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Damping Improvement by Facts Devices: A Comparison Between STATCOM, SSSC and UPFC

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Abstract: This study discusses and compares different control techniques for damping undesirable electromechancial oscillations in power systems by using Series /Shunt FACTS controllers. Static Compensators (STATCOM) Static Synchronous Series Compensators and Unified Power Flow Controllers (UPFC). The following disturbances are simulated on a Single Machine Infinite Bus System and the rotor angle/rotor speed deviation response is studied with and without the effect of FACTS controllers: Step change in turbine input and a three-phase fault on the line. The dynamic model of the FACTS controllers has been derived from the circuit theory fundamentals and the simulation results provide useful information on the transient rating of the converter based FACTS controllers. MATLAB/SIMULINK is used for running the dynamic simulations.

Key words: Power system oscillations, STATCOM, SSSC, UPFC, SIMULINK

INTRODUCTION

As power systems became interconnected, areas of generation were found to be prone to electromechanical oscillations. These oscillations have been observed in many power systems worldwide. The use of high gain voltage regulation in order to improve first swing transient stability exacerbated the oscillations. As the level of power transmission rose, largely through existing interconnections, which were becoming weak and inadequate, load characteristics added to the problem causing spontaneous oscillations. The oscillations may be local to a single generator or generator plant (local oscillations, 1.0-2 Hz), or they may involve a number of generators widely separated geographically (interarea oscillations 0.2-0.8 Hz). If not controlled these oscillations may lead to total or partial power interruption (Kundur, 1994). Electromechanical oscillations are generally studied by modal analysis of a linearized system model. Power System Stabilizer (PSS) is possibly the first measure that has been used to improve damping and is well described by Klein (1991) and Xiaoqing and Ali (1994).

The availability of Flexible A.C. Transmission system (FACTs) controllers such as Static Var Compensators (SVCs), Static Compensator (STATCOM), Thyristor Controlled Series Compensators (TCSCs), Static Synchronous Series Compensators (SSSC) and Unified Power Flow Controllers (UPFC) has led their use to damp electro mechanical oscillations. Angquist *et al.* (1993) compares damping capabilities of the controllable reactive power elements namely SVC (Static Var Compensator) and Controllable Series Capacitor (CSC). A nonlinear control scheme for the TCSC (thyristor controlled series capacitor) for the enhancement of transient stability is proposed by James *et al.* (1995) and Lei *et al.* (2005).

Energy function approach is used for comparing the damping capabilities of STATCOM and SSSC by Haque (2006). Hopf Bifurcation theory was used to analyze the oscillation stability of a multimachine power system (Mithulananthan *et al.*, 2003).

Along with power system stabilizers now FACTS stabilizers are used for damping oscillations in the power system. It is important to arrive at the transient rating of the FACTS controller, which differs from continuous rating of the FACTS controller.

The objective of the present research, is to investigate the damping capabilities of Series Connected and shunt FACTS controllers namely UPFC, SSSC and STATCOM in damping power system oscillation and to arrive the transient rating of FACTs controllers.

MATHEMATICAL MODEL OF THE POWER SYSTEM WITH AND WITHOUT FACTS DEVICES

Consider a simple Single Machine Infinite Bus (SMIB) system shown in Fig. 1 without any FACTS device. The system consists of a single machine

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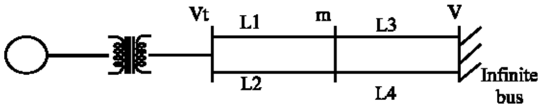

Fig. 1: Single machine infinite bus system single line diagram

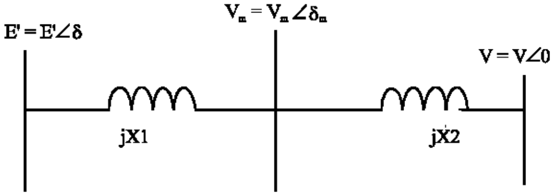

Fig. 2: Equivalent circuit of the single machine infinite bus system

connected to an infinite bus through two identical transmission lines. The equivalent circuit of the system is shown in Fig. 2 where X1 represents the equivalent reactance between machine internal bus and the intermediate bus m. and X2 represents the equivalent reactance between the bus m and the infinite bus. The dynamic data for this system can be had from ref (Kundur, 1994).

