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Nonlinear Control Design of Series FACTS Devices for Damping Power System Oscillation

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Abstract: Problem statement: The disturbance in the complicated network of power system may cause in nonlinear response. Static Synchronous Series Compensator (SSSC) is a power electronic based device that has the capability of controlling the line current. This study applies the SSSC to decrease the over line current in power system during dynamic state. **Approach:** This study proposes the control strategy of a SSSC to enlarge the stability region of a simple power system. The control is determined very carefully to satisfy the Lyapunov's stability criterion and is found to be a non-linear function of system states. The proposed nonlinear control of SSSC for damping power system oscillation is investigated through the sample system. **Results:** The maximum generator rotor angle of the faulted system without a SSSC is continuously oscillation and the maximum value is much more than the system with a SSSC. **Conclusion:** SSSC based the proposed nonlinear control can damp power system oscillation.

Key words: Power system stability, power system oscillation, FACTS devices, static synchronous series compensator, Static Synchronous Series Compensator (SSSC), Single Machine Infinite Bus (SMIB), voltage injection, voltage source, short circuit

INTRODUCTION

Modern power system network is getting much more complicated and heavily loaded than ever before. The consequences of such are the difficulty of power flow and risk of stability problem. Flexible AC Transmission System (FACTS) devices have been proposed to improve stability of power system (Barbuy *et al*., 2009; Heraldo *et al*., 2009; Osuwa and Igwiro, 2010; Omar *et al*., 2010; Zarate-Minano *et al*., 2009). They have proposed many methods to improve stability of power system such as load shedding, High Voltage Direct Current (HVDC), Flexible AC Transmission System (FACTS), (Hannan *et al*., 2009; Kumkratug, 2010a; 2010b; 2010c; Hassan *et al*., 2010a; 2010b; Magaji and Mustafa, 2009; Meshkatoddini *et al*., 2009).

A Static Synchronous Series Compensator (SSSC) is a member of the FACTS family that is connected in series with power system. The SSSC consists of a solid state voltage source converter with GTO thyristor switches or other high performance of semi-conductor and transformer. The SSSC can electrically mimic reactor and capacitor by injecting a shunt current in quadrature with the line voltage. The reactive power (or current) of the SSSC can be adjusted by controlling the magnitude and phase angle of the output voltage of the shunt converter (Al-Husban, 2009; Mustafa and Magaji, 2009).

The disturbance in the complicated network of power system may cause in nonlinear response. This study presents the nonlinear control of SSSC for damping power oscillation. The proposed control is based on Lyapunov's theory. The simulation results are tested on a sample system. The effect of SSSC on damping power system oscillation is investigated in various cases.

MATERIALS AND METHODS

Mathematical model: Consider a single machine infinite bus system with a SSSC as shown in Fig. 1a. The equivalent circuit of the system is shown in Fig. 1b where the SSSC is represented by a variable synchronous voltage source of V_s (Al-Husban, 2009) and the generator is modeled by a constant voltage source behind transient reactance. Reactance X_1 represents the sum of generator transient reactance and transformer leakage reactance and X_2 represents the equivalent reactance of the parallel lines. The leakage reactance of the series transformer of SSSC can be included either in X_1 or X_2. The phasor diagram of the system is shown in Fig. 2 for various operating conditions of the SSSC. It can be seen in Fig. 2 that, for given E' and V, the SSSC voltage V_s changes only the magnitude of the current but not its angle.

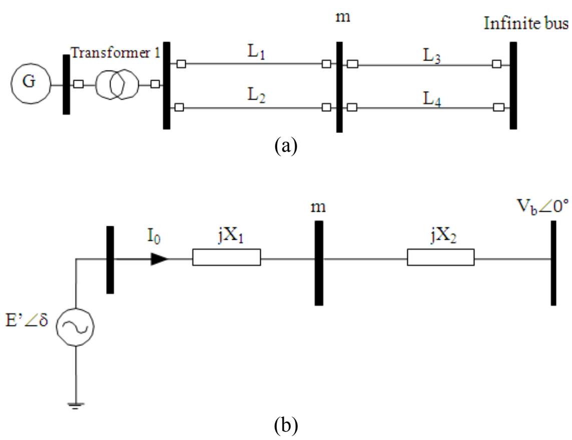

Fig. 1: Single machine infinite bus system (a) schematic diagram (b) equivalent circuit

