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Transient Energy Analysis for STATCOM and SSSC Applications

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Abstract: This study concentrates on studying the effects of two Flexible AC Transmission System (FACTS) devices, namely Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) on power system electromechanical oscillation damping. The study is based on the concept that the rate of dissipation of transient energy is used as a measure of system damping. The proposed technique of evaluating system damping is studied for a Single Machine Infinite Bus (SMIB) system installed with STATCOM and SSSC. The damping of power oscillations of a two-machine system by a Power Oscillation Damping (POD) controller for FACTS devices is also described. Results from analytical and digital simulation studies reveal that the series connected SSSC is more effective than the shunt connected STATCOM on damping power system oscillations.

Key words: POD, power system oscillations, SEP, SMIB, SSSC, STATCOM

INTRODUCTION

Oscillations of generator angle or line angle are generally associated with transmission system disturbances and can occur due to step changes in load, sudden change of generator output, transmission line switching and short circuits. The low frequency transient oscillations with poor damping are caused by interaction between the electrical transmission system and the mechanical system of the generators. The natural frequency of this electromechanical power oscillation is in the range of 1 Hz or below. It is important to damp these oscillations as quickly as possible because they cause mechanical wear in power plants and many power quality problems. The system is also vulnerable if further disturbances occur (Hingorani and Gyugyi, 1999). If the electromechanical oscillations are not properly controlled in electric power system operation, it may lead to a partial or total system outage. In some cases, e.g., when the power oscillation has a low frequency, Power System Stabilizers (PSS) are less effective. Then an optional method of introducing FACTS devices in power systems to improve damping of oscillations (Gyugyi, 2000; Song and Johns, 1999) is used. Since, Static Var Compensator (SVC) and Thyristor-Controlled Series Capacitor (TCSC) require fully rated capacitor or reactor bank, the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC) are used to supply or absorb reactive power.

Dynamic control of generator output power is the key point in suppressing electromechanical oscillations or improving damping of a power system. The speed ω can be considered as an appropriate control signal for improving damping of the generator by regulating its output power. In this study, the Transient Energy Function (TEF) method (Haque, 2006) is exploited to evaluate damping of a power system in the presence of FACTS devices. The transient energy function has two components, Kinetic Energy (KE) and Potential Energy (PE). During faulted period, the electrical output power of the machine decreases drastically whereas the input power to the prime mover remains constant and thus, overall system gains some excess energy. This excess energy accelerates the machines and that causes to increase the kinetic energy and potential energy components of the energy function. When the fault is cleared, energy conversion (from kinetic energy to potential energy and vice versa) process takes place. For a stable situation, the machines initially oscillate and ultimately settle at the Stable Equilibrium Point (SEP) where, the transient energy is zero. Thus, the transient energy gained in faulted period is dissipated during the energy conversion process in post fault period before the system reaches the SEP. The faster the energy dissipates,

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the quicker the system reaches the SEP. The SMIB system with STATCOM and SSSC is simulated using Matlab/simulink.

Another simulation was carried out by considering two power generating stations and a resistive load. The STATCOM is connected at the midpoint of the transmission line connecting the substations. A three-phase fault is applied at a bus. Another circuit is developed with SSSC, which can be connected anywhere along the transmission line. The simulation results show that SSSC with POD (Power Oscillation Damping) controller will be more effective in damping power system oscillations compared to STATCOM with POD controller.

MATERIALS AND METHODS

Mathematical model of SMIB system with and without FACTS devices: Consider a simple Single-Machine Infinite Bus (SMIB) system of Fig. 1a without any FACTS device. The system consists of a single machine connected to an infinite bus through two identical transmission lines. The equivalent circuit of the system is shown in Fig. 1b, where, X_1 represents the equivalent reactance between the machine internal bus and the intermediate bus m and X_2 the equivalent reactance between bus m and the infinite bus.

The magnitude of the machine internal voltage and 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 Eq. 1 and 2 (Haque, 2006).

$$\frac{d\delta}{dt} = \omega \quad (1)$$

$$\frac{d\omega}{dt} = \frac{1}{M}\left[P_m - P_e - D\omega\right] \quad (2)$$

Here, δ, ω, M, P_m and D are the rotor angle, rotor speed, moment of inertia, input mechanical power and damping coefficient, respectively of the machine.