The magnitude of the machine internal voltage and the infinite bus voltage is represented by E' and V, respectively. The dynamics of the machine in the classical model can be represented by the following differential equations.

$$\frac{d\delta}{dt} = \omega \tag{1}$$

$$\frac{d\omega}{dt} = \frac{1}{M}(Pm - Pe - D\omega) \tag{2}$$

Here δ, ω, M, Pm and D are the rotor angle deviation, rotor speed deviation, moment of inertia, input mechanical power and damping coefficient, respectively of the machine. The electrical output power Pe of the machine in Fig. 2 can be written as

$$Pe = Pmax\ Sin\delta \tag{3}$$

Where:

$$P\max = \frac{E'V}{X1 + X2} \tag{4}$$

Modeling of STATCOM: STATCOM is a shunt-connected reactive-power compensation device that is capable of generating and /or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable reactive power at its output terminal (Mathur *et al*., 2000).

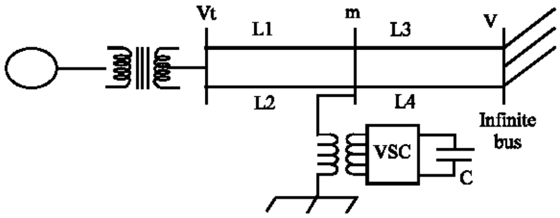

Fig. 3: Schematic diagram of SMIB system with a STATCOM

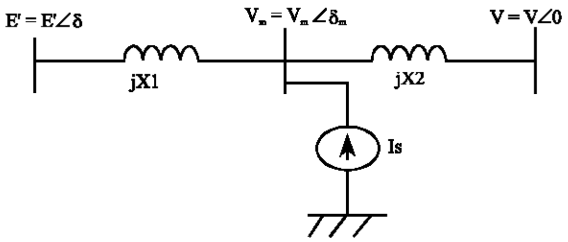

Fig. 4: Equivalent circuit of the SMIB system with STATCOM

The STATCOM is placed in the bus m and is represented by a shunt reactive current source Is as shown in Fig. 3 and 4.

Where

$$Is = Is\, e^{j(\delta m \pm \pi/2)} \tag{5}$$

Here

$$\delta m = \tan^{-1}\left(\frac{E'X2\sin\delta}{VX1 + E'X2Cos\delta}\right) \tag{6}$$

With the STATCOM the output power Pe of the machine can be written as

$$Pe = PmaxSin\delta + f1(\delta)\, Is \tag{7}$$

Where

$$f1(\delta) = \frac{E'X2}{X1 + X2} Sin(\delta - \delta m) \tag{8}$$

is positive when δ oscillates in between zero and π.

Equation 7 suggests that Pe can be modulated by modulating the shunt reactive current I_s.

For enhancement of power system damping the shunt reactive current can be modulated in proportion to the rotor speed deviation ω. With this control signal Is can be expressed as

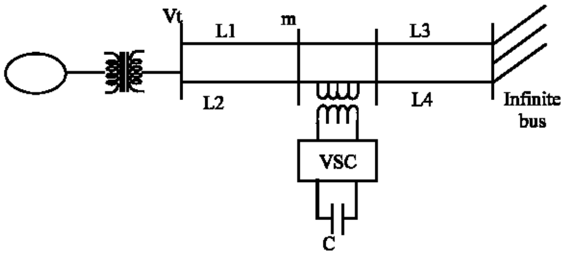

Fig. 5: SMIB system with a SSSC-schematic diagram

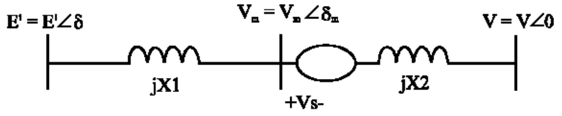

Fig. 6: Equivalent circuit of the SMIB system with SSSC

$$I_s = K_1\ \omega,\ -Is^{max} \le Is \le Is^{max} \tag{9}$$

K_1 is a positive constant.

