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Transient Design Studies for the Transmantaro Series-Compensated Transmission System

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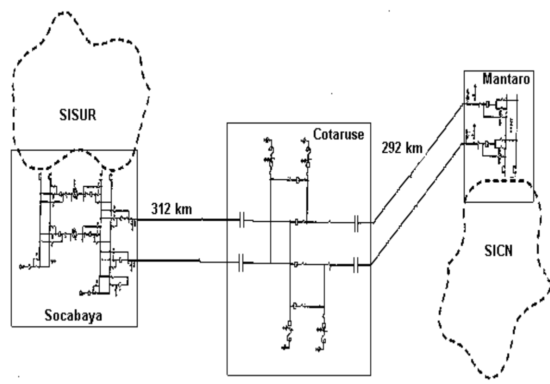
Abstract - **The Transmantaro series-compensated link interconnects the Peruvian northern SICN and southern SIS transmission systems. Extended electromagnetic transient design studies were performed to establish different requirements on the substation equipments. Statistical analyses of Transient Recovery Voltage (TRV) were performed to determine circuit breakers specifications. Temporary Over voltages (TOV) were studied to establish transformer energization philosophy and over voltage protective schemes. The results of these studies are summarised in this report. Special design considerations for the series-compensated interconnection system, interaction between shunt reactors and series capacitors for voltage measurements implemented in the automatic switching system are also discussed.**

Keywords: Series-Compensation Systems, Temporary Overvoltages (TOV), Transient Recovery Voltages (TRV), Automatic Switching Systems, Special Protection System.

Figure-1: The Transmantaro SICN-SIS 220 kV Interconnection System



I. INTRODUCTION

In October 2000, the north-south Peruvian Transmantaro transmission link was put in commercial operation. This system is owned and operated by Transmantaro, a subsidiary of Hydro-Québec. Designed for a maximum transit capacity of 300 MW, it interconnects the SICN transmission system from the Mantaro substation to the Socabaya substation located on the SIS system in the South of Peru. The Transmantaro interconnection is comprised of a double circuit 220 kV line of about 600 Km. An intermediate substation with a ring bus arrangement is located near the middle of the interconnection as illustrated in Fig. 1. In this substation, four series capacitor banks compensating between 50 and 60 % of the lines are implemented. Four 50 Mvar three phase (five leg) iron core shunt reactors are automatically switched by an automatic switching system to maintain steady state voltage profiles on the interconnection. This paper presents the results of electromagnetic transient studies for the design and specification of substation equipment. These studies covered several aspects such as: Transient recovery voltage on the 220kV breakers, temporary and switching overvoltages, energy stresses on MOV and implementation of protection and automatic switching schemes. The electromagnetic transient studies were performed with DCG-EMTP.

II. TRV ACCROSS LINE CIRCUIT BREAKERS

The presence of series capacitor banks on transmission lines substantially increases TRV stresses across line circuit breakers due to the presence of trapped charges on series capacitor banks [1]. Furthermore, temporary over voltages can appear on long radial transmission lines in case of total load rejection. In these conditions, out of phase and unloaded line interruption will result in severe TRV stresses on line circuit breakers [2]. To reduce stresses, line surge arresters were installed at both ends of each line. TRV stresses on the 220 kV circuit breakers were analysed for the following interruption conditions:

A. TRVs caused by fault clearing

To establish the worst TRV stresses on the 220 kV circuit breakers, various types of faults were applied at 6 different locations along the line for both line sections. Random sequence of fault initiation and clearing time for 100 statistical cases were simulated. Results, summarized in table 1, show worst TRVs obtained. The series compensation has an impact on the breaker by increasing the stress during fault clearing. To reduce stress on backup circuit breaker, series capacitors will be bypassed when live breakers are out of service for maintenance purposes.

Breaker Location	**Worst TRV (KV peak)**
Line from Mantaro to Cotaruse stations	
Mantaro	528
Mantaro *	349
Cotaruse N	636
Line from Cotaruse to Socabaya stations	
Cotaruse S	636
Socabaya	553

* indicate worst TRVs for series capacitor bypass condition

Table-1: Worst TRV Stresses on Circuit Breakers for Fault Clearing

The study shows that the TRVs were most severe for faults applied at far end of line with respect to breaker locations, where interrupted currents were less than 10% of rated short-circuit breaking current specified for breakers.

