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Subsynchronous Resonance Study and Torsional Vibration Monitoring Program in the National Electric System of Chile

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SUMMARY

This paper shows the results of the Subsynchronous Resonance Study (SSR) and the Torsional Vibration Monitoring Program carried out for several thermal generating units at risk of SSR in the Chilean National Electric System (SEN), all of them close to a 500 kV system with series compensation. Initial theoretical analyses detected possible SSR conditions between the electrical system and 11 generating units in 6 thermal power plants. Therefore, the installation of torsional protection was instructed, and the Torsional Vibration Monitoring Program was developed to determine the real risk of SSR and to contrast the theoretical results with the records of the connection tests of the series capacitor banks.

More detailed theoretical analyses showed risk of Torsional Interaction (TI) in the 11 generating units already mentioned, for various degrees of series compensation and under normal (N-0) and contingency (N-1, N-2 and higher) operating conditions. The most critical case involved the Guacolda power plant (5 steam-coal units), since the analyses concluded that there was a risk of TI under normal operating conditions and with all the series compensation connected, caused by a sharp electrical resonance aligned directly with the 2nd torsional frequency of its units. These analyses were performed by calculating the electrical damping, using the frequency scanning method, with the Power Factory DIgSILENT software.

The monitoring program did not show SSR conditions at any of its stages. This was consistent with the results of the study for the first stages of the program (up to 4 of the 5 banks connected), where the SSR analyses showed that all units should be stable under N-0 conditions. However, for the last stage (i.e. with all series compensation connected) there were differences between the theoretical results and the field tests since the SSR predicted for the Guacolda units under N-0 conditions was not observed.

Because of this, the SSR analysis was repeated for the last stage, but this time reproducing the same operating conditions under which the test was actually performed. This updated analysis showed a stable behavior of Guacolda, in accordance with the tests. It was concluded that the actual conditions under which the test was performed caused the electrical resonance to shift about 2 Hz from the grid conditions modeled in the original analysis, enough to keep all torsional modes stable.

It is concluded that the results of the theoretical analyses performed with the SEN electrical model and the frequency scanning method seems to be consistent with the tests performed. It should be noted that, in addition to the basic aspects of methodology, modelling and topology of the electric system, changes in the system's generation scenario may be relevant in the appearance of conditions propitious to the existence of SSR.

KEYWORDS

Subsynchronous Resonance (SSR) - Series Compensation – Turbogenerators - Frequency Scanning - Torsional Interaction (TI) - Torsional Vibrations - Torsional Modes - Undamping

1. INTRODUCTION

Subsynchronous Resonance Studies (SSR) were carried out to detect possible resonance conditions between the Chilean 500 kV system with series compensation in the northern zone of the National Electrical System (SEN) and nearby thermal generating units. The results of these studies concluded that there is a risk of SSR in 11 generating units in 6 thermal power plants. Figure 1 shows a simplified diagram of the transmission system in the area of interest and the generating units at risk:

