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Effects of a STATCOM, a SCRC and a UPFC on the Dynamic Behavior of a 45 Bus Section of the Brazilian Power System

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***Abstract* – Flexible AC Transmission Systems (FACTS) devices are power electronics based shunt or series devices that are connected to the power network and can improve the system performance and the quality of supply. Application of three types of FACTS devices, a STATCOM, a SCRC and a UPFC, is studied in a 45 bus multimachine power system, as part of the Brazilian power system. The system is exposed to various transient and dynamic disturbances, and the performance of the system reinforced with the FACTS devices is compared with the original system. Simulation results are provided that indicate the effectiveness of these FACTS devices in the overall system behaviour.**

I. INTRODUCTION

A typical power system consists of generators, transformers, transmission lines, switches and active or passive compensators. Such a network is highly nonlinear and non-stationary with various uncertainties associated with it. In practice, the network is prone to various faults and disturbances, such as three phase short circuits, switching on/off shunt loads and/or transmission lines and suchlike. While a strong system can tolerate a fault and move to a new steady state post fault condition as fast as possible, a weak system might suffer from internal instability or poor damping when exposed to transient and dynamic disturbances.

Reinforcing a power system can be done by increasing the voltage level or adding extra transmission lines. However, these solutions require considerable investment and in most cases are not cost effective. *Flexible AC Transmission System* (FACTS) devices can be a solution to these problems. These are power electronics based compensators that can increase the reliability of the system and improve its performance during transient or dynamic disturbances [1].

This paper focuses on the applications of three types of FACTS devices on a large power network: A shunt connected *Static Compensator* (STATCOM), a series connected *Series Capacitive Reactance Compensator* (SCRC), and a *Unified Power Flow Controller* (UPFC). The STATCOM can improve the voltage profile at the point of connection to the network, the SCRC can regulate the active and reactive power flow through the transmission lines, and the UPFC does both.

The multimachine power network considered in this paper (Fig. 1) represents part of the Brazilian power network. It is a 45 bus 10 generator system and has two voltage levels of 525 kV and 230 kV. The generator dynamics are taken into account.

The STATCOM, the SCRC and the UPFC are added to the power network and the system is exposed to various faults and disturbances. Simulation results show the effects of the FACTS devices on the dynamic behavior of such a large power network, and allow a detailed comparison with the uncompensated system. Applying FACTS devices drastically improves the performance of this power network during transient as well as dynamic disturbances.

II. MULTIMACHINE POWER SYSTEM

All the generators in Fig. 1 are modeled in detail, with the AVR, exciter, turbine and governor dynamics taken into account. The system is simulated in the PSCAD/EMTDC environment.

The main characteristics of the power system are as follows:

- Two voltage levels of 525 kV and 230 kV,
- 14 transmission lines at 525 kV,
- 41 transmission lines at 230 kV,
- 24 load buses,
- 7 buses with shunt compensation,
- Total installed capacity of 8,940 MVA.

