TRANSIENT DESIGN STUDIES FOR AUTOMATIC SWITCHING OF SHUNT REACTORS ON THE TRANSELEC SYSTEM

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***Abstract* – To maintain adequate voltage regulation on the 525 kV series compensated system required for the integration of the new Ralco hydropower plant, an automatic switching scheme will be implemented for switching shunt reactors in the Charrúa, Ancoa and Alto Jahuel substations both at the 525 kV and the 230 kV voltage levels during system disturbances. Individual automatic reactor switching systems will act locally at each substation to close or trip shunt reactors in response to system events and local voltage conditions. General reactor switching philosophy and performance requirements applied to automatic switching systems will be presented. Switching actions to control local voltage are based on direct and precise measurement of system voltage amplitudes following events. Impact of switching and inrush transients on voltage measurement will be presented. Adequate filtering of three phase voltage is required to provide correct selectivity.**

Keywords: Automatic Switching, Voltage Control, Voltage Measurement, Modes of oscillation, Switching Transients, Temporary Over-voltages, Inrush Transients, Series-Compensated Transmission Systems.

I. INTRODUCTION.

With the integration of the new Ralco hydropower plant, the Chilean series-compensated transmission system, as illustrated in Fig. 1, will consist of two single-circuit 525 kV lines of more than 400 km length. These lines will interconnect from North to South, the three 525 kV substations namely: Alto Jahuel, Ancoa and Charrúa. In order to increase the power transfer on these two lines several line compensation alternatives have been analyzed. The implementation of four series-capacitor banks at the Ancoa 500-kV substation together with the addition of automatically switched 525 kV 84 Mvar shunt reactors at all line terminals are the best cost efficient solutions in terms of system stability performance and voltage regulation during system disturbances [1]. Furthermore, at the Alto Jahuel and Ancoa substations, the 230 kV 82 Mvar shunt reactors will be automatically switched according to conditions on the 525 kV system.

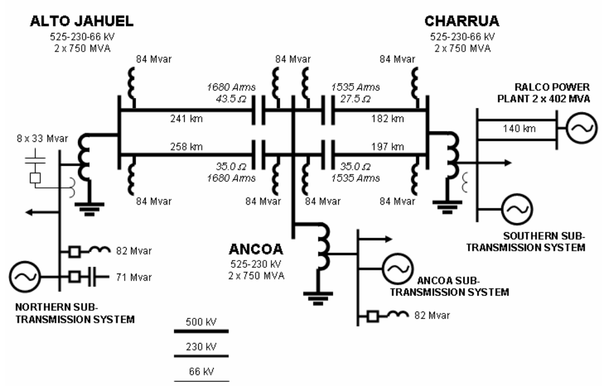


Fig. 1 The Chilean 500-kV Series-Compensated Transmission System

This paper presents the switching philosophy and design requirements for the shunt reactor automatic switching system that will be implemented in all 525 kV substations. Electromagnetic transient studies performed to establish filtering constraints will be presented.

II. FUNCTIONAL CHARACTERISTICS OF AUTOMATIC SWITCHING SYSTEM

The integration of the Ralco hydropower plant will increase the loading on the 525 kV network. Following system events, adequate system voltage control will require switching of shunt reactors both at the 525 kV and the 230 kV levels. Reactor switching will be performed by an automatic switching system (MAIS) that will be implemented in the Charrúa, Ancoa and Alto Jahuel substations. Very fast switching provided by FACTS devices such as SVCs is not necessary for the folowing reasons:

- Rapid voltage control required to maintain the system's transient stability will be provided by the series compensation installed at the Ancoa substation.
- Increased loading on the system following the loss of lines could lead to low voltages. On load automatic tap changers are not widely used on the Transelec system. However, at the load, low voltages could lead to operations of on load tap changers should there be any. To be on the safe side and as a provision for more extensive use, switching actions should be performed

before transformer taps operate. Tap changer time delays are typically in the range of 20 to 30 s.

- The power system has a large number of shunt reactors both at 525 and 230 kV that can be operated.

The automatic switching of shunt reactors by circuit breakers has proven to be the most attractive solution for the proposed function. Moreover, Hydro-Québec TransÉnergie has successfully implemented such a system in 22 substations on the 735 kV network [2] [3]. These units have been in operation since 1996. A similar system has also been implemented on the Transmantaro interconnection in Peru [4].