Modeling of SSSC: SSSC is a series-connected synchronous voltage source that can vary the effective impedance of a transmission line by injecting a voltage containing an appropriate phase angle in relation to the line current. If the injected voltage is in phase with the line current, then the voltage would exchange the real power. On the other hand if the injected voltage injected in quadrature with line current, then reactive power would be exchanged (Mathur *et al*., 2000).

Consider that a SSSC is placed near bus m in the system as shown in the Fig. 5 and 6. The SSSC is represented by a series voltage source Vs.

The series voltage injected by the SSSC is given by

$$Vs = Vs\ e^{J(\theta \pm \pi/2)} \tag{10}$$

Where, θ is the angle of the line current and is given by (11)

$$\theta = \tan^{-1}\left(\frac{V - E'\cos\delta}{E'\sin\delta}\right) \tag{11}$$

With the SSSC the machine power Pe can be written as

$$Pe = P\max\sin\delta + f2(\delta)Vs \tag{12}$$

Where:

$$f2(\delta) = \frac{P\max \sin\delta}{\left(E'^2 + V^2 - 2E'V\cos\delta\right)^{1/2}} \tag{13}$$

$f_2(\delta)$ is positive when δ oscillates in between 0 and π.

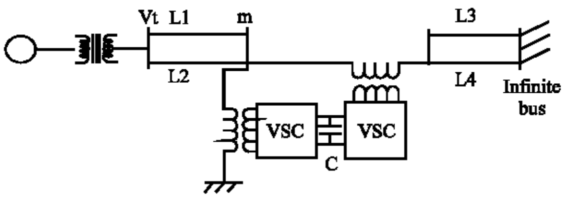

Fig. 7: SMIB system with a UPFC schematic diagram

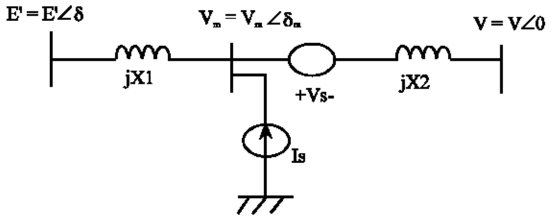

Fig. 8: SMIB system with a UPFC equivalent circuit

Pe can be modulated by properly controlling the value of Vs.
Vs can be expressed as

$$V_s = K_2\ \omega,\ -Vs^{max} \le Vs \le Vs^{max} \tag{14}$$

K_2 is a positive constant.

Modeling of UPFC: Unified Power Flow Controller is the most versatile FACTS controller developed so far, with all encompassing capabilities of voltage regulation, series compensation and phase shifting. It can independently control both the real and reactive power flows in a transmission line. It comprises two voltage-sourced converters coupled through a common DC terminal. One Voltage Source Converter (VSC) is connected in shunt with the line through a coupling transformer and the other VSC is inserted in series with the transmission line through an interface transformer.

The series converter exchanges both real and reactive power within the transmissionline. The shunt-connected converter 1 is used mainly to supply the real power demand of converter 2, which derives from the transmission line itself. The shunt converter maintains constant voltage of the dc bus. Thus the net real power drawn from the AC system equal to the losses of two converters and their coupling transformers. The equivalent circuit of UPFC can be represented as a shunt current source and a variable voltage source as formulated by Navabi and Iravani (1996). The single line diagram and equivalent circuit are given in Fig. 7 and 8.

The mathematical expressions of Static Synchronous Series Compensator (SSSC) and Static Compensator (STATCOM) will be combined to show the damping improvement of the system with UPFC.