B. TRVs caused by out of phase interruption and during unloaded line opening.

The Transmantaro interconnection will be synchronized at the Socabaya station. Under normal conditions, a synchrocheck relay installed in the Socabaya 220 kV station only permits closure of the breaker when voltages on both sides are in phase. However, misoperation or erroneous breaker manoeuvre could result in unsynchronized closure of the interconnection and subsequent out of phase line tripping. This condition would also result in line tripping of the remote end under no load conditions.

Events such as breaker failures or delayed operation of protection systems could cause system separation or full load rejection. Under these circumstances, the Transmantaro interconnection could be exposed to important temporary overvoltages and the duration must be limited by tripping the remote end of unloaded lines. To establish the worst TRV stresses on the 220 kV breakers associated with out of phase and unloaded line interruption, 100 random simulations were performed. Worst TRVs obtained are summarized in table 2.

These high TRV stresses imposed on line breakers are considerably higher than normally seen on 220 kV breaker equipment. The presence of trapped charge in the series capacitors and long line switching resulted in stresses that were closer to 362 kV class equipments.

Breaker location	**Worst TRV for Out of Phase**	**Worst TRV for Unloaded opening**
Line from Mantaro to Cotaruse stations		
Mantaro	N/A	395
Cotaruse N	632	N/A
Line from Cotaruse to Socabaya stations		
Cotaruse S	693	471
Socabaya	596	489

Table-2: Worst TRV Stresses on Circuit Breakers for Out of Phase and unloaded line opening

III. CONTROL OF TEMPORARY AND SWITCHING OVERVOLTAGES

A system separation leaving long unloaded transmission lines connected to generators can lead to severe temporary over-voltages [3]. This is the case for the Transmantaro interconnection. Because of the overall system length (609 km) substantial temporary over-voltages can occur for events involving total load loss or system separation. In the Socabaya station, 220-138kV transformers left connected to the unloaded 600 km series compensated interconnection could lead to severe overvoltages. As a first line of defence local protective actions are taken to ensure that equipment is tripped when required so that overvoltages do not appear. Therefore, to ascertain that transformers are not left connected to a long unloaded series compensated line; both sides of the transformers are tripped simultaneously for all events calling for transformer trip (transformer and bus bar protections). Line reclosing actions are timed so that lines reclose from the strongest source side first and no reclosing action is permitted without synchrocheck. However, to reduce the duration of overvoltages, should they appear, transfer tripping and overvoltage protections were implemented. In the Mantaro and the Socabaya substations, three overvoltage protection levels were implemented on each 220 kV line terminals. These protections measure all phase line to ground voltages and order a three-phase line trip at both ends if any voltage exceeds the following threshold for set time span:

- Voltage exceeding 1.6 p.u. For 125 ms
- Voltage exceeding 1.4 p.u. For 250 ms
- Voltage exceeding 1.25 p.u. For 1 s.

In the Cotaruse substation, single line to ground faults on the line side of the series capacitor banks will result in 60 Hz overvoltages of more than 1.6 p.u. (See section A). Overvoltage protections were therefore set at following levels:

- Voltage exceeding 1.4 p.u. For 250 ms
- Voltage exceeding 1.25 p.u. For 1 s.

A. Overvoltages on Unfaulted Phases During a Single Line to Ground Fault on the Line Side of the Series Capacitor Bank.

60 Hz over-voltages are observed on the unfaulted phases for a line to ground fault on the line side in the Cotaruse substation. Voltages are shown in Fig-III.1 a.

