernet network.

The wide-area communications network provider guarantees a 512 kbps transmission rate and high network reliability. The transmission delays in the network are insignificant and do not impact the overall operating time of the wide-area SCS. The network provider ensures the overall visibility of the network nodes at the substations and the control center.

Each PMCU sends two data streams over the Ethernet network. Fig. 7 shows the two synchrophasor message streams sent by one PMCU. Stream 1 goes to the control center PDC for publishing and archiving. Stream 2 goes to the online SPU, where control logic runs. There is a second, offline SPU that receives a repeated set of the synchrophasor messages received by the online SPU, and this second SPU is used to test and qualify control logic using the same data that the online SPU receives. AMM has found the offline SPU concept to be very useful for testing control logic and validating the programmed algorithms using active power system data. When the algorithm has been verified, it is sent to the online SPU for actual use.

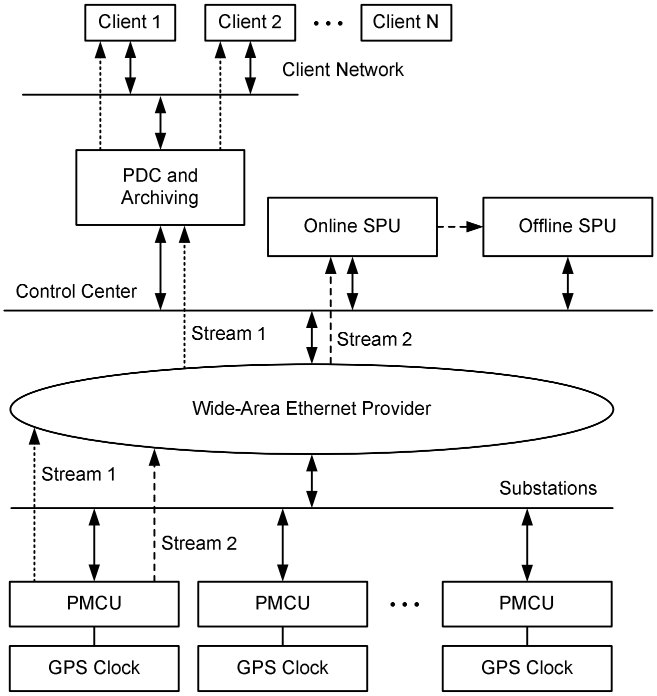


Fig. 7. Synchrophasor data paths across the Ethernet network

The architecture in Fig. 7 is typical for synchrophasor systems. In this application, no redundancy has been planned for the system. The software PDC that runs in a server computer collects synchrophasor messages at 30 times per second and publishes the data to several visualization clients in the control center.

The hardware where the software PDC is installed has a very large data storage capacity. It is equipped with 2 TB of storage. The system is set up to store every measurement sent to the PDC, and the system stores about 2 GB per day.

The visualization clients of the software PDC are deployed in several computers in the control center. The client software also archives the synchrophasor data in the client computer. The operators at the control center use this information to monitor the power system, as Fig. 4 and Fig. 5 illustrate.

C. Control With Synchrophasor Data

Fig. 7 shows the SPU receiving Stream 2 from a PMCU. The SPU can time-align synchrophasor messages from up to 20 PMCUs and has an IEC 61131 engine to customize the required logic.

The time-aligned synchrophasors, analog quantities, and binary bits in the IEEE C37.118 message sent by the PMCUs are available to the programmable logic engine of the SPU and can be used as inputs to prebuilt functions, like AND and OR logic gates, math functions, and timers. Advanced functions like modal analysis are also included in the SPU to create advanced algorithms. Furthermore, the SPU can send trip commands to the PMCUs. Fig. 8 illustrates the data and command exchange between one of the PMCUs and the SPU. The IEEE C37.118 data stream carries the synchronized measurements to the SPU. With the same network configuration, the SPU sends control bits embedded in the IEEE C37.118 command message. In this application, the PMCUs decode the commands to trip the corresponding circuit breakers.