The electrical output Power (P_e) of the machine can be written as:

$$P_e = P_{max}\sin\delta \quad (3)$$

Where,

$$P_{max} = \frac{E'V}{X_1 + X_2} \quad (4)$$

The transient energy E of the system can be expressed as Haque (2006):

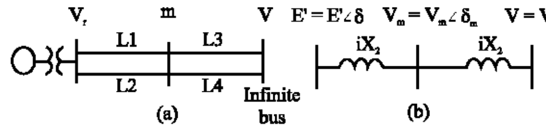

Fig. 1: A single-machine infinite bus system: a) single-line diagram and b) equivalent circuit

$$E(\delta,\omega) = \frac{1}{2}M\omega^2 + \left[-P_m(\delta - \delta_s) - P_{max}(\cos\delta - \cos\delta_s)\right] \quad (5)$$

where:

δ_s = Machine angle at the post fault SEP

The first term on the right hand side of the Eq. 5 depends on ω and is called the kinetic energy and the rest of the terms (within the square bracket) depends on δ and is called the potential energy.

The time derivative of the energy function can be written as:

$$\begin{aligned}\dot{E}(\delta,\omega) &= \frac{dE}{dt} = \frac{\partial E}{\partial\omega}\left(\frac{d\omega}{dt}\right) + \frac{\partial E}{\partial\delta}\left(\frac{d\delta}{dt}\right) \\ &= M\omega\left(\frac{d\omega}{dt}\right) + (-P_m + P_{max}\sin\delta)\frac{d\delta}{dt}\end{aligned} \quad (6)$$

Using Eq. 1, 2 and 6 can be rewritten as:

$$-\dot{E}(\delta,\omega) = (D\omega^2 + P_e\omega - P_{max}\,\omega\sin\delta) \quad (7)$$

Note that $-\dot{E}$ can be considered as the rate of dissipation of transient energy. In the absence of a FACTS device, P_e is governed by Eq. 3 and for such a case Eq. 7 becomes

$$-\dot{E}(\delta,\omega) = D\omega^2 \quad (8)$$

Thus, without any FACTS device, the rate of dissipation of transient energy depends on the damping coefficient D. The objective of this study is to improve the rate of dissipation of transient energy by properly modulating the machine output power P_e with the help of FACTS devices.

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.

The STATCOM is placed in the bus m and is represented by a shunt reactive current source I_s as shown in Fig. 2 (Haque, 2004a). Where:

$$I_s = I_s e^{j(\delta_m \pm 90^\circ)} \tag{9}$$

$$\delta_m = \tan^{-1}\left(\frac{E'X_2 \sin\delta}{VX_1 + E'X_2\cos\delta}\right) \tag{10}$$

With the STATCOM, the output power P_e of the machine can be written as Haque (2004a):

$$P_e = P_{max}\sin\delta + f_1(\delta)I_s \tag{11}$$

Where,

$$f_1(\delta) = \frac{E'X_2}{X_1 + X_2}\sin(\delta - \delta_m) \tag{12}$$

$f_1(\delta)$ is positive when δ oscillates in between 0 and π.

Equation 11 suggests that P_e can be varied by modulating the shunt reactive current I_s. For power system damping enhancement, the shunt reactive current can be modulated in proportion to the rotor speed deviation ω. With this control signal, I_s can be expressed as:

$$I_s = k_1\omega, -I_s^{max} \le I_s \le I_s^{max} \tag{13}$$

where:

k_1 = A positive constant

Using Eq. 11, 13 and 7 can be rewritten as:

$$-\dot{E}(\delta,\omega) = [D + k_1 f_1(\delta)]\omega^2 \tag{14}$$

The 1st term within the square bracket in the Eq. 14 is the natural damping coefficient D and the 2nd term can be considered as the additional damping coefficient (D_{STAT}) provided by the STATCOM:

$$D_{STAT} = k_1 f_1(\delta) = k_1\frac{E'X_2}{X_1 + X_2}\sin(\delta - \delta_m) \tag{15}$$

From Eq. 15, it is inferred that the value of D_{STAT} depends strongly on the generator parameters E' and δ.

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.

