Optimal Control Design of Static Synchronous Series Compensator for Damping Power System Oscillation

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Abstract: Problem statement: In power systems, there exists a continuous challenge to improve dynamic performance of power system. **Approach:** The Static Synchronous Series Compensator (SSSC) is a power electronic based device that has capability of controlling the power flow through the line both in steady state and dynamic sate. This study applied the SSSC to damp power system oscillation. The optimal control design is applied to derive the control strategy of SSSC. The simulation results are tested on a Single Machine Infinite bus. The proposed method is equipped in sample system with disturbance. The generator rotor angle curve of the system without and with a SSSC is plotted and compared. **Results:** It was found that the system without a SSSC has high variation whereas that of the system with a SSSC has much smaller variation. **Conclusion:** From the simulation results, the SSSC can damp power system oscillation.

Key words: Power system, Flexible AC Transmission Systems (FACTS), static var compensator, thyristor controller series, static synchronous compensator, unified power flow controller, control strategy, optimal control

INTRODUCTION

The recent blackout in northeast United States, followed by similar incidents in England, Italy and Scandinavia have illustrated the vulnerability in modern power system. It challenges power engineering to find the new methods for improving dynamic performance of power system. Flexible AC Transmission System (FACTS) controllers, based on the rapid development of power electronics technology, have been proposed for power flow control in steady state and dynamic state. The various forms of FACTS devices are the Static Var Compensator (SVC), Thyristor Controlled Phase Shifter Transformer (TCPST), Thyristor Controller Series Capacitor (TCSC), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC) and Inter-line Power Flow Controller (IPFC) (Barbuy *et al.*, 2009; Prechanon Kumkratug, 2011; Rudez and Mihalic, 2009).

The control strategy of FACTS devices plays an important role for effective improvement of dynamic performance of a power system. Many research used in linear control schemes of SSSC for this purposes. However, modern power system is a large and complex network and disturbances usually cause in nonlinear

response (Ahmad and Mohamed, 2009; Hafaifa *et al.*, 2009; Hojat *et al.*, 2010; Samimi *et al.*, 2009; Majee and Roy, 2010; Bagher *et al.*, 2009; Chamsai *et al.*, 2010).

This study presents the control strategy of a SSSC for improving power system dynamic performance. The concept of optimal control is applied to derive control of SSSC. The control strategy is then applied to a SSSC placed in a power system to investigate the improvement of the power system dynamic performance.

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 (Ahmad and Mohamed, 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.
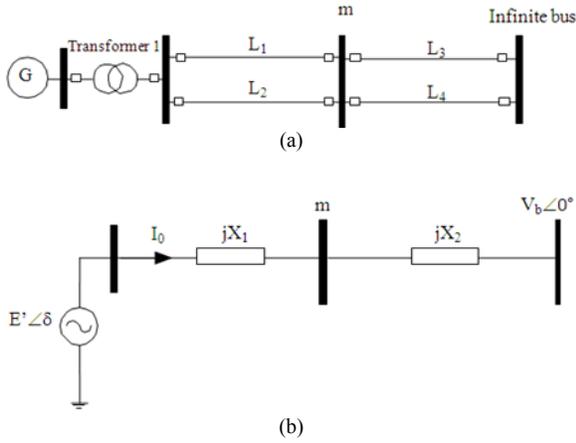
(a)

(b)

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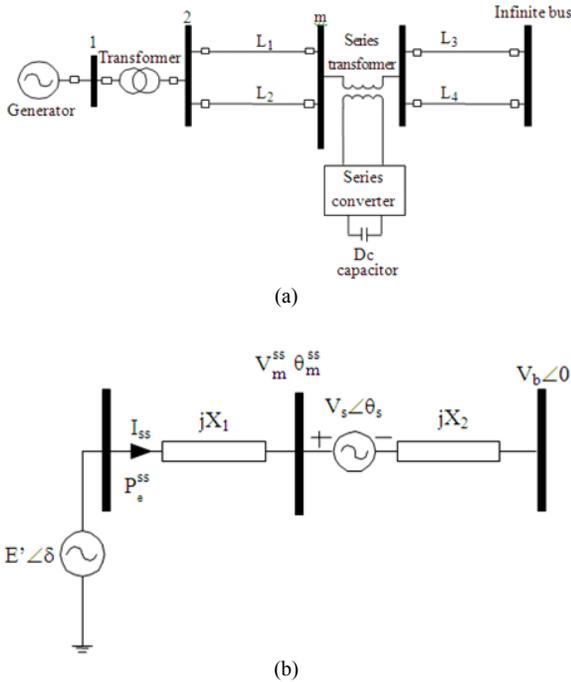

(a)

(b)

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

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.

