MODELING AND INVESTIGATION OF THE TCSC IN BRAZILIAN NORTH/SOUTH INTERCONNECTION

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***Abstract* – This paper presents a modeling and investigation of different Thyristor-controlled Series Capacitor (TCSC) control strategies to damp low frequency inter-area oscillation in the Brazilian North/South interconnection. Two new cooperative control methods are proposed and investigated. As a result, it is shown that the TCSC performance is better if global energy flows are used in the cooperative control of the four TCSCs which control the north-south interconnection.**

***Keywords* - Low frequency oscillations, North/South interconnection, TCSC (Thyristor Controlled Series Capacitor).**

I. INTRODUCTION

In 1999 the North/Northeast and South/Southeast/Central-West Brazilian systems were interconnected by a 500 kV AC transmission line, with approximately 1000 km of extension and 1300 MW of maximum capacity, as shown in Fig. 1. This interconnection, called North/South Interconnection established the connection between Imperatriz and Serra da Mesa substations [1]-[5].

During the North/South interconnection planning, a low-frequency oscillation mode, about 0.2 Hz, was identified [6]. In order to provide enough damping for this oscillation mode, two TCSCs were installed: one (of them) in Imperatriz substation and the other in Serra da Mesa substation.

Fig. 1. North/South interconnection.

In 2004, more two TCSCs were incorporated into the second circuit of the Brazilian North/South interconnection, totalizing four TCSCs in the two parallel transmission lines of this interconnection. Three different manufacturers were contracted to furnish the four TCSCs. This diversity of TCSCs manufacturers has resulted in a complex problem, in the sense of control coordination. The main difficulties are: assuring a coordinated performance between the controllers and choosing the correct reference signal for the controllers.

This paper discusses the performance of the TCSCs controllers operating with two different acquisition methods to determining the control signal references. The influence and the impact of the control methodologies were also checked. For this, the TCSCs including their different control systems, as well as a detailed part of the Brazilian transmission system and the hydroelectric power plants involved with the matter is being investigated were modeled in the PSCAD/EMTDC that simulation program.

II. CONTROL STRATEGIES OF THE TCSCs

This section shows the control block diagrams of each TCSC controller and describes briefly their functionalities. The main objective of the control system is to mitigate the low frequency power oscillation verified on North/South Interconnection.

Fig. 2 depicts a simplified diagram of the Brazilian North/South interconnection. This diagram shows that the measured power flow (p1) at north end of circuit_1 is the control reference to the TCSC_1. The measured power flow (p3) at south end of circuit_1 is the control reference to the TCSC_3. However, TCSC_2 and TCSC_4 use the total measured power flow (pt) (sum of the power flows in the two lines) as a control reference. This is the actual configuration of the TCSCs controllers, already in commercial operation.

A. The TCSC installed in Imperatriz Substation – Circuit 1.

The control strategy used in the TCSC installed in Imperatriz (circuit #1) is known as “phasor-POD” [7]. It is based on the fact that the frequency of the inter-area power oscillation is "well known”. Hence, this control methodology continuously extracts a phasor representing the low-frequency power oscillation at this "known frequency" from

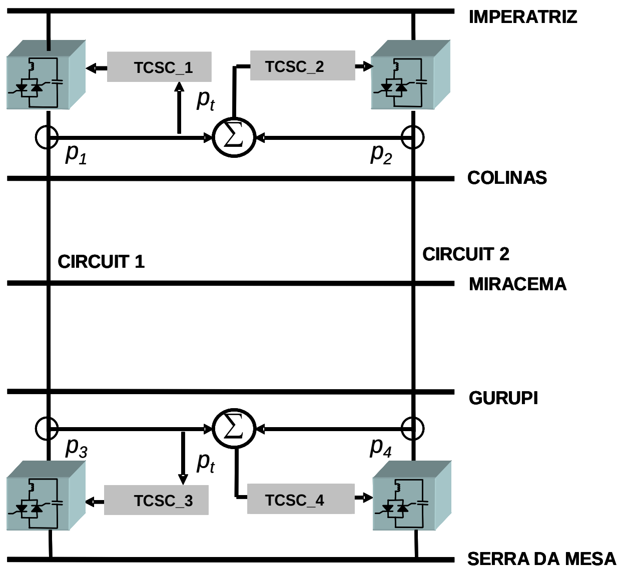

Fig. 2: Actual configuration in the Brazilian North/South interconnection.