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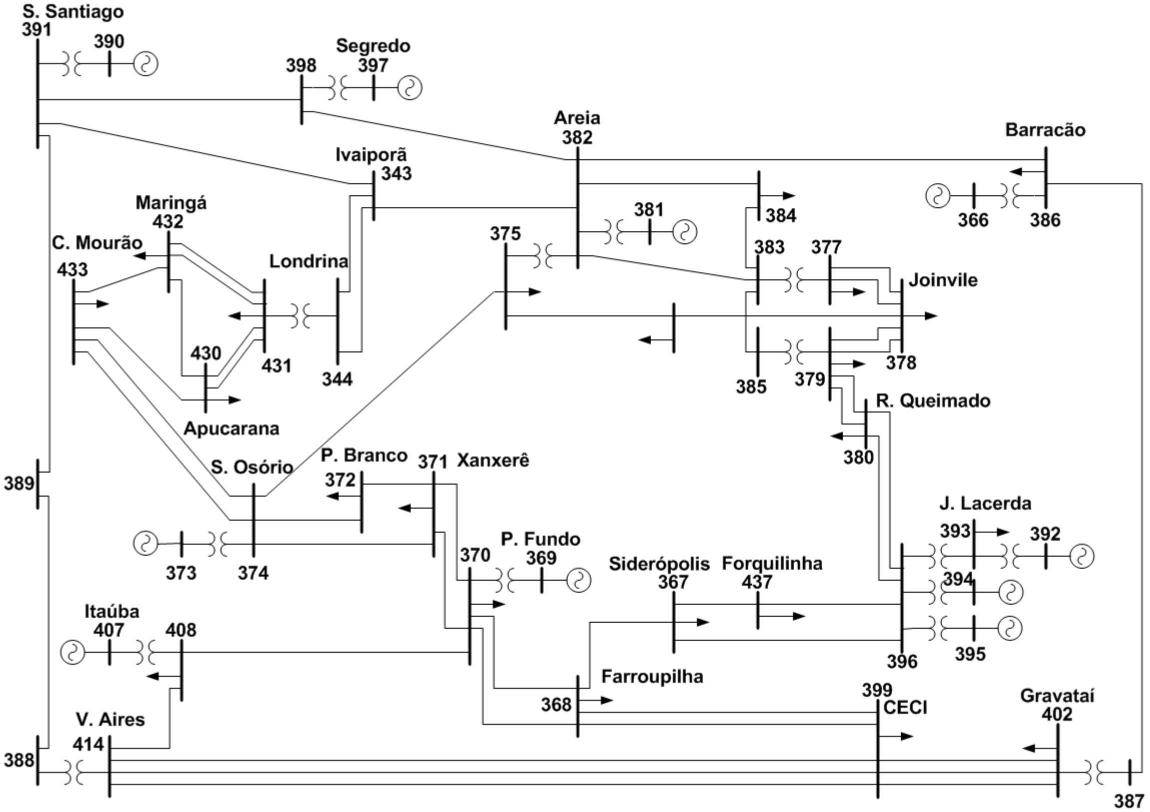

Fig. 1. One line diagram of the 45 bus 10 machine section of the Brazilian power system.

III. FACTS DEVICES

It is known that the power transfer limit and the quality of supply can be drastically improved by insertion of voltage or current into a power system. This can be achieved by use of power electronics switches and converters. The technology is called Flexible AC Transmission System (FACTS) [1]-[3].

FACTS devices are usually classified into two groups depending on how they generate reactive power:

- Devices which have an inductor or a capacitor as reactive elements being controlled by power electronic switches, e.g. *Static Var Compensator* (SVC), *Thyristor Controlled Series Capacitor* (TCSC),
- Devices in which the reactive power producer is the power electronic converter itself. These devices do not have any capacitors or inductors as reactive power elements. The STATCOM, SCRC and UPFC belong to this category.

According to their application, FACTS devices can be categorized as shunt compensators, series compensators or both shunt-series compensators. Each type of FACTS device has a different impact on the overall system performance [4] (Table I.).

Table I. Impact of FACTS devices on system performance.

Application	**Shunt FACTS Devices**	**Series FACTS Devices**	**UPFC**
Voltage Control	High	Low	High
Load Flow Control	Low	Medium	High
Transient Stability	Low	High	High
Oscillation Damping	Medium	High	High

A. Static Compensator (STATCOM)

A STATCOM, also known as a Static Condenser or Advanced SVC, is a shunt FACTS device which is connected to the network in parallel and can control the voltage at the point of connection to the network by injecting reactive power to the network or drawing reactive power from it. The schematic diagram of a STATCOM is shown in Fig. 2. It is an inverter which is connected to the power system through a step up transformer. Ideally a STATCOM should only inject reactive power to the system, and the active power exchange with the network should on average be almost zero (except for a small quantity to compensate for the internal losses).

Two types of STATCOMs are mainly used based on the inverter type: voltage sourced inverter (VSI) STATCOM and current sourced inverter (CSI) STATCOM. There can also be a third type, a STATCOM that is composed of both VSI and CSI inverters in order to reduce switching losses and harmonic distortions simultaneously [5]. A VSI STATCOM is considered in this study.

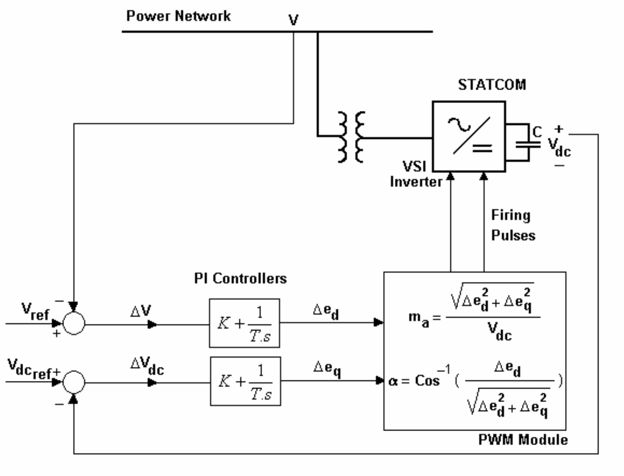

Fig. 2. Schematic diagram of a STATCOM controller.

