Improving Power System Transient Stability with Static Synchronous Series Compensator

Prechanon Kumkratug

Division of Electrical Engineering, Faculty of Engineering at Si Racha,
Kasetsart University, 199 M.6, Tungsukhla, Si Racha, Chonburi, 20230, Thailand

Abstract: Problem statement: Modern power system consists of the complicated network of transmission lines and carries heavy demand. Thus they cause in the stability problem. One of the major interests of power utilities is the improvement of power system transient behavior. **Approach:** Static Synchronous Series Compensator (SSSC) is a power electronic based device that has the capability of controlling the power flow through a line. This study applies the SSSC to improve transient stability of power system. To verify the effect of the SSSC on transient stability, the mathematical model and control strategy of a SSSC is presented. The SSSC is represented by variable voltage injection with associate transformer leakage reactance and the voltage source. The series voltage injection model of SSSC is modeled into power flow equation and thus it is used to determine its control strategy. This study uses machine speed deviation to control it. The swing curves of the three phase faulted power system without and with a SSSC is tested and compared in various cases. **Results:** The swing curve of system without a SSSC gets increases monotonically and thus the system can be considered as unstable whereas the swing curves of system with a SSSC can be considered as stable. **Conclusion:** SSSSC can improve transient stability of power system.

Key words: Power system stability, transient stability, FACTS devices, static synchronous series compensator, generating stations, Static Synchronous Series Compensator (SSSC), Single Machine Infinite Bus (SMIB), transformer leakage, voltage injection, voltage source

INTRODUCTION

From the energy utilization point of view, electricity is still being regarded as mighty means of energy carrier. Nowadays, the demand of electricity has dramatically increased and a modern power system becomes a complex network of transmission lines interconnecting the generating stations to the major loads points in the overall power system in order to support the high demand of consumers. The complicated network causes the stability problem. Transient stability improvement is one of the important aspects in modern power system (Al-Rawi *et al.*, 2007; Babainejad and Keypour, 2010; Sahoo *et al.*, 2010; Parry and Gangatharan, 2005). 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 and Chan, 2006; Chettih *et al.*, 2008; Seyed *et al.*, 2008a).

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; Seyed *et al.*, 2008b).

This study presents the method of improving transient stability of power system using a SSSC. The mathematical model of power system equipped with a SSSC is systematically derived. The presented mathematical model is applied to design control strategy of a SSSC. The simulation results are tested on a Single Machine Infinite bus system. The effect of gain control of a SSSC on stability improvement is also investigated.

MATERIALS AND METHODS

Mathematical model: Figure 1a shows the single line diagram of Single Machine Infinite Bus (SMIB) system without a SSSC 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 represented by a constant voltage source (E') behind transient reactance (X'_d).
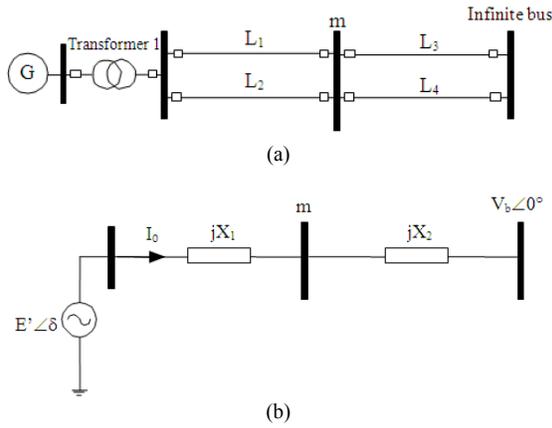
(a)

(b)

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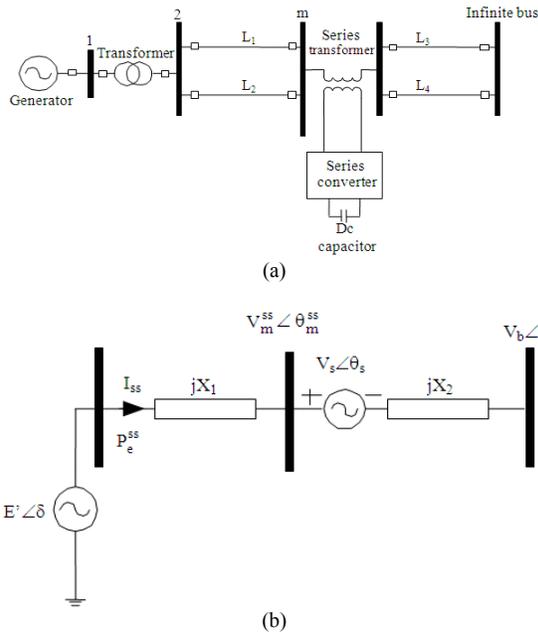