A. Objectives in the Design of MAIS and Basic Functions

The automatic switching of shunt reactors (MAIS) is intended to control voltage on the system after a contingency, in order to ensure proper system behavior. More precisely, the main objectives guiding the design of MAIS are as follows:

- restore voltage on the 525 kV system within the voltage operation limits (ideally before operation of the tap changers);
- only operate the required number of shunt reactors and avoid a massive operation of reactors;
- not interact with normal system operation.

The two basic functions that MAIS must be able to perform are the closing and tripping of shunt reactors in response to local conditions.

MAIS must also be able to order the switching of shunt reactors in response to an external signal i.e. trip signal issued from a protection system.

B.Main Characteristics of MAIS

Each of the three 525 kV substations will be equipped with a MAIS system. Each MAIS is entirely independent and only allows the closing or tripping of the reactors located in the same substation in response to local conditions. Stability studies were performed to establish the required actions of each of the MAIS systems. Since each MAIS is independent, coordination in the operation of all MAIS on the system must be assured by a careful choice of settings associated with each MAIS. Generally speaking, two parameters are used to provide this coordination: the **amplitude** of the direct sequence voltage and the **duration.** Preliminary design studies were carried out to determine the required switching operations and to ensure that MAIS is **reliable, safe** and **selective** for the system. The basic considerations for the design of such a system are as follows:

- That a functional redundancy can be provided by the MAIS installed at adjacent substations, should a particular MAIS fail to operate when required.
- That the unwanted operation of a MAIS (switching when not required) has no significant effect on the system.
- That it is possible to discriminate among the various events that can occur on the system and to switch the reactors taking into account the location, duration and size of the undervoltages or overvoltages resulting from these contingencies.

As an example, actions of MAIS is shown in Figure 2 for a system event consisting in a line to ground fault at Ancoa followed by the loss of the faulted 525 kV line.

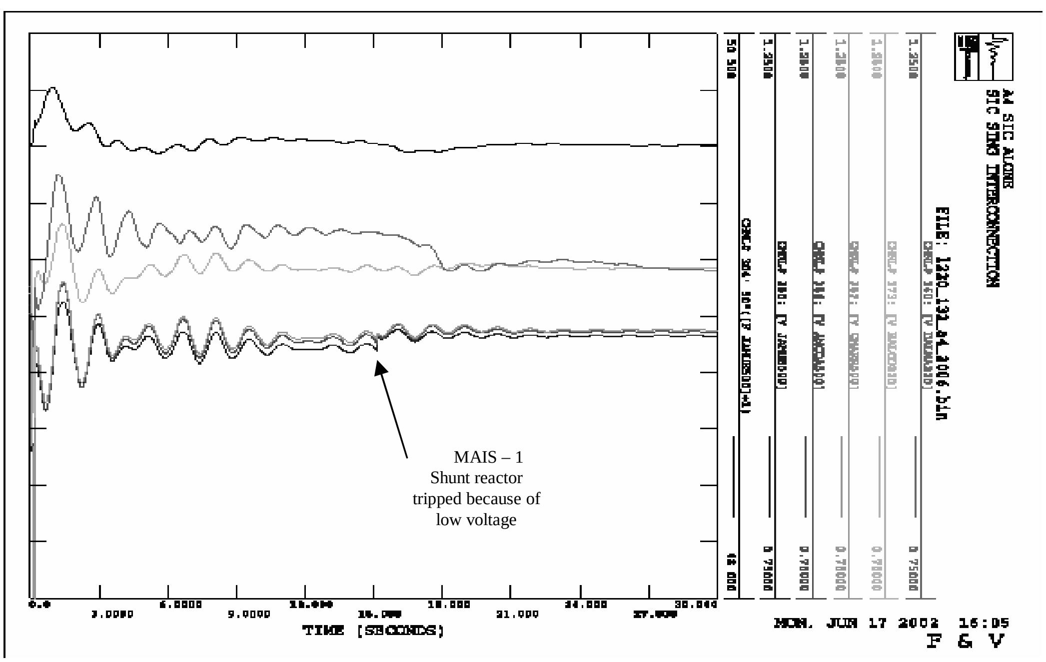


Fig 2: 1L-G Fault at Ancoa 525 kV with the Loss of Ancoa – Alto Jahuel 525 kV Line

The behavior of the MAIS system following a contingency at the Ancoa substation is indicated by the arrow. It can be seen that MAIS (using only local variables) trips a shunt reactor because voltages are low.