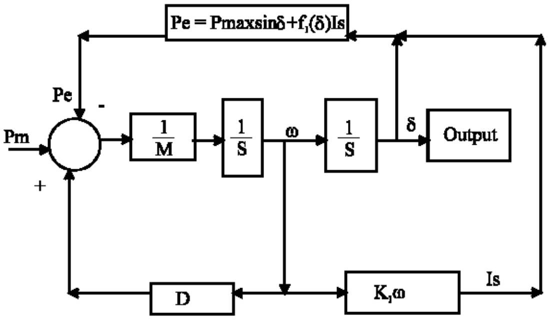

Fig. 9: Simulation diagram with STATCOM

SIMULATION BLOCK DIAGRAM OF THE SYSTEM WITH STATCOM

Figure 9 represents the simulation model for dynamic analysis of power system with STATCOM. Is = K_1 ω represents the shunt reactive current modulated by the statcom in proportion to speed deviation of the machine

Pm : Step change in Mechanical Input to turbine.
Pe : Electrical power output of the machine.
M : Machine moment of inertia.
ω : Rotor speed deviation.
δ : Rotor angle le deviation.
D : Damping coefficient.

SIMULATION DIAGRAM OF THE SYSTEM WITH SSSC

Figure 10 represents the simulation model for dynamic analysis of power system with SSSC. Vs = K_2 ω represents the series voltage injected by the SSSC in proportion to speed deviation of the machine.

Pm : Step change in Mechanical Input to turbine.
Pe : Electrical power output of the machine.
M : Machine moment of inertia.
ω : Rotor speed deviation.
δ : Rotor angle deviation.
D : Damping coefficient.

With UPFC both the loops K_1ω (shunt current modulation) and K_2 ω (Series voltage modulation are present).

RESULTS

Step change in the Turbine Mechanical Input, Δpm = 0.1 p.u.

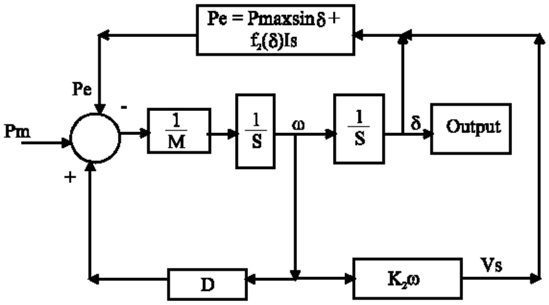

Fig. 10: Simulation diagram with SSSC

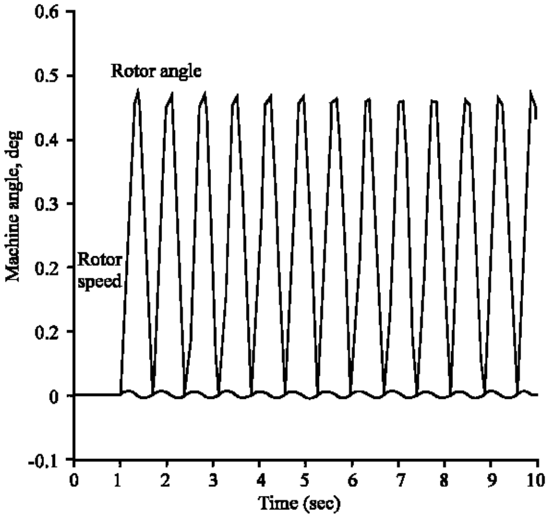

Fig. 11: Rotor speed deviation and rotor angle deviation response

Without FACTS controller: From Fig. 11 it is clear that there are sustained rotor angle oscillations with poor damping. The peak overshoot is 0.49 p.u for Rotor angle deviation.

STATCOM: Step change in Mechanical Input to the Turbine Δpm = 0.1 p.u.

From Fig. 12 it is clear that with STATCOM the speed deviations damp out in 5 sec and the peak overshoot is 0.15 for Rotor angle deviation.

SSSC: Step change in Mechanical Input to the Turbine Δpm = 0.1 p.u.

From Fig. 13 it can be observed that the Rotor angle/speed deviations damp out in 2 sec and the peak overshoot is only 0.025 per unit, for rotor angle deviation which is very low compared to that of the STATCOM response.