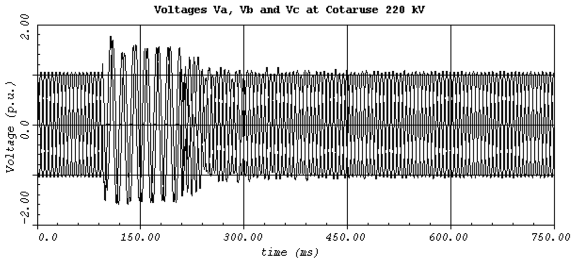


FIG-III.1a: Voltages at the Cotaruse 220 kV Bus bar

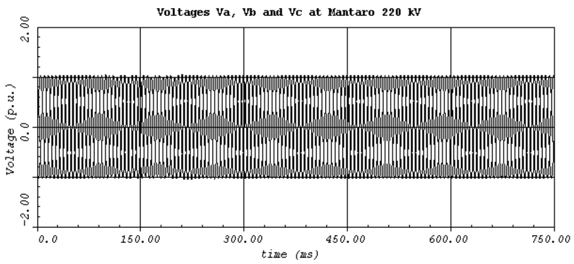


FIG-III.1 b: Voltages at the Mantaro 220 kV Substation

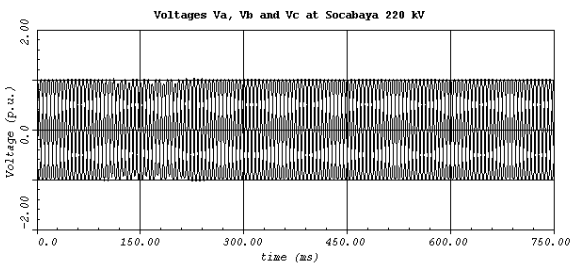


FIG-III.1c: Voltages at the Socabaya 220 kV Substation

Overvoltages disappear either when fault is cleared by the line protection (6 cycles) or after bypass of the capacitor bank (4 cycles) and no additional protective action is required. This phenomenon was accounted for in the Cotaruse substation equipment design. Fig-III.1b and c show the voltages at the Mantaro and Socabaya substations during the same events. No over voltage was observed in these substations.

B. Control of Temporary Over Voltages for Total Load Loss and System Separation.

1- Total Loss of Load at the 138 kV Socabaya Station

In normal operating conditions, the Socabaya 220 kV substation feeds two double circuit lines. If one double circuit line is out of service, a fault on the 138 kV section could leave the 220-138 kV transformers connected to the an unloaded 600 km interconnection. Harmonic overvoltages caused by transformer saturation could appear. To prevent this situation from happening, both the 220 kV and 138 kV transformer breakers are tripped. A delay of 2,5 cycles between low and high side tripping was simulated. Fig-III.2.1a-e shows voltages at different locations on the interconnection. A voltage dip is observed at the Mantaro substation during the fault. Fault clearing does not result in any overvoltage at that location. Temporary over voltages are observed at the Cotaruse and Socabaya 220 kV substations.