It is important to note that the flexibility in the design of the MAIS system allows a substantial provision for future needs on the Transelec system. A detailed study, taking into account various system operating conditions, power dispatches and system contingencies must be carried out to determine the individual settings for each MAIS.

The following sections provide a more detailed description of the various functions available in the MAIS system.

III. DESIGN SPECIFICATIONS

MAIS will order the closing or tripping of shunt reactors according to a number of variables, the most important of which is voltage amplitude. MAIS is intended to be adaptable and will order:

- Closing of shunt reactors in overvoltage condition;
- Tripping of shunt reactors in undervoltage condition;
- Tripping of shunt reactors in response to a voltage drop with respect to an average value;
- Closing or tripping of shunt reactors in frequency variation conditions;
- Reactor tripping from external signal when there are loss of lines;
- Closing or tripping of shunt reactors as a function of a combination of any or all of these previously processed signals.

MAIS evaluates the availability and the state of all reactors in the substation and includes several supervision functions among which an anti-hunting function. All operation orders are subject to adjustable time delays.

Specific reactor tripping is required in the Charrúa substation following a 2 phase to ground fault on one of the Ralco 220 kV lines. Therefore, the 220 kV Ralco line protection systems will supply a trip signal to MAIS wich will then automatically select shunt reactors, issue trip signals and verify that the selected reactors have changed state.

A. Closing or Tripping with Voltage Thresholds

Closing or tripping of shunt reactors is ordered when an adjustable voltage threshold is exceeded for a preset time delay. Many separate overvoltage (adjustable from 1.0 to 1.2 p.u.) and undervoltage thresholds (adjustable from 0.85 to 1.0 p.u.) are available. Timers can be associated with each threshold. One reactor is switched when a switching order is issued.

Events such as loss of one or more phases of a voltage transformer, tripping of the busbar where the voltage measurement is taken, fault on one phase or other failures must be detected because they can trigger unwanted under-voltage shunt reactor tripping. Undervoltage tripping must be disabled upon detection of any such event.

In order to increase MAIS availability, when a single phase is judged abnormal, MAIS automatically goes into " emergency mode ". At this point, the phase whose measurement is declared faulty is no longer considered, and a degraded measurement of the voltage is made using the two sound phases. The average value of the two amplitudes available makes it possible to obtain a rough estimate of the amplitude of the positive sequence of the fundamental voltage. If more than one phase is declared abnormal, the MAIS involved becomes inoperative. Different but less selective thresholds are used in emergency mode.

B. Tripping in Response to Voltage Variation from a Mean Value

The current mean value is continuously estimated during a certain time. The instantaneous amplitude of the positive sequence is continuously compared to this mean value. When the difference between instantaneous value and mean value exceeds an ajustable threshold, the current mean value becomes the reference mean value for a preset ajustable time and tripping function becomes operative.

Shunt reactor tripping is ordered when the amplitude of the positive sequence drops of a certain value below the reference mean value during a certain adjustable time. The voltage dip threshold is available and adjustable from 0.02 to 0.10 p.u. and time setting is adjustable from 0 to 60 seconds.

C. Closing or Tripping in Response to a Frequency Condition

Closing or tripping of shunt reactors can be ordered when an adjustable frequency threshold or frequency gradient threshold is exceeded. Many separate frequency settings (adjustable from 47.0 to 53.0 Hz) and frequency gradient settings (adjustable from -5.0 to +5.0 Hz/second) are available.

D. Closing or Tripping in Response to an External Signal

Closing or tripping of shunt reactors can be also ordered by an external signal. MAIS is intended to be adaptable and allows an external signal to switch a reactor in a coordinated fashion. The two following sections provide a description of external signals presently known.

E. Tripping in Function of the Reactive Power Produced by Dynamic Compensators

Reactive power produced by a synchronous and static compensator in the network is compared to an adjustable threshold. When this threshold is exceeded for an adjustable preset time, a shunt reactor tripping is ordered.

Setting coordination is necessary to reset shunt reactor tripping orders when the thresholds aren't exceeded anymore because of preceding tripping in the same substation.

An adjustable dead time is necessary before a new tripping order is allowed in function of reactive power output from the same compensator.

F. Local and Remote Reactor Tripping

In the Charrúa substation, a two phase to ground fault on one of the two 220 kV lines from the Ralco hydropower station requires the trip of shunt reactors. Protection systems will detect the fault condition and will send an external signal to MAIS after analysis of the contingency.

