Nonlinear Control Design of Shunt Flexible AC Transmission System 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 Compensator (STATCOM) is a power electronic based device that has the capability of controlling the line current. This study applies the STATCOM to decrease the over line current in power system during dynamic state. **Approach:** This study proposes the control strategy of a STATCOM 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 STATCOM for damping power system oscillation is investigated through the sample system. **Results:** The maximum generator rotor angle of the faulted system without a STATCOM is continuously oscillation and the maximum value is much more than the system with a STATCOM. **Conclusion:** STATCOM based the proposed nonlinear control can damp power system oscillation.

Key words: Power system stability, power system oscillation, FACTS devices, 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; Hassan *et al*., 2010a; Fernandes *et al*., 2009; Omar *et al*., 2010; Osuwa and Igwiro, 2010; Santos *et al*., 2010). 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), (Al-Husban, 2009; Hassan *et al*., 2010b ; Kumkratug, 2010; Meshkatoddini *et al*., 2009; Hannan *et al*., 2009; Zarate-Minano *et al*., 2010).

A Static Synchronous Compensator (STATCOM) is a member of the FACTS family that is connected in shunt with power system. The STATCOM consists of a solid state voltage source converter with GTO thyristor switches or other high performance of semi-conductor and transformer. The STATCOM can electrically mimic reactor and capacitor by injecting a shunt current in quadrature with the line voltage. The reactive power (or current) of the STATCOM 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 STATCOM 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 STATCOM on damping power system oscillation is investigated in various cases.

MATERIALS AND METHODS

Mathematical model: Fig. 1a shows the single line diagram of the Single Machine Infinite Bus (SMIB) system with a STATCOM at bus m. First consider the system without the STATCOM and the corresponding equivalent circuit is shown in Fig. 1b. Here X_1 is the equivalent reactance between the machine internal bus and the bus m and X_2 is the equivalent reactance between bus m and the infinite bus. The generator is representing by a constant voltage source (E') behind transient reactance. The equivalent circuit of the system with a STATCOM is shown in Fig. 1c where the STATCOM is represented by a shunt current. Note that the injected current of the STATCOM is always in quadrature with its terminal voltage.

(a)

(b)

(c)
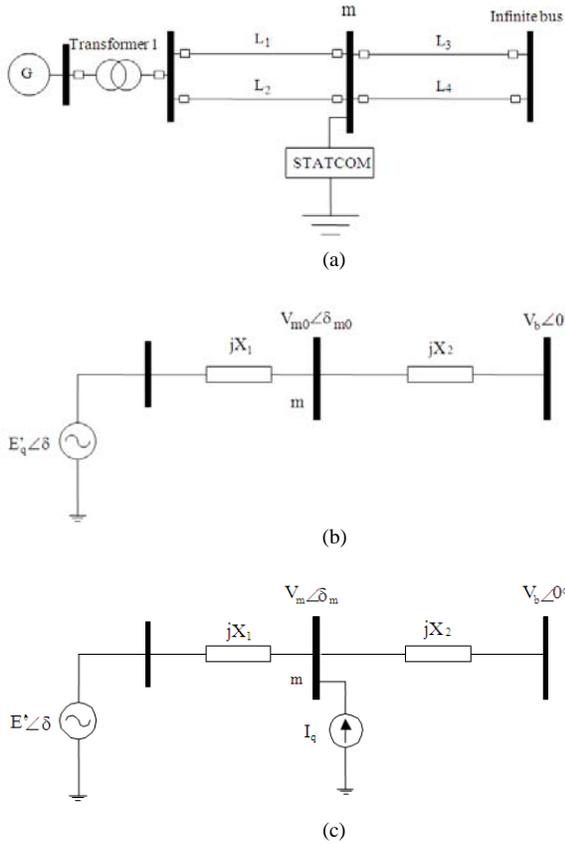
Fig. 1: A Single Machine Infinite Bus (SMIB) system with STATCOM; (a) A single line diagram; (b) Equivalent circuit of SMIB system without STATCOM; (c) Equivalent circuit of SMIB system with a STATCOM represented by a current injection model