(a)

(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

Consider the system without a SSSC as shown in Fig. 1, the line current is given by:

$$\mathbf{I}_0 = \frac{E' - V_b}{jX}$$
$$= \frac{(E'\cos\delta + jE'\sin\delta) - (V_b)}{jX} \quad (1)$$
$$= (\frac{E'}{X}\sin\delta) + j(-\frac{E'}{X}\cos\delta + \frac{V_b}{X})$$

Here $X = X_1 + X_2$:

$$\theta = \tan^{-1}\left[\frac{V_b - E'\cos\delta}{E'\sin\delta}\right] \quad (2)$$

The output electrical power of the system without a SSSC is given by:

$$P_e^0 = \frac{E'V_b}{X}\sin\delta \quad (3)$$

Now, consider the system with a SSSC as shown in Fig. 2. The Fig. 2b represents the equivalent circuit of Fig. 2a. The SSSC is represented by a series voltage injection (V_s) and transformer leakage reactance. From Fig. 2b, the line current of the system with a SSSC is given by:

$$\mathbf{I}_{ss} = \frac{E' - V_s - V_b}{jX} = \left[\frac{E' - V_b}{jX}\right] + \left[\frac{-V_s}{jX}\right] \quad (4)$$

From the Eq. 1 and 4, the line current of the system with a SSSC is given by:

$$\mathbf{I}_{ss} = \mathbf{I}_0 + \Delta\mathbf{I} \quad (5)$$

Here $\Delta\mathbf{I} = \frac{-V_s}{jX}$

From Eq. 1 and 4, ΔI is the additional component of the system of a SSSC. The output electrical power equation of generator can be expressed by:

$$P_e^{ss} = \text{Re}[E'(\mathbf{I}_{ss})^*]$$
$$= \text{Re}[E'(\mathbf{I}_0)^*] + \text{Re}[E'(\Delta\mathbf{I})^*] \quad (6)$$

The first term of Eq. 6 represents the system without a SSSC. The second term is the additional component from the SSSC (ΔP_e^{ss}) rewritten by:

$$P_e^{ss} = P_e + \Delta P_e^{ss} \quad (7)$$

The ΔP_e^{ss} is written by:

$$\Delta P_e^{ss} = \text{Re}\left[E'\left(\frac{-V_s}{jX_2}\right)^*\right] = \text{Re}\left[E'\angle\delta\left(\frac{-V_s\angle\theta_s}{jX}\right)^*\right]$$
$$= \frac{E'V_s}{X}\sin(\delta - \theta_s) \quad (8)$$

When V_s is positive, the SSSC supplies the reactive power to the system, it is called capacitive mode and then the series voltage angle θ_s is in lagging with the line current as shown in Fig. 3b whereas V_s is negative, the SSSC absorbs the reactive power to the system, it is called reactive mode and then the series voltage angle θ_s is in leading with the line current as shown in Fig. 3c. With the capacitive mode the Eq. 8 is given by:

$$\Delta P_e^{ss} = \frac{E'V_s}{X}\cos(\delta - \theta) \tag{9}$$
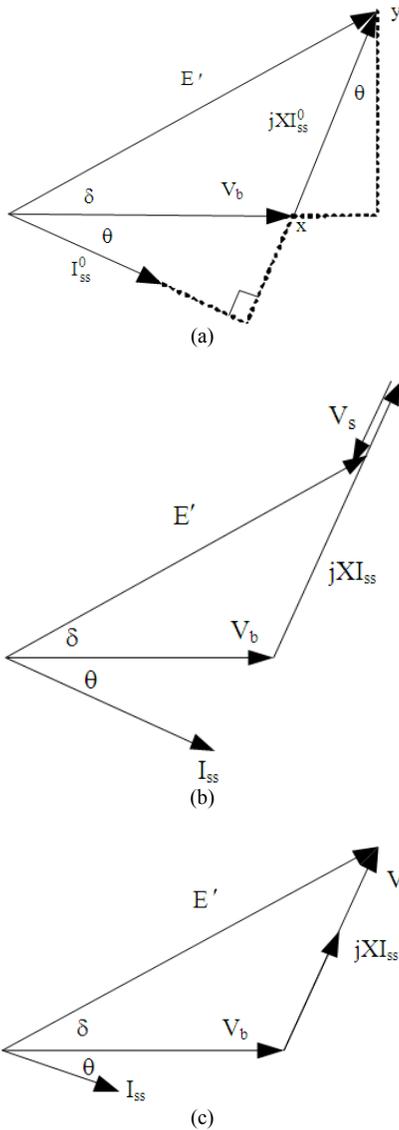