the measured power flow in circuit_1 (p_1). Fig. 3 shows the control block diagram applied to TCSC_1, in Imperatriz Substation [7].

1) Phasor Estimation: The Phasor-POD (Power Oscillation Damping) approach separates the portion of oscillating power from the measured power of the line as follows.

$$p(t) = P_{av} + \mathrm{Re}\left\{\Delta P_e^{\theta t}\right\}, \tag{1}$$

where:

$p(t)$ - Instantaneous power line measured in circuit_1;

P_{av} - Average line power;

ΔP_e- Power phasor that represents the main power oscillation in a rotating coordinate systems at frequency θ.

The power phasor estimation determines the average line power (P_{av}) and the power phasor (ΔP_e). Thus, the damping signal ($D(t)$) is determined from P_{av} and (ΔP_e).

2) Control mode - A monitoring algorithm switches the control strategy between normal mode and bang-bang mode. The normal mode is used when the equivalent compensating reactance of the TCSC varies continuously in a capacitive region, limited by pre-defined minimum and maximum reactance values ($X_{min,C}$, $X_{max,C}$). Alternatively, the TCSC may operate in a unique pre-defined value in the inductive region (X_L). The bang–bang operation mode is activated when high levels of power oscillation are detected. In this mode, the TCSC can assume only three reactance values.

B. TCSC installed in Serra da Mesa Substation- Circuit 1.

In Serra da Mesa Substation (circuit #1), the control system designed to damping the inter-area oscillation mode is called POD (Power Oscillation Damping). The simplified block diagram for this strategy is presented in Fig. 4 [7]. This control system also uses the measured power flow (p3) as reference signal.

1) Transfer function and Lead-Lags blocks – The transfer function is composed by washout and lead-lag filters blocks. The washout block extracts the power oscillation signal and the lead-lags filters adjust the phase-shift signal by -90º, approximately.

2) Power Oscillating Damping (POD) – When this function is activated, a continuously varying reactance order is generated by the control system. If this function remains disabled, a lower-level of compensation will be supplied by the TCSC.

3) Anti-Windup Control (AWC) – This function was designed to release the TCSC action when facing a large power variation which may be caused, for instance, by large amount of load rejection. The AWC function also acts in the transfer function limits at the beginning of a disturbance, avoiding an improper control operation. A time interval of 5s has been used to switch back from the AWC to the POD control mode. In other words, this time interval is used to separate control actions compatible for frequencies below or above 0.2Hz.

4) Thyristor Switched Reactor (TSR) - The TSR mode is activated when the TCSC assumes only a value of reactance on the inductive region.

C. The TCSCs installed in Imperatriz and Serra da Mesa Substations – Circuit 2

For the second transmission line of the north/south interconnection, two TCSCs from a third manufacturer were set into it. The control strategy for these devices is known as Power Swing Damping Control (PSDC) [7]. The PSDC input signal is the total power flow (pt) in the interconnection. Fig. 5 shows the control block diagram of the PSDC strategy. The PSDC control system is composed of the following parts:

1) Power swing transfer function (PSTF) – The transfer

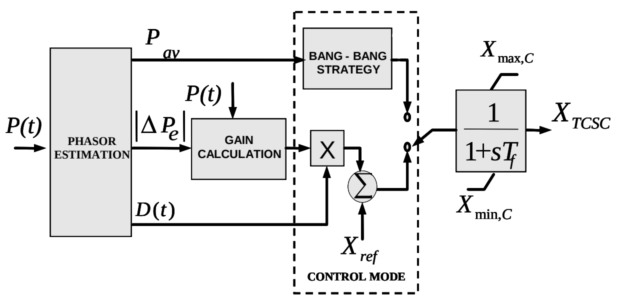

Fig. 3: Simplified detailed block diagram of control system of the TCSC installed on Imperatriz substation.