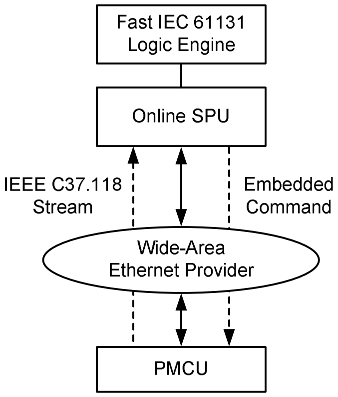


Fig. 8. Synchrophasor and command data exchange

IV. WIDE-AREA SUPPLEMENTARY CONTROL SCHEME IMPLEMENTATION

Fig. 2 and Fig. 9 show the two Guatemala interconnections. The interconnection in the north connects to Mexico. The two lines from Moyuta and Aguacapa connect to El Salvador in the south.

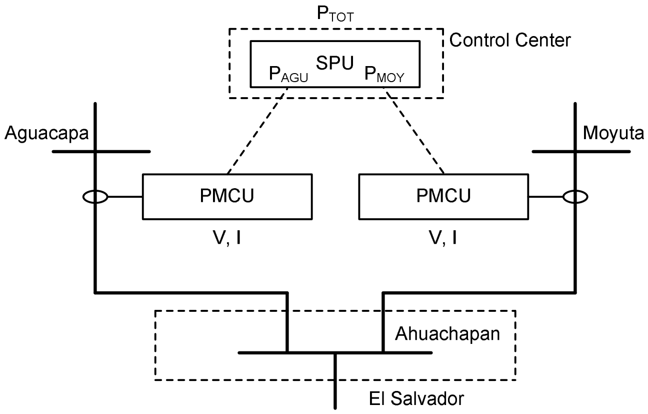


Fig. 9. Interconnection between Guatemala and El Salvador

At Aguacapa and Moyuta, two PMCUs stream synchronized measurements to the online SPU at the control center (see Fig. 9). This SPU collects the voltage (V) and current (I) phasors and calculates the active power flow exchange between Guatemala and El Salvador. P_{AGU} is the active power of the Aguacapa line, and P_{MOY} is the active power of the Moyuta line. The SPU calculates the total power flow ($P_{TOT} = P_{AGU} + P_{MOY}$) using the synchronized measurement from both terminals.

The coherency of the measurement in P_{TOT} can be used to implement decisions based on its magnitude as well as its modal content obtained from modal analysis.

A. Power Level Scheme

A power level scheme was previously implemented by programming the protective relays on the Aguacapa and Moyuta lines. These magnitude level checks were not reliable because decisions were made on measurements from individual lines.

An SCS that is based on the architecture shown in Fig. 9 and uses the total power exchange P_{TOT} to open the interconnection is a better choice than the power level scheme implemented in protective relays. Table I shows the power thresholds and their corresponding delays to disconnect Guatemala from the Central American power system.

TABLE I
INTERCONNECTION TRIP POWER LEVELS AND DELAYS

P_{TOT} (MW)	Delay (ms)
200	1,200
245	600
297	300

Since the implementation of the power level SCS, there has been an occurrence that demanded a disconnection from El Salvador.

The power exchange for this event is shown in Fig. 10. Before the sudden increase of power in the interconnection, the Moyuta line was receiving power from El Salvador. When the instability was detected, both lines were sending power to El Salvador. The interconnection to El Salvador was disconnected using the logic programmed in the SPU located at the AMM control center.

