TRANSIENT PERFORMANCE OF 500-kV EQUIPMENT FOR THE CHILEAN SERIES-COMPENSATED TRANSMISSION SYSTEM

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Abstract **– To assess the transient performance of 500-kV equipment required for the integration of the new Ralco hydropower plant, an exhaustive electromagnetic transient (EMTP) study was performed for the design of the Chilean series-compensated transmission system. This study covered several aspects such as: the switching over-voltages (SOV) along the 500-kV lines, the temporary over-voltages (TOV) in the 500-kV system and the inrush transients due to transformer energization during various system restoration scenarios. All those aspects were thoroughly investigated. The efficiency of the line-terminal 336-kV surge arresters to control switching over-voltages along the 500-kV lines was clearly demonstrated. A special protection scheme has been devised to limit the TOV duration as well as the energy stresses in the 336-kV surge arresters in case of full load (or full generation) rejection. Furthermore, the use of pre-insertion resistors or controlled switching devices to suppress the inrush transients due to transformer energization has also been investigated. Finally, the analysis of sub-synchronous resonance (SSR) between the 500-kV series-capacitor banks and several existing thermal power plants in the Chilean network indicated that these phenomena are unlikely to occur.**

Keywords – Switching Over-voltages (SOV), Temporary Over-voltages (TOV), Surge Arresters, Inrush Transients, Pre-insertion Resistors, Controlled Switching, Sub-synchronous resonance (SSR) Phenomena, Series-Compensated Transmission Systems.

I. INTRODUCTION.

The Chilean series-compensated transmission system, as illustrated in Fig. 1, consists of two single-circuit 500-kV lines of more than 400-km length. These lines interconnect from North to South, the three 500-kV substations namely: Alto Jahuel, Ancoa and Charrua. In order to increase the power transfer on these two lines with the integration of the new Ralco hydropower plant, 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 effectiveness solutions in term of: system stability performance, voltage regulation during system disturbances and load division between parallel lines. Moreover, at the Alto Jahuel substation, there are eight 33-Mvar switched shunt capacitors installed on the 66-kV windings of the two power transformers and one 71-Mvar on the 230-kV bus bar. These shunt capacitors are manually switched

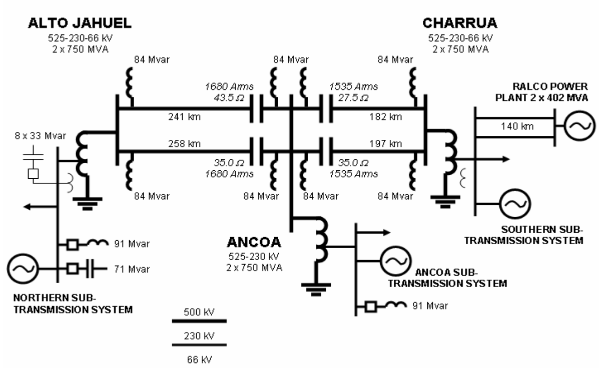


Fig. 1 The Chilean 500-kV Series-Compensated Transmission System

according to the load-flow conditions in the Northern sub-transmission system. Furthermore, at the Alto Jahuel and Ancoa substations, the 242 kV-91 Mvar shunt reactors will be automatically switched according to the load-flow conditions in the 500-kV system. This paper presents the results of the electromagnetic transient study that was performed for the design and specification of 500-kV equipment in the Chilean series-compensated transmission system. This study covered several aspects such as: the switching over-voltages along the 500-kV lines, the temporary over-voltages in the 500-kV system, the inrush transients due to transformer energization during various system restoration scenarios and the analysis of sub-synchronous resonance between the 500-kV series-capacitor banks and several existing thermal power plants in the Chilean network. Under the peak load-flow condition, with all transmission components in service (configuration N-0), the power transfer from Charrua to Ancoa is approximately 1300 MW and the one from Ancoa to Alto Jahuel is 1400 MW. These power transfer conditions could be maintained following the loss of one parallel 500-kV line: i.e. one line between Alto Jahuel and Ancoa (configuration N-1A) or one line between Ancoa and Charrua (configuration N-1B). Furthermore, the Ancoa sub-transmission system could be isolated from the 500-kV lines in the configurations N-0, N-1A and N-1B. In these later cases, the power transfer on the 500-kV lines will be limited to 1300 MW. For the interpretation of the study results, p.u. values are defined on the base voltage of 408.2 kVpeak (or 187.8 kVpeak) for the 500-kV (or 230-kV) system.