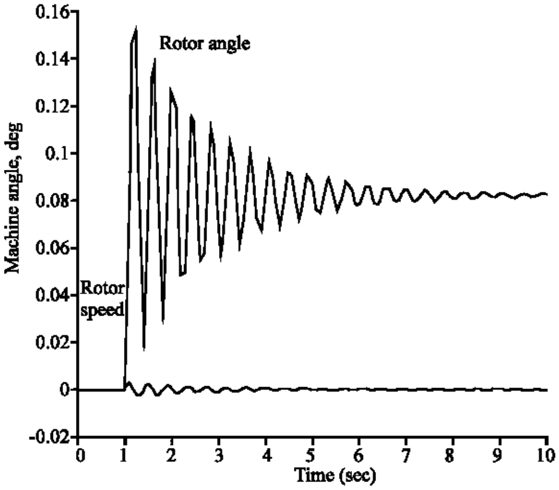

Fig. 12: Rotor speed deviation and rotor angle deviation response with STATCOM

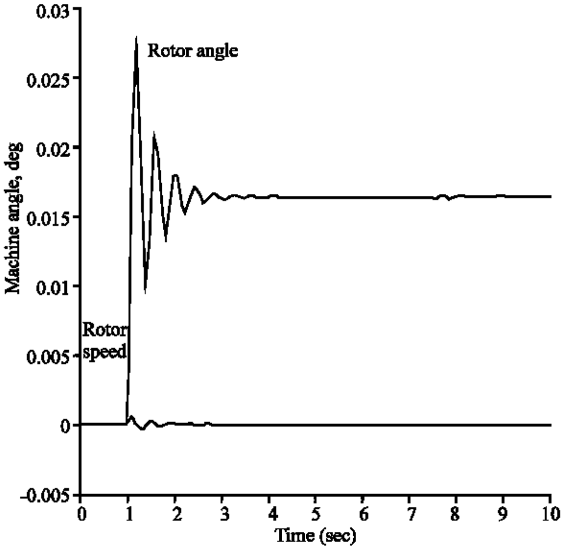

Fig. 13: Rotor speed deviation and rotor angle deviation response with SSSC

UPFC: Step change in Mechanical Input to the Turbine Δpm = 0.1 p.u.

From Fig. 14 we find that the Rotor angle/speed oscillations are damped out in 6 sec and the peak overshoot is 0.0016 per unit.

Without FACTS (Three Phase fault at Bus m in the system).

There are sustained oscillations for a three phase to fault on bus m (Fig. 15). The peak over shoot for the rotor angle is 40 per unit.

STATCOM: Three Phase fault at Bus m in the system.