The dynamics of the generator, without the STATCOM, can be expressed by the following differential equations 1 and 2:

$$\dot{\delta} = \omega \tag{1}$$

$$\dot{\omega} = \frac{1}{M}\left[P_m - P_{e0}\right] \tag{2}$$

Here δ, ω M and P_m, are the rotor angle, speed, input mechanical power, moment of inertia and output mechanical power, respectively, of the generator. P_{e0} is output electrical power of generator without the STATCOM and is given by Eq. 3-7:

$$P_{eo} = \frac{E'V_{mo}}{X_1}\sin(\delta - \delta_{mo}) \tag{3}$$

Here, V_{mo} and δ_{m0} represent the voltage magnitude and angle at bus m without the STATCOM and are given by:

$$\delta_{m0} = \tan^{-1}\left[\frac{X_2 E' \sin\delta}{X_2 E'_q \cos\delta + X_1 V_b}\right] \tag{4}$$

$$V_{m0} = \left(\frac{X_2 E' \cos(\delta - \delta_m) + X_1 V_b \cos\delta_m}{X_1 + X_2}\right) \tag{5}$$

In general form, equations (1) and (2) can be written as:

$$\dot{x} = f_0(x) \tag{6}$$

Where:

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

And:

$$f_0(x) = \begin{vmatrix} f_{01}(x) \\ f_{02}(x) \end{vmatrix} = \begin{vmatrix} \omega \\ \dfrac{P_m - P_{e0}}{M} \end{vmatrix}$$

Now, consider the system with the STATCOM at bus m as shown Fig. 1c. The injected current of the STATCOM for capacitive mode of operation can be expressed as:

$$\mathbf{I}_q = I_q \angle \delta_m - 90^0 \tag{7}$$

With the STATCOM, the voltage magnitude and angle at bus m can be written as Eq. 8 and 9:

$$\delta_m = \tan^{-1}\left[\frac{X_2 E' \sin\delta}{X_2 E'_q \cos\delta + X_1 V_b}\right] \tag{8}$$

$$V_m = \left(\frac{X_2 E' \cos(\delta - \delta_m) + X_1 V_b \cos\delta_m}{X_1 + X_2}\right) + \left(\frac{X_1 X_2}{X_1 + X_2}I_q\right) \tag{9}$$

Note that δ_m of (8) is exactly the same as δ_{m0} of (4). That is the STATCOM current does not change the angle of the voltage at bus m. However, the voltage magnitude of bus m depends on the STATCOM current

I_q as can be seen in (9). Note that the first term on the right hand side of (9) is the same as V_{m0} of (5) and the second term represent the contribution of the STATCOM current. Thus V_m can be expressed as:

$$V_m = V_{m0} + C_1 I_q \qquad (10)$$

Where:

$$C_1 = \frac{X_1 X_2}{X_1 + X_2}$$

Using Fig. 1c, the output electrical power P_e of generator, with the STATCOM, can be written as:

$$P_e = \frac{E' V_m}{X_1} \sin(\delta - \delta_m) \qquad (11)$$

Using (10) and (11), P_e can be expressed as:

$$P_e = P_{e0} + C_2 I_q \sin(\delta - \delta_m) \qquad (12)$$

Where:

$$C_2 = \frac{E' C_1}{X_1}$$

It may be mentioned here that the above equations are derived for capacitive mode of operation of the STATCOM. For inductive mode of operation, I_q in (9), (10) and (12) needs to be replaced by $-I_q$. Thus the dynamic equations of the generator with the STATCOM becomes Eq. 13:

$$\dot{x} = f(x, u) = f_0(x) + u f_1(x) \qquad (13)$$

Where:

$$u = I_q$$

And:

$$f_1(x) = \begin{bmatrix} f_{11}(x) \\ f_{12}(x) \end{bmatrix} = \begin{bmatrix} 0 \\ \dfrac{-C_2 \sin(\delta - \delta_m)}{M} \end{bmatrix}$$

The system states x and function f_0 are already defined in (6). It may be mentioned here that the damping of a system can be improved by controlling the output electrical power of generator which depends on both angle δ and STATCOM current I_q.