II. Switching Over-voltages (SOV)

Switching over-voltages on the Chilean series-compensated transmission system were analyzed for the following events:

A. SOV During a Line Energization and Reclosing.

The system configurations N-0, N-1A and N-1B were used to analyze SOV along the 500-kV lines. Statistical tests involving 100 switching simulations per test with the Gaussian random closing orders to breaker poles, as illustrated in Fig. 2, were performed to obtain the maximum SOV. Moreover, it was assumed that shunt reactors at both line terminals are switched-off during line energization and reclosing. Furthermore, a trapped charge of 1.0 p.u. was set on the line being re-energized in order to cover the application of fast line reclosing in the 500-kV system.

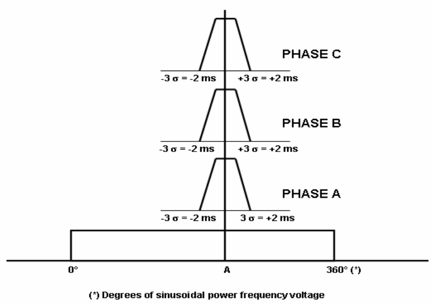


Fig. 2 Breaker pole random closing orders for the simulation of SOV during line energization and reclosing

- *SOV Without Surge Arrester*

Severe SOV during a line re-energization were observed on the system configurations N-1A and N-1B. The maximum SOV on the Alto Jahuel-Ancoa line reached 2.84 p.u. whereas the maximum SOV on the Ancoa-Charrua line was 2.73 p.u., as illustrated in Fig. 3 and 4. The insulation response to slow-front over-voltages of the Alto Jahuel-Ancoa-Charrua 500-kV lines is estimated by the following formula [1]:

$$U_{50} = 1080 \,\mathrm{Ln}(0.46d + 1) \qquad (1)$$
$$= 1064.3 \text{ kVpeak } (\approx 2.60 \text{ p.u.})$$

Where d = 3.65m, is the minimum conductor-to-tower clearance for the 500-kV lines and U_{50} is the switching impulse flashover voltage at 50% probability. Without surge arresters, SOV stresses are too high for the actual design of the 500-kV lines. It is therefore recommended to install permanent 336-kV surge arresters at both line terminals in order to reduce SOV stresses.

- *SOV With 336-kV Line-Terminal Surge Arresters*

SOV along the 500-kV lines were also analyzed with the presence of 336-kV surge arresters at both line terminals. Simulation results, as shown in Fig. 5 and 6, indicate that the maximum SOV on the Alto Jahuel-Ancoa and the Ancoa-Charrua lines are respectively reduced to 2.18 p.u. and 2.12 p.u., which are acceptable for the actual design of these 500-kV lines.