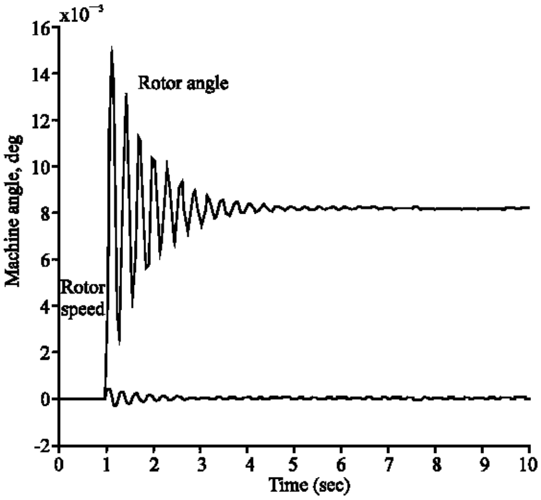

Fig. 14: Rotor speed deviation and rotor angle deviation response with UPFC

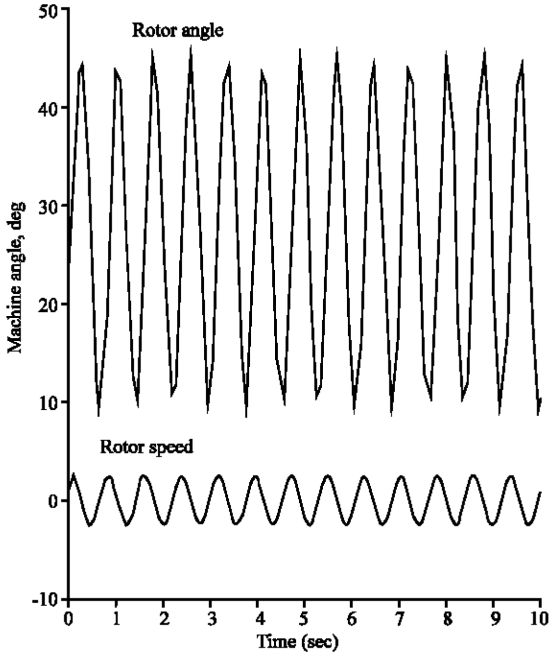

Fig. 15: Rotor speed deviation and rotor angle response without FACTS

From Fig. 16 it can be observed that rotor angle deviation settles down in 3 sec and the peak overshoot is 16 per unit for Rotor angle deviation. The value of reactive current injected by the STATCOM is Is max = 0.056 p.u.; Is min = -0.073 p.u from the Fig. 17.

SSSC: Three Phase fault at Bus m in the system.

From Fig. 18 it is observed that the rotor angle oscillations decay in 4 sec and the peak over shoot is 12 per unit for Rotor angle deviation.

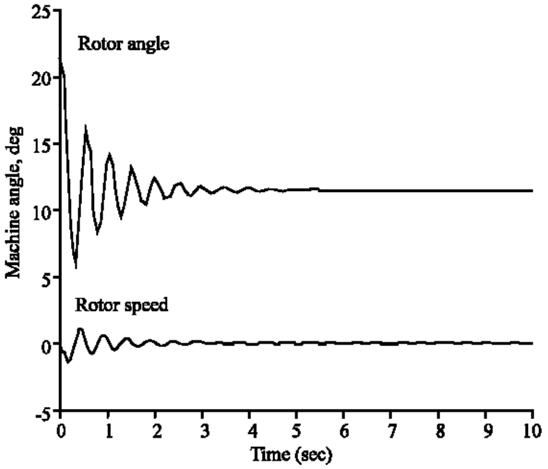

Fig. 16: Rotor speed deviation and rotor angle deviation response with STATCOM at bus m

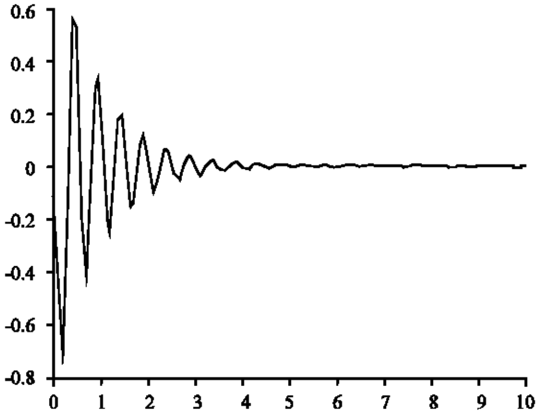

Fig. 17: Reactive current injected by STATCOM

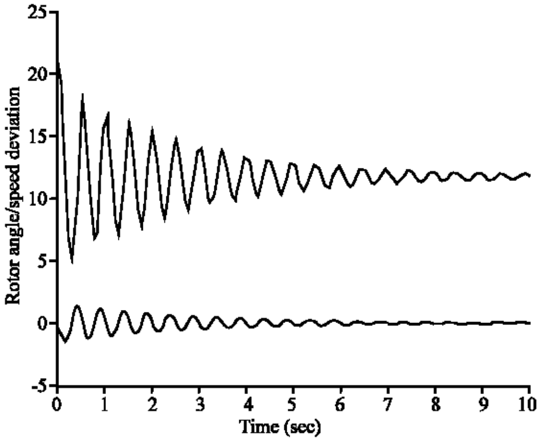

Fig. 18: Rotor speed deviation and rotor angle response with SSSC

The corresponding rating of the series inverter of SSSC is found to be Vsmax = 0.0136 per unit and Vsmin =