In theory the DC link capacitance of the STATCOM can be very small since its magnitude does not play a significant role in the steady state fundamental frequency reactive power generation. However in practice, a larger capacitor may be needed in order to reduce DC link voltage ripple and improve the performance under system unbalanced conditions [6].

Various papers have been published, which propose linear or nonlinear control schemes for a STATCOM [7]-[9]. The method used in this paper is based on the control scheme suggested by [7]. Figure 2 shows the schematic diagram of the proposed controller. The line voltage error ΔV and DC link voltage ΔV_{dc} are passed through two PI controllers, which in turn generate the control signals Δe_d and Δe_q respectively. These values in turn determine the inverter modulation index and phase shift:

$$m_a = \frac{\sqrt{\Delta e_d^2 + \Delta e_q^2}}{V_{dc}}, \qquad (1)$$
$$\alpha = Cos^{-1}\left(\frac{\Delta e_d}{\sqrt{\Delta e_d^2 + \Delta e_q^2}}\right).$$

B. Series Capacitive Reactance Compensator (SCRC)

A SCRC is a series FACTS device which is connected in series with the transmission line and injects a controllable voltage perpendicular to the line current of the power network (Fig. 3). This is equivalent to providing a controllable capacitive compensation, which is independent of the line current. Moreover, a SCRC with a properly designed external controller is capable of improving the damping of the low frequency power oscillations in a power network.

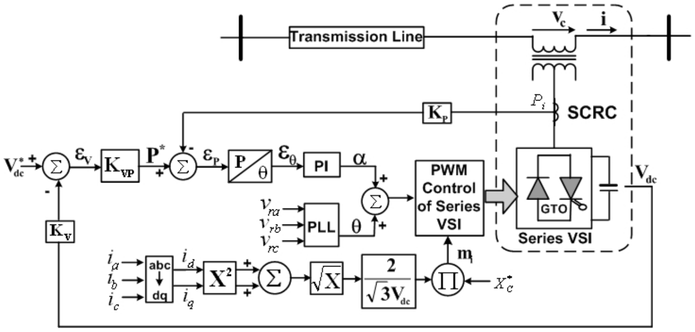

Fig. 3. Schematic diagram of the SCRC internal controller.

The schematic diagram of the SCRC internal control scheme is shown in Fig. 3. The main objectives are ensuring that the injected controllable voltage at the AC terminal of the inverter remains in quadrature with the transmission line current at steady state, as well as keeping the DC link voltage of the inverter constant during steady state. The detailed description of the internal controller appears in [12].

By extending the original work of Ooi *et al* [10] for a SCRC based on the voltage sourced PWM converter, Rigby and Harley reported an improved internal control scheme for the SCRC [11]. They also proposed a power oscillation damping scheme by applying a properly designed conventional external linear controller (CONVEC) to the SCRC (Fig. 4) [12].

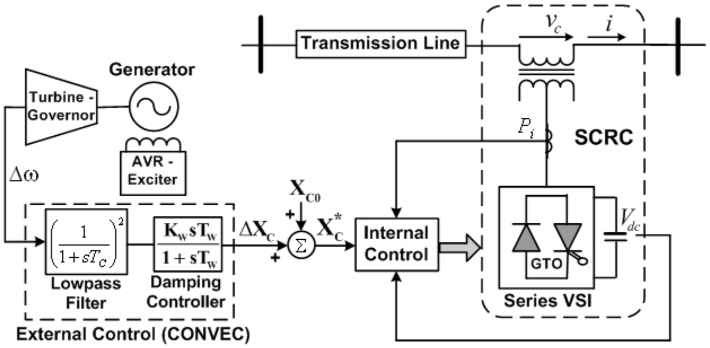

Fig. 4. Schematic diagram of the SCRC external controller.