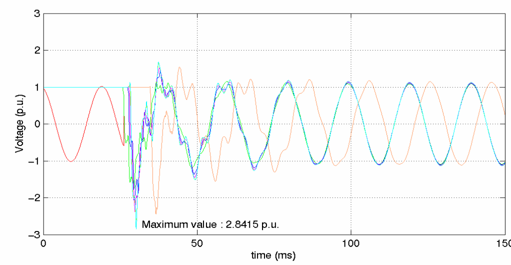


Fig. 3 SOV along the Alto Jahuel-Ancoa 500-kV line – (N-1A) without surge arrester

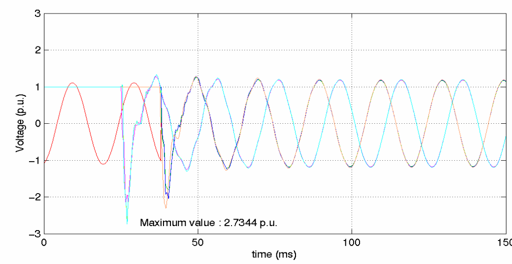


Fig. 4 SOV along the Ancoa-Charrua 500-kV line – (N-1B) without surge arrester

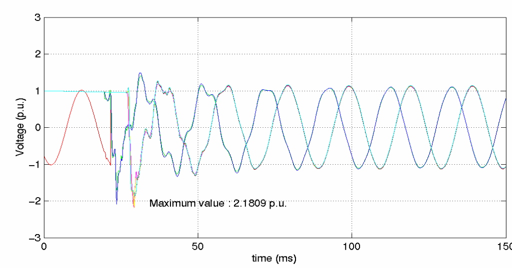


Fig. 5 SOV along the Alto Jahuel-Ancoa 500-kV line – (N-1A) with 336-kV arresters at both terminals

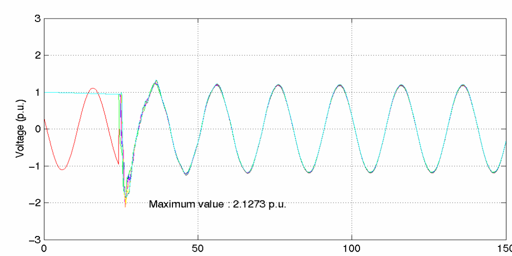


Fig. 6 SOV along the Ancoa-Charrua 500-kV line – (N-1B) with 336-kV arresters at both terminals

B. SOV During a Line Fault

Line fault initiation and clearing could also produce high SOV along series-compensated lines [2]. For the Chilean series-compensated transmission system, the configurations N-0, N-1A and N-1B were also used to analyze SOV during a line fault. Four types of faults: phase-to-ground (P-G), phase-to-phase ungrounded (P-P-UG), phase-to-phase-to-ground (P-P-G) and three-phase-to-ground (3P-G), were analyzed. Six fault locations along the 500-kV lines were considered in the study. Furthermore, statistical tests involving 100 uniform random fault initiation and trip orders, as illustrated in Fig. 7, were also performed to obtain the maximum SOV. The simulation results, as shown in Fig. 8, indicate that with the presence of 336-kV surge arresters at both line terminals, the maximum SOV along the 500-kV lines is limited to 2.09 p.u. during a P-P-UG fault at location 1 on the Ancoa-Charrua line, which is still acceptable for the actual design of the 500-kV lines.

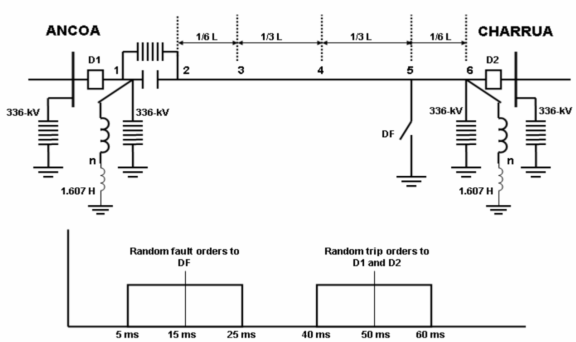


Fig. 7 Fault locations and random fault and trip orders for the Charrua-Ancoa line