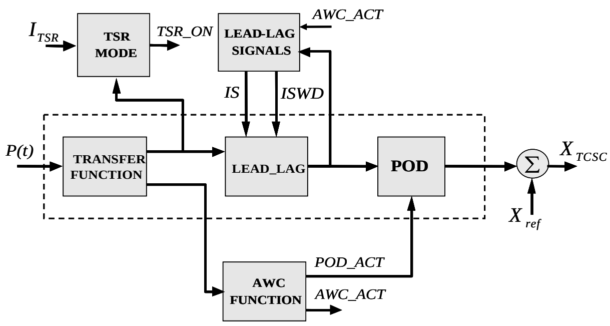

Fig. 4: Control strategy of the TCSC installed on Serra da Mesa substation.

function is composed by a washout stage and three lead-lags filters. The washout function extracts the average value of the total active power flow, pt. The lead-lag filters provide the appropriate phase shift between the input signal (pt) and the output signal (dpo).

2) Gain Calculation – The effective gain of the TCSC controller is adjusted in function of the oscillation magnitude (dPSW) and the total power flow (pt) in North/South inter-connection, as shown in Fig. 5. In fact, the control system uses a lower gain when the power interchange between north and south is high and an increased gain during low power flow. Additionally, the gain is also increased when severe power oscillations are detected.

3) Bias Calculation - The "bias" control is set so that the power oscillation component of reactance will be within the range of Xmin and Xmax, including the effect of high line current when reducing the usable range. The "bias" also becomes the operator setpoint when no disturbances are causing swings on the grid.

III. MODELLING OF THE TCSC IN PSCAD/EMTDC

A. Power Circuit of the TCSC

The TCSC power circuit is constituted by three basic components: the series capacitor bank, the thyristor valve and the thyristor controlled reactor (TCR). Fig. 6 shows the TCSC power circuit implemented in the PSCAD/EMTDC program. The control signals g1 to g6 represent the firing pulses of the thyristors. There are three operation modes defined by three different sequence of firing pulses: a) blocked TCR: no firing pulses are generated and there is no current passing through the reactors; b) full TCR: the firing angle of the thyristor valves are at 90^O so that the reactors are fully inserted in parallel with the series capacitor; c) controlled TCR: firing pulse between 90^O and 180^O (excluding the prohibit range of firing angle where resonance occurs).

B. Equivalent Reactance of the TCSC

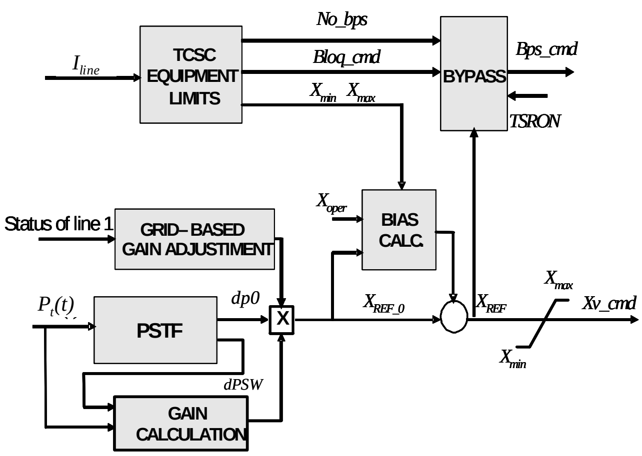

Fig. 5: Control of the TCSCs #2 and #4 installed on Imperatriz and Serra da Mesa substations (line #2).