The objective of the CONVEC is to damp out the transient power oscillations of the system. It is based on the fact that by varying the amount of the series capacitive compensating reactance X_C in a transmission line and therefore the total line reactance, it is possible to control the transient imbalances between the electrical output power and the mechanical input power. These two values are responsible for the low frequency power oscillations [1],[13]. It was reported in [12] that the speed deviation of a generator $\Delta\omega$ can be used to produce a supplementary control signal ΔX_C for external control (Fig. 4). This supplementary signal is then added to a steady state fixed setpoint value X_{C0} to form the total command signal for the compensating series reactance X_C^* at the input of the SCRC internal reactance.

C. Unified Power Flow Converter (UPFC)

The UPFC is the most versatile of the FACTS devices. A UPFC connected to a transmission line can provide control over the real and reactive power flow in the line, voltage control in the shunt bus and damping control to the power flow oscillations [1].

A UPFC is composed of a three phase dual inverter (Fig. 5) which can operate in both directions as needed ("4-quadrant"). Capacitors are connected across the DC bus to reduce the ripple in the rectified voltage as well as to provide constant voltage support for short duration disturbances. Each *Gate Turn-off Thyristor* (GTO) is triggered in a controlled manner according to the need for real and reactive power in the transmission line. As it is preferable and less expensive to use GTOs with lower voltage ratings than the transmission line voltages, both the series and the shunt branches of the UPFC are connected to the power network through step down transformers.

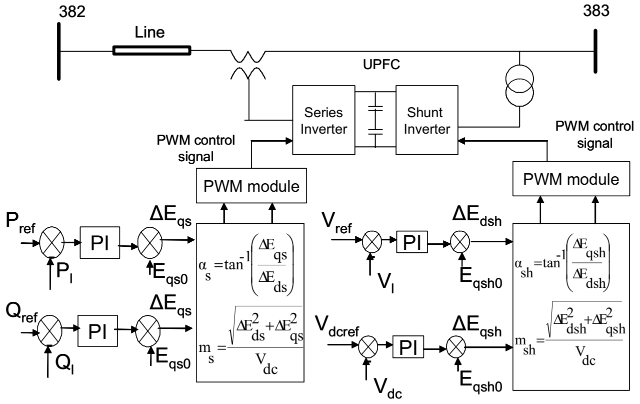

Fig. 5. Schematic diagram of a UPFC controller.

The principle of operation of the UPFC is based on the fact that the real and reactive power can be adjusted by adjusting the voltage magnitude and angle differences between two nodes. The voltage of the node where the series transformer is connected is changed by adding a small voltage in series with the line voltage, while the voltage of the sending end bus is maintained by injecting reactive support through the shunt transformer. The magnitude and phase angle of the injected voltage with respect to the sending end bus voltage are controlled to deliver specified real and reactive power through the transmission line [7].

Shunt Branch Control:

Control of the shunt inverter is similar to the STATCOM control and is achieved by varying the direct and quadrature components of the shunt inverter voltage. The shunt bus voltage can be controlled using the direct voltage component ΔE_{dsh}, while the DC bus voltage as well as the reactive power injection can be controlled using the quadrature component of the shunt inverter ΔE_{qsh}. The modulation index m_{sh} and the inverter phase shift angle α_{sh} for PWM control is therefore calculated as in (2):

$$m_{sh} = \frac{\sqrt{\Delta E_{dsh}^2 + \Delta E_{qsh}^2}}{V_{dc}}, \qquad (2)$$

$$\alpha_{sh} = tan^{-1}\left(\frac{\Delta E_{qsh}}{\Delta E_{dsh}}\right),$$

A simplified structure of the UPFC shunt branch controller is shown in Fig. 5, details of which can be found in [7].

Series Branch Control:

For the series inverter, the decoupled direct and quadrature component control is used in order to generate the PWM signal [7]. The basic concepts and the formula for deriving the inverter modulation index and the output phase shift are similar to the shunt branch control. For the series inverter the direct axis voltage injection component (ΔE_{ds}) is generated from the reactive power error (deviation from the setpoint) while the quadrature component (ΔE_{qs}) is generated from the real power error (deviation from the setpoint). The modulation index m_s and phase shift angle α_s is then calculated using (3). The simplified PI control scheme is shown in Fig. 5.

$$m_s = \frac{\sqrt{\Delta E_{ds}^2 + \Delta E_{qs}^2}}{V_{dc}},$$

$$\alpha_s = tan^{-1}\left(\frac{\Delta E_{qs}}{\Delta E_{ds}}\right) \qquad (3)$$

IV. SIMULATION RESULTS

The three FACTS devices are installed at different locations in the power network and the performance of each FACTS device is evaluated during the transient and dynamic disturbances, with the other two devices deactivated. The power system is first simulated in the PSCAD/EMTDC environment in order to reach the steady state.