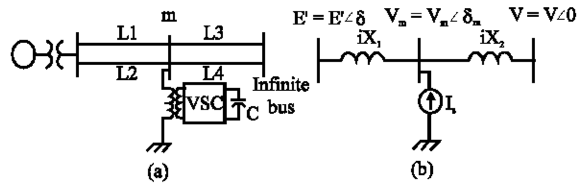

Fig. 2: The SMIB system with a STATCOM a): Schematic diagram and b) Equivalent circuit

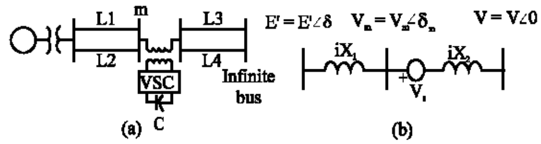

Fig. 3: The SMIB system with a SSSC a): Schematic diagram and b): Equivalent circuit

On the other hand, if the injected voltage is in quadrature with the line current, then reactive power would be exchanged. Consider that a SSSC is placed near bus m in the system shown in Fig. 3. The SSSC is represented by a series voltage source V_s. The series voltage injected by the SSSC is given by

$$V_s = V_s e^{j(\theta \pm 90^0)} \tag{16}$$

where:

θ = The angle of the line current and is given by

$$\theta = \tan^{-1}\left(\frac{V - E'\cos\delta}{E'\sin\delta}\right) \tag{17}$$

With SSSC, the machine power P_e can be written as Haque (2004b).

$$P_e = P_{max}\sin\delta + f_2(\delta)V_s \tag{18}$$

Where,

$$f_2(\delta) = \frac{P_{max}\sin\delta}{\left((E')^2 + V^2 - 2E'V\cos\delta\right)^{1/2}} \tag{19}$$

$f_2(\delta)$ = Positive when δ oscillates in between 0 and π

P_e = Can be modulated by properly controlling the value of V_s

When ω is used as control signal, V_s can be expressed as:

$$V_s = k_2\omega, -V_s^{max} \le V_s \le V_s^{max} \tag{20}$$

where:

k_2 = A positive constant

Using the Eq. 18 and 20, the Eq. 7 can be rewritten as:

$$-\dot{E}(\partial,\omega) = [D + k_2 f_2(\delta)]\omega^2 \quad (21)$$

The additional damping provided by the SSSC is represented by the 2nd term in Eq. 21 and it can be rewritten as:

$$D_{sssc} = k_2 f_2(\delta) = k_2 \frac{P_{max}\sin\delta}{\left((E')^2 + V^2 - 2E'V\cos\delta\right)^{1/2}} \quad (22)$$

From Eq. 22, it is inferred that the value of D_{SSSC} also depends strongly on the generator parameters E' and δ.

RESULTS AND DISCUSSION

Performance of STATCOM and SSSC for damping power system oscillations is simulated using MATLAB 7.5 and the simulation results are shown in Fig. 4-11 for various values of Gain K.

From the simulation results of the mathematical model, it is inferred that the damping of the power system is improved with the help of FACTS devices and it is also noted that when gain K is increased, the settling time is decreased for SSSC as compared to that for STATCOM.

From the Fig. 4 and 5, it is inferred that when K is increased from 0.5-1.5, the machine angle takes more time to reach the final steady state value. The response is faster with SSSC than with STATCOM. Similarly, from the graphs shown in Fig. 6 and 7, it is noted that as K is increased from 0.5-1.5, the speed ω gets decreased with STATCOM than that with SSSC. The Fig. 8 and 9 shows that as K is increased from 0.5-1.5, the settling time of STATCOM current and SSSC voltage increases.

From the Fig. 10 and 11, it is proved that the faster the energy dissipates the quicker the system reaches the SEP. When gain K is increased from 0.5-1.5, the rate of dissipation of transient energy is faster with SSSC than with STATCOM. From the Fig. 12, it is clear that SSSC provides better damping at lower load angles around SEP than the STATCOM.

SSSC with POD (Power Oscillation Damping) controller for a two-machine power system: The Static Synchronous Series Compensator (SSSC), one of the key FACTS devices, consists of a voltage-sourced converter and a transformer connected in series with a transmission line. The SSSC injects a voltage of variable magnitude in quadrature with the line current, thereby emulating an inductive or capacitive reactance. This emulated variable reactance in series with the line can then influence the transmitted electrical power. The SSSC is used to damp power oscillation on a two-machine system following a 3-phase fault.