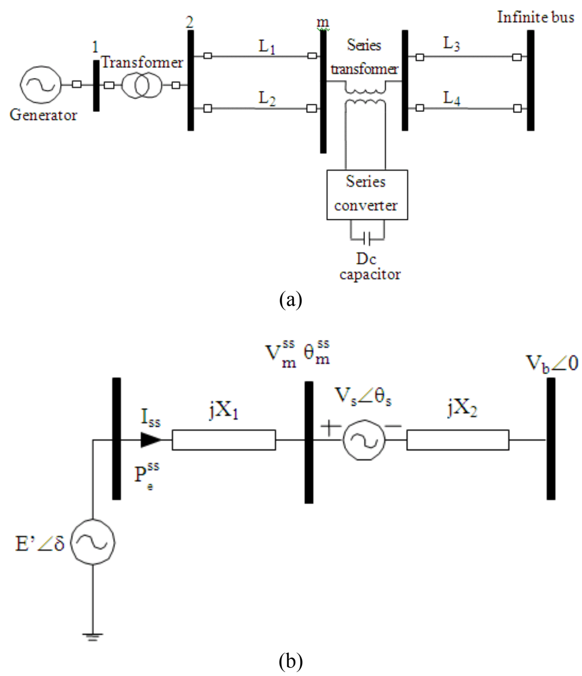

Fig. 2: Single machine infinite bus system with a SSSC (a) schematic diagram (b) equivalent circuit of system with a SSSC represented by a series voltage injection

When $V_s = 0$, the current I_0 of the system can be written as:

$$\mathbf{I_0} = \frac{\mathbf{E'} - \mathbf{V}}{jX} \tag{1}$$

Here, $X = X_1+X_2$. The angle θ of the current can be written as:

$$\theta = \tan^{-1}\left(\frac{V - E'\cos\delta}{E'\sin\delta}\right) \tag{2}$$

From Fig. 1b, the general equation of the current can be written as:

$$\mathbf{I} = \frac{\mathbf{E'} - \mathbf{V_s} - \mathbf{V}}{jX} = \left(\frac{\mathbf{E'} - \mathbf{V}}{jX}\right) + \left(\frac{-\mathbf{V_s}}{jX}\right) = \mathbf{I_0} + \Delta\mathbf{I} \tag{3}$$

Here ΔI is an additional term appears because of the SSSC voltage V_s. The electrical output power P_e of the generator can be written as:

$$P_e = \Re\left\{\mathbf{E'}\mathbf{I}^*\right\} = P_{e0} + \Delta P_e \tag{4}$$

Here, P_{e0} is the generator output power without SSSC ($V_s = 0$) and is given by:

$$P_{e0} = P_{max}\sin\delta \tag{5}$$

where, $P_{max} = E'V/X$. The additional power term ΔP_e appears in (4) is due to the SSSC voltage V_s and can be written as:

$$\Delta P_e = \Re\left\{\mathbf{E'}\left(\frac{-\mathbf{V_s}}{jX}\right)^*\right\} = \frac{E'V_s}{X}\sin(\delta - \alpha) \tag{6}$$

When V_s lags the current by 90° (α = θ-90°), ΔP_e becomes:

$$\Delta P_e = \frac{E'V_s}{X}\cos(\delta - \theta) \tag{7}$$

After some mathematical manipulations of (2), the term cos(δ-θ) can be expressed as:

$$\cos(\delta - \theta) = \frac{V}{E'}\cos\theta \tag{8}$$

From Fig. 3, cosθ can be written as:

$$\cos\theta = \frac{E'\sin\delta}{xy} = \frac{E'\sin\delta}{\sqrt{E' + V^2 - 2E'V\cos\delta}} \tag{9}$$