A. Case Study 1- STATCOM

After completing the load flow analysis on the power system in Fig. 1, it was observed that the bus 378 (Joinvile) has the lowest voltage in the network. Moreover, there are several transmission lines and shunt loads that are connected to it. A STATCOM is connected to this bus (Fig. 6) in order to control the voltage during the dynamic disturbances and improve the voltage stability. The system is first initialized without the STATCOM. After 100 seconds of steady state the STATCOM is activated with its voltage reference set so that it can maintain the steady state voltage at bus 378.

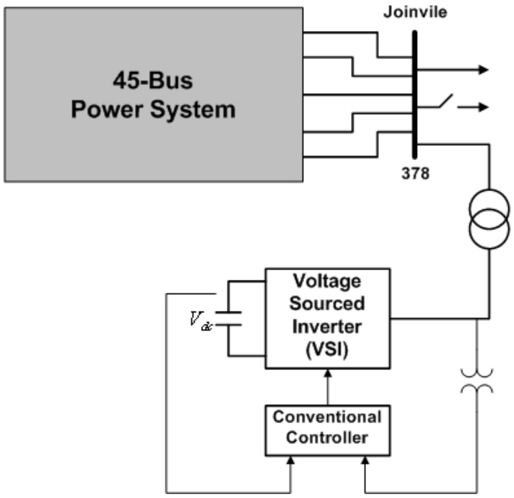

Fig. 6. STATCOM connected to the multimachine power system.

In the first transient test, the two transmission lines between the buses 378 and 379 are disconnected after 111 seconds of steady state. Figure 7 shows the rms voltage at bus 378 with and without the STATCOM installed. Clearly the uncompensated system suffers from a voltage drop, whereas the reinforced system manages to maintain its steady state voltage.

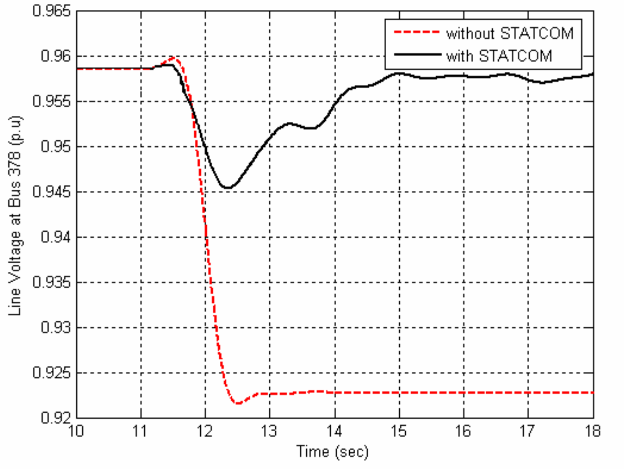

Fig. 7. Voltage at bus 378 (Fig. 1) when two transmission lines are disconnected.

The two transmission lines are now reconnected to the system and 11 seconds later a shunt load of 110 MVA with a lagging power factor of 0.91 is then switched on to bus 378. Figure 8 shows the line voltage and clearly indicates that the STATCOM is able to return the voltage to the steady state value, while the uncompensated system experiences a significant voltage drop. Figure 9 shows the reactive power injected by the STATCOM into the network during switching on the 110 MVA load.

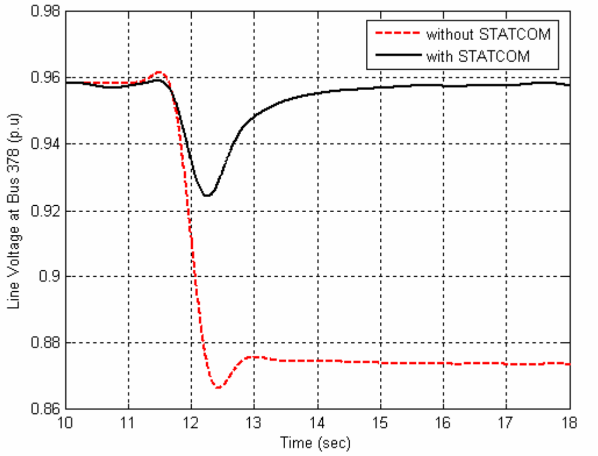

Fig. 8. Voltage at bus 378 (Fig. 1) when a shunt load is switched on.