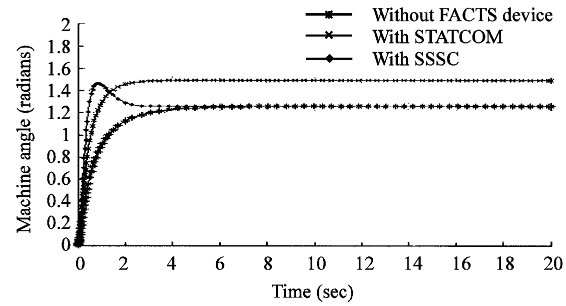

Fig. 4: Machine angle δ (radians) vs. time (sec) for gain K = 0.5

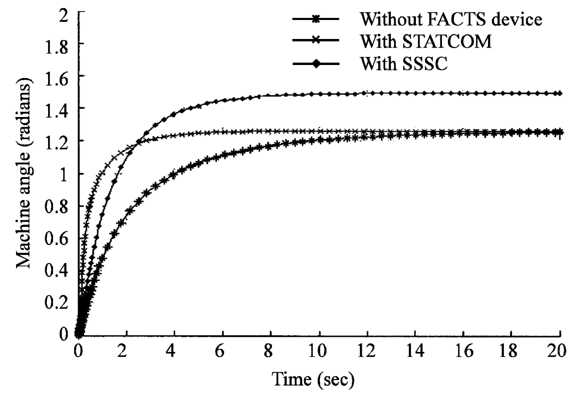

Fig. 5: Machine angle δ (radians) vs. time (sec) for gain K = 1.5

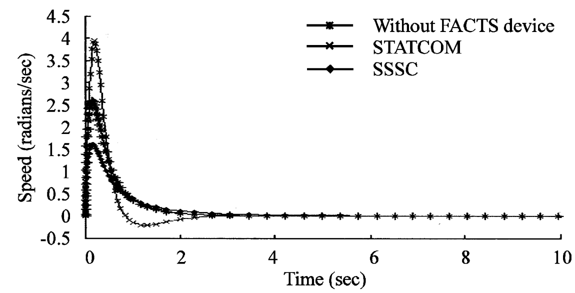

Fig. 6: Speed (radians/sec) vs. time (sec) for gain K = 0.5

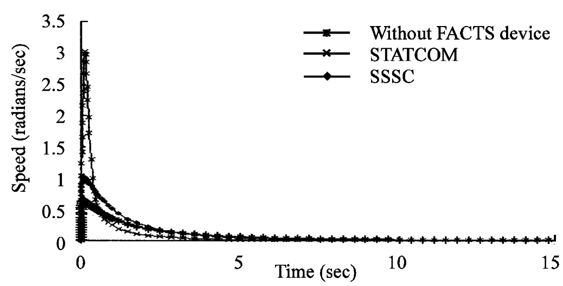

Fig. 7: Speed (radians/sec) vs. time (sec) for gain K = 1.5

Figure 13 shows a two-machine power system installed with SSSC with one major load center at bus B3. The 1st power generating substation has a rating of