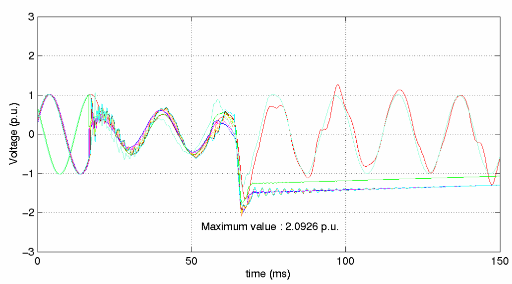


Fig. 8 SOV along the Ancoa-Charrua line during a P-P-UG fault at location 1 – (N-0) with 336-kV arresters at both terminals

III. TEMPORARY OVER-VOLTAGES (TOV)

Important TOV can occur on long AC transmission system in case of load shedding or generation rejection. The use of single-phase auto-reclosing (SPAR) system to maintain power transfer during a spurious single-phase fault on a transmission line can also produce high TOV should this scheme not operate properly [3]. Moreover, the presence of series-capacitor banks could aggravate the power frequency over-voltages on the sound phases during a phase-to-ground fault [4]. Therefore, TOV on the Chilean series-compensated transmission system were thoroughly investigated for the following events:

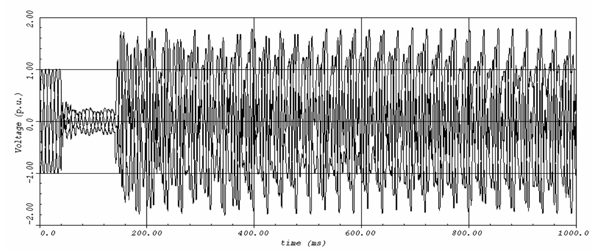
A. Load Shedding and Generation Rejection

A severe fault on Alto Jahuel (or Charrua) 230-kV bus bar could result in a full load shedding (or full generation rejection) in the Chilean 500-kV transmission system. Following a load shedding (or a generation rejection), TOV due to the Ferranti effect appear on long and lightly loaded lines that are still connected to remaining generators. Severe TOV conditions were observed in the configuration N-0 with the Ancoa sub-transmission system isolated from the 500-kV lines.

- *Load Shedding at Alto Jahuel 230 kV*

Following a full load shedding at Alto Jahuel 230 kV, the two unloaded 525-230-66 kV transformers are left connected to long and lightly loaded series-compensated lines while the eight 33-Mvar shunt capacitors remain on the 66-kV windings of these two transformers. Sustained low frequency oscillation superimposed to the fundamental frequency TOV having a magnitude of 1.80 p.u. appear on the 500-kV lines. Under these conditions, the 336-kV surge arresters at Alto Jahuel are subjected to an energy stress of 7.5 MJ during 850 ms following the load shedding, as illustrated in Fig. 9.a and 9.b.

a) TOV at Alto Jahuel 500 kV



b) Energy stresses in 336-kV surge arresters at Alto Jahuel

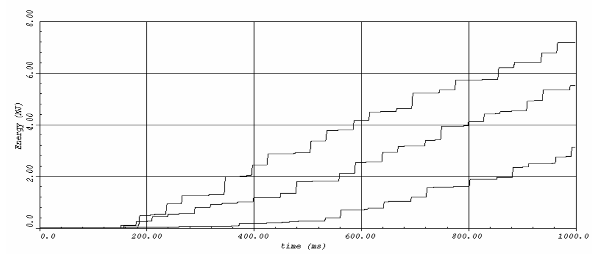


Fig. 9 Full load shedding at Alto Jahuel 230 kV – (N-0) with the isolated Ancoa sub-transmission system

- *Generation Rejection at Charrua 230 kV*

As illustrated in Fig. 10, with the power transfer from Charrua to Alto Jahuel, TOV following a full generation rejection at Charrua 230 kV are much less severe than those due to full load shedding at Alto Jahuel 230 kV. The energy stresses on the 336-kV surge arresters are not critical under this condition. However, in case of the reverse power transfer from Alto Jahuel to Charrua, TOV and energy stresses in the 336-kV surge arresters following a full generation rejection at Charrua 230 kV would be as much severe as those observed in case of full load shedding at Alto Jahuel.