Using (7)-(9), ΔP_e can be expressed as:

$$\Delta P_e = CV_sP_{e0} \tag{10}$$

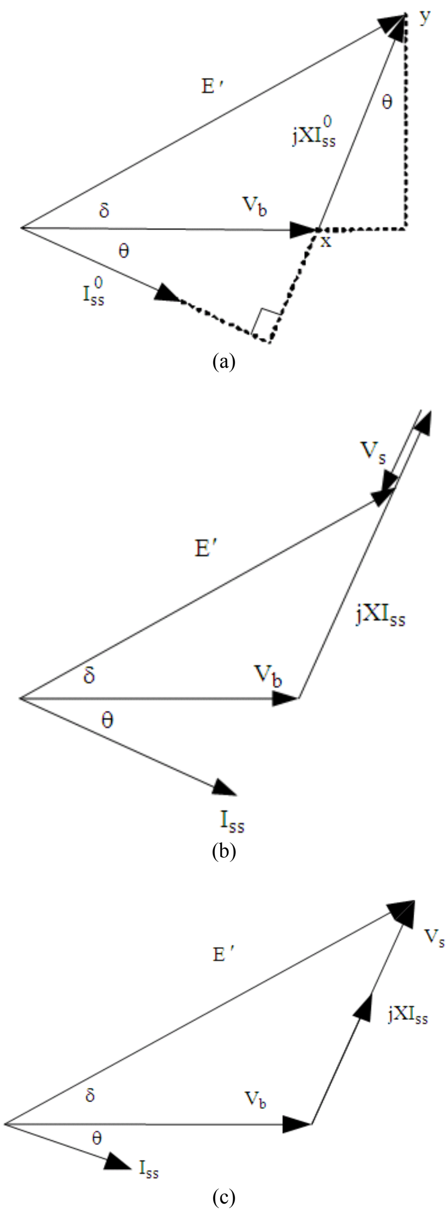

Fig. 3: Phasor diagram (a) without a SSSC (b) with a SSSC operating in capacitive mode (c) with a SSSC operating in reactive mode

Where:

$$C = \frac{1}{\sqrt{(E')^2 + V^2 - 2E'V\cos\delta}}$$

Note that C≥ 0 for all possible values of E', V and δ. When V_s leads the current by 90° (α = θ + 90°), ΔP_e can also be determined from (10) by replacing V_s by-V_s.

Thus the electrical output power of the generator in the presence of a SSSC becomes:

$$P_e = P_{e0} + CV_sP_{e0} \quad (11)$$

The dynamic of the generator, in classical model, can be expressed by the following differential equations:

$$\dot{\delta} = \omega \quad (12)$$

$$\dot{\omega} = \frac{1}{M}[P_m - P_e - D\omega] \quad (13)$$

Here δ, ω, P_m, D and M are the rotor angle, speed deviation, input mechanical power, damping constant and moment inertia, respectively, of the generator. Equation 12 and 13 can be rewritten in the following general form"

$$\dot{x} = f(x,u) = f_0(x) + uf_1(x) \quad (14)$$

Where:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \delta \\ \omega \end{bmatrix}$$

$$u = V_s \;\; f_0(x) = \begin{bmatrix} f_{01}(x) \\ f_{02}(x) \end{bmatrix} = \begin{bmatrix} \omega \\ \frac{P_m - P_{e0}}{M} \end{bmatrix}$$

$$f_1(x) = \begin{bmatrix} f_{11}(x) \\ f_{12}(x) \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{-CP_{e0}}{M} \end{bmatrix}$$

Control strategy: This study applies the Lyapunov's stability criterion to derive strategy of SSSC. The Lyapunov's function *E* of the system may be considered as:

$$E(\delta,\omega) = \frac{1}{2}M\omega^2 - P_m\delta - P_{max}\cos\delta + C_0 \quad (15)$$

Here, C_0 is a constant that makes E(x) = 0 at the post fault stable equilibrium point. The Lyapunov 's stability criterion is defined by $\dot{E}(x) \le 0$ for all x. Using (14), the time derivative of E can be written as:

$$\dot{E}(x) = \frac{\partial E(x)}{\partial x} \times \frac{\partial x}{\partial t} = \nabla E(x)f_0(x) + \nabla E(x)uf_1(x) \quad (16)$$

The first term on the right side of (16) represents $\dot{E}(x)$ of the system without SSSC and can be expressed as:

$$\nabla E(x) f_0(x) = [(-P_m + P_{max}\sin\delta) \quad M\omega] \times \begin{bmatrix} \omega \\ \dfrac{P_m - P_{e0} - D\omega}{M} \end{bmatrix} = 0 \quad (17)$$

Note that (17) is at least negative semi-definite for all values of ω. The contribution of SSSC appears in the second term on right hand side of (16) and which can written as:

$$\nabla E(x) f_1(x) = [(-P_m + P_{max}\sin\delta) \quad M\omega] u \begin{bmatrix} 0 \\ \dfrac{-CP_{e0}}{M} \end{bmatrix} \quad (18)$$

$$= -CP_{max} u\omega \sin\delta$$

To satisfy the negative semi definiteness criteria of Lyapunov 's concept, the second term of (16) must also be satisfied in same criteria. This can be satisfied by properly selecting the value of the control u of (18). One of the possible candidates of u is:

$$u = K\ \omega \sin\delta \quad (19)$$

where, K is a gain. It can be seen in (19) that the control is a nonlinear type and it depends on the system states δ and ω.