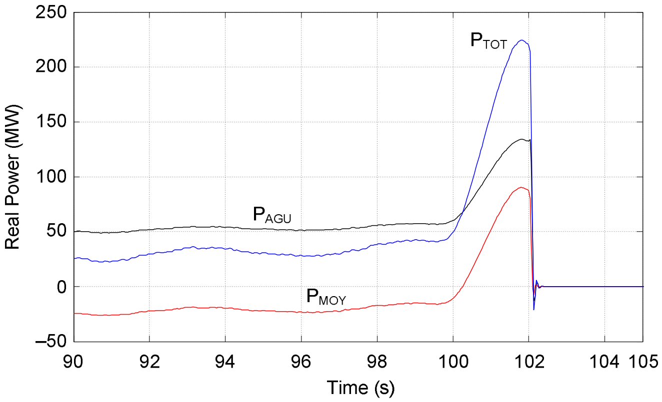


Fig. 10. Operation of the SCS based on active power levels

B. Modal Analysis Scheme

A real-time modal analysis scheme is also part of the SCS. Modal analysis uses synchrophasors to estimate power system oscillation modes and their associated amplitude and damping ratio. Low damping ratio values are good indicators of possible unstable oscillations. Therefore, having an early indicator to alert operators or a control scheme that triggers a remedial action to prevent growing oscillations that can cause system collapse is beneficial to the operation of the power system [4]. Typical oscillation modes for inter-area oscillations are in the order of 0.2 to 0.7 Hz and local-area oscillations are in the order of 0.7 to 2.0 Hz [5].

Fig. 3 shows an actual event experienced in the interconnection to El Salvador. Notice the growing oscillations. Modal analysis is a tool to identify oscillation modes and determine whether the oscillations are damped or growing.

Modal analysis is a mathematical technique used to decompose a signal in terms of its natural frequencies and associated amplitude and damping (refer to the appendix for a detailed description).

$$y(t) = \sum_{i} A_{m\_i} \bullet e^{\sigma_i \bullet t} \bullet \cos\left(2\pi \bullet f_{m\_i} \bullet t + \phi_{m\_i}\right) \qquad (1)$$

Equation (1) illustrates how to obtain the original signal from its components (modes). The signal being studied is the sum of several modes at different frequencies. The mathematical technique estimates the frequency (f), amplitude (A), damping coefficient (σ), and relative phase (ϕ) of each of the components of the signal using data from an observation window. If the damping coefficient is positive, the mode will tend to grow without bounds.

A real-time modal analysis uses an observation window to dynamically provide the estimation of these parameters to a user-defined real-time logic and threshold comparison. The frequencies identified are the modes in the data window.

1) Identification of Oscillation Modes

Based on the operating experience and recorded data of oscillatory events from AMM, oscillating modes that cause instability were identified and used in a modal analysis scheme that detects these undesired oscillations.

After stability studies and post-event analyses of events causing unstable oscillations, the oscillation mode of interest was identified to implement a modal analysis-based algorithm that detects unstable operating conditions.

One such analysis is shown in Fig. 11. Modal analysis on the active power flow from Guatemala to El Salvador showed a 0.19 Hz oscillation with a decreasing damping ratio that eventually became negative, as indicated by the growing oscillation in the power exchange. Additional system events also confirmed that the 0.19 Hz mode typically results in underdamped oscillations. This analysis used a 20-second observation window of synchrophasor data recorded at 30 messages per second.

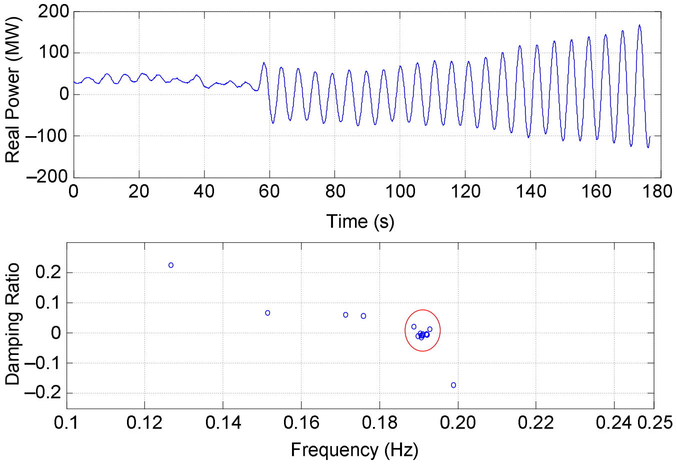


Fig. 11. Modal analysis identifies 0.19 Hz oscillations

2) Real-Time Modal Analysis Scheme

The modal analysis scheme shown in Fig. 12 is used to detect power system oscillations in real time (refer to the appendix for a description of modal analysis). This scheme uses synchrophasors to calculate the active power exchange between Guatemala and El Salvador, similar to the power level scheme (Table I).