Control strategy: Liapuvov's second or direct method is a very powerful tool of assessing the stability of a non-linear system. In this study, the concept of the Lyapunov's stability criterion is used to select control strategy of the STATCOM. A positive definite Lyapunov function V of the simple SMIB system can be considered as (Zarate-Minano *et al.*, 2010) Eq. 14:

$$V(\delta, \omega) = \frac{1}{2} M \omega^2 - P_m \delta - (E' V_b / X_1) \cos \delta + C_0 \qquad (14)$$

The basis of the Lyapunov's stability theory is that the time derivative of V(x) must be negative semi-definite along the post fault trajectory. The time derivative of V(x) can be written as:

$$\dot{V}(x) = \frac{\partial V}{\partial x} \frac{dx}{dt} = \frac{\partial V(x)}{\partial x}[f_0(x) + u f_1(x)]$$

$$= \frac{\partial V(x)}{\partial x} f_0(x) + \frac{\partial V(x)}{\partial x} u f_1(x) \qquad (15)$$

Thus the Lyapunov's stability criterion can be satisfied by making both terms on the right hand side of (15) as negative semi-definite. The first term on the right hand side of (15) represents $\dot{V}$ without the STATCOM and is given by Eq. 16:

$$\dot{V}_0(x) = \frac{\partial V(x)}{\partial x} f_0(x)$$

$$[-P_m + P_{e0} \quad M\omega] \begin{bmatrix} \dfrac{P_m \omega - P_{e0}}{M} \end{bmatrix} = 0 \qquad (16)$$

The second term on the right hand side of (15) represents the contribution of the STATCOM to $\dot{V}$ and is given by:

$$\dot{V}_1(x) = \frac{\partial V(x)}{\partial x} u f_1(x)$$

$$= [-P_m + P_{e0} \quad M\omega] u \begin{bmatrix} 0 \\ \dfrac{-C_2 \sin(\delta - \delta_m)}{M} \end{bmatrix} \qquad (17)$$

$$= -u C_2 \omega \sin(\delta - \delta_m)$$

One of the possible candidates of u that guarantees the negative semi-definiteness criterion of (17) can be considered as:

$$u = K \omega \sin(\delta - \delta_m) \qquad (18)$$

Here, K is a positive constant. Note that for positive values of X_1 and X_2, the angle δ_m in Fig. 1c always lies in between zero and δ. When $-\pi \leq \delta \leq \pi$, the sign of sin ($\delta$-$\delta_m$) becomes the same as the sign of sin δ. Thus without changing the sign criterion of $\dot{V}$, the control u of (18) can also be considered as:

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

It can be seen in (19) that the proposed control is a non-linear function of generator angle and speed. When the STATCOM is not placed near the generator, these signals need to be estimated from some local information.

RESULTS

The proposed nonlinear control of STATCOM for damping power system oscillation will be investigated through the sample system. Figure 2 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
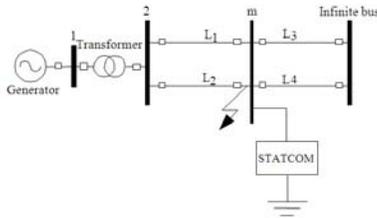
Fig. 2: Sample system
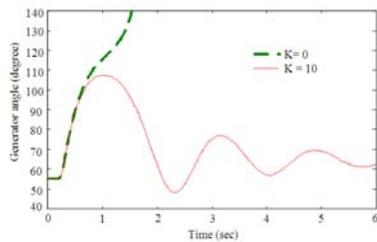
Fig. 3: The generator rotor angle of the system with and without a STATCOM
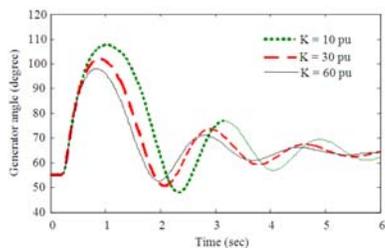
Fig. 4: The generator rotor angle of the system with various gains of STATCOM

It is considered that a 3-phase fault appears on line L1 and it is cleared by opening the faulted line. Figure 3 shows the generator rotor angle curve of the system with and without a STATCOM. Figure 4 shows the generator rotor angle curve of the system with various gains of a STATCOM.

DISCUSSION

It can be observed from the simulation results that the system without a STATCOM (K = 0) the generator rotor angle increases monotonously and it is considered as unstable whereas the system with a STATCOM (K=10) can be considered as stable. This study also investigates the effect of increasing the gain on damping improvement. With the K= 10, the maximum generator rotor angle is around 107°. With K=120, the maximum is decreased to 97°.

CONCLUSION

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

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