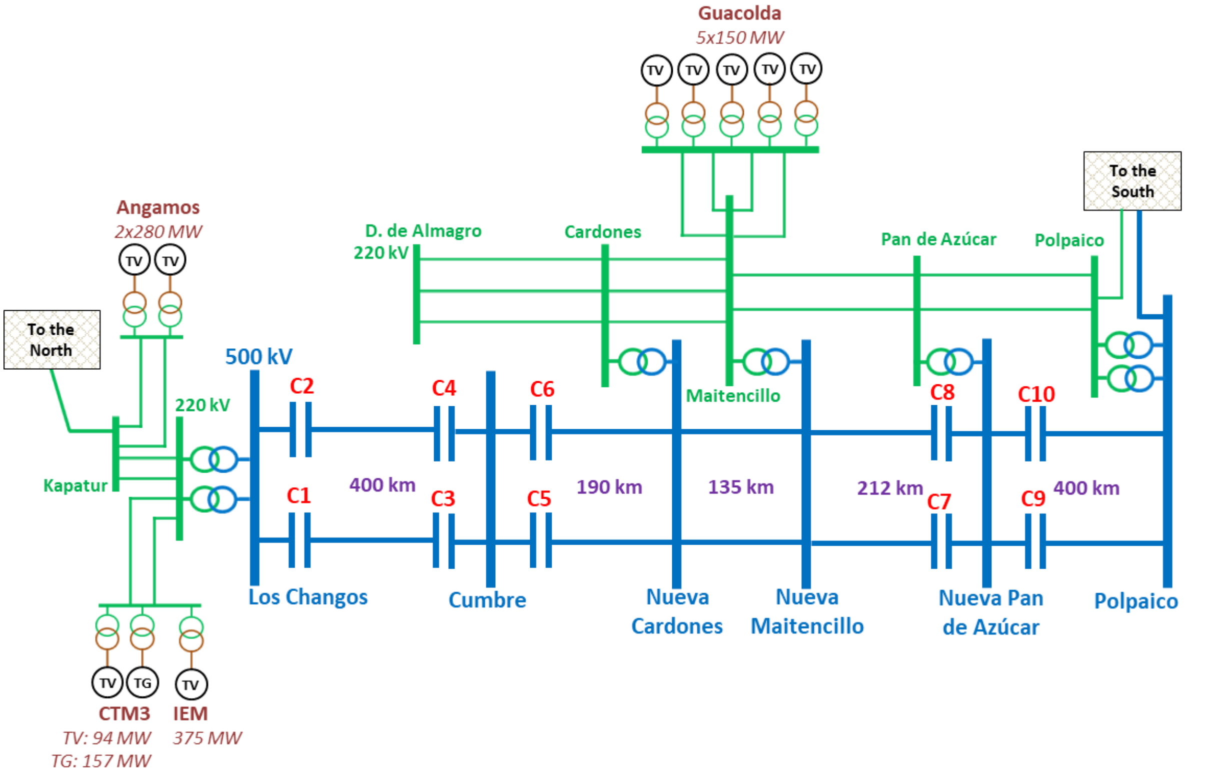

Fig. 1. Simplified topology of the studied electrical system

In view of the study results, the installation of torsional protection and subsynchronous oscillation monitoring systems in the units at risk was instructed. Likewise, a subsynchronous resonance monitoring program was designed and developed with the main objective of verifying, during actual system operation, the possible SSR detected in the studies. The program was extended between March and November 2019.

2. METHODOLOGY

2.1. Subsynchronous Resonance Study

The study used the technique of frequency scanning, which determines the equivalent impedance as a function of the frequency seen from the neutral of the synchronous generator under analysis. This method is effective in the study of the Induction Generator Effect (IGE), besides providing information about eventual phenomena associated with Torsional Interaction (TI) and Torque Amplification (TA) [1], [2]. The advantage of this method lies in the simplicity of its implementation and in its capacity for analyzing the three aspects of SSR just mentioned.

For the modeling of the electrical system, the synchronous generator under analysis is represented by its equivalent as a function of frequency in the subsynchronous range, which corresponds to its induction generator model. Similar units in the same power plant are scanned in parallel, as if they were a single unit. The rest of the synchronous generator units in the system are represented by their subtransient reactances. The electrical system is modelled by its respective positive sequence admittance matrix. The calculations were performed with the frequency sweep function of the Power Factory DIgSILENT software and with the complete database of the SEN.

The more detailed analyses and the monitoring program focused on the phenomenon of Torsional Interaction as this is the most critical for the units analyzed. TI is the phenomenon of self-excitation of the combined mechanical system (turbine-generator unit) and a series capacitor compensated electric network when the subsynchronous rotor motion developed damping torque is negative and greater in magnitude than the mechanical damping torque of the rotor [3]. TI self-excitation can be triggered by disturbances or switching on the grid (of small or large magnitude) that excite the unit's natural torsional oscillation modes. The electrical damping provided by the electric network, as a function of the mechanical frequency, can be calculated using the following expression [4], [6]:

$$D_e(f_m) = -\left(\frac{f_o - f_m}{2 \cdot f_m}\right) \cdot \frac{R(f_o - f_m)}{|Z(f_o - f_m)|^2} + \left(\frac{f_o + f_m}{2 \cdot f_m}\right) \cdot \frac{R(f_o + f_m)}{|Z(f_o + f_m)|^2} \ [p.u.] \quad (1)$$

TI risk from electrical damping shall be verified if there is a frequency $f_m \in \{f_\text{n} - 1\ Hz, f_\text{n} + 1\ Hz\}$ such that:

$$D_e(f_m) \leq 0.1 \quad (2)$$

Where :

Z, R: reactance and series resistance of the electrical grid-generator system as seen from the neutral of the generator under study.

f_0: nominal frequency of the electrical network.

f_m: mechanical frequency of the turbine-generator system.

f_n: natural frequency of mechanical torsional oscillation of the turbine-generator system.

Note: ±1 Hz for frequency and 0.1 for damping represent a safety criterion.

If the sign of the expression for D_e is negative, D_e gives a negative damping contribution (undamping). The turbogenerator system is considered stable if the module of the electrical damping imposed by the electrical system is less than the mechanical damping (Dm), i.e. [4], [5]:

$$|D_e(f_m)| < |\mathrm{Dm}| \quad (3)$$

To calculate the mechanical damping, it is necessary to consider the torsional model of the turbine-generator system and the results of the torsional tests, which is discussed next.