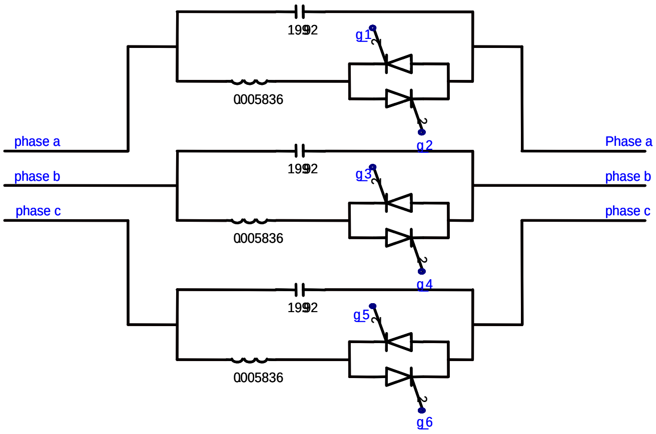

Fig. 6. Power circuit of TCSC model in PSCAD/EMTDC.

The equivalent reactance of the TCSC [XTCSC (α)] as a function of the firing angle α is given by [5]:

$$X_{TCSC} = -X_C + C_1\left[\frac{2(\pi-\alpha)+\sin 2(\pi-\alpha)}{\pi}\right]$$
$$+ C_2\left[\frac{k\tan k(\pi-\alpha)-\tan(\pi-\alpha)}{\pi}\right] \qquad (2)$$

where,

$\omega_0 = \sqrt{1/LC}$, $k = \omega_0/\omega$

$X_C = 1/\omega C$, $X_L = \omega L$

$X_{LC} = X_C \cdot X_L/(X_C - X_L)$

$C_1 = (X_C + X_{LC})$,

$C_2 = \dfrac{4 \cdot X_{LC}{}^2 \cos^2(\pi-\alpha)}{X_L}$.

The TCSC controller varies properly the firing angle α to damp the power oscillation. Fig. 7 shows the equivalent reactance of the TCSC at the fundamental frequency as a function of the firing angle (α) determined in (2). In this case, the parameters of TCSC installed on circuit_2 were used.

In North/South interconnection, all TCSCs operate only in the capacitive region (-3 pu ≤ XTCSC ≤ -1 pu). The firing angle varies approximately from 147.6º to 180º, where 180º

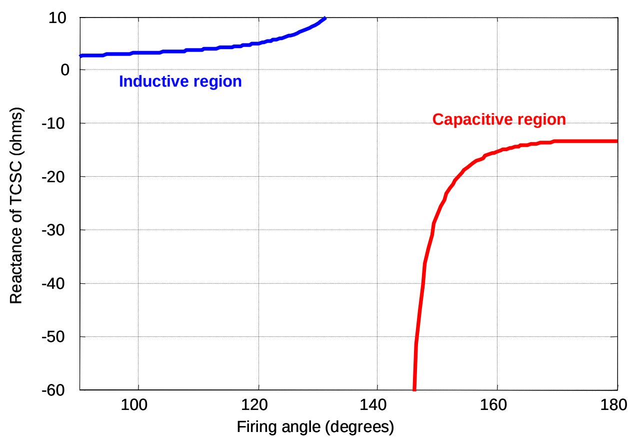

Fig 7: The equivalent reactance of TCSC as function firing angle.

corresponds to the TCR blocked mode of operation, and –1 pu corresponds to X_{TCSC} = –13.27 Ω. The full TCR mode of operation (firing at 90º) is actually deactivated.

In section II, it was shown that the four TCSCs installed in the north/south interconnection use three different control strategies. Moreover, there are two different types of power measurements that satisfy the input signals of those controls: the local reference signal (the power flow of that line where the TCSC is connected, p1), and the global reference signal (the sum of the power flow in the two lines, pt). Simulation results will show that the TCSCs can react in quite different behaviors. For some types of disturbances, very poor performance was verified. This encouraged the authors to investigate new cooperative control strategies, with minimal changes in the actual measurements available in the present configuration.