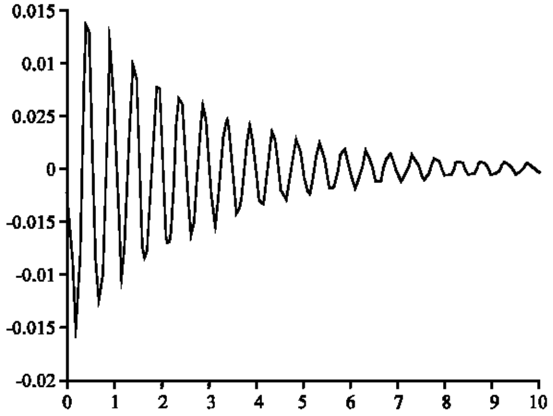

Fig. 19: Series voltage injected by the SSSC after the disturbance UPFC (Three phase fault at Bus m in the system)

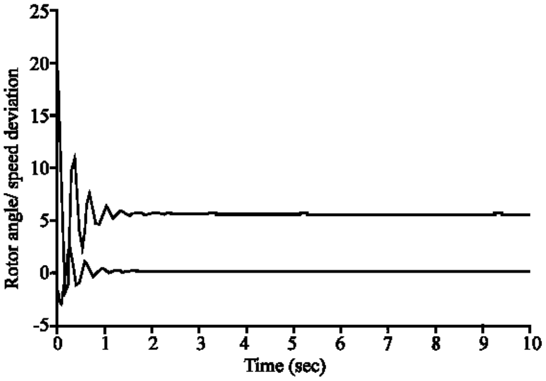

Fig. 20: Rotor speed deviation and rotor angle response with UPFC

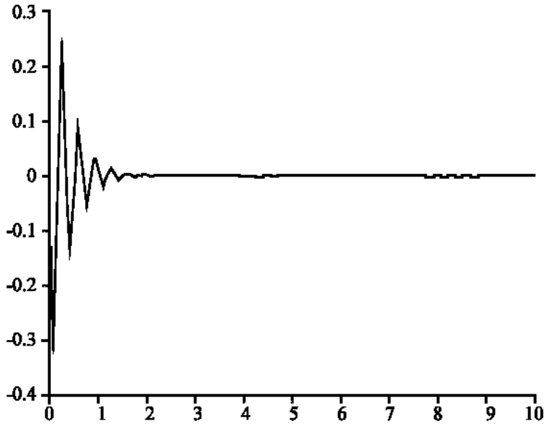

Fig. 21: Series voltage injected by UPFC when the shunt reactive current is zero UPFC with both shunt current and series voltages modulated proportional to speed deviation (K1 = 0.5 K2 = 0.1)

Table 1: Comparison of settling time and peak overshoot with different facts controllers. The optimum values of gains K1 and K2 are given in the table

	STATCOM Is = $K_1 \omega$; K_1 = 0.5		SSSC Vs = $K_2\omega$; K_2=0.1		UPFC with shunt reactive current zero Is = $K_1 \omega$; Vs=$K_2\omega$; K_1=0; K_2 =0.1		UPFC with both vs and is Modulated Is = $K_1 \omega$; Vs = $K_2\omega$; K_1=1; K_2 =0.1	
Disturbance	Δδ(p.u)	Ts (Sec)	Δδ(p.u.)	Ts (Sec)	Δδ (p.u)	Ts (Sec)	Δδ(p.u)	Ts (Sec)
3 Phase fault at bus m	10	3	10	1	10	1.2	5	0.5

