Automatic Triggering of the Interconnection between Mexico and Central America using Discrete Control Schemes

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***Abstract*—In the current energy exchange market it is essential to guarantee continuity and quality of supply both in steady state and during contingencies that might occur in any subsystem of interconnected systems. In this work it is shown how the geographical and topological characteristics of the subnetworks directly affect the quality and reliability in the energy exchange, especially when subsystems are interconnected without asynchronous ties that prevent power, frequency or voltage oscillations. This paper describes the problems faced by the interconnection between Mexico and the countries that define the Interconnected Electric System of the Central American Countries (SIEPAC). Different oscillations that have occurred are analyzed. Discrete control schemes to automatically trigger the 400 KV circuit that interconnects the systems of Mexico and Guatemala are proposed.**

***Index Terms*—Inter-area oscillations, Phasor Measurement Units (PMU) and Wide-Area Measurement System (WAMS).**

I. Introduction

THE Mexican power system is comprised by three independent networks: 1) the national interconnected system, 2) the north Baja California system and 3) the southern Baja California system, as shown in Figure 1. The Mexican interconnected system integrates substations trough a transmission network of 400 KV and 230 KV. This system covers an area of more than 300 km between two distant borders: with USA in the north and with both Guatemala and Belice in the south. The interconnection between Mexico and Central America realizes the coupling of two systems with a proportion of approximately 5 to 1 in terms of total MW of capacity installed. At the beginning of 2009, the first tests to interconnect Mexico and Guatemala were made through a 400 KV circuit connecting the substations of Tapachula Potencia (THP) in the south of Mexico with Los Brillantes (LBR) in Guatemala, forming the THP-LBR circuit (Figure 1). The main network in Guatemala is synchronized using a 400/230 KV and a 225 MVA power transformer located in the LBR substation. The power system of Guatemala is connected to the rest of the Central American countries: El Salvador, Honduras, Nicaragua, Costa Rica and Panama and together they form the Interconnected Electric System of Central American Countries (SIEPAC) as shown in Figure 2. Synchronizing the Mexican power system to the SIEPAC network involves the synchronization of a network of 230 KV with over more than 2000 km.

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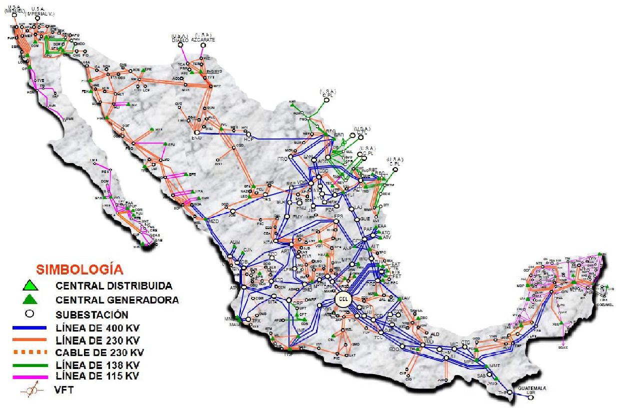

Fig. 1. The Mexican Electric Power System

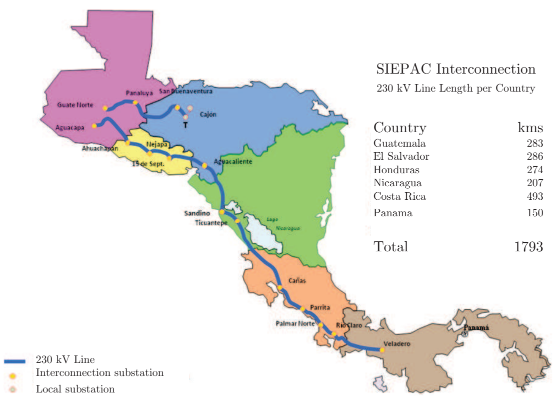

Fig. 2. Interconnected Electric System of Central American Countries (SIEPAC)

After several analyses and infrastructure build-up, the synchronization of the Mexican system to each of the countries (one by one) that form SIEPAC was scheduled. The first interconnection was made on April 2009 to synchronize the systems of Mexico and Guatemala. It was agreed to close the interconnection in the Guatemalan substation LBR in order to have adequate voltage control by regulating the reactive power in the machines located in the southeast of Mexico. The interconnection was monitored using the Syncrophasor Measurement System (SIMEFAS) of the Federal Electric Company (CFE) in Mexico [1], [2].