2.2. Torsional models

Those responsible for the generating units provided information on their torsional models and results of torsional tests that determined the natural frequencies of subsynchronous torsional oscillation and mechanical damping. The torsional frequencies measured in the field turned out to be slightly different from those originally obtained from the rotodynamic model, which allowed these values to be updated.

On the other hand, desynchronization torsional measurements (unit off-line) allowed to obtain the no-load mechanical damping, that is, without the electrical system damping. The data was provided in terms of logarithmic decrement (logdec, decay per cycle), which can be converted into the damping used for SSR analyses (in s^{-1}) by means of the following expression [1]:

$$\sigma\mathrm{m}_\mathrm{nl} = \mathrm{logdec} \cdot f_n \ [\mathrm{s}^{-1}] \quad (4)$$

Since the SSR analysis calculates the electrical system damping (D_e) in p.u. on generator MVA base, to be able to compare these values it is necessary to convert the no-load mechanical damping (σm_{nl}) to the electrical damping base by means of the following expressions [5], [6]:

$$\mathrm{Dm_{nl}} = \sigma \mathrm{m_{nl}} \cdot 4\mathrm{H_m}\text{ , if } \mathrm{Q_{gen}} = 1 \quad \text{or} \quad \mathrm{Dm_{nl}} = \sigma \mathrm{m_{nl}} \cdot 2\mathrm{J_m} / [\mathrm{Q_{gen}}]^2\text{ , if } \mathrm{Q_{gen}} \neq 1 \qquad (5)$$

Where the modal inertia J_m and H_m is estimated from the mode shape plots and elements inertia, and where the mode shape of the generator "Q_{gen}" is estimated from the mode shape plots. Both the inertias of the torsional model and the mode shape plots were provided by those responsible for the generator units.

To estimate the full-load mechanical damping it is assumed to be ten times greater than the no-load damping: $Dm_{fl} = 10 \cdot Dm_{nl}$. For intermediate load values a linear relationship between the values of Dm_{nl} and Dm_{fl} is assumed.

The following table shows the data of the natural frequencies of torsional oscillation, logdec and mechanical damping calculated for the Guacolda and Angamos units:

Unit	S [MVA]	Unit Type	Freq-Mode 1	Measured Logdec	Sigma	Damping Mode 1 (Top I Bar on De plots)	Freq-Mode 2	Measured Logdec	Sigma	Damping Mode 2 (Top I Bar on De plots)
Guacolda 1	176.5	Steam (TV)	21.4	0.00077	0.016	-0.10	27.9	0.00025	0.007	-0.5
Guacolda 2	176.5	Steam (TV)	21.4	0.00077	0.016	-0.10	27.9	0.00025	0.007	-0.5
Guacolda 3	178.8	Steam (TV)	19.2	0.00019	0.004	-0.03	28.1	0.00100	0.028	-6.5
Guacolda 4	178.8	Steam (TV)	18.3	0.00027	0.005	-0.06	28.0	0.00029	0.008	-1.9
Guacolda 5	181.2	Steam (TV)	18.3	0.00027	0.005	-0.06	28.0	0.00029	0.008	-1.9
Angamos 1	325.8	Steam (TV)	16.7	0.00250	0.042	-0.52	37.8	0.00025	0.009	-16.8
Angamos 2	330.9	Steam (TV)	16.7	0.00250	0.042	-0.52	37.8	0.00025	0.009	-16.8

Table 1. Torsional data for use in SSR analysis

2.3. Monitoring program

The program was divided into six stages, all for N-0 operating conditions, starting without the series compensation (Stage 1) and continuing with the sequential connection of the five (5) pairs of series capacitor banks of the 500 kV transmission system, culminating in Stage 6 with all the series compensation connected. In the results graphs presented later in this paper, the representation of the states of the series compensation is done by numbering the pairs of capacitor banks as follows:

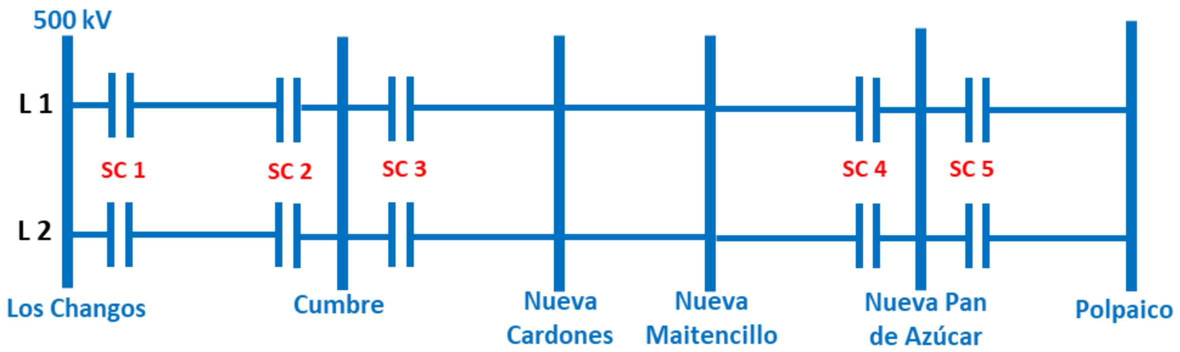

Fig. 2. Series capacitor bank designation

The “x” symbol is used to designate the "bypass" status of a series capacitor, and the number designating the bank is used to designate the connection status. Thus, the connection configuration of the capacitor banks for each stage is as follows:

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
L1 : x-x-x-x L2 : x-x-x-x	L1: x-x-x-4 L2: x-x-x-4	L1: x-x-3-4-x L2: x-x-3-4-x	L1: x-2-3-4-x L2: x-2-3-4-x	L1: x-2-3-4-5 L2: x-2-3-4-5	L1: 1-2-3-4-5 L2: 1-2-3-4-5

Table 2. Monitoring program stages. Series capacitor bank connection configuration

The connection configuration of the banks was defined with the objective of minimizing the SSR risks for each stage and subject to the operational conditions of the SEN at the time of testing. It should be noted that as of Stage 3, the 2x500 kV line between the Nueva Pan de Azúcar and Polpaico substations was put into service.

The alarm and trip levels of the protections were calculated and adjusted by the manufacturers of the torsional protections considering aspects of fatigue and life time of the turbogenerator rotor components.

3. RESULTS

3.1. Subsynchronous Resonance Study

Preliminary studies analyzed 21 power plants close to the 500 kV system with series compensation between Los Changos and Polpaico substations. Of these 21 units, risk was detected in 11 of them. Of the SSR phenomena analysed, it was concluded that there was no risk of instability due to the induction generator effect (IGE). On the other hand, it was concluded that there was a risk of TI and TA, both in normal operation and in contingency conditions (N-1, N-2 and higher), and for various degrees of series compensation and connection configurations of the series capacitor banks.

The more detailed theoretical analyses and the associated torsional vibration monitoring program focused on the TI phenomenon, considered to be the most critical for the generating units. Furthermore, the TI phenomenon by electrical undamping was the one possible to be observed and measured in the monitoring program tests.

The most critical case corresponded to the Guacolda power plant (5 steam-coal units), since the analyses concluded that there was a risk of TI under N-0 grid conditions and with all the series compensation connected, caused by an electrical resonance aligned with the 2nd torsional frequency of its units. This can be seen in the following figure:

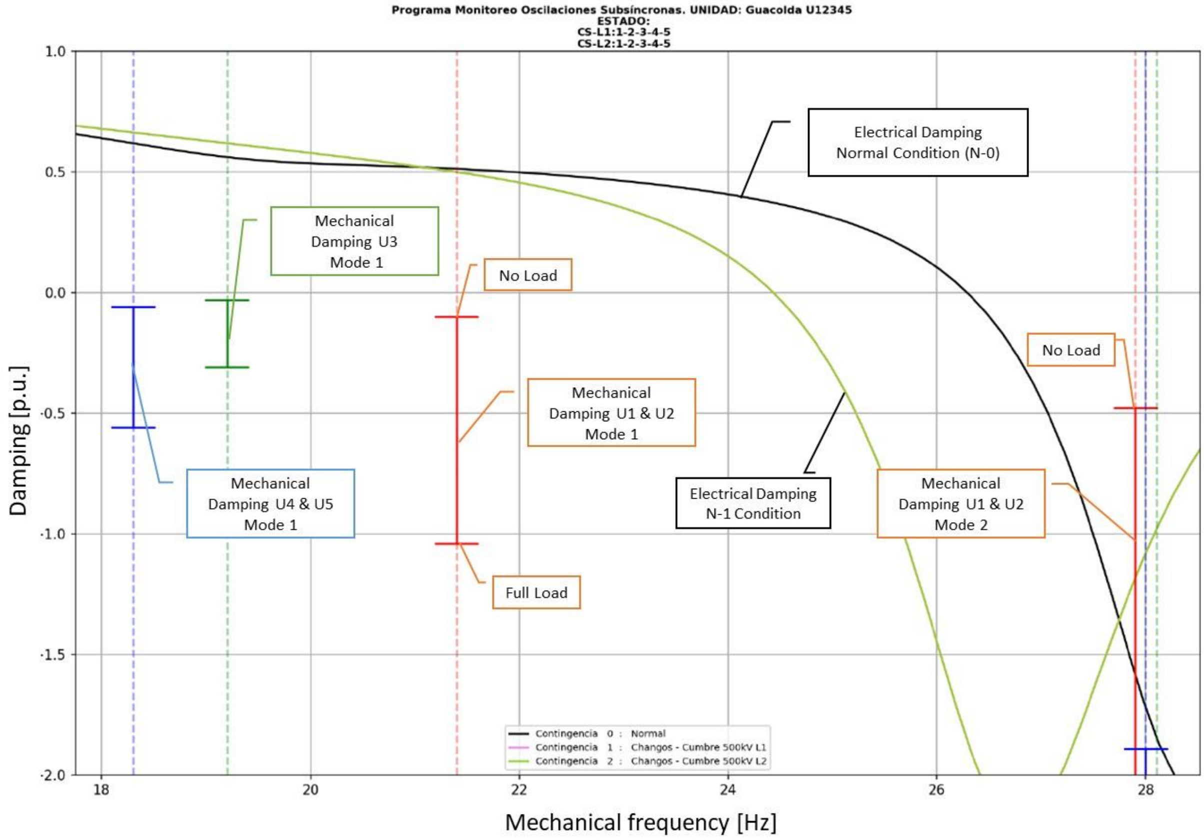

Fig. 3. Electrical damping v/s mechanical damping for Guacolda units (Stage 6)

In the figure 3, the curves represent the electrical damping in a subsynchronous frequency range between 17.5 and 29 Hz. The "I" bars represent the mechanical damping (which is always positive but in the plot is negative just for graphical comparison effects) of the units at the frequencies corresponding to the torsional modes of the units, from no-load to full-load.

It is observed that around the 2nd torsional mode of Guacolda units 1 and 2 (frequency of 27.9 Hz), the black curve (representing the electrical damping in normal operation) cuts the red bar (representing the mechanical damping of Guacolda units 1 and 2). This represents a risk of SSR since, in module, the electrical damping (which is negative in this case) becomes greater than the mechanical damping of the unit at that natural frequency of oscillation and for a given range of unit load (the lower the load of the unit, the lower the mechanical damping that it can oppose to the negative electrical damping, increasing the risk of SSR).

As already indicated, the risks of TI due to electrical undamping were detected for N-0 and N-1 (and higher) operating conditions, as can be seen in the figure 4:

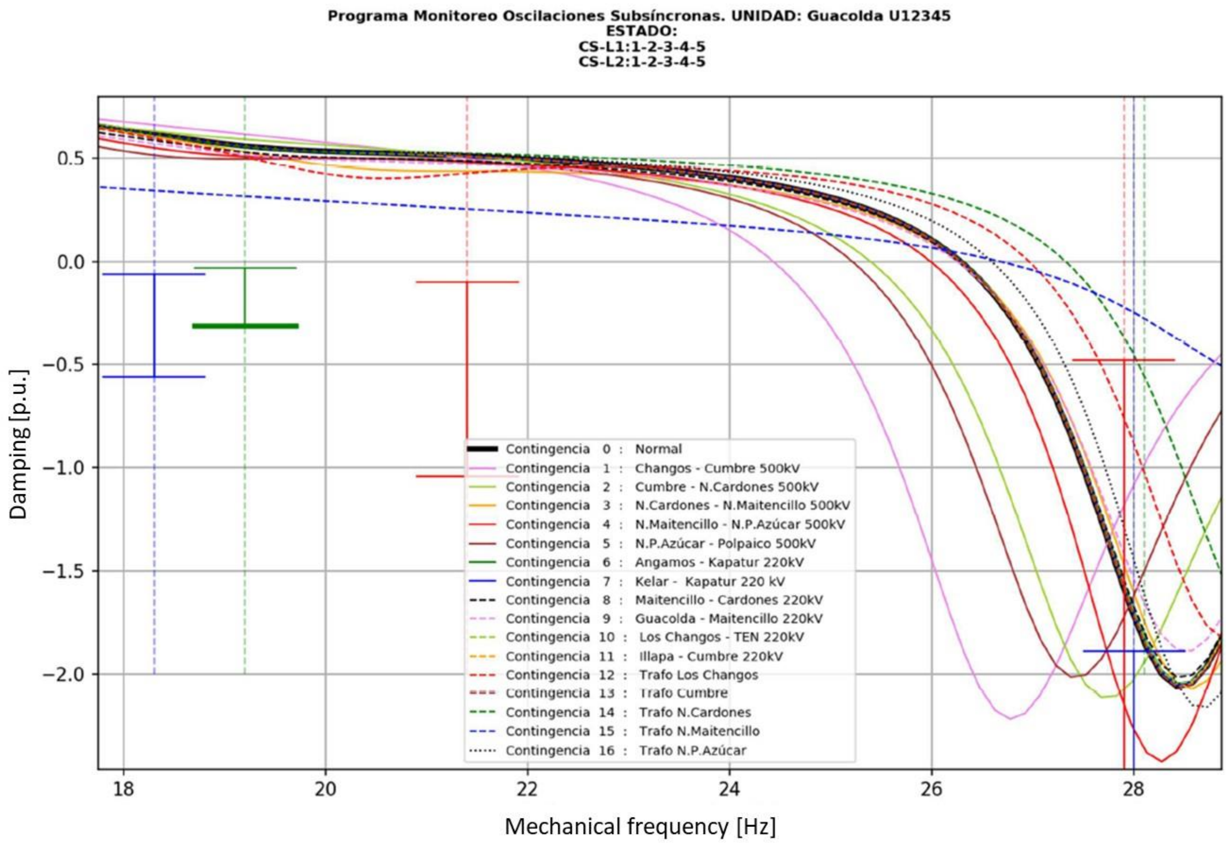

Fig. 4. Electrical damping v/s mechanical damping for Guacolda units on N-0 and N-1 (Stage 6)

Under N-0 conditions, the rest of the units showed no SSR risk for Stage 6.

3.2. Monitoring program

Stage 1: All the series capacitor banks between Los Changos and Nueva Pan de Azúcar were on bypass. For the generating units, adjustments and tests of their torsional protections were made, which allowed to obtain the torsional frequencies and mechanical damping based on real measurements.

Stages 2 to 5: Some generating units recorded low magnitude torsional vibrations due to the connection of the capacitor banks, far from the alarm levels of the torsional protections. The response was in line with the previous SSR risk simulations.

Stage 6: No unstable SSR conditions were observed. Analysis of test records confirmed that the insertion of the series capacitor banks excited torsional vibrations in several of the monitored units, but all measured vibrations were well below the alarm and trip levels of the torsional protections and showed positive damping. An example of the response observed is shown in Figure 5:

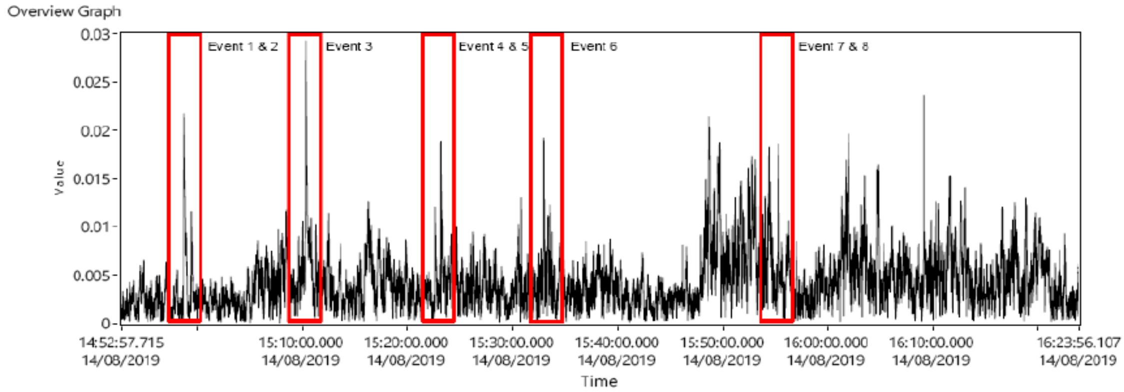

Fig. 5. Angamos Unit 1. Linear trend of the 1st mode torsional vibration amplitudes (°pp)

Figure 5 shows the records for the 1st torsional mode vibration amplitude of Angamos Unit 1 for the various capacitor switching events performed during the test. Figure 6 shows a more detailed plot of the torsional vibration amplitudes for the 1st and 2nd torsional modes for the switching event of one of the two series capacitors of Los Changos substation. It can be seen how the first torsional mode is stimulated up to a peak of approximately 3 times the normal steady-state value. The oscillations decay back to steady state in approximately 10 to 15 s. The 2nd torsional mode is not stimulated by the connection of the capacitor due to the very low mode shape at the generator for this mode. The simulations performed for this condition correctly predicted a stable and well-damped torsional response.