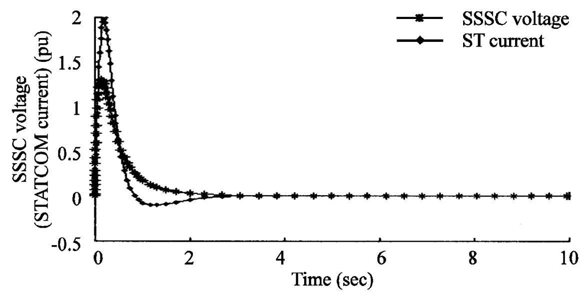

Fig. 8: SSSC voltage (STATCOM current) vs. time (sec) for gain K=0.5

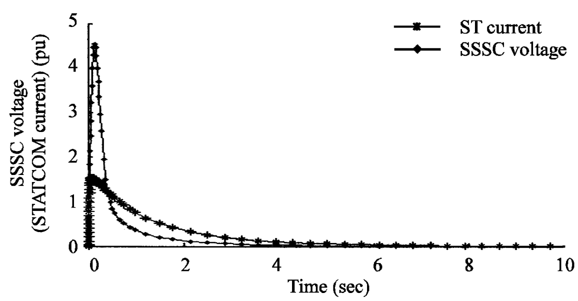

Fig. 9: SSSC voltage (STATCOM current) vs. time (sec) for gain K=1.5

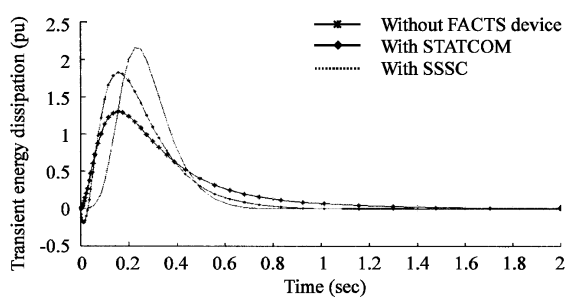

Fig. 10: Transient energy (pu) vs. time (sec) for gain K = 0.5

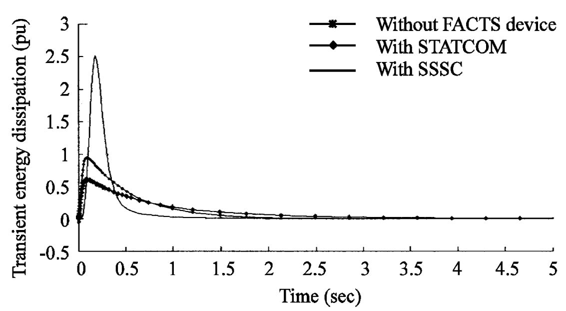

Fig. 11: Tansient energy (pu) vs. time (sec) for gain K = 1.5

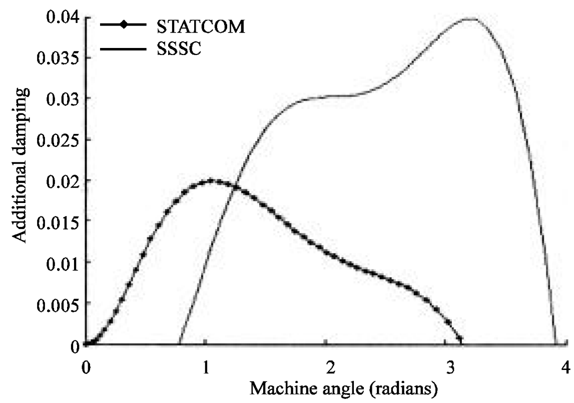

Fig. 12: Additional damping (pu) vs. machine angle δ (radians)

2100 MVA (Angquist *et al*., 1993) and the other one has a rating of 1400 MVA. The load center of approximately 2200 MW is modeled using a dynamic load model where the active and reactive powers absorbed by the load are a function of the system voltage. The generating substations are connected to this load by the transmission lines L1, L2 and L3. The line L1 is 280 km long and the line L2 is split into 2 segments of each 150 km length in order to simulate a three-phase fault (using a fault breaker) at the midpoint of the line. The line L3 is of 100 km length.

The SSSC is placed in series with the line L1. It has a rating of 100 MVA and is capable of injecting up to 10% of the nominal system voltage. It is a typical 3-level PWM SSSC having a nominal voltage of 40 kV with an equivalent capacitance of 375 μF. On the AC side, its total equivalent impedance is 0.16 pu on 100 MVA base. This impedance represents the transformer leakage reactance and the phase reactor of the IGBT bridge of an actual PWM SSSC. The SSSC injected voltage reference is normally set by a POD (Power Oscillation Damping) controller. The POD controller consists of an active power measurement system, a general gain, a low-pass filter, a washout high-pass filter, a lead compensator and an output limiter. The inputs to the POD controller are the bus voltage at B2 and the current flowing in L1. The single line diagram of a two-machine system with SSSC is shown in Fig. 13.

The above single line diagram using SSSC without and with POD controller is simulated using Matlab software package and the simulation results are shown in Fig. 14 and 15.

STATCOM with POD (Power Oscillation Damping) controller for a two-machine power system: The Static Synchronous Compensator (STATCOM) is one of the key