For this first interconnection, CFE developed a synchroscope using measurements from phasor measurement units (PMUs) located in the substation LBR, in Guatemala. However, since ordinary PMUs cannot perform control actions such as automatic synchronization, signals such as frequency,

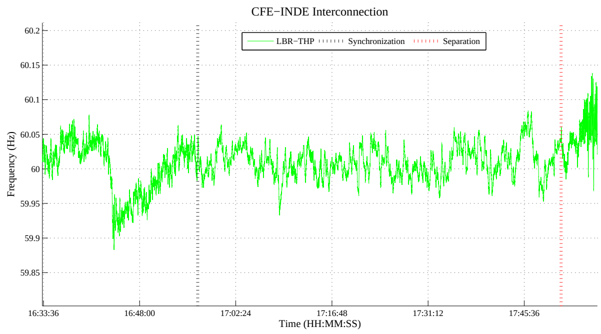

Fig. 3. Frequency during the first synchronization of the Mexican and Guatemalan systems.

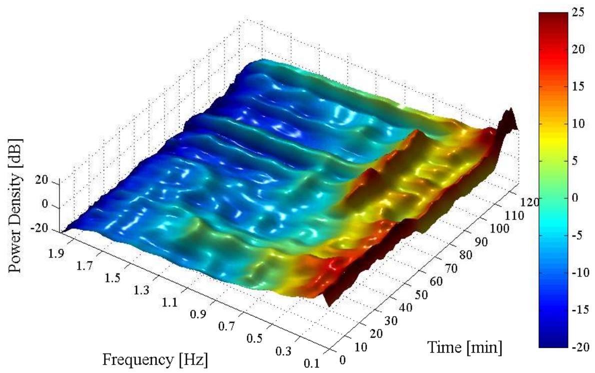

Fig. 4. Change of frequency in the dominant oscillatory mode from 0.28 Hz to 0.7 Hz, after the synchronization.

voltage, angle difference and speed were sent to a conventional synchronizer to carry out the necessary control actions. Figure 3 shows the frequency during the first interconnection of the two systems. After the synchronization, the oscillatory mode (0.28 Hz) of the Mexican system changes to low-damped 0.7 Hz mode in the new combined Mexican-Guatemalan system, as seen on Figure 4, [3], [4].

II. Synchronization Process to Couple the Mexican System to SIEPAC

The process to integrate all the SIEPAC countries with the Mexican system was slow. The process was designed to prioritize stability during the interconnection of each new system. In the same form, the process was designed to analyze the impact of specific loads and generation on each of the systems that were being integrated; the objective was to determine adequate operating conditions for permanent interconnections. During the synchronizations, different amount of real power (0, 60, 90 and 120 MW, respectively) were transferred among the systems through the circuit THP-LBR, in the borders of Mexico and Guatemala. Figure 5 shows that during all synchronizations the magnitude of the first swing in the real power was proportional to the angular difference between the systems at synchronism; this is because each synchronization was carried out in similar operating conditions. However, the oscillatory mode visible during each case was different

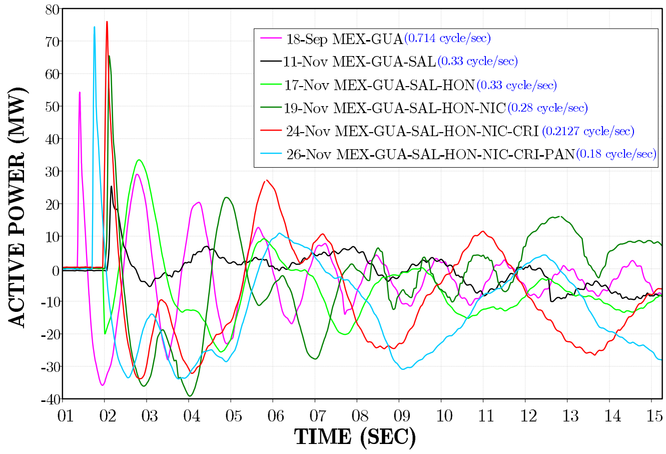

Fig. 5. Real power flow in the circuit THP-LBR during the synchronization of each system.

as a result of the change in inertia and machine control contributions from each new system [5], [6], [7].