G. Combination

Overvoltage, undervoltage, frequency and frequency gradient detection as well as external signals from other systems can be combined to check several conditions simultaneously and then issue an appropriate switching order. A time delay and an amount of reactive power to be switched must be associated with each combination.

H. Execution of Shunt Reactor Switching

In a given substation, MAIS selects the reactors to operate and orders operations taking their availability into account. The state and the availability of each reactor is evaluated locally based on the measurements of the voltage present on the line terminal and current present in the reactor. A reactor that has been tripped by protection is considered unavailable.

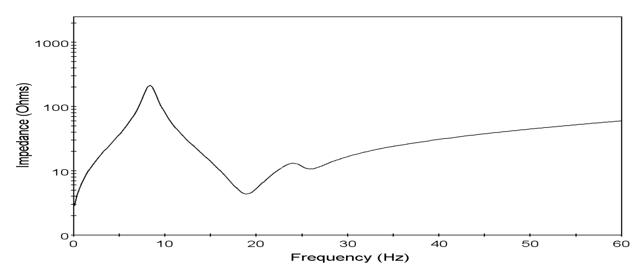
The execution of each operation is checked and another operation must be ordered in replacement if the first ordered operation has not occurred. The order of priority in which the reactors are operated can be modified locally. It is also possible to withdraw one reactor from operation while MAIS continues to operate normally with the other reactors.

Threshold settings must be selected with care to avoid hunting in substations where closing and tripping functions are selected simultaneously in response to voltage conditions. It is necessary to avoid selecting closing and tripping thresholds that are too close to each other. However, MAIS constantly analyzes the operation sequences and an anti-hunting function will block any operation that constitutes more than two operations in reverse directions within a certain time lapse.

IV. VOLTAGE MEASUREMENT

A. System Behavior

The three-phase voltage is measured on a 525 kV busbar at each of the substations in which MAIS is installed. Adequate selectivity of the various MAIS units is obtained through precise measurement of voltage amplitudes. This is particularly difficult in a series compensated system because of subsynchronous resonances which produce subsynchronous oscillations. This is mostly a concern at the Ancoa substation because of the presence of four series capacitor banks. Generally speaking, measuring equipment is designed in such a way as to eliminate DC components encountered during transients on a network. This will not be the case of subsynchronous oscillations and adequate filtering must be implemented. Subsynchronous distorsions of voltage waveforms are influenced by the equipement connected to the same busbar. Interractions with shunt reactors will cause parallel resonances at very low frequencies. Furthermore, at the Ancoa substation, the presence of 525-230 kV transformers will also influence voltage measurement. Planned futur expansion of the 525 kV network would result in the transfer of one of the Ancoa transformers. During maintenance of the remaining transformer, the 230 kV system would be isolated from the 525 kV at Ancoa. This will have an impact on the subsynchronous resonance frequencies. Top curve of Figure 3 shows the frequency response of the network impedance at the Ancoa 525 kV substation when the 525-230 kV transformer is in service and only one shunt reactor is connected. Bottom curve shows the frequency response when the transformer is out for maintenance.



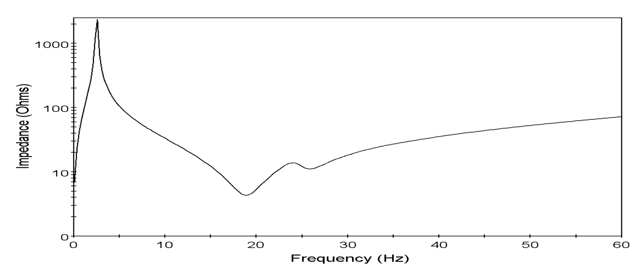


Fig. 3 Frequency Response at Ancoa 525 kV
with One 525 kV Shunt Reactor
Top: Transformer In Bottom: Transformer Out

It is possible to observe a strong subsynchronous parallel resonance at 3 Hz when the transformer is absent. The presence of the transformer substantially increases the frequency of the parallel resonance (8 Hz) and reduces the amplitude of the impedance. However, the low frequency signal causes some saturation of the transformer which produces harmonics and intermodulations. These phenomena have already been discussed in detail in references [3], [4] and [5]. Figure 4 shows the waveform of the voltage at Ancoa 525 kV (top curve) after fault clearing. A subsynchronous oscillation with an amplitude of about 0.20 p.u. at a frequency of 3 Hz is easily discernible. System damping is very small and voltage amplitudes will be distorted for many seconds. The direct sequence voltage obtained with a standard discrete fourier filtering technique over a cycle (bottom curve) exceeds the requirements and could prevent proper operation of the MAIS system.