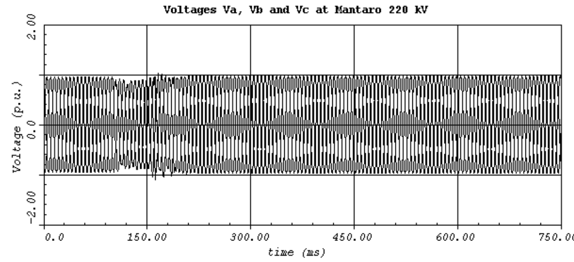


FIG-III.2.1a Voltages at Mantaro 220 kV

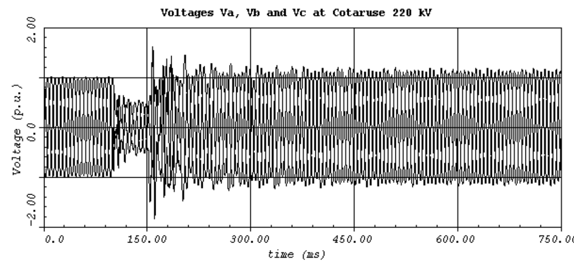


FIG-III.2.1b Voltages at Cotaruse 220 kV

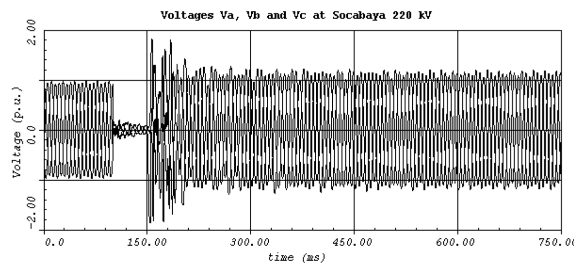


FIG-III.2.1c Voltages at Socabaya 220 kV

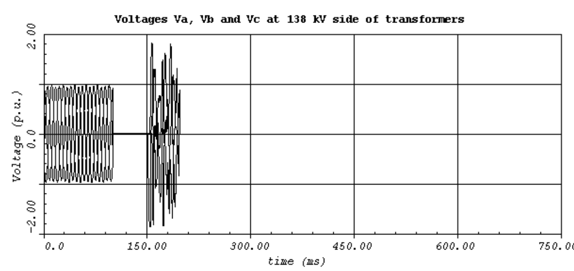


FIG-III.2.1d Voltages at 138 kV Side of Transformers

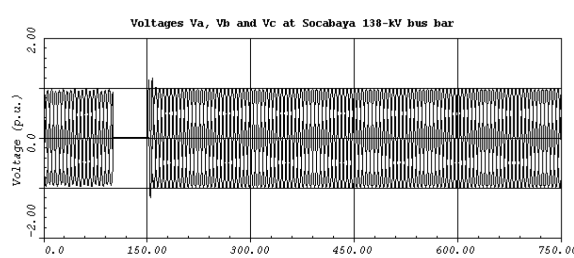


FIG-III.2.1e Voltages at Socabaya 138 kV

These temporary over voltages cause no concern for equipment as they were accounted for in the design of the interconnection. The Socabaya 138 kV section maintains voltage levels close to normal operating conditions.

2. System Separation at the Mantaro Substation

Temporary over voltages can appear when the interconnection is left connected to the southern system after a system separation in the Mantaro substation. A three-phase fault was simulated at the Mantaro station. A transfer trip initiates opening of Mantaro-Cotaruse lines at both ends. A delay of 2,5 cycles is assumed before tripping at the Cotaruse substation. The over voltage protections set at 1,25 p.u. will trip both Cotaruse-Socabaya lines after 1 second. FIG III.2.2 a-d shows the voltages on the interconnection after system separation. The trapped voltage on the opened line oscillates and decays quickly (FIG.III.2.2a).This oscillation is due to the presence of a resonance between the shunt reactor at the end of the open line and the line capacitance.