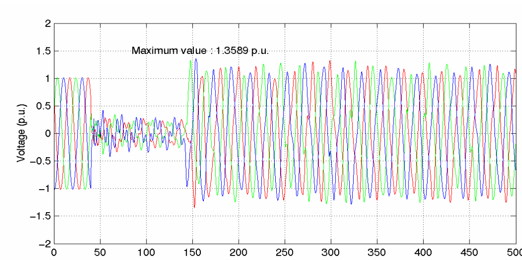


Fig. 10 TOV at Charrua Following a generation rejection at Charrua – (N-0) with the isolated Ancoa sub-transmission system

These TOV are mainly caused by the oscillation between the unloaded transformers at Charrua and the lightly loaded series-compensated lines.

- *TOV Protection Scheme*

From the previous two scenarios, TOV in the Chilean 500-kV transmission system in case of full load shedding (or full generation rejection) are mainly caused by the oscillation between the unloaded power transformers (with or without 66-kV shunt capacitors) and the lightly loaded series-compensated lines. These TOV conditions would appear in both the directions of power transfer from Charrua to Alto Jahuel and the reverse. In order to reduce the TOV duration and the energy stresses on the 336-kV surge arresters, it is recommended to implement fast transfer trips from 230-kV to 525-kV side for all the 525-230-66 kV and 525-230 kV power transformers. However, these transfer trips would not be initiated in case of full load (or full generation) rejection caused by the opening of all 230-kV line circuit breakers. Therefore, it is recommended to implement, as a back up, over-voltage protections including remote transfer trip features for all the 500-kV line terminals. The time delay and the threshold setting for these over-voltage protections should be coordinated with the TOV withstand capability of 336-kV surge arresters.

B. Faulty Operation of SPAR Systems

Severe TOV due to faulty operation of SPAR systems were observed on the configurations N-1A and N-1B.

- *Single-Phase Faulty Trips at Only One Line End*

A faulty operation of SPAR system could initiate a single-phase opening at only one line end without having a fault. Fig. 11 shows the worst TOV at Alto Jahuel during a single-phase faulty trip at the Alto Jahuel line end. Over-voltage protection previously recommended for each line end should detect these single-phase TOV and sends three-phase trip orders to both line ends.

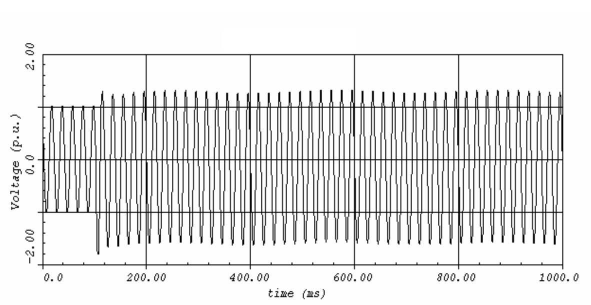


Fig. 11 TOV at Alto Jahuel due to single-phase faulty trip at the Alto Jahuel line end – (N-1A)

- *Unsuccessful Single-Phase Reclosing at One Line End*

Unsuccessful single-phase reclosing at one line end could produce high single-phase TOV on the 500-kV lines, as illustrated in Fig. 12. Again, over-voltage protection on each line end should detect these single-phase TOV and sends three-phase trip orders to both line ends.