RESULTS

The proposed nonlinear control of SSSC for damping power system oscillation will be investigated through the sample system. Figure 4 shows the sample system. The system parameters are:

$M=5.6$, $X_t = 0.1$, $X'_d = 3$, $X_{L1}=0.4$, $X_{L2}=0.4$, $X_{L3}=0.9$, $X_{L4}=0.4$, $P_m=0.9$

It is considered that a 3-phase fault appears on line L1 and it is cleared by opening the faulted line. Figure 5 shows the generator rotor angle curve of the system with and without a SSSC. Figure 6 shows the generator rotor angle curve of the system with various gains of a SSSC.

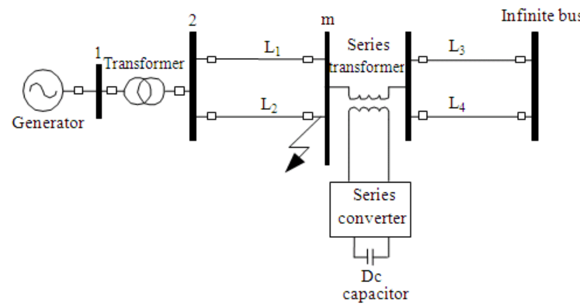

Fig. 4: Sample system

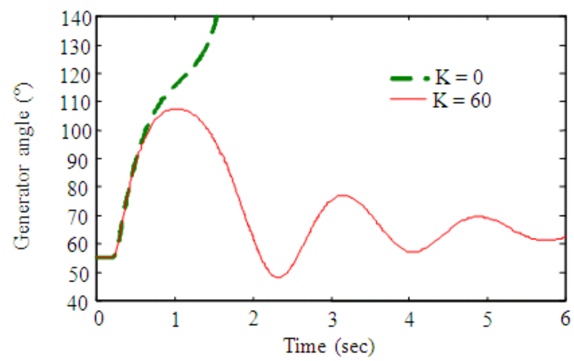

Fig. 5: The generator rotor angle of the system with and without a SSSC

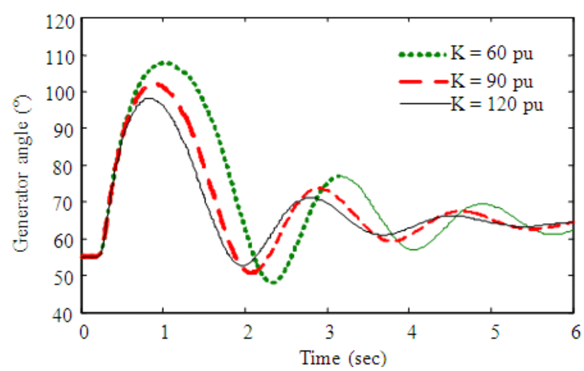

Fig. 6: The generator rotor angle of the system with various gains of SSSC

DISCUSSION

It can be observed from the simulation results that the system without a SSSC (K = 0) the generator rotor angle increases monotonously and it is considered as unstable whereas the system with a SSSC (K = 30) can be considered as stable. This study also investigates the effect of increasing the gain on damping improvement.

With the K= 30, the maximum generator rotor angle is around 110°. With K = 120, the maximum is decreased to 98°.

CONCLUSION

Static Synchronous Series Compensator (SSSC) is shunt FACTS devices. It has capability of improving power system oscillation. This study presents the nonlinear control of Static Synchronous Series Compensator (SSSC) for damping power system oscillation. The proposed control strategy is derived from Lyapunov's theory. The proposed nonlinear control of a SSSC is tested on sample system. It was found that the SSSC can damp power system oscillation. The maximum of the generator rotor angle can be decreased by increasing the gain.

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