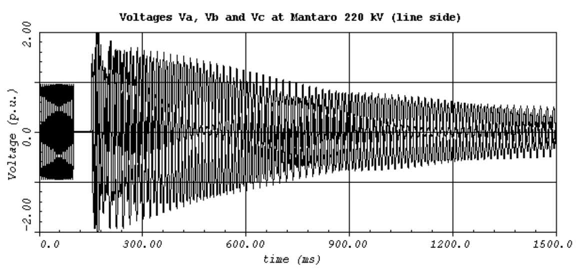


FIG-III.2.2a Voltages on Open Line at Mantaro 220 kV

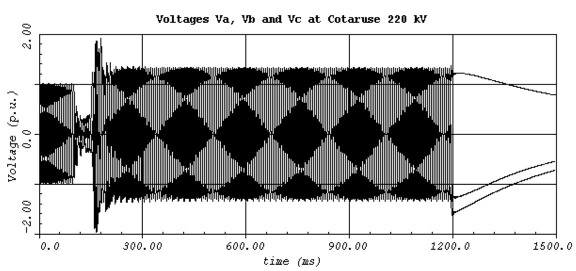


FIG-III.2.2b Voltages at Cotaruse 220 kV

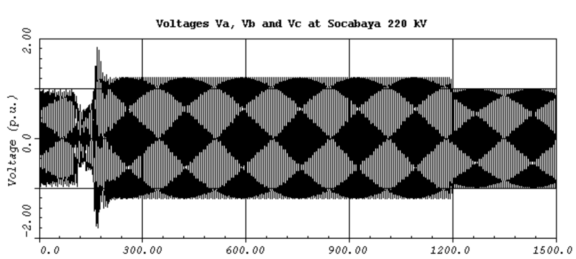


FIG-III.2.2c Voltages at Socabaya 220 kV

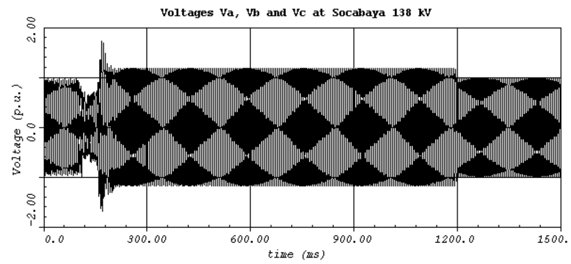


FIG-III.2.2d Voltages at Socabaya 138 kV

3. System Separation at the Cotaruse Substation

In this event, a fault is applied on both circuits of the double circuit line to the north of the Cotaruse substation leading to a system separation at the Cotaruse station. Lines to the south are left unloaded with no shunt reactors connected. Temporary overvoltages between 1,25 and 1,4 p.u. appear at the Cotaruse substation (FIG-III.2.3a). Overvoltage protections set at 1.25 p.u. will tip remaining lines on the interconnection after 1 second. FIG-III.2.3 b-c show voltages at different locations on the interconnection. Voltages at the Socabaya substation are restored to normal operating levels after unloaded open lines are tripped.

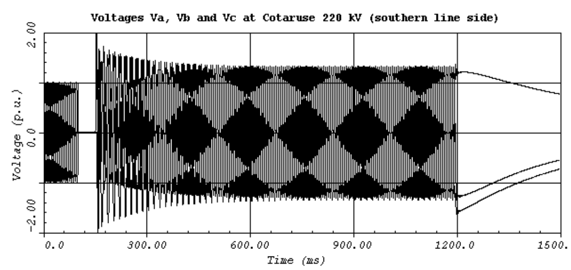


FIG-III.2.3a Voltages at Cotaruse 220 kV

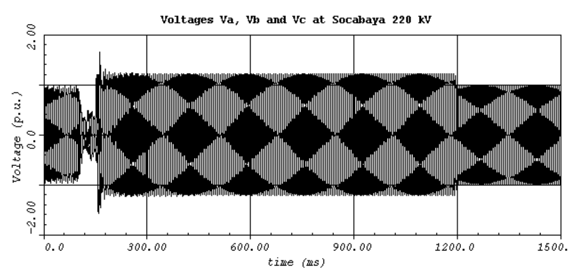


FIG-III.2.3b Voltages at Socabaya 220 kV

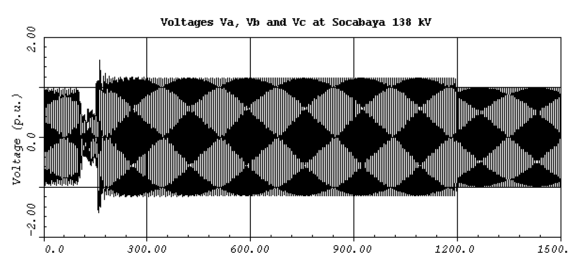


FIG-III.2.3c Voltages at Socabaya 138 kV

C. Temporary over voltages after transformer energization in the Socabaya station.

As discussed in section B, energization from the 220 kV section in the Socabaya substation can create over voltages and is not recommended. Transformer energization will be done from the 138 kV side. Transformer energization was first simulated with no closing resistor. For this event, a residual flux of ±85% on two phases and 15% on the third was assumed. FIG-III.3a and b show voltages on the Socabaya 138 kV section and inrush currents after transformer energization. To reduce harmonic content in the waveform, both 138 kV breakers were equipped with a closing resistance of 400 ohms with an insertion time of 14 ms. FIG-III.3c and d show results with closing resistance. Very little transient and harmonics are observed.