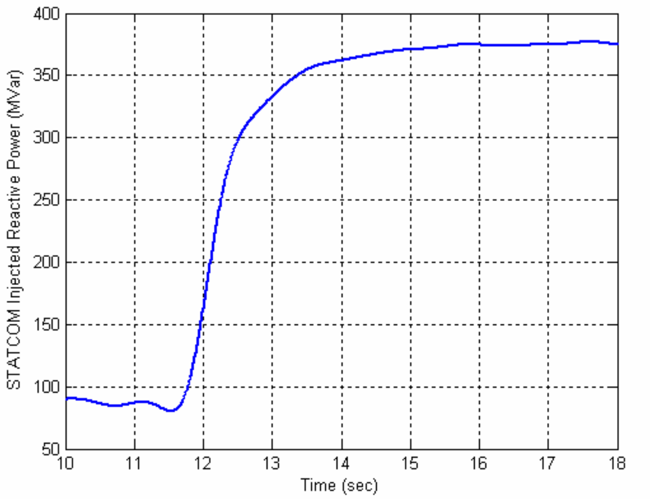

Fig. 9. Reactive power injected by the STATCOM when a shunt load is switched on.

Another possible location for installing the STATCOM can be on either one of the buses 430 to 433, due to the fact that several transmission lines and shunt loads are connected to these buses and they are relatively far from the other generating units. Similar results can be obtained by placing the STATCOM in any of these locations.

B. Case Study 2- SCRC

The section of the power network which consists of buses 375 to 380 is rather weak compared to the other parts of the system. This is the area where a large amount of load is concentrated, all of them being served by only three transmission lines 382-383, 382-384 and 375-378. Having either one of these lines disconnected after a short circuit can cause a severe disturbance to the whole system.

Therefore a SCRC (with external and internal controllers) is placed on the transmission line between the buses 382 (Areia) and 383 (Curitiba). Insertion of the SCRC in this location helps regulate the power flowing through these two transmission lines. In addition, it can significantly improve the power oscillation damping of most of the generators around this area, especially when a three-phase short circuit occurs in the load area. For the external control part (CONVEC in Fig. 10), the speed deviations of the synchronous generator at bus 373 is needed.

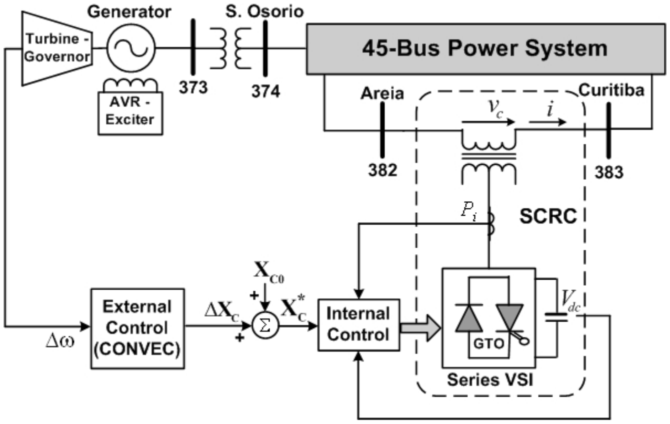

Fig. 10. SCRC connected to the multimachine power system.

Each generator phase angle is compared with the reference generator at bus 397 (Segredo). By applying 300 ms three phase short circuit tests at different locations in the above mentioned area, large low frequency power oscillations are observed at buses 369, 373, 392, 394, 395 and 407. Since the generator at the bus 373 has the largest power rating among the other generators in that area, its speed deviation is used as the input applied to the SCRC external controller. The speed deviation is passed through two first order low pass filters and a damping controller (consisting of a proportional gain and a washout filter) to form a supplementary control signal for the internal controller (Fig. 4).

After the 45 bus power system is initialized and reaches steady state, the SCRC with a set point value of $X_{C0} = 25$ ohms is applied to the system at 100 seconds, in order to provide a 33% capacitive reactance compensation. Figure 11 shows the line 382-383 current in phase A. It can be seen that the capacitive compensation by the SCRC increases the line current and therefore the transmitted active power.