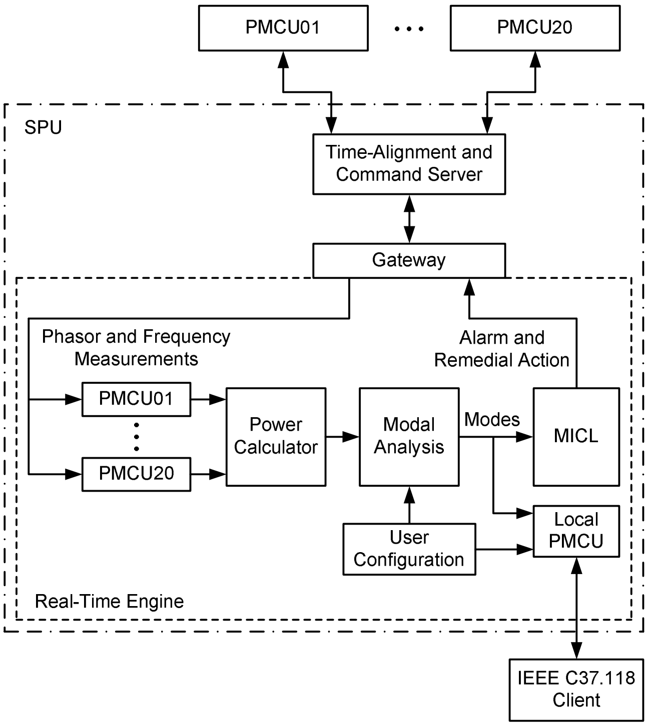


Fig. 12. Modal analysis scheme of the real-time power system

The modal analysis scheme also uses the time-synchronized power measurements of the two lines that interconnect these two countries. This active power sum P_{TOT} is the input signal to modal analysis. Modal analysis calculation results include the following information for each mode: amplitude, phase, frequency, damping, and damping ratio. The results of the modal analysis calculations are configured in the local PMCU server to output the modal analysis data to an external IEEE C37.118 client for monitoring purposes. The modal analysis calculation results are also available to the mode identification and control logic (MICL). MICL identifies a particular mode frequency, issues oscillation alarms and trip commands when the mode amplitude exceeds a user-programmable threshold, and enables the damping ratio check. Low damping ratio values (less than 0.05 per unit) activate the damping ratio alarm. If the mode damping ratio is decreasing and its amplitude is increasing, the logic activates a remedial action command. The alarms and remedial action command are routed to selected external devices through the command server.

3) AMM Mode Identification and Control Logic

Fig. 13 shows the AMM algorithm that identifies a particular mode of oscillation when a mode frequency is within a particular band determined by the application.

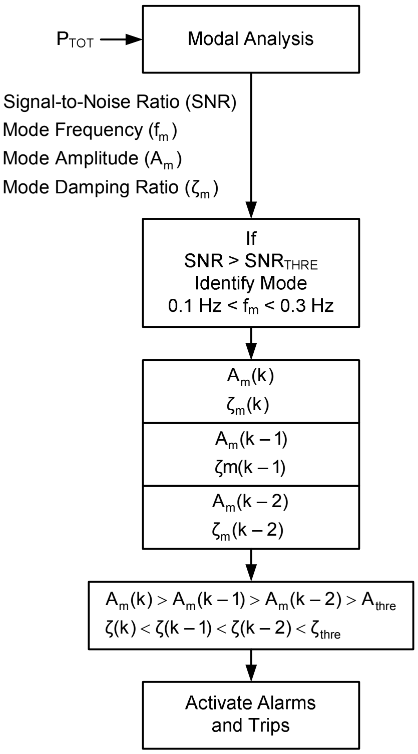


Fig. 13. Mode identification and control logic of AMM

In this case, the 0.19 Hz mode is an indicator of a possible unstable operating condition because of the interconnection with El Salvador. AMM defined a band between 0.1 and 0.3 Hz to identify unstable oscillations between Guatemala and El Salvador. Modal analysis uses an observation window of 20 seconds with 10-second updates. If the algorithm identifies a growing oscillation based on the amplitude and damping ratio of the identified mode, as Fig. 13 illustrates, the modal analysis scheme sends a command to trip the two lines to El Salvador.