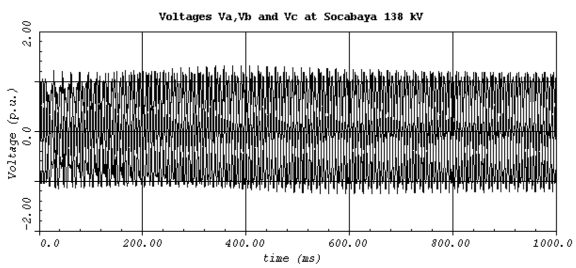


FIG-III.3.a Voltages at Socabaya 138 kV after Transformer Energization (no insertion resistance)

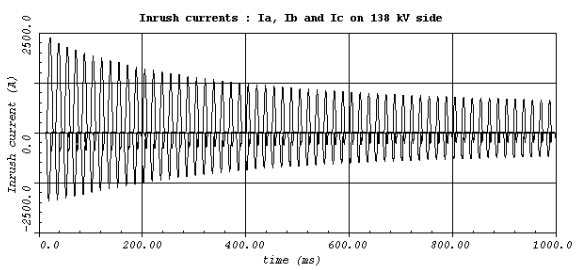


FIG-III.3b Inrush Current on 138 kV Side

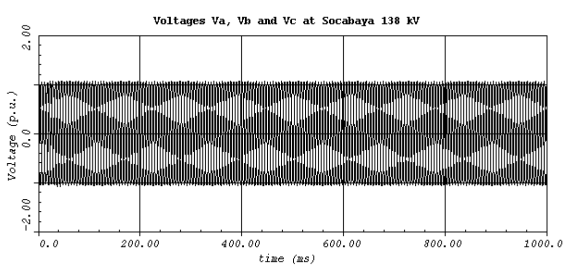


FIG-III.3c Voltages at Socabaya 138 kV kV after Transformer Energization (with 400 ohms resistance)

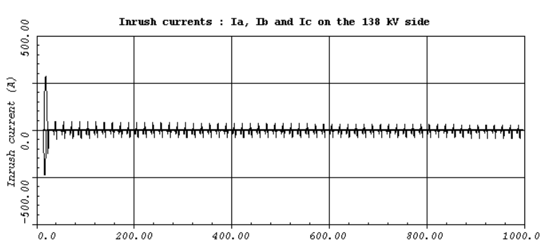


FIG-III.2.3c Inrush Current on 138 kV side

IV. ENERGY STRESSES ON MOVs

Four series capacitor banks are installed at the Cotaruse station. This compensation represents about 50% of total line impedance for the Mantaro-Cotaruse double circuit line (56 ohms) and about 60% for the Cotaruse-Socabaya line (72 ohms). Due to high altitude of Cotaruse substation, no controlled bypass gap was installed. Therefore these series capacitor banks are only protected by MOVs connected in parallel. During a fault, the MOVs limit the maximum overvoltage across the series capacitor bank to their protective level , which was chosen as 2.3 times the rated peak voltage of series capacitor bank. The varistors must therefore be designed to absorb the energy associated with such conditions. Once the fault is cleared, the MOVs cease to conduct and the banks are reinserted. For severe faults were current and energy stresses could rapidly exceed design values of capacitor banks and MOVs, protective actions are taken and the capacitor banks are bypassed by closing of the bypass breaker (total maximum bypass time of 4 cycles). For external faults to the line where the series capacitor bank is installed, no bypass is allowed under normal fault clearing conditions and a total fault clearing time of 6 cycles is used. In order to establish the design criteria of the capacitor bank, energy stresses on MOVs were evaluated for a maximum bypass time of 4 cycles for internal faults and total fault clearing time of 6 cycles for external faults. Internal and external faults were simulated for various types of faults and fault locations. Simulation results are summarized in table 3 indicating the worst energy absorption in MJ for each series capacitor bank, for single-line-to-ground (1p-g) and three-phase-to-ground (3p-g) faults located within the line protection zone (internal) or on an adjacent line (external).

Series capacitor bank	**Internal Fault**		**External Fault**	
	E 1p-g	**E 3p-g**	**E 1p-g**	**E 3p-g**
Cotaruse North	8,75	21,5	1,7	3,65
Cotaruse South	11,75	25,5	negligible	5

Table-3: Worst Energy absorption on MOVs for various fault types and locations

MOVs are designed for the worst internal faults and no bypass is needed for external faults and capacitor banks will remain in service.