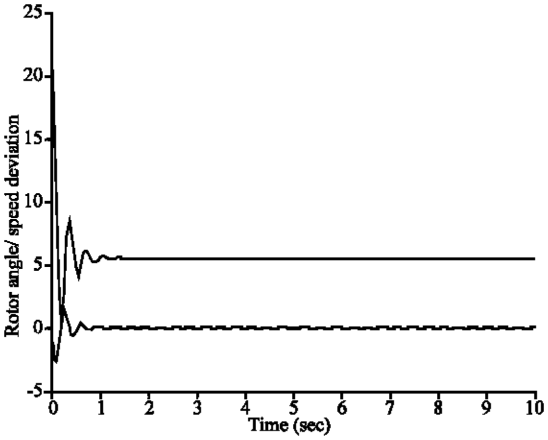

Fig. 22: Rotor angle/speed response of the system with UPFC (both shunt current and series voltage modulated)

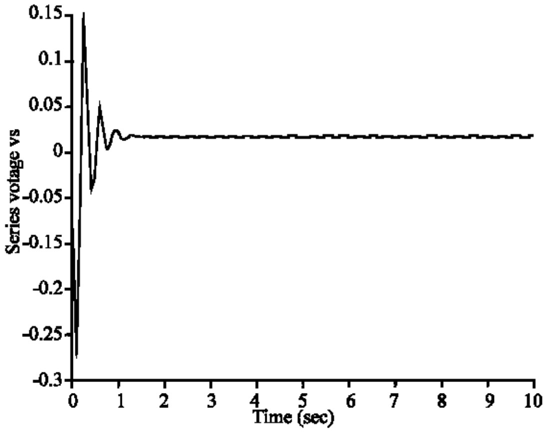

Fig. 23: Series injected voltage by UPFC

-0.016 per unit. For the simulation the value of K_2 is found to be 0.01. The series voltage injected by SSSC is shown in Fig. 19.

From Fig. 20 it is observed that the rotor angle oscillations take 1 sec to damp out completely and the corresponding peak overshoot is 10.8 per unit for rotor angle deviation. The transient voltage rating of the series converter in this case is found to be 0.24 per unit and -0.32 per unit.

Figure 21 and 22 shows about the series voltage injected by UPFC. The value of Vs = K_1 ω chosen is 0.1 with shunt reactive current made zero.

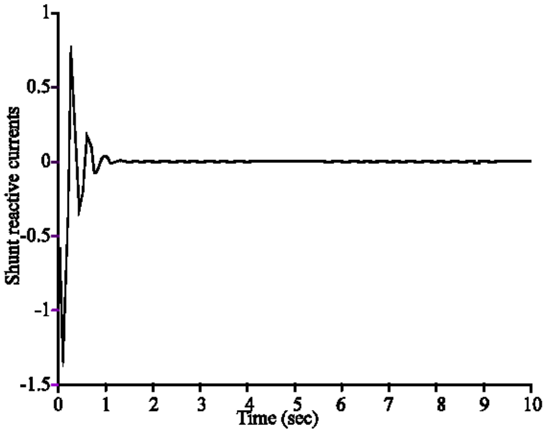

Fig. 24: Shunt reactive current injected by UPFC

Figure 23 and 24 shows the series injected voltage by UPFC and shunt modulated current.

DISCUSSION

From Table 1 we observe that the dynamic response of the system with SSSC is quite satisfactory with a settling time of 1 sec. On the other hand, it takes 3 sec for the oscillations to settle down for the STATCOM. The shunt converter rating of the STATCOM to achieve the same level of damping is more (K_1 = 0.5). The UPFC is very effective for damping the oscillations when both the series and shunt converters are modulated. When the shunt converter current is blocked K_1 = 0 the performance of the UPFC is comparable to that of the SSSC.

CONCLUSION

Simulation results have yield information on the dimensioning and the transient rating of the UPFC for a practical application. For step change in mechanical input to the turbine SSSC damps the oscillations quickly compared to the SSSC The transient rating of UPFC is found to be more than that of STATCOM and SSSC. The results give useful information on the transient rating of FACTs controllers for small disturbance/large disturbance stability enhancement.

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