After the synchronization of the systems and readjusting some controllers and stabilizers in machines of Central America, two schemes were successfully applied, designed to open the interconnection between Mexico and Guatemala (following faults in the Mexican network): a single pole tripping and reclosing scheme in the THP-LBR circuit and a discrete control scheme.

III. Discrete Control Schemes to Interconnect Mexico-SIEPAC System

A. Automatic tripping due to low frequency and inverse power flow between Mexico and Guatemala

Currently in operation, the objective of this scheme is to protect the Central American network against sudden loss of generation in Mexico. The scheme utilizes power flow computed from PMU measurements from Mexico to Guatemala. This scheme monitors the power flow direction, when the frequency drops, an undesirable inverse power flow from SIEPAC to Mexico may occur having considerable impact on the Central American network.

During the first commercial operating period of the THP-LBR circuit, several emergency situations have occurred with successful operation of this control scheme. Different operations of this scheme have been used to identify the optimal conditions to trigger the interconnection and minimize risk. The first operation of this control scheme was on March 2010 with the loss of 778 MW of generation in the north of Mexico. Up to this date, the low frequency limit was set to 59.75 Hz with an inverse power flow of 135 MW and operating times of 0.33 and 0.5 sec, respectively. This event helped to conclude that it was possible to reduce the risk of oscillations in Central America by readjusting the frequency limits to a new value of 59.85 Hz and a new inverse power flow limit of 110 MW constant during 20 cycles.

On June 2010 a new event occurred, the loss of 1490 MW of generation from a thermoelectric station located southwest of Mexico. The interconnection Mexico-SIEPAC was successfully opened having a frequency of 59.72 Hz, an inverse power flow of 189 MW after 20 continuous cycles of frequency below 59.87 Hz and inverse power flow of 110 MW.

A third operation of this scheme occurred on July 2010 as a consequence of 2166 MW of generation loss from two thermoelectric stations (in two different stages), both located northeast Mexico. The frequency in the Mexican network raised 59.65 Hz following the loss of the first station to finally set on 59.5 Hz after the loss of the second station. Although the operation of the control scheme was correct, the execution time was slow (57 sec). The problem was caused by the number of stages in which the event occurred, and in addition, because the limit of the inverse power flow was reached after the loss of the second station when the frequency was already 59.75 Hz with an inverse power flow of 125 MW.

B. *Automatic line tripping due to low voltage*

In order to maintain voltage stability, the installation of a remedial protection scheme is being analyzed. It requires opening the interconnection during disturbance events in Central America and also considers events where primary and backup protections do not operate. In such conditions, this type of faults may cause voltage drops in the south of Mexico and consequently activate the operation of low voltage protections. This scheme is being designed by CFE in Mexico based on the analysis of a similar disturbance which occurred on January 2011. A fault in a 230 KV transmission line in Guatemala lasting 45.5 sec produced a drop in the voltage at the THP bus, reducing the voltage from 400 KV to 370 KV and to 105 KV in the 115 KV bus. Under this conditions, the coordination of the protection schemes in Mexico are designed to operate in the THP-LBR circuit. For this reason is important to implement an intelligent scheme, to detect voltage drops where the origin of these faults are in Central America, to adequately open the interconnection Mexico-SIEPAC preventing voltage drops in the 400 KV and 115 KV buses in THP that eventually could lead to a collapse in the south of Mexico.

C. *Automatic line tripping due to power oscillations*

The two previous schemes can aid in maintaining the exchange of energy among the systems. However, is important to analyze the triggering of the interconnection with Central America when Mexico presents frequency, voltage and phase angle problems as well as overload in the circuits or in the 400/230 KV transformer in the station LBR in Guatemala. In such conditions, the interconnection produces power and frequency oscillations requiring the tuning of power systems stabilizers and readjusting automatic voltage regulators (AVR) from machines operated by diverse companies in Central America [3], [7], [8].