V. AUTOMATIC SWITCHING OF SHUNT REACTOR

Design specifications for the overall interconnection system required that steady state voltage profiles be maintained within ± 5% of the operating voltage. To satisfy this criterion 50 Mvar shunt reactors were installed at each line terminal in the Cotaruse station. Under normal operating conditions, reactors are switched in to maintain a good voltage profile during light load conditions. As the load increases, reactors are switched out. As an indication, Table 4 shows the number of shunt reactors that are required under various load conditions on the interconnection.

MODE	Transit in the interconnection (MW)				
	SICN-SIS 0 MW	SICN-SIS 100 MW	SICN-SIS 200 MW	SICN-SIS 300 MW	SIS-SICN 300 MW
Normal	4	4	3	2	3
N-1 Ma-Co	4	4	3	1 (M)	1 (M)
N-1 Co-So	4	4	3	1 (M)	1 (M)
1 Trf	4	4	3	2	3
So-Mo	4	4	3	2	3

(M) indicates that automatic actions are required to remove a shunt reactor when one circuit is lost

Table-4: Number of shunt reactors in the Cotaruse station for various system conditions and transit level.

Under normal conditions where all the lines are in service, 2 shunt reactors would be switched out for a 300 MW transit from the SICN system to the SIS system. If one of the circuits trips, an additional reactor must be switched out. Because reactors are installed at the line terminal, this could already be the case. If it is not, one additional reactor must be tripped. This is done with the use of an automatic shunt reactor switching system similar to the one implemented on the Hydro-Québec 735 kV network [4,5]. Voltage amplitude at the Cotaruse station is constantly monitored. If measured voltage falls below a set percentage value with respect to the average monitored voltage, a reactor is automatically selected and tripped. To achieve proper detection and correct operation, good sensitivity and precision in measurement are required. However, series capacitor banks interact with shunt reactors resulting in a parallel resonance as shown in figure V-I.

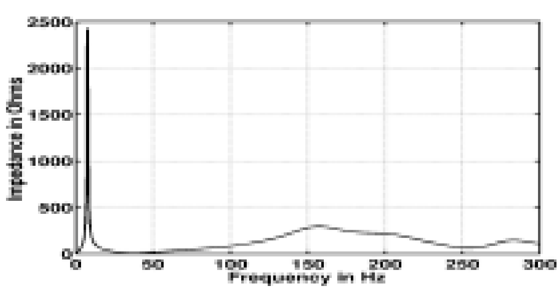


FIG.V-I Frequency scan at Cotaruse substation

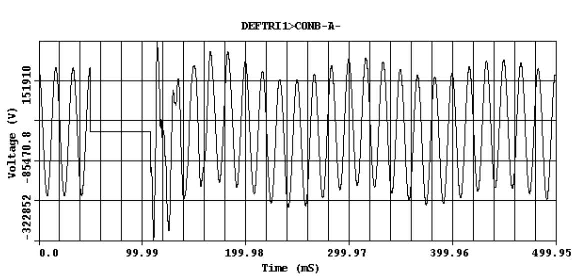


FIG.V-I1 Voltage after fault clearing at Cotaruse

Low frequency oscillations in the range of 5 to 20 Hz develop. FIG.V-II shows post fault voltage at the Cotaruse station. This low frequency component in voltage is filtered and phasor amplitudes are not affected. The precise phasor measurement-filtering algorithm implemented in the automatic switching system was adequate for this application.

VI. CONCLUSION

Extensive electromagnetic transient studies were performed for the design of the Transmantaro series compensated interconnection. From these studies, the following conclusions could be drawn:

■ TRVs are more severe on series compensated system. To reduce stresses on line circuit breakers, line surge arresters with a MCOV of 156 kV rms were installed at both ends of each circuit. Breaker specifications were upgraded to values close to 362 kV class equipment. To reduce stresses on existing backup breakers, series capacitor banks will be bypassed when live breakers are out of service for maintenance purposes.

■ Over voltages can appear on long unloaded lines. A transfer trip and over voltage protection scheme was implemented on the interconnection. Result show that coordinated protection actions and settings will efficiently limit over voltages and duration in all cases.

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