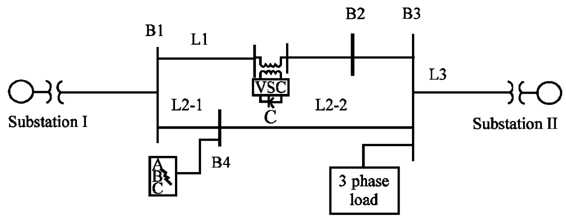

Fig. 13: Single line diagram for a two-machine system with SSSC

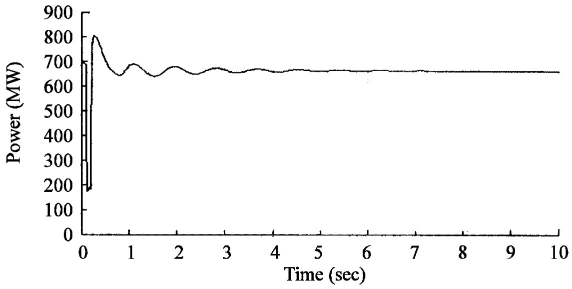

Fig. 14: Power oscillation damping provided by SSSC without POD controller

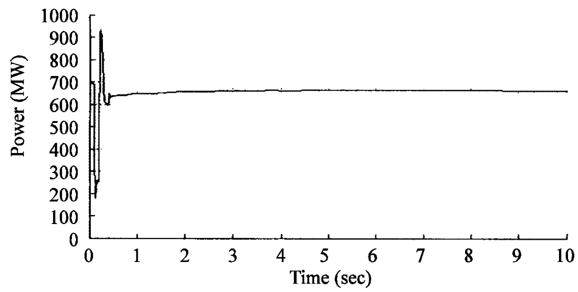

Fig. 15: Power oscillation damping provided by SSSC with POD controller

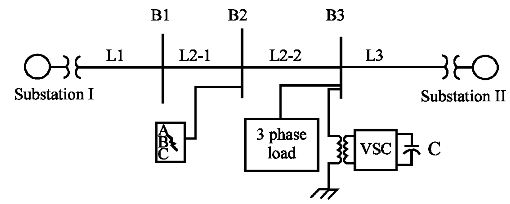

Fig. 16: Single line diagram for a two-machine system with STATCOM

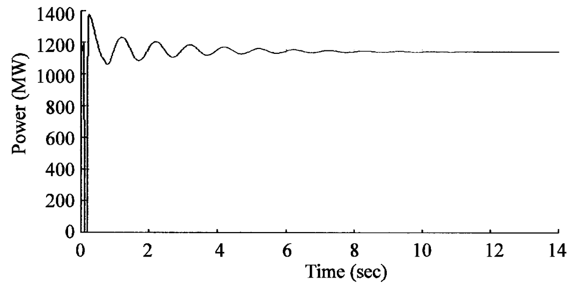

Fig. 17: Power oscillation damping provided by STATCOM without POD controller

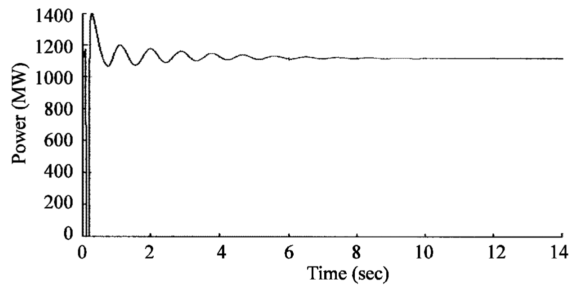

Fig. 18: Power oscillation damping provided by STATCOM with POD controller

FACTS devices. Based on a voltage-sourced converter, the STATCOM regulates system voltage by absorbing or generating reactive power. Contrary to a thyristor-based Static Var Compensator (SVC), the STATCOM output current (inductive or capacitive) can be controlled independent of the AC system voltage. As shown in Fig. 16, the STATCOM is located at bus B3 and has a rating of ±100 MVA. It is a typical 3-level PWM STATCOM having a DC link nominal voltage of 40 kV with an equivalent capacitance value of 375 μF. On the AC side, its total equivalent impedance is 0.22 pu on 100 MVA base. This impedance represents the transformer leakage reactance and the phase reactor of the IGBT bridge of an actual PWM STATCOM (Angquist *et al*., 1993).

The system consists of 2 power generating substations and one major load center at bus B3. The 1st power generating substation has a rating of 2100 MVA and the other one has a rating of 1400 MVA. The load center of approximately 2200 MW is modeled using a dynamic load model where the active and reactive powers absorbed by the load are a function of the system voltage. The transmission line L2 is split into 2 segments of 100 km each in order to simulate a three-phase fault (using a fault breaker) at the midpoint of the line. The 2nd generation substation is also connected to the load by the line L3 of 200 km length. The POD controller consists of an active power measurement system, a general gain, a low-pass filter, a washout high-pass filter, a lead compensator and an output limiter. The inputs to the POD controller are the bus voltage at B2 and the current flowing in L1. The single line diagram for the system with STATCOM is shown in Fig. 16.

From the simulation results for SSSC and STATCOM shown in Fig. 14, 15, 17 and 18, it is inferred that the damping of oscillations can be effectively done with the help of SSSC with POD controller. Hence, it is well proven that in damping power system oscillations, the SSSC with POD controller is more effective than the STATCOM with POD controller.

CONCLUSION

The transient energy is used as a tool to assess the effectiveness of FACTS devices to dampen power oscillations. Improvement of system damping is achieved by careful modulation of machine output power during oscillations with the help of STATCOM and SSSC. Simulation results indicated that both the STATCOM and SSSC can significantly improve system damping. It is also observed that the SSSC can provide effective damping than the STATCOM.

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