IV. NEW COOPERATIVE CONTROL SYSTEMS

The two TCSCs in circuit #1 use their own power flow as input to their controllers, whereas the other two TCSC in circuit #2 use the total (sum of circuits #1 and #2) power flow in their controllers. This was identified as one problem to coordinate the TCSCs controllers. Hence, two alternative control strategies were developed using the total power flow for all TCSCs controllers.

Fig. 8 shows an alternative control using the total power flow as input to the two TCSCs controllers at the Imperatriz substation (compare with the actual configuration shown in Fig. 2). The same procedure was adopted for the TCSCs #3 and #4 in Serra da Mesa substation. This is a very simple modification, since all the three control strategies were preserved as they are. Only the local power flow inputs for TCSC #1 and #3 were replaced by the total power flow measurements. After some adjustment in the controller gains, this simple modification has proved to be very effective, as it will be shown later, in the simulation results section.

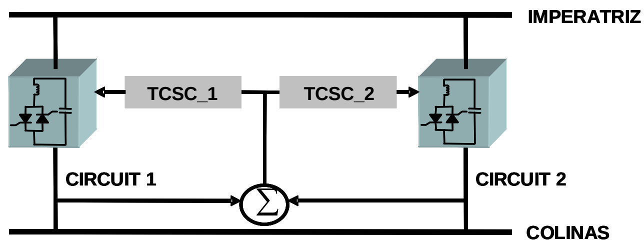

Fig. 8: North/South interconnection with global power flow information for both TCSC controllers (Control_1).

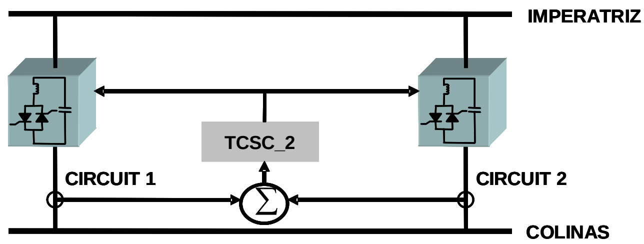

Fig. 9: North/South interconnection with global power flow input and a unique controller for both TCSCs (Control_2).

A second developed alternative control that is depicted in Fig. 9. Now, the difference is that only one controller for both TCSCs in each substation is applied. In this case, just a few modifications were done, the identical control strategy already in operation in TCSCs #2 and #4 of the circuit #2 was elected as a unique for all four TCSCs.

V. SIMULATIONS RESULTS

The Brazilian North/South Interconnection implemented in PSCAD/EMTDC is shown Fig. 10. The system is formed by two machines that represent the equivalent power generation in north/northeast and south/southeast regions in