Using modal analysis from PMUs, the dominant oscillation frequencies have been determined in different points of both systems. A multi-node modal analysis tool was developed to detect relevant oscillatory modes, identify the contribution to each mode from every measurement location, and performing aggregation of coherent nodes [3], [4].

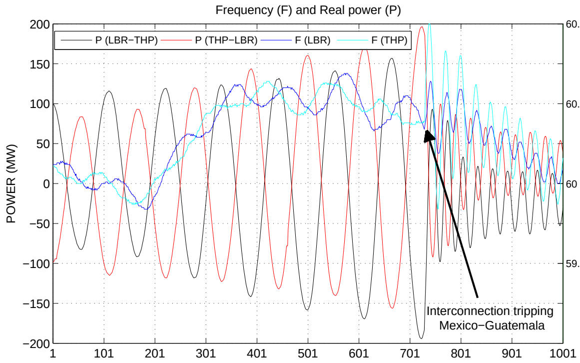

Fig. 6. Real power and frequency in the extremes of the circuit THP-LBR, after the second event.

One of the most relevant low frequency oscillations occurred on December 2010. During a low demand day a sudden load increase occurred, exciting an oscillatory mode of 0.2 Hz between the Mexico-SIEPAC systems. The interconnection between Guatemala and El Salvador was manually opened and the frequency of the oscillations increased to 0.68 Hz, which tripped the interconnection between Mexico and Guatemala at THP-LBR. When the 0.2 Hz oscillations were detected in SIEPAC, the full Mexico-SIEPAC system was interconnected and the damping of the oscillatory mode was negative, as a consequence, growing oscillations of up to 341 MW were detected in the circuit THP-LBR. The interconnection between Guatemala and El Salvador was manually opened and the frequency of the oscillation increased from 0.2 to 0.68 Hz with a (positive) damping ratio of (0.88%) which later changed to zero maintaining the oscillations in the system.

Figure 6 shows the details of the tripping in the interconnection between Mexico-Guatemala. Here the frequency and real power were computed by PMUs on both extremes of the circuit THP-LBR. In the same figure, the disconnection time of the Central American system can be observed, as well as the change of frequency of the oscillation. Figure 7 shows frequency vs active power (F-P) curves for the THP-LBR circuit before and after the triggering of the interconnections. For comparison, two oscillation periods prior to the triggering of the system are shown. The vertical oscillation becomes horizontal with more sensitivity to the frequency and less power oscillation.

In the THP substation there is enough power injection to feed the local 115 KV load and the 400 KV circuit to Central America. This line can be considered as the equivalent of the Central American system and can represent the behavior of the frequency with respect of the power flow before and after of the triggering of the interconnection Guatemala-El Salvador.

During the same event was possible to monitor and analyze the behavior of the voltage at the THP and LBR nodes. Figure 8 shows the voltage and reactive powers. Note that the voltages at the stations do not exceed 410 and 406 KV, respectively. This shows that the machines located at the south of Mexico were correctly adjusted to provide constant voltage independently of loading conditions.