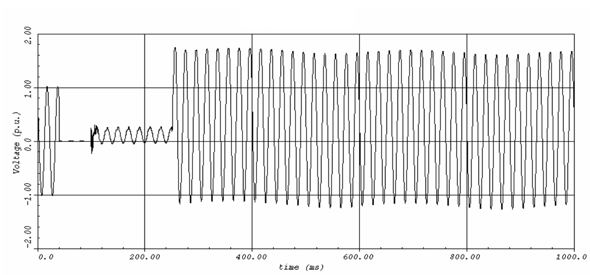


Fig. 12 TOV at Alto Jahuel due to unsuccessful single-phase reclosing at the Alto Jahuel line end – (N-1A)

- *Line Energization With a P-G Fault at Remote End*

Line energization with a permanent P-G fault at remote line end could also generate high TOV on the sound phases as shown in Fig. 13. Normally, line protection should detect this fault condition and send three-phase trip orders to clear the P-G fault. However, the SPAR system on the line being energized should be temporarily inhibited in order to avoid the repetition of this TOV condition.

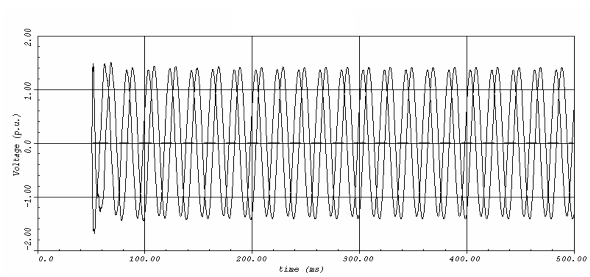


Fig. 13 TOV at Ancoa with a permanent P-G fault during the energization of the Ancoa-Charrua line from Charrua– (N-1B)

C. TOV on the Sound Phases During a P-G fault

Power frequency TOV on the sound phases during a P-G fault have been analyzed for the configurations N-0, N-1A and N-1B. The maximum TOV was found for the configuration N-1A as shown in Fig. 14. It should be mentioned that these power frequency TOV disappear when the P-G fault is cleared. However, the thresholds and time delays of over-voltage protections on the 500-kV line terminals should be coordinated with these TOV levels in order to ensure a safe operation.

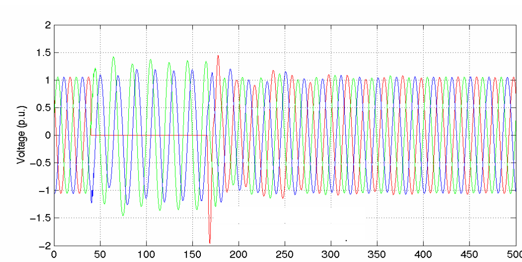


Fig. 14 Power frequency TOV on the sound phases at Ancoa during a P-G fault at the line of one series-capacitor bank – (N-1A)

IV. Inrush Transients

The energization of a power transformer could results in severe TOV due to harmonic components in the transformer inrush currents [4]. The inrush transients during the energization of a power transformer at Charrua were analyzed for the system restoration scenarios from the 230-kV side and from the 500-kV side.

A. System Restoration from the 230-kV Side

In this scenario, the 500-kV system is restored from one 402-MVA generator unit of Ralco hydropower plant. The 525-230-66 kV power transformer at Charrua is energized from the 230-kV side after the energization of the Ralco-Charrua line, as illustrated in Fig. 15. TOV with high harmonic contents having the magnitude of 1.82 p.u., as shown in Fig. 16, appear during transformer energization. The maximum inrush current on the 230-kV side reaches 2564 Apeak. These TOV and inrush current would be stressful to the 525-230-66-kV transformer and to other system equipment.

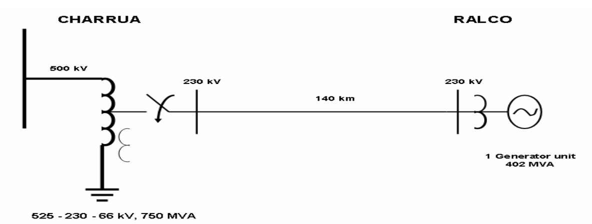


Fig. 15 System Restoration From Ralco Power Plant

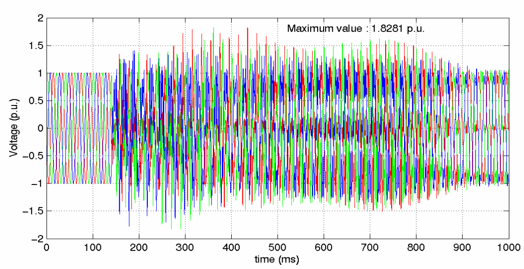


Fig. 16 TOV During the Energization of 525-230-66-kV Transformer at Charrua from 230-kV side.