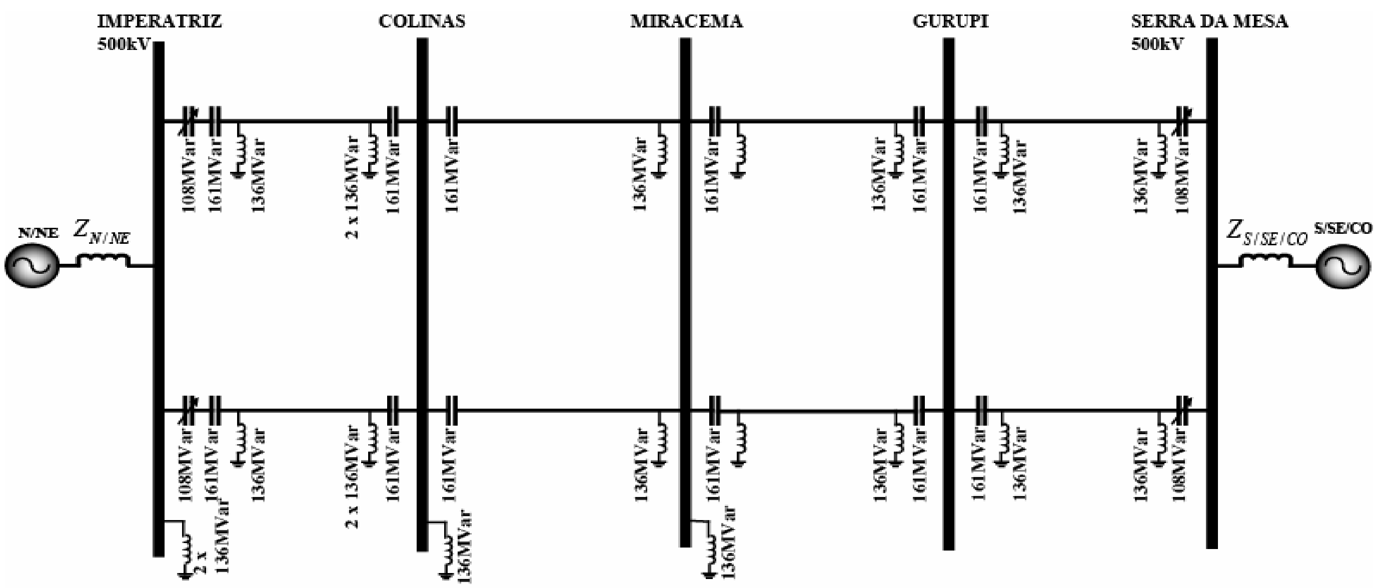

Fig. 10: Unifilar diagram of the Brazilian North/South interconnection.

Brazil, respectively. The parallel transmission lines (circuit #1 and #2) are represented by π circuits. The main characteristics of the North/South interconnection and the system profile used on simulations are presented in Table II.

Table II
Main characteristics of North/South interconnection

Nominal voltage	500kV
Nominal Current	1,5kA
Inductive compensation	100%
Fixed series compensation	54%
Variable series compensation	15%(Maximum level)
Maximum Interchange N-S	1100 MW
Frequency Oscillation	0.3 Hz
Electrical parameters of transmission lines	$R_+=1{,}8025.10^{-5}$(Ω/m/phase) $R_0=3{,}43985.10^{-4}$(Ω/m/phase)
	$X_+=2{,}68349.10^{-4}$(Ω/m/phase) $X_0=1{,}29951.10^{-3}$(Ω/m/phase)
	C_+=161Mho/m C_0=257,7Mho/m

A. Three-phase to ground fault

A three-phase to ground fault was simulated by connecting small resistors to ground in Miracema Substation, during 65s < t < 65.05 s.

The three-phase fault in Miracema Substation causes a severe disturbance in the system. First, the actual configuration as presented in Fig. 2 was simulated. For this case, Fig.11 shows that the voltage in TCSC #1 increases from 20 kV to 120 kV. The transmission line currents also increase transitorily in the same order of magnitude (more than three times the nominal value).

Fig. 13(a) and (b) show the reactance orders inserted by each TCSC.

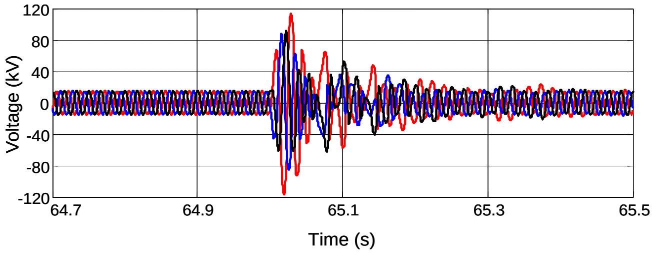

Fig. 11: TCSC_1 Voltages obtained with the actual configuration, in Imperatriz substation.