When $V_s = 0$, the current I_0 of the system can be written as Eq. 1:

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

Here, $X = X_1 + X_2$. The angle θ of the current can be written as Eq. 2:

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

From Fig. 1b, the general equation of the current can be written as Eq. 3:

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

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 Eq. 4:

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

Here, P_{e0} is the generator output power without SSSC ($V_s = 0$) and is given by Eq. 5:

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

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 Eq. 6:

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

When V_s lags the current by 90° ($\alpha = \theta-90°$), ΔP_e becomes Eq. 7:

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

After some mathematical manipulations of (2), the term $\cos(\delta-\theta)$ can be expressed as Eq. 8:

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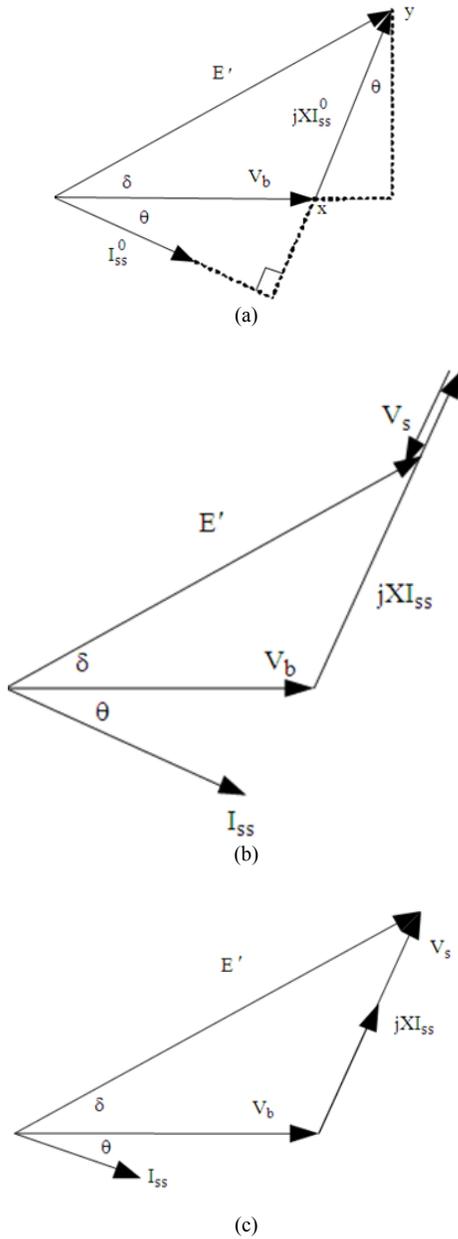
(a)

(b)

(c)

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

From Fig. 3, $\cos\theta$ can be written as Eq. 9:

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

Using (7)-(9), ΔP_e can be expressed as Eq. 10:

$$\Delta P_e = CV_s P_{e0} \tag{10}$$

Where:

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

Note that $C \geq 0$ for all possible values of E', V and δ. When V_s leads the current by 90° ($\alpha = \theta + 90°$), 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 Eq. 11:

$$P_e = P_{e0} + CV_s P_{e0} \tag{11}$$

The dynamic of the generator, in classical model, can be expressed by the following differential equations 12 and 13:

$$\dot{\delta} = \omega \tag{12}$$

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

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 Eq. 14:

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

Where:

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

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

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

Control strategy: The control strategy of the SSSC in a single machine infinite bus system is determined from the pole-placement design method. With liberalized swing equation of Eq. 12 and 13. The new equations in state variable from are given by Eq. 15:

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (15)$$

Here:

X = Matrix consisting of δ and ω, respectively
A and B = The constant matrix

The u is the input control strategy of SSSC given by Eq. 16:

$$u(t) = -Kx(t) \qquad (16)$$

Here, K is the constant gain control.
The quadratic performance index is given by Eq. 17:

$$J = \int_{t_0}^{t_f} (x'Qx + u'Ru)dt \qquad (17)$$

Here:

R = Control weight coefficient
Q = State weight coefficient

The minimized value of Eq. 17 can be obtained by using Lagrange multipliers method. After some mathematical manipulations, we obtains Riccati equation (18):

$$PA - A'P - Q + PBR^{-1}B'P = 0 \qquad (18)$$

The gain controls the concepts of optimal control are the elements in P satisfied the Eq. 18.