4) Operational Experience

Time-synchronized measurements provide additional insight into power system operating conditions. Fig. 14 shows the active power flows from Guatemala to El Salvador in the Aguacapa-Ahuachapan line, from El Salvador to Guatemala in the Moyuta-Ahuachapan line, and the total power exchange (the sum of the two power flows) from Guatemala to El Salvador. Notice the existence of circulating power flow when the power exchange is low (Fig. 10 illustrates a similar operating condition). Also observe the power exchange fluctuations, which can be an indication of a system prone to instability.

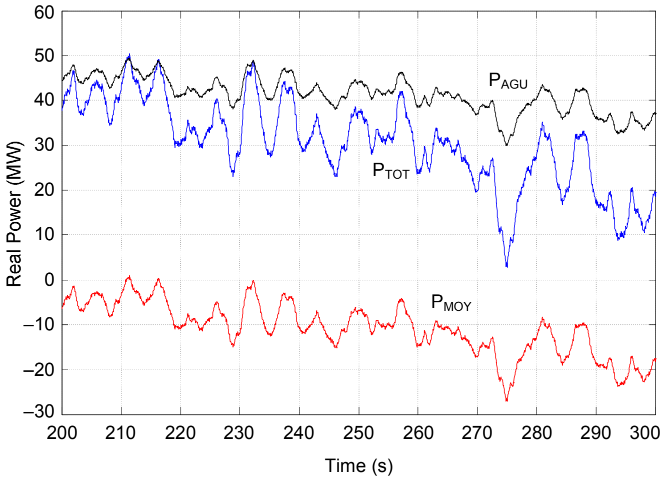


Fig. 14. Active power flow exchange in the interconnection between Guatemala and El Salvador

5) *Implications of the Modal Analysis Scheme for the Guatemalan Power System*

One of the direct benefits of the modal analysis scheme has been satisfying the Mexican power system requirements. Without this scheme in service, the Mexican power system limited the interconnection with Guatemala to specific times of the day. The reason had to do with the secure operation of the Mexican power system and any unwanted oscillation associated with the Central American system. With the modal analysis scheme in service, the interconnection between Mexico and Guatemala does not have time-of-day restrictions, providing Guatemala and the rest of the Central American countries with a more stable power system and additional energy resources.

V. FIRST OPERATION OF THE WIDE-AREA SUPPLEMENTARY CONTROL SCHEME

The modal analysis scheme was commissioned on June 8, 2012. On July 28, 2012, the interconnected SIEPAC power system was operating on two islands. The larger island included the power systems of Mexico, Guatemala, El Salvador, and Honduras. The smaller island included the power systems of Nicaragua, Costa Rica, and Panama. Undamped active power oscillations between Guatemala and El Salvador started to occur right after the synchronization of the two networks, as Fig. 15 illustrates. The wide-area SCS correctly identified the oscillation mode of 0.22 Hz and issued a trip command to open the interconnection between Guatemala and El Salvador. Fig. 16 shows the frequencies of the two networks before and during the power oscillation and after the opening of the interconnection. We can observe that the two systems maintained stability. The frequency of the Guatemala-Mexico network settles around 60.09 Hz and the rest of Central America at 59.95 Hz.

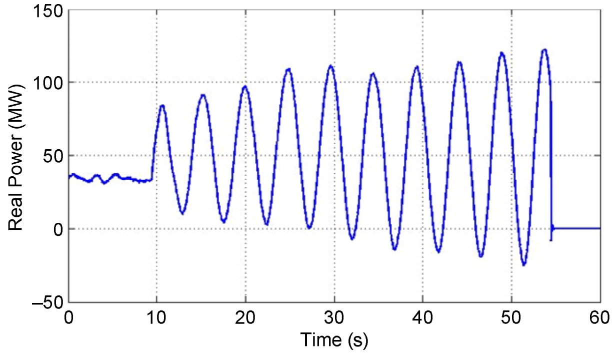


Fig. 15. Undamped active power oscillations and operation of the wide-area supplemental control scheme