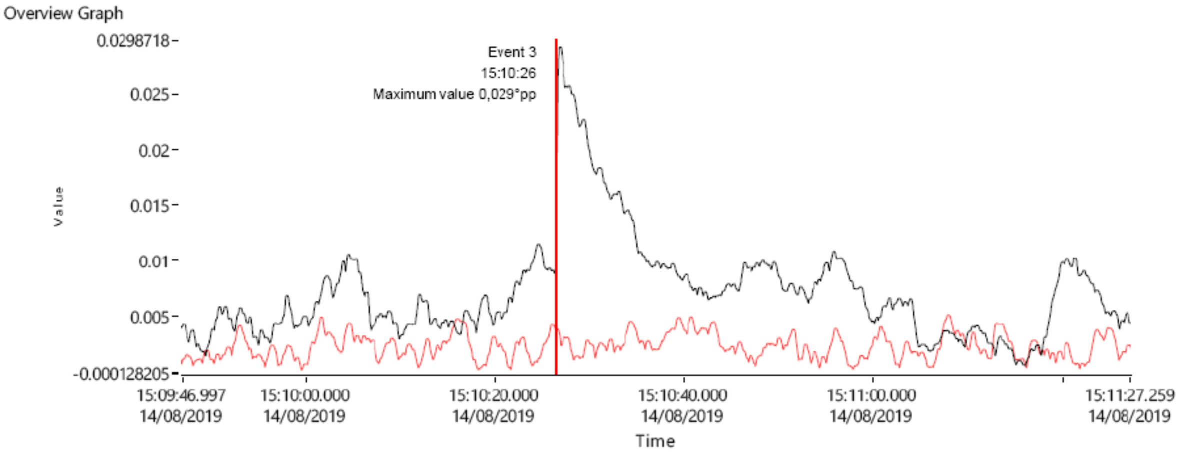

Fig. 6. Angamos Unit 1. Vibration amplitudes of the 1st (black) and 2nd (red) torsional vibration modes during Los Changos series capacitor connection

In the case of the Guacolda units, unlike the previous theoretical analyses, the results of the Stage 6 tests did not show any condition of undamped subsynchronous oscillation in the monitored units. This can be seen in Figure 7 which shows the response of Unit 2 to two switching events.

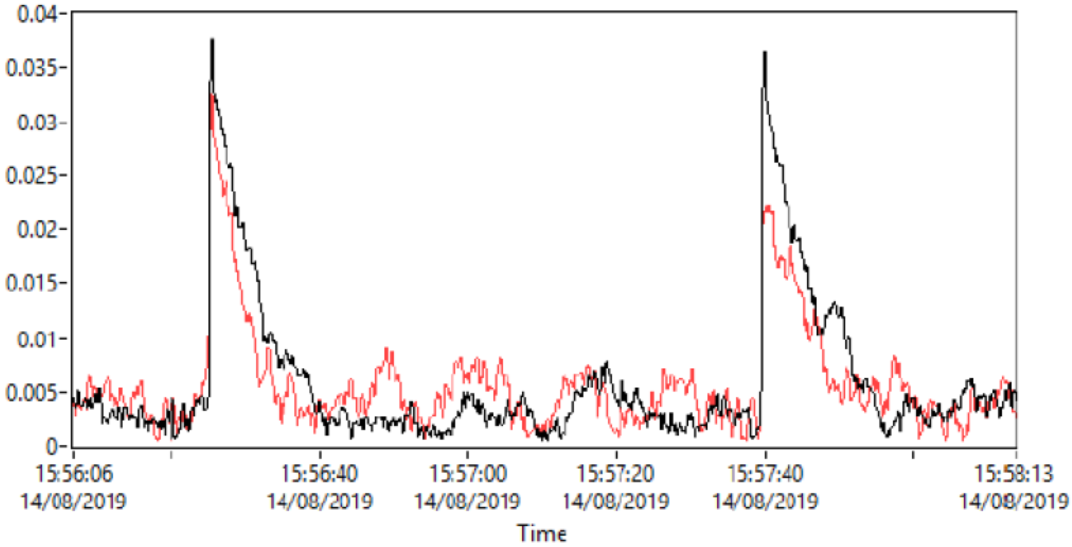

Fig. 7. Guacolda Unit 2. Vibration amplitudes of the 1st (black) and 2nd (red) torsional vibration modes during Los Changos series capacitors connection

Although the previous SSR risk analyses considered the same topology and operating conditions of the transmission system under which the tests were conducted on August 14, 2019, the exact generation conditions at the time of the test were not the same. Due to this, the electrical damping calculations were again performed trying to reproduce the same system generation conditions at the time the test was performed (15:00 h). The results can be seen in the figure 8 below:

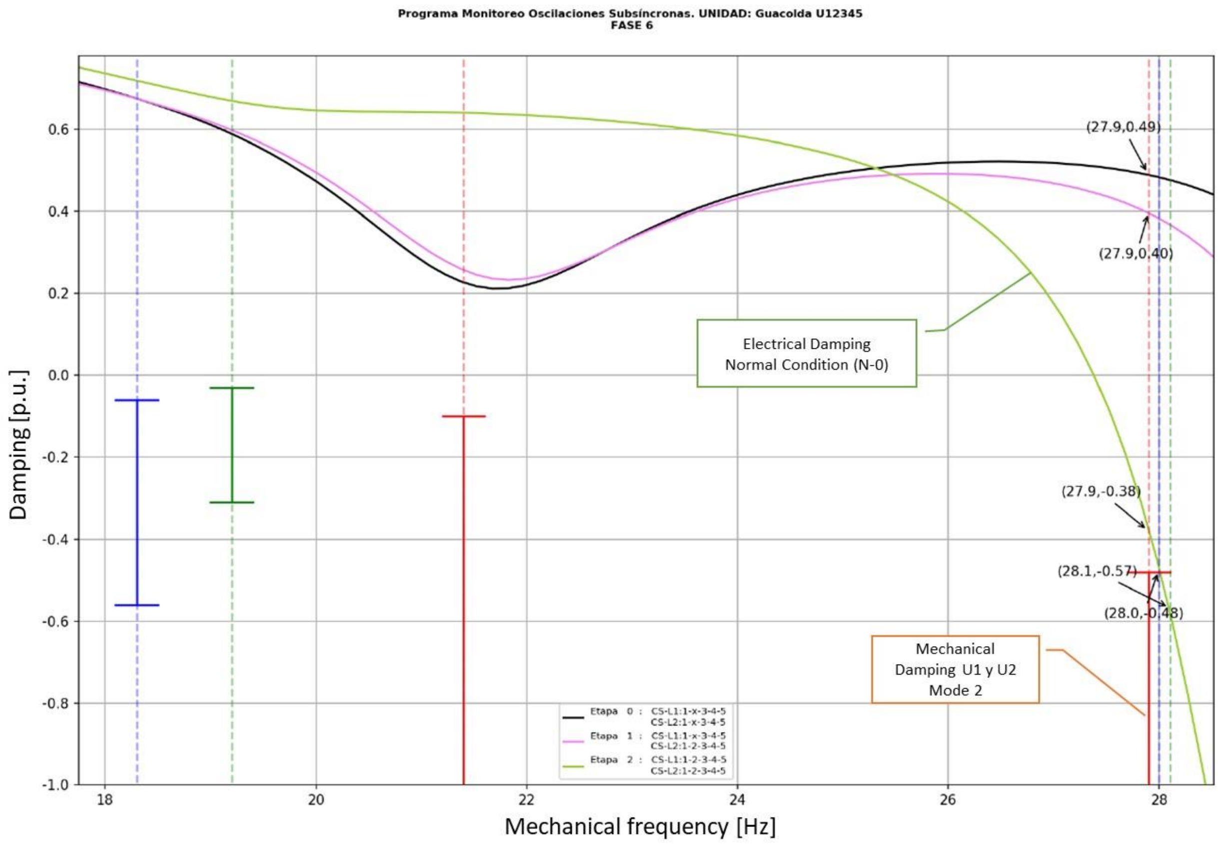

Fig. 8 Electrical damping v/s mechanical damping for Guacolda units on the test day for Stage 6

The figure 8 shows that the electrical damping curve (negative in the frequency range of the 2nd torsional mode of the Guacolda units) does not cut the mechanical damping I-bars of the Guacolda units, indicating a stable condition from the point of view of the Torsional Interaction phenomenon. It is concluded that a change in the system dispatch conditions caused a shift in the electrical resonance frequency of about 2 Hz, enough for the magnitude of module of the electrical damping to be less than the mechanical damping of the Guacolda units.

4. **CONCLUSIONS**

No phenomena associated with Subsynchronous Resonance were observed at any stage of the monitoring program and for any of the monitored units. This was consistent with previous theoretical SSR risk analyses carried out for the first five stages of the monitoring program. However, for Stage 6, i.e. with all serial compensation connected, the previous theoretical analyses showed risk to the Guacolda units, which was not observed in the tests. New risk analyses for Stage 6, but this time reproducing the real dispatch operating conditions under which the test was performed, showed stable Guacolda behavior, in accordance with the tests.

Given the above, it can be deduced that it is relevant that the theoretical analyses seek to reproduce the exact operating conditions of the network at the time of the tests. In the case of this paper, the generation that is online at the time of the test seems to be one of the most important aspects that would explain the differences between the theoretical analyses and the results of the tests of the monitoring program. Other important aspects are related to the load level of the units at risk (the higher the load level, the lower the SSR risk) and the accuracy of the torsional model and estimates of the mechanical damping of the turbo-generator.

It is therefore concluded that the results of the theoretical analyses performed with the electrical model of the SEN and the frequency scanning method appear to be consistent with the tests performed. In addition to the basic aspects of methodology, modelling and topology of the electricity system, changes in the system's generation scenario may be relevant in the appearance of conditions propitious to the existence of SSR.

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