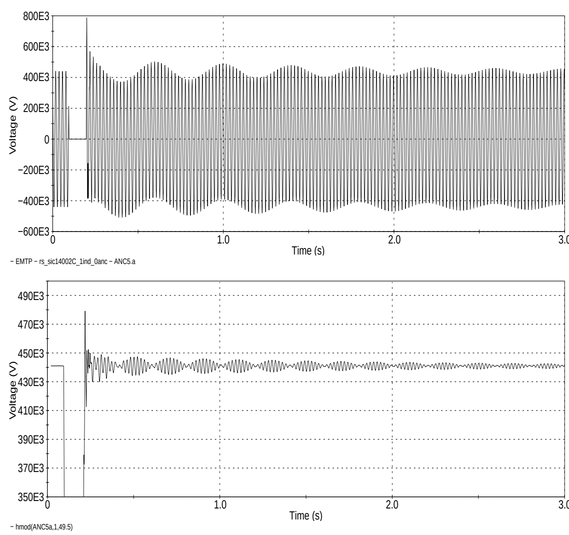


Fig. 4 Voltage Waveform (top) and Phasor Amplitude (bottom) at Ancoa for a 525 kV Busbar Fault with One Shunt Reactor 500-220 kV Transformer Out of Service.

The presence of a 525-230 kV transformer connected to the same busbar as the series capacitors will create additionnal interactions. Direct sequence voltage will be more difficult to measure. Figure 5 shows inrush currents flowing in the transformer after fault clearing.

These inrush currents will introduce further distortions by modulating phasor voltage amplitudes at either one or two times the subsynchronous parallel resonance frequency around the fondamental of 50 Hz. The frequency of the modulating effect will vary with the type of contingency, system conditions prior to fault, time of fault initiation and breaker pole dispersion Figure 6 shows voltage waveform and measured phasor amplitude for a fault on the 525 kV busbar in the presence of the 525-230 kV transformer.

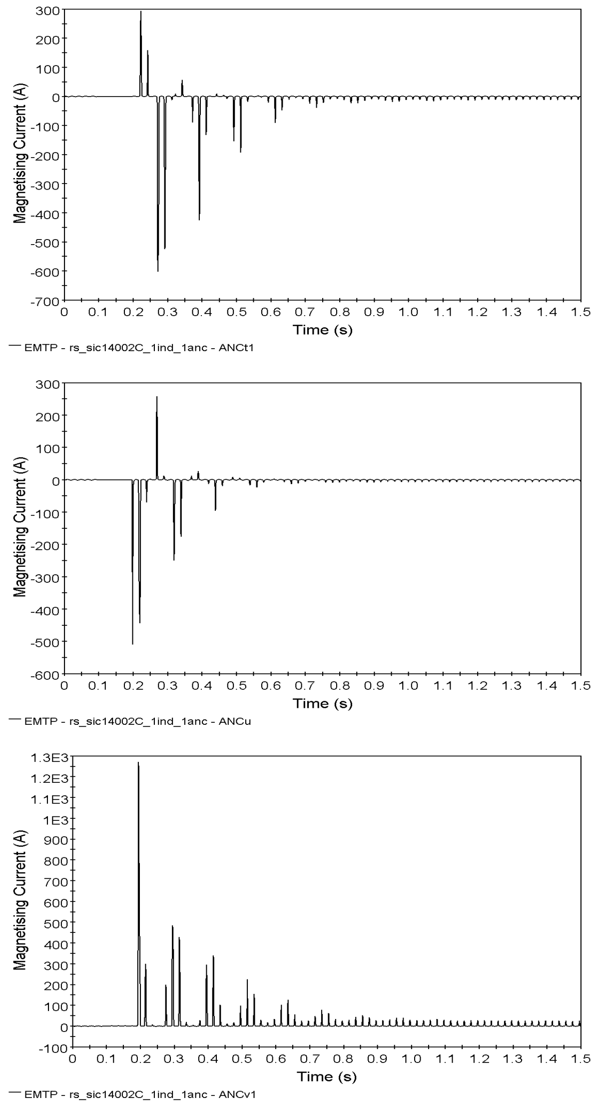


Fig. 5 Inrush Currents in phases a, b and c of the 500-220 kV Transformer at Ancoa Following a 3ϕ fault