B. System Restoration from the 500-kV Side

In this scenario, the 500-kV system is restored from one 263-MVA generator unit of the Pehuenche hydropower plant. The power transformer at Charrua is energized from the 500-kV side after the energization of the Ancoa-Charrua line, as illustrated in Fig. 17. TOV with high harmonic contents having the magnitude of 1.93 p.u. appear during transformer energization, as shown in Fig. 18. The maximum inrush current on the 500-kV side reach 1130 Apeak. Under this TOV condition, the 500-kV line would be tripped by over-voltage protection and the system restoration would not be completed. Moreover, the oscillation between the series-compensated line and the unloaded transformer would prolong high magnitude transformer inrush currents.

C. Remedy Measures to Suppress Inrush Transients

Important harmonic TOV and inrush currents were observed during transformer energization from the 230-kV side or from the 500-kV side at the Charrua substation. The following remedy measures for the suppression of inrush transients due to transformer energization have been investigated:

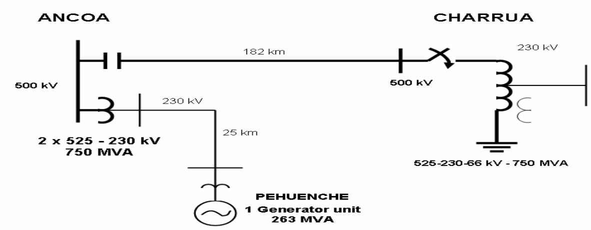


Fig. 17 System Restoration From Pehuenche Power Plant

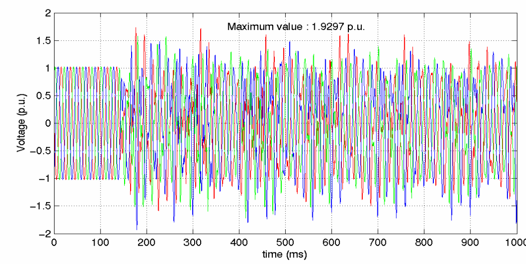


Fig. 18 TOV During the Energization of 525-230-66-kV Transformer at Charrua from 500-kV side.

- *Pre-insertion Resistors*

The effects of pre-insertion resistors of 400 Ω-14 ms on the 230-kV side and of 2000 Ω-14 ms on the 500-kV side were analyzed. The simulation results, as summarized in Table I, indicate that the use of pre-insertion resistors allows to suppress harmonic TOV and inrush currents during transformer energization at Charrua. However, the pre-insertion resistors on the 230-kV side are less expensive than those on the 500-kV side. Therefore, it is recommended to apply this solution on the 230-kV side.

- *Controlled Switching Devices*

As an alternative solutions for pre-insertion resistors on the 230-kV side, the effects of controlled switching devices on a single-break 230-kV circuit breaker were also investigated. The switching control strategy developed in [6] was applied in this study. The simulation results, as summarized in Table I, show that controlled switching devices on the 230-kV circuit breakers will also successfully suppress inrush transients during transformer energization at Charrua.

Table I Effects of remedy measures on inrush transients during transformer energization at Charrua

Remedy measures	**Transformer energization from the 230-kV side**		**Transformer energization from the 500-kV side**	
	TOV/ Duration	Max. Inrush Current	TOV/ Duration	Max. Inrush Current
Pre-insertion Resistors (*)	1.12 p.u./ 20 ms	91 Apeak	1.25 p.u./ 40 ms	85 Apeak
Controlled Switching	No over-voltage	7 Apeak	Not analyzed	Not analyzed

(*) Pre-insertion resistors of 400 Ω - 14 ms for the 230-kV side and of 2000 Ω - 14 ms for the 500-kV side.