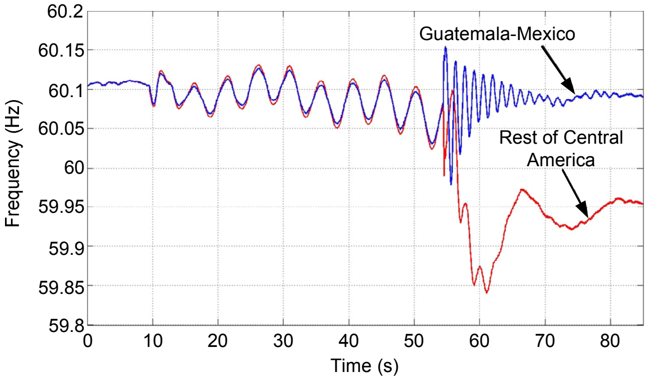


Fig. 16. Frequencies of the Guatemala-Mexico and the rest of Central America networks before and after system separation

Fig. 17 shows the active power flow from the Guatemala Este substation to the Moyuta substation in Guatemala. The oscillations in frequency (see Fig. 16) and active power (Fig. 17) subsided following the disconnection of the power system network south of Guatemala. Notice that the active power oscillations prior to the synchronization are significantly reduced following the disconnection. This reduction is due to the strong interconnection with the Mexican power system.

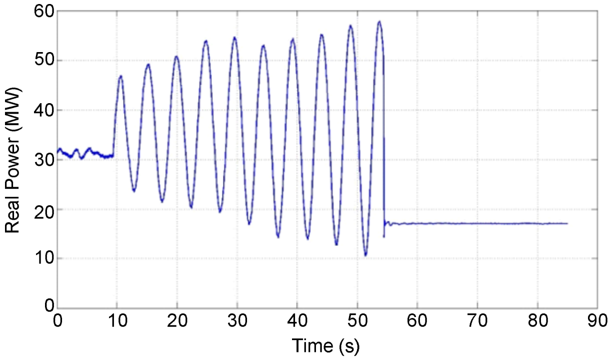
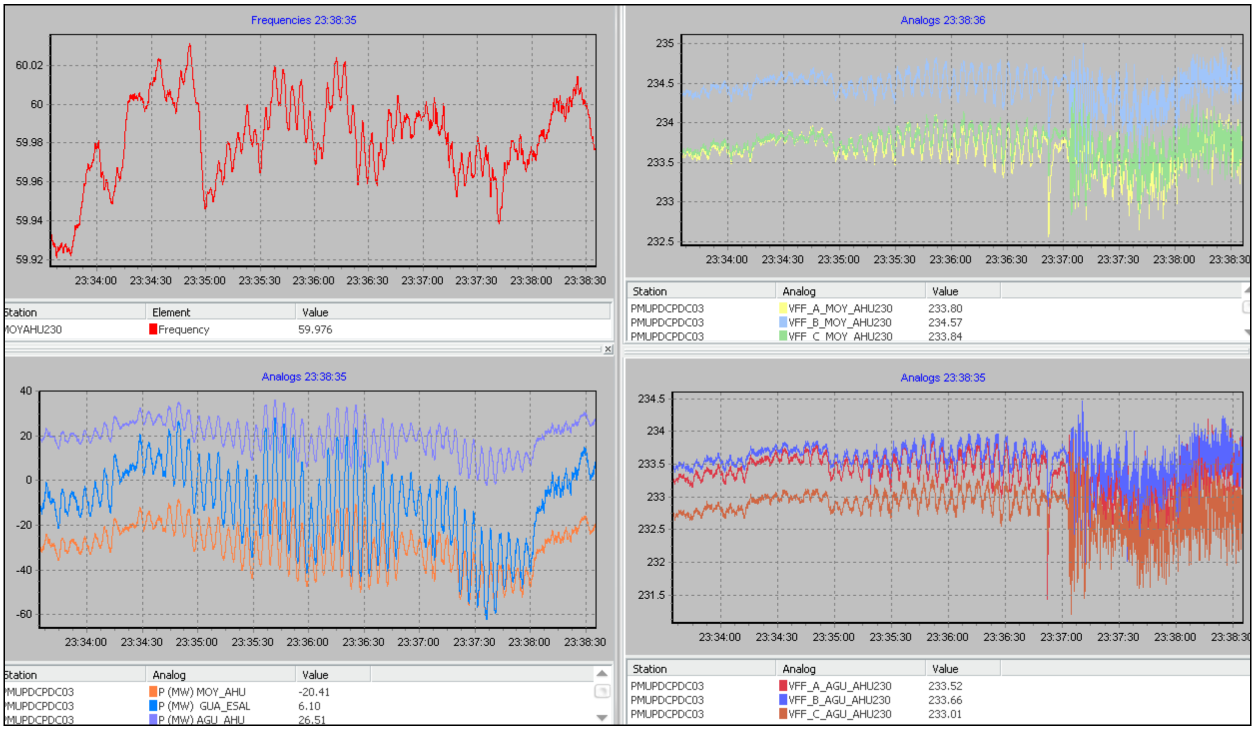