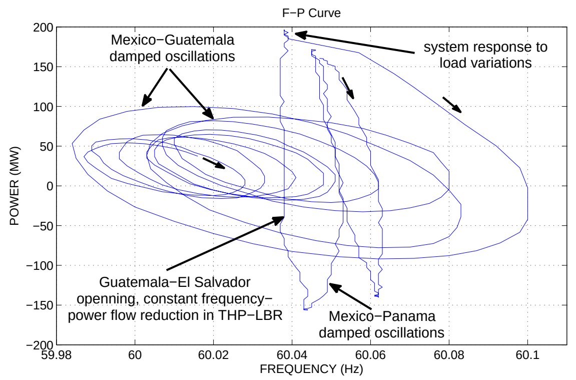

Fig. 7. Frequency vs. Active Power curve for THP-LBR

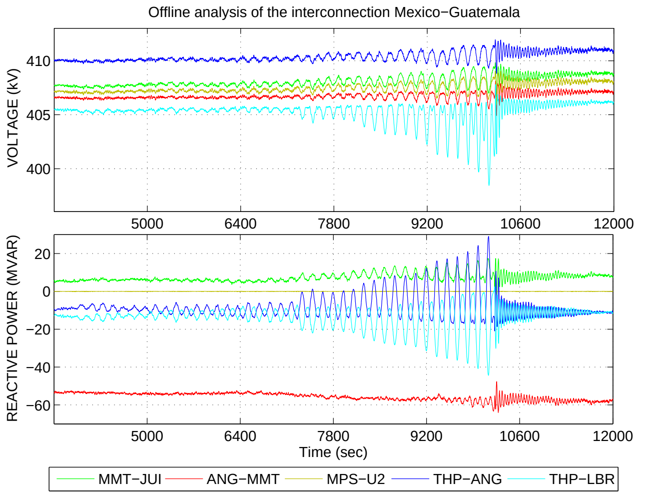

Fig. 8. Voltage and power flow of the circuit THP-LBR during the topology changes of the network.

After opening the interconnection between Guatemala and El Salvador the frequency of the oscillatory modes increased up to 0.68 Hz. Different coherent groups were formed in the north of Mexico, the Yucatan peninsula and the south-east of Mexico with Guatemala, where hydroelectric units in Mexico had the largest contribution due to its dimensions and connectivity. With the provision of PMUs in Central America, it would be possible to determine more accurately how the different coherent groups are being formed at different operating conditions.

IV. REMEDIAL SCHEMES FOR SYSTEM INTERCONNECTION

The remedial schemes currently installed in the different interconnections are designed to automatically trip when an abrupt loss of load or generation in the Mexican system occurs. They are also configured to avoid overloads in the network and the electric equipment in the Central American system. The following protection schemes are utilized:

- ESIM001. Load disconnection in the central area due to overload in the transformer substation LBR (400 KV/230 KV and 225 MVA), in Guatemala.
- ESIM002. Opening interconnection due to trips on line Los Brillantes-Siquinala-Escuintla.
- ESIM003. Generation and load trip scheme due to simultaneous trip on lines Guatemala Sur- Escuintla 1 and 2.
- ESIM004. El Salvador interconnection trip due to problems in Central America.
- ESIM005. Mexican interconnection trip due to problems in the Mexican system.
- ESIM006. Mexican interconnection trip due to over-generation in Mexico.
- ESIM007. Interconnection trip with El Salvador due to limit violations.

Due to the longitudinal characteristics of the system, low frequency oscillations appear when the whole interconnection is stressed. Different analysis based on measurements from the SIMEFAS WAMS system have been carried out. Offline studies show that it is possible to calculate up to four dominant oscillatory modes using Prony analysis on signals such as voltage, frequency, power or phase angle.

An on-line tool was developed to monitor these modes. Considering that each mode has its own origin, from their frequency is possible to simultaneously calculate in real time the participation of each coherent group in one oscillation of the system. Using SIMEFAS one dominant mode was selected and monitored for a specific time frame in order to activate an alarm, an output a contact to the trip the interconnection circuit. An analysis of the interconnection between the systems of Mexico and Central America was made and different events were reviewed. An oscillation of 0.18Hz was detected with values of 200 MW peak to peak and negative damping during more than 20 sec. Events with high risk of instability can trigger distance protections without blocking the oscillation and eventually produced cascading faults in one or both systems. In the interconnection between Guatemala and El Salvador, there exists an automatic circuit triggering scheme which activates when oscillations of more than 175 MW during more than 0.7 sec. occur. This scheme has to be adjusted for each operating condition.

To adjust this protection scheme, offline simulations were carried out for one scenario matching an event on November 2010 where oscillations in the Guatemalan system occurred resulting in the automatic disconnection of the interconnection with El Salvador after exceeding the power and length of time limits. The system operator also observed undamped oscillations and opened the interconnection with Mexico islanding the Guatemalan system.