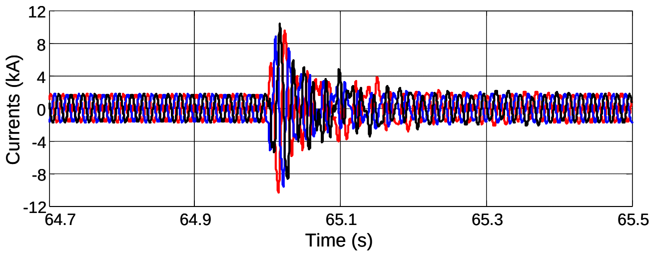

Fig. 12: TCSC_1 currents obtained with the actual configuration, in Imperatriz substation.

As it can be observed in these results there are significative differences in the operation of the control system, as mentioned on section II.

The new cooperative control systems have proved to be more effective in damping power oscillations. For the same

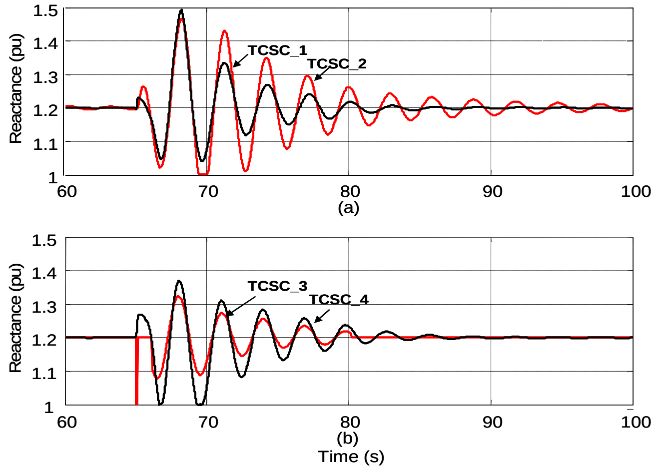

Fig. 13: Reactance orders calculated by each TCSC with the actual configuration, (a) Imperatriz (b) Serra da Mesa.

disturbance as applied before, other two simulation cases were performed, one for each new cooperative control as presented in Fig. 8 and 9. For comparison, Fig. 14 (a) and (b) show the total power flow in the lines (p_t) measured in Imperatriz/Colinas and Gurupi/Serra da Mesa lines, respectively. All the three control strategies are plotted together in these figures. In these simulation results, the control system of Fig. 8 is identified as Control_1, whereas that of Fig. 9 is identified as Control_2. Both are compared with the actual configuration shown in Fig. 2. The oscillation is damped by TCSCs operation with a global reference signal in 15 s, approximately. This result shows that TCSC has a better performance operation with this configuration. Moreover, it was verified that just one control with a global reference signal provided the best results.

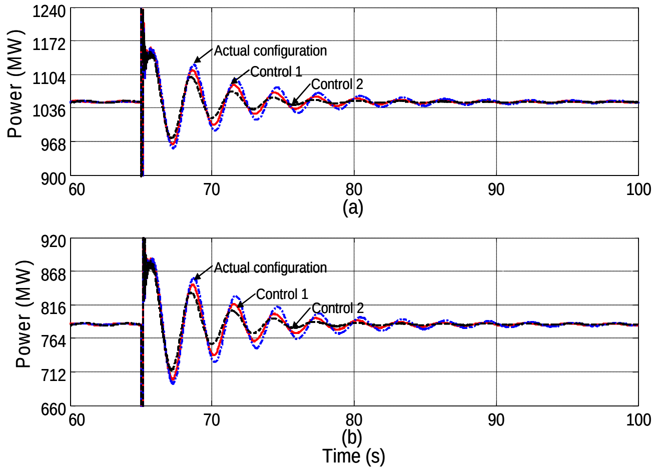

Fig.14: Global Active power flow with local and global signal reference. (a)Imperatriz and (b) Serra da Mesa

B. Single-phase to ground fault

A Single-phase to ground fault was simulated by connecting small resistors to ground in Gurupi Substation, during 65s < t < 65.08 s, followed by the loss of Gurupi/Serra da Mesa transmission line.