V. SUB-SYNCHRONOUS RESONANCE (SSR)

The integration of the Ralco hydropower plant and overall reinforcement of the Chilean 500-kV transmission system will involve the addition of four 500-kV series-capacitor banks at the Ancoa substation. These series-capacitor banks will bring the 500-kV line series-compensation close to 50%. In the Chilean network, no thermal power plant feeds directly into the 500-kV lines. However, to address any concern of potential sub-synchronous interactions between the Ancoa series-capacitor banks and thermal power plants feeding into the Chilean network, a total 28 power production units in 28 different thermal power plants were screened for potential SSR interactions using a pessimistic screening process. This assessment was performed for two different network configurations: full network and low hydropower configuration where Pehuenche and Pengue hydropower plants are out of service. Frequency responses were evaluated for all the power production units at the low voltage side of step-up transformers. Furthermore, the power production units most susceptible to SSR interactions were also set in a pessimistic radial configuration and frequency responses were evaluated. Fig. 19 and 20 are the typical frequency responses at a power production unit in the CELPAC power plant for the full network and the low hydropower configuration. Finally, risk assessments for potential SSR interactions were also performed for all the power production units. Results indicate that susceptibility for SSR interactions is extremely low for all thermal power units under study.

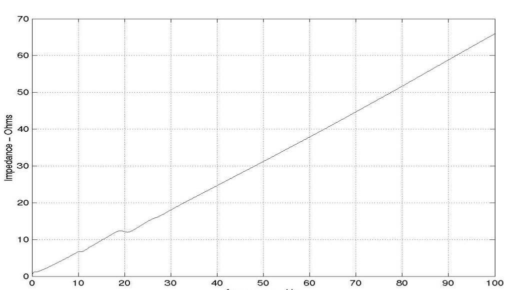


Fig. 19 Frequency response at the CELPAC power production unit – Full network

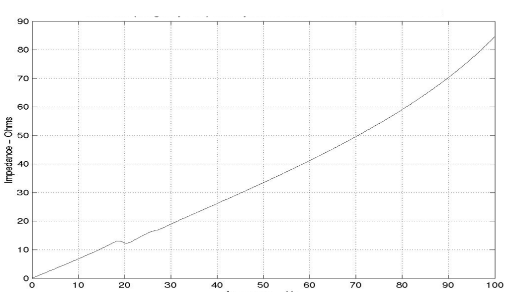


Fig. 20 Frequency response at the CELPAC power production unit – Low hydropower configuration

VI. CONCLUSIONS

Extensive electromagnetic transient study has been performed for the design of the Chilean 500-kV series-compensated transmission system. In light of these study results the following main conclusions could be drawn:

- Without surge arresters, switching over-voltages are too high for the actual design of the 500-kV lines. The presence of the line-terminal 336-kV surge arresters allows to reduce switching over-voltage stresses to acceptable levels for the actual design of these 500-kV lines.
- The implementation of fast transfer trips from 230-kV to 525-kV side for all the 525-230-66 kV and 525-230 kV power transformers together with the addition of over-voltage protections including remote transfer trip features for all the 500-kV line terminal allow to efficiently control the TOV duration in the 500-kV system as well as the energy stresses in the 336-kV surge arresters.
- Severe harmonic TOV and inrush currents could appear during transformer energization from the 230-kV side or from the 500-kV side at the Charrua substation. The use of pre-insertion resistors or of controlled switching devices on the 230-kV side will allow to suppress harmonic TOV and inrush currents during the transformer energization at Charrua.
- The susceptibility for SSR interactions with the 500-kV series-capacitor banks at the Ancoa substation is extremely low for all the thermal power production units under study.

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