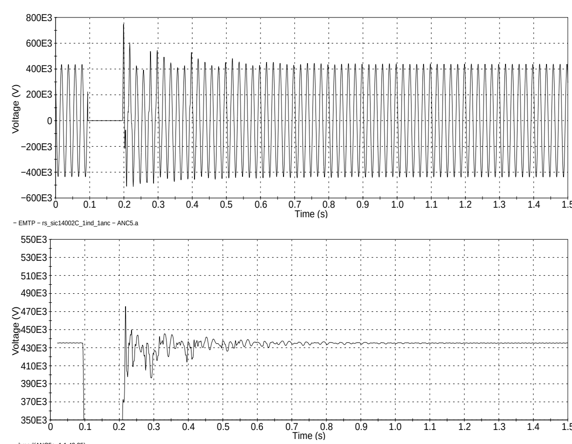


Fig 6 Voltage Waveform and Phasor Amplitude at Ancoa for a 525 kV Busbar Fault – 525-230 kV Transformer In Service.

In order to obtain the necessary selectivity for the MAIS system to correctly carry out its functions, the overall error for the whole measurement link, including errors due to the measurement transformer and filtering of transient phenomena, must be less than 1.0% on the whole voltage range from 0.85 to 1.2 p.u.

Respect for the precision constraint, which must be less than 1.0% in the whole measurement chain, has forced the specification of voltage measurement transformers whose precision is better than 0.3% in the presence of a waveform seriously disturbed by very low frequency oscillations [6].

B. Filtering Requirements

In order to determine the necessary filtering, a screening study was conducted to determine the maximum amplitudes of the transient oscillations at various frequencies of interest. The results appear in Table 3.

All oscillations listed in Table 3 are not present simultaneously with the maximum amplitude. Subsynchronous parallel resonances are mainly present near the series compensation and amplitudes will be greater if the site of the disturbance is close to the series compensation; characteristically, they can last as much as 4 seconds. These transient oscillations will also be influenced by the system operating conditions. Values indicated correspond to the worst conditions with respect to filtering requirements.

TYPE	FREQUENCY (Hz)	MAXIMUM AMPLITUDE OBSERVED (p.u.)
Ancoa Substation		
Subsynchronous Parallel Resonances	3 to 15	0.15
Series Resonances	17 to 24	~0.03
Intermodulation[1]	50+/-(8 to 16)	0.05
Charrúa and Alto Jahuel Substations		
Subsynchronous Parallel Resonances	3 to 15	0.02
Series Resonances	17 to 24	~0.01
Intermodulation	50+/-(5 to 20)	Less than .01
Common to all		
Oversynchronous Parallel Resonances	60 to 90	0.10
Harmonics	N*50 N=1,2,3…	Fast Transient

Table 3 Frequency and Amplitude of Voltage Waveform Distortions on the 525 kV Transelec System in Transient Conditions

Some swithching actions may be required quickly. Therefore MAIS must filter these parasitic oscillations with a measurement time in the order of 200 ms.

[1] Intermodulation is only present if a 525-230 kV transformer is in service. In that case lowest sub synchronous parallel resonance is at 8 Hz.

The filtering requirements were obtained following extensive EMTP type transient studys. However possible modeling and parametre divergence could cause either amplittudes, frequencies or damping to vary. The specified range in frequency is large and covers potentiel differences. However amplitudes and damping are more difficult to establish and switching actions of the MAIS unit closest to the series compensation could be delayed. In this case, units in the two other subsations would offer adequate redundancy. Failure of any MAIS unit is always possible and this should be taken into account with proper coordinated setings for all units.

VI. CONCLUSIONS

A 525 and 230 kV automatic shunt reactor switching system (MAIS) is required to control voltage following system events on the series compensated Transelec power system. Automatic shunt reactor switching systems will be installed in all three 525 kV substations. Each MAIS system is entirely independent and will be able to close or trip shunt reactors in response to local conditions. In spite of the problems caused by the presence of subsynchronous oscillations, adequate filtering must be provided to ensure that MAIS is a selective and reliable mean to control voltage within the desired operating range following system contingencies.

AGKNOWLEDMENTS

The authors would like to express their thanks to HQI Transelec Chile S. A. for the permission to publish these study results.

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