Fig. 17. Active power flow of the Guatemala Este-Moyuta line before and after system separation

VI. ARCHIVING AND OPERATOR INTERFACE

AMM archives all measurements (voltages and currents) and derived quantities (power and dP/dt). This archiving system allows AMM to review and study power system events. AMM uses the archived data to produce reports, further analyze the power system behavior, and validate the wide-area SCSs.

The archiving process fills 2 GB of data storage every day. The server in the control center has the capacity to store close to 2 years of measurements at this rate.



tation	Element	Value
OYAHU230	🟥 Frequency	59.976

Station	Analog	Value
PMUPDCPDC03	VFF_A_MOY_AHU230	233.80
PMUPDCPDC03	VFF_B_MOY_AHU230	234.57
PMUPDCPDC03	VFF_C_MOY_AHU230	233.84

tation	Analog	Value
MUPDCPDC03	P (MW) MOY_AHU	-20.41
MUPDCPDC03	P (MW) GUA_ESAL	6.10
MUPDCPDC03	P (MW) AGU_AHU	26.51

Station	Analog	Value
PMUPDCPDC03	🟥 VFF_A_AGU_AHU230	233.52
PMUPDCPDC03	VFF_B_AGU_AHU230	233.66
PMUPDCPDC03	VFF_C_AGU_AHU230	233.01

Fig. 18. Typical operator displays showing measured voltages, frequency, power flow, and modal analysis-identified modes

Fig. 18 illustrates one of the operator displays in the control center. The displays are fully configurable by the operator. The operator can use the visualization software to access and display the archived measurements.

VII. CONCLUSION

This paper presents an innovative wide-area control scheme based on synchrophasors that is in service in Guatemala. This scheme identifies abnormal operating conditions and opens the interconnection with El Salvador to maintain the stability of the power system.

The scheme based on real-time modal analysis calculations identifies modes in the band of 0.1 to 0.3 Hz. It opens this interconnection if the amplitude of this mode increases and its damping ratio decreases.

Having this modal analysis-based SCS in service allows the Guatemalan network to be connected to the Mexican network. This interconnection improves the stability of the Central American power system and provides more electrical energy resources to this region.

VIII. APPENDIX

A. *Modal Analysis in Brief*

Modal analysis is a signal decomposition mathematical technique. It recognizes frequency modes and associated constants from a signal.

B. *Signal Modal Representation*

Modified Prony analysis (MPA) is used to perform modal analysis. MPA uses the linear combination of multiple exponential oscillation modes to approximate an original signal, x[n], that a device samples at fixed time intervals. For an array of data samples x[1], …, x[N], MPA estimates $\hat{x}[n]$ according to (2) for $1 \le n \le N$ [3].

$$\hat{x}[n] = \sum_{m=1}^{M} A_m e^{\sigma_m nT} \cos(2\pi f_m nT + \varphi_m) \qquad (2)$$

where:

$\hat{x}[n]$ is the estimated signal.
M is the number of modes.
m is the signal mode.
A_m is the amplitude of mode *m*.
σ_m is the damping constant of mode *m* in s^{-1}.
f_m is the frequency of mode *m* in hertz.
φ_m is the phase of mode *m* in radians.
T is the sampling interval in seconds.