Due to the loss of Gurupi/Serra da Mesa transmission line all power flow passes through the circuit #2. In this situation, in Serra da Mesa substation, only one TCSC should be able to damp the oscillations. Simulations with the three control strategies proposed were realized. Some results obtained with the actual configuration are also presented. Fig. 15(a) and (b) show the reactance orders inserted by each TCSC with the actual configuration.

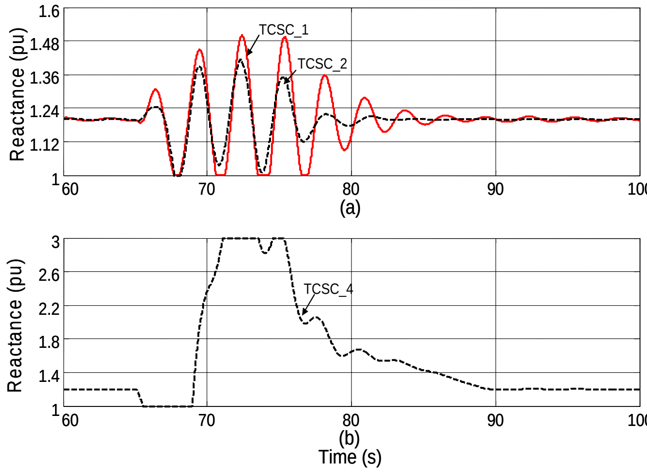

Fig. 17: Reactance orders calculated by each TCSC with the actual configuration, (a) Imperatriz (b) Serra da Mesa.

Fig. 18 (a) and (b) show the total power flow in the lines (p_t) measured in Imperatriz/Colinas and Gurupi/Serra da Mesa lines. All the three control strategies are plotted together in these figures. In this case, it is also possible to observe the improvement of TCSCs performance to damp the oscillations using the modifications proposed in their control strategies (Control_1 and Control_2).

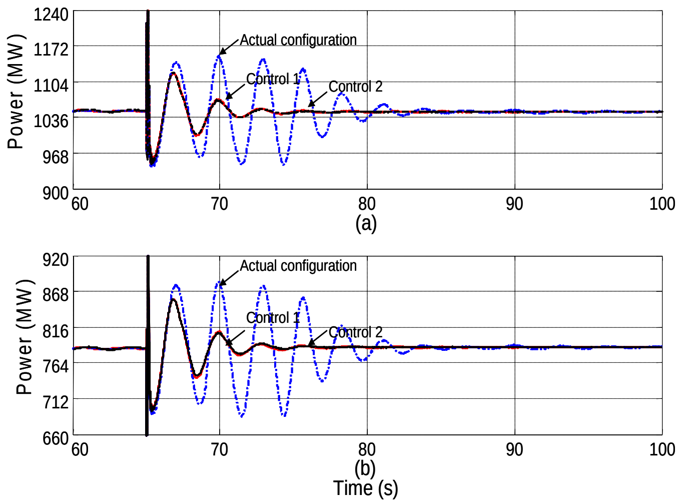

Fig.16: Global Active power flow with local and global signal reference. (a)Imperatriz and (b) Serra da Mesa

In these simulation results, Control_1 and Control_2 presented similar performances. Owing to the balanced distribution of the power flow for all TCSCs control strategies.

VI. CONCLUSION

This paper has presented a modeling and investigation of different Thyristor-controlled Series Capacitor (TCSC) control strategies to damp low frequency inter-area oscillation in the Brazilian North/South interconnection using PSCAD/EMTDC.

It also has been proposed and investigated two control methods. In the first case (Control_1) the TCSCs presented an improved performance than the actual configuration because they use the total power flow as input in their control strategies.

In the second developed alternative control was used a unique controller for both TCSCs in each substation (Control_2). This control method mitigated the low-frequency oscillation more effective than the others control strategies. It occurred because was used the total power flow as input signals and the unique control strategy for all TCSCs.

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