RESULTS

The proposed control of a power system with a SSSC is tested on system of Fig. 1a. The system data are:

$E' \angle \delta = E' \angle \delta = 1.23 \angle 45$, Vb=1.0, X'_d=0.3, X_t=0.1, X_{L1}=X_{L2}=0.5, X_{L3}=X_{L4}=1, H=6, f=50 Hz, D=0.01;

It is considered that a three-phase self clearing fault appears at line 1 near bus m and it is cleared at 200 msec. Fig. 2 shows the swing curve of the system without and with a SSSC based optimal control.

DISCUSSION

It can be seen in Fig. 4 that, without the SSSC (k = 0), the maximum and the minimum rotor angle are around 124 and 3 degree, respectively. The damping of the system can be improved by using SSSC based optimal control. With the proposed method, the maximum and the minimum rotor angle are around 100 and 30 degree, respectively and the system can return to stable equilibrium point by 4 sec.
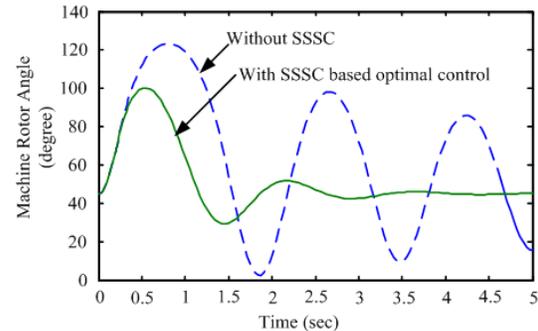

Fig. 4: Swing curve of the machine without SSSC and with a SSSC based optimal control

CONCLUSION

This study presents optimal control of a Static Synchronous Series Compensator (SSSC) in a power system to enhance power system dynamic performance. The control strategy of the SSSC is selected very carefully in the concept of optimal control. It is found that the SSSC control depends on both nonlinear function of machine angle and speed. The simulation results are tested on Single Machine Infinite Bus (SMIB) system. From the simulation results, it was fond that the SSSC with proposed control strategy can improve power system dynamic performance.

REFERENCES

Ahmad, M.A. and Z. Mohamed, 2009. Hybrid fuzzy logic control with input shaping for input tracking and sway suppression of a gantry crane system. Am. J. Eng. Applied Sci., 2: 241-251. DOI: 10.3844/ajeassp.2009.241.251

Bagher, M., B. Sharifian, M.R. Feyzi, S.H. Hosseini and R. Valinia, 2009. Implementing a vector controller using 68k processors. Am. J. Eng. Applied Sci., 2: 488-493. DOI: 10.3844/ajeassp.2009.488.493

Barbuy, H.S., A. Rocco, L.A.P. Fernandes and G.C. Guimaraes, 2009. Voltage collapse risk associated to under-voltage capacitive compensation in electric power system operation. Am. J. Applied Sci., 6: 646-651. DOI: 10.3844/ajassp.2009.646.651

Chamsai, T., P. Jirawattana and T. Radpukdee, 2010. Sliding mode control with PID tuning technique: An application to a DC servo motor position tracking control. Energy Res. J., 1: 55-61. DOI: 10.3844/erjsp.2010.55.61

Hafaifa, A., F. Laaouad and M. Guemana, 2009. A new engineering method for fuzzy reliability analysis of surge control in centrifugal compressor. Am. J. Eng. Applied Sci., 2: 676-682. DOI: 10.3844/ajeassp.2009.676.682

Hojat, A.H.M., K.A. Rahim and L. Chin, 2010. Firm's environmental performance: A review of their determinants. Am. J. Econ. Bus. Admin., 2: 330-338. DOI: 10.3844/ajebasp.2010.330.338

Kumkratug, P., 2011. Nonlinear control design of series facts devices for damping power system oscillation. Am. J. Applied Sci., 8: 124-128. DOI: 10.3844/ajassp.2011.124.128

Majee, N.C. and A.B. Roy, 2010. Asymptotic behavior of an artificial neural network defined on multipartite directed graph. OnLine J. Biol. Sci., 10: 44-49. DOI: 10.3844/ojbsci.2010.44.49

Rudez, U. and R. Mihalic, 2009. Dynamic analysis of transition into island conditions of Slovenian power system applying underfrequency load shedding scheme. IEEE Bucharest Power Tech. DOI: 10.1109/PTC.2009.5282175

Samimi, A., H.Z. Aashtiani and A.K. Mohammadian, 2009. A shor-term management strategy for improving transit network efficiency. Am. J. Applied Sci., 6: 241-246. DOI: 10.3844/ajassp.2009.241.246