In order to evaluate the impact of the SCRC on the transient stability of the system, a 300 ms three phase short circuit is applied to line 382-383 (next to bus 383) at 120 seconds. After that the line is disconnected from the network. Figure 12 shows the phase difference $\delta_{373,\ 397}$ between the generator bus 373 and the reference bus 397. The results indicate the impact of the SCRC with and without the external controller. Clearly, the damping control of the low frequency power oscillations by the CONVEC during the post-fault transient is more efficient than that of the SCRC without the external controller.

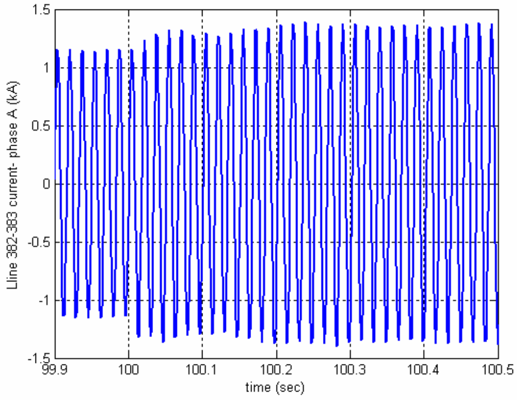

Fig. 11. Capacitive reactance compensation by the SCRC- line 382-383 current in phase A.

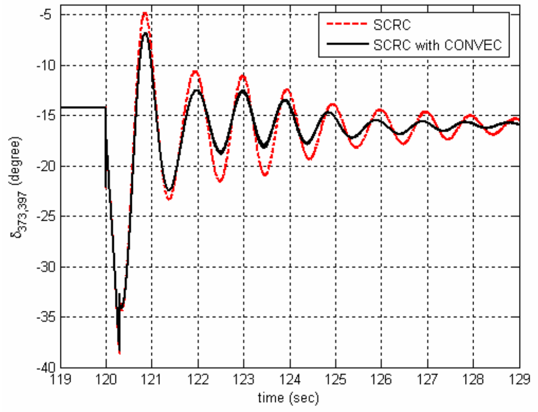

Fig. 12. Phase different $\delta_{373,\ 397}$ during a 300 ms three phase short circuit test.

C. Case Study 3- UPFC

Load flow analysis indicates that bus 378 (Joinvile) is a weak bus in the system that needs local Var compensation due to support the low voltage condition. Any of the transmission lines connected to bus 378 could be a suitable location for the UPFC for Var compensation; however, in that case no generator damping control would be achieved by the introduction of the UPFC as there is no generator nearby. Therefore, the UPFC is connected between buses 382 and 383 in the 45-bus power system. The shunt branch of the UPFC is connected to bus 383 (Fig. 13) to provide voltage support at bus 378. Also, the series branch can control the real and reactive power flow in the transmission line between bus 382 and 383, thereby providing some damping control to the generator connected to the bus 381 during transient disturbances (Fig. 13).

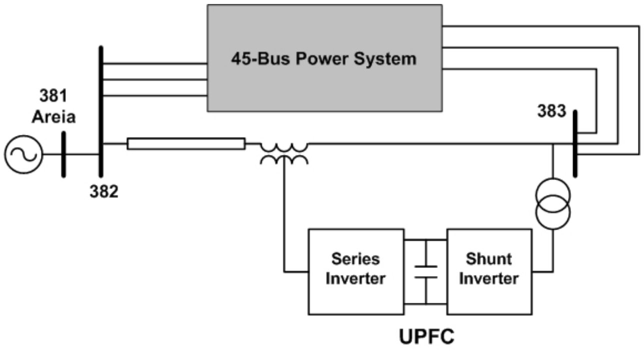

Fig. 13. UPFC connected to the multimachine power system.

Figure 14 shows the results when the reference value for the active power flow through the transmission line 382-383 is changed from 700 MW to 800 MW. In another test, the reactive power reference of the UPFC is changed from 0 to 50 MVar. The corresponding result is shown in Fig. 15.

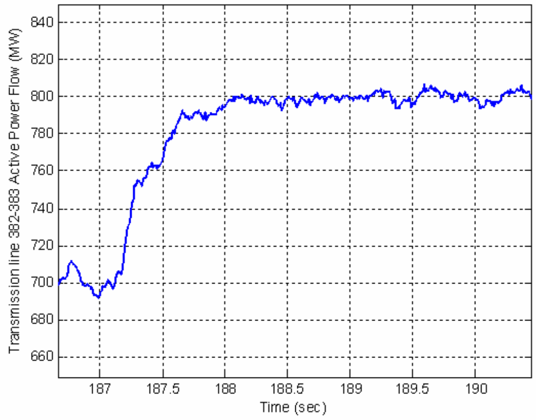

Fig. 14. Active power flow through the transmission line 382-383.