After adjusting the protection scheme, the online tool application was evaluated offline using the simulation results showing satisfactory performance. It is possible the online tool for real time operation (including control actions), however, this requires the calibration for each oscillatory mode and operating conditions which can be carried out by utilizing frequency or power signals. Figure 9 shows damping calculations for a signal during a short period. When the oscillation is constant, its damping is zero and the action to be implemented needs first to consider if the magnitude of the oscillation is dangerous to the system. When this evaluation has been made for different locations of the system and for a specific oscilla-

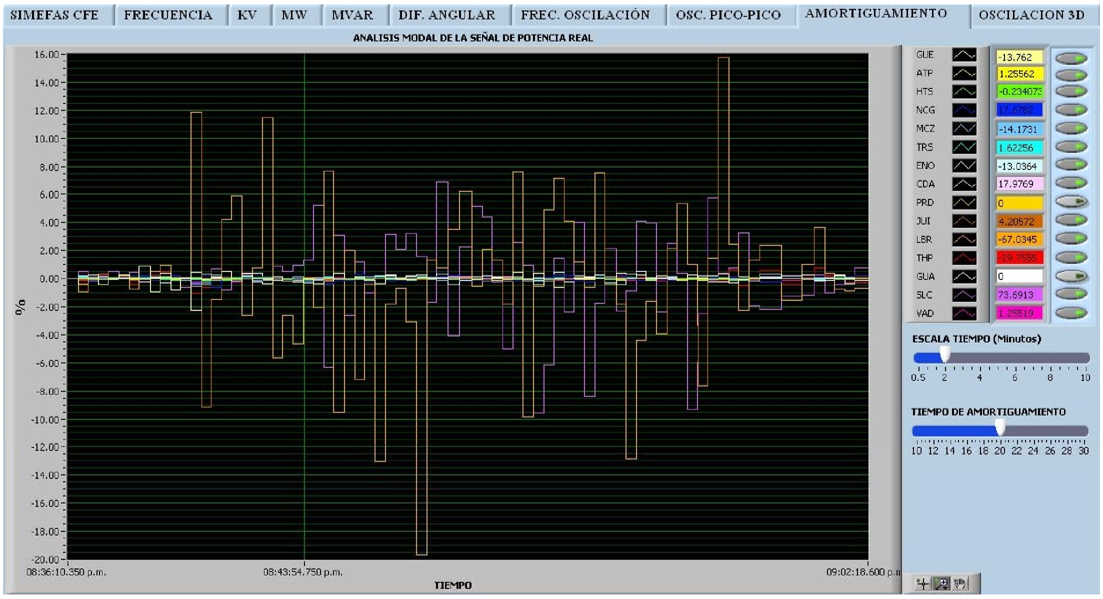

Fig. 9. Damping ratio calculation of the real power.

tory mode, then it is possible to determine the participation of each group or machine in the oscillation and the participation degree of coherent machines in the system.

In the current evaluation period for this automatic scheme, it has been possible to confirm from different events that the oscillatory mode changes according to the disconnection of each of the SIEPAC subsystems. Some examples are the loss of the subsystem Costa Rica-Panama during an earthquake in Costa Rica on September 2012 or the partial loss and collapse of the Panama system in February 2013, among others.

V. Conclusions

After analyzing the different phenomena which have occurred under contrasting operating conditions, we are implementing discrete control schemes that allow us to preserve the integrity of the system or disconnect the SIEPAC network following a sudden loss of load, generation and line trips. To implement the scheme described in the subsection III-C, the interconnection of Mexico and Guatemala requires a clear identification of each oscillatory mode following the trip of any section of the Central American network. Some other actions to be considered in order to avoid undesirable protection triggering that might affect the service life of switches and power transformers are described below:

- Length of time to measure, calculate and take a decision to open the interconnection.
- Damping ratio estimation to determine the alarm or the triggering of the circuit.
- If the damping ratio is negative, is highly important to determine the admissible length of time before the growing oscillation makes the system unstable.
- When the system is oscillating and the damping ratio is zero, this means that the system is already unstable and the decision to disconnect the interconnection is based in 1) the number of oscillations in the time frame selected and 2) the peak to peak value of the oscillation.
- Opening of the interconnections of the systems can produce and increase oscillations from different modes in remote locations which are electrically weak.

When synchronous interconnections between systems with radial characteristics exist, the frequency variations are more evident in the extremes of the dominant path [8]. The most convenient is to have back-to-back HVDC link to isolate the systems from variations or faults in any subsystem. An alternative to maintain the integrity of the system while adjusting the change of inertia caused by the loss of one area is to adjust PSS controls using signals from PMUs in synchronous machines with larger participation [9].

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