1) *Damping Ratio*

Modal analysis uses (3) to calculate the damping ratio (ζ_m) from the frequency and the damping constant and to determine the rate of decay in the oscillation amplitude.

$$\zeta_m = -\frac{\sigma_m}{\sqrt{\sigma_m^2 + (2\pi f_m)^2}} \qquad (3)$$

A negative damping ratio (positive σ_m) indicates an increasing oscillation, an unwanted operating condition that can lead to power system instability if action is not taken within a few seconds.

2) Signal-to-Noise Ratio

Modal analysis also compares the estimated signal against the original signal. Modal analysis uses (4) to calculate the SNR in dB, which measures the quality of the component fit into a data window. MPA is a linear approximation technique, so it will produce a low SNR value if the data sample array contains nonlinear transitions. In power systems, discrete switching events, such as line tripping, can cause nonlinear transitions. The SNR value normally improves as a switching event leaves the observation window of modal analysis and the power system settles into pure oscillation mode. A high SNR value (greater than 80 dB, for example) indicates that the analysis result is a good approximation of the original signal.

$$\mathrm{SNR} = 10\log_{10}\left(\frac{\sum_{n=1}^{N} x[n]^2}{\sum_{n=1}^{N}\left(x[n]-\hat{x}[n]\right)^2}\right) \qquad (4)$$

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X. BIOGRAPHIES

José Vicente Espinoza graduated from the University of San Carlos – Guatemala with a degree (Licenciatura) in Electronics Engineering in 1998. Currently, he works at Administrador del Mercado Mayorista (AMM), the wholesale and system operator in Guatemala. He has been with AMM since October 1998, and he is a coordinator in the department of electrical studies and the representative of the System Operator and Market Operator (SO/MO) for Guatemala to the Technical Security Committee of the Central American System Operator. He has participated in the electrical studies that determined the maximum power transfer between Guatemala and El Salvador, small signal studies, operational security among the Central American countries, and the maximum power transfer capability from Mexico to Central America. Also, he participated in the design and proposal of the SCS (Supplemental Control Scheme) and its implementation. He is now in charge of the AMM synchrophasor project denoted as “Implementation of PMUs and PDCs in the National Interconnection System in Guatemala.”

Armando Guzmán received his BSEE with honors from Guadalajara Autonomous University (UAG), Mexico. He received a diploma in fiber-optics engineering from Monterrey Institute of Technology and Advanced Studies (ITESM), Mexico, and his MSEE and MECE from the University of Idaho, USA. He served as regional supervisor of the Protection Department in the Western Transmission Region of the Federal Electricity Commission (the Mexican electrical utility company) in Guadalajara, Mexico, for 13 years. He lectured at UAG and the University of Idaho in power system protection and power system stability. Since 1993, he has been with Schweitzer Engineering Laboratories, Inc., in Pullman, Washington, where he is a fellow research engineer. He holds numerous patents in power system protection and metering. He is a senior member of IEEE.

Fernando Calero received his BSEE in 1986 from the University of Kansas, his MSEE in 1987 from the University of Illinois (Urbana-Champaign), and his MSEPE in 1989 from the Rensselaer Polytechnic Institute. From 1990 to 1996, he worked in Coral Springs, Florida, for the ABB relay division in the support, training, testing, and design of protective relays. Between 1997 and 2000, he worked for Itec Engineering, Florida Power and Light, and Siemens. In 2000, he joined Schweitzer Engineering Laboratories, Inc. and presently is a senior automation systems engineer.

Mangapathirao (Venkat) Mynam received his MSEE from the University of Idaho in 2003 and his BE in electrical and electronics engineering from Andhra University College of Engineering, India, in 2000. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2003 as an associate protection engineer in the engineering services division. He is presently working as a lead research engineer in SEL research and development. He was selected to participate in the U.S. National Academy of Engineering (NAE) 15th Annual U.S. Frontiers of Engineering Symposium. He is a member of IEEE.

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