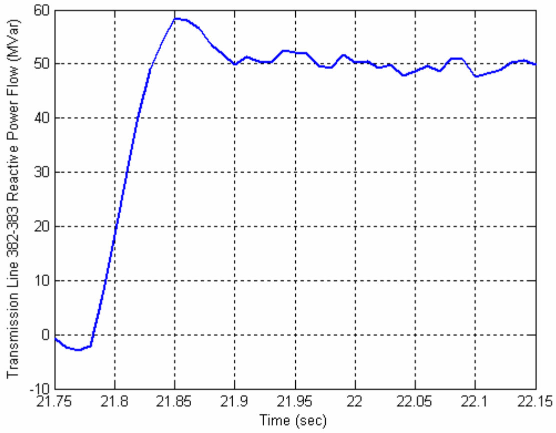

Fig. 15. Active power flow through the transmission line 382-383.

In a further test, a *150* ms three phase short circuit is applied to the system on bus 385. Figure 16 shows the transmission line damping with and without the UPFC in the system. It can be seen that the UPFC improves the damping of the low frequency power oscillations in the transmission line. This in turn can help the damping of the speed deviations of the closest generators.

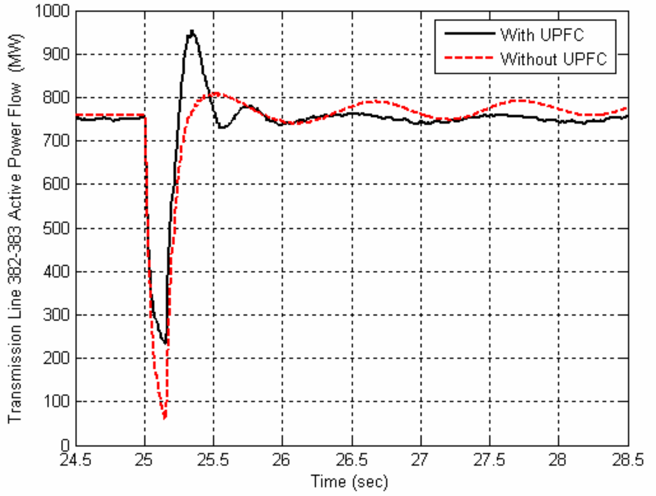

Fig. 16. Active power flow through the transmission line 382-383 during a three phase short circuit.

V. CONCLUSION

FACTS devices are power electronics based reactive compensators that are connected to the power network and are capable of improving the system dynamic/transient performance and the quality of supply. A large power system (45 bus 10 generator system) is considered in this study as a part of the Brazilian power network. Three different FACTS devices have been added to this network and their impacts on the system performance are analyzed: a STATCOM, a SCRC and a UPFC.

A STATCOM is a shunt FACTS device that is connected to the network in parallel and can control the voltage at the point of connection to the system. While STATCOM has little effect on the damping control of the system, it is extremely efficient in controlling the voltage. Simulation results are shown that indicate that the performance of the system after installing the STATCOM is drastically improved during disturbances such as switching on/off a transmission line or a shunt load. The STATCOM manages to maintain the steady state voltage, while the uncompensated system would suffer from a permanent voltage drop.

A SCRC is a series FACTS device that can control the power flow through the transmission line. Such a device is added to the system and the simulation results provided indicate that the SCRC can control the power flow through the transmission line where it is connected. Moreover, it can improve the transient behavior of the system during a large scale fault, such as a three phase short circuit. An additional external control scheme is applied to the SCRC that can further improve the system damping compared to the conventional control scheme.

A UPFC is the most versatile FACTS device, which has a series as well as a shunt branch, which can perform as a SCRC and a STATCOM respectively. The UPFC can be used for improving the system performance during steady state, as well as transient conditions. The simulation results provided indicate that the UPFC is able to change the active and reactive power flow through the transmission line to which it is connected, therefore improving the load flow characteristics of the system. It can also be used for many other applications, including but not limited to voltage control, transient and dynamic damping and suchlike.

ACKNOWLEDGEMENTS

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