(a)

(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 the Eq. 2, it can be written by:

$$E'\sin\delta\sin\theta = V_b\cos\theta - E'\cos\delta\cos\theta \tag{10}$$

With some mathematical manipulations of Eq. 10, it can be written by:

$$\cos(\delta - \theta) = \frac{V_b}{E'}\cos(\theta) \tag{11}$$

From the phasor diagram as shown in Fig. 3, it indicates that the SSSC doesn't change the line current angle. However, the SSSC affects on the line current magnitude. When V_s lags line current 90°, the line current magnitude is increased and when V_s leads line current 90°, the line current magnitude is decreased as can be seen in Fig. 3.

From the Fig. 3, the cosine of the line current angle is given by:

$$\cos(\theta) = \frac{E'\sin(\delta)}{xy}$$
$$= \frac{E'\sin(\delta)}{\sqrt{(E')^2 + (V_b)^2 - 2E'V_b\cos(\delta)}} \tag{12}$$

From Eq. 9 and 12, the additional component of output electrical power is:

$$\Delta P_e^{ss} = \frac{V_s E'V_b}{X\sqrt{(E')^2 + (V_b)^2 - 2E'V_b\cos\delta}}\sin\delta \tag{13}$$

From Eq. 7 and 13, the output electrical power of system with a SSSC is given by:

$$P_e^{ss} = P_e + \frac{V_s P_e}{\sqrt{(E')^2 + (V_b)^2 - 2E'V_b\cos\delta}} \tag{14}$$

It can be seen from Eq. 14 that the output electrical power flow can be controlled by a SSSC. With positive value of V_s, the output electrical power is increased whereas with negative value of V_s, the output electrical power is reduced.

Transient stability control: The transient stability of power system as shown in Fig. 2a can be expressed by following equations:

$$\dot{\delta} = \omega \tag{15}$$

$$\dot{\omega} = \frac{1}{M}[P_m - P_e] \tag{16}$$

Here, δ, ω and P_m are the rotor angle, speed deviation, mechanical input power and moment of inertia, respectively of machine. The stability of the system can be improved by increasing the electrical output power when its speed deviation is positive and decreasing the power when speed deviation is negative. Thus the control strategy of SSSC is given by:

$$V_s = k\omega \tag{17}$$

Here, k is constant gain control

RESULTS

The proposed model of power system equipped with a SSSC of Fig. 2a is investigated in this section. 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 L_1 and it is cleared by opening the faulted line. Figure 4 shows the swing curve of the system without (K = 0) and with various gains (K) OF a SSSC. Table 1 summarizes the maximum and minimum swing curve of Fig. 4.
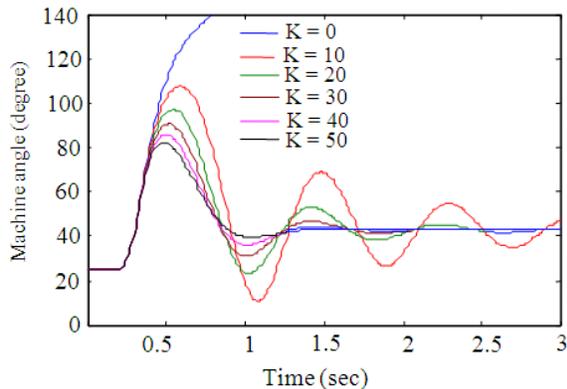

Fig. 4: Swing curve of the system without and with various gains of a SSSC

Table 1: Maximum and minimum machine angle with various cases gains of SSSC

K	δ_{max} (degree)	δ_{min} (degree)
0	-	-
10	177.68	10.99
20	97.19	23.25
30	90.55	31.05
40	85.75	36.14
50	82.14	39.36

DISCUSSION

It can be observed from the simulation results that with t_{cl} = 120 msec and without a SSSC (K = 0), the system is considered as unstable. However, with a SSSC, the system is considered as stable. With K = 10, the maximum and minimum machine angle are 177.68 and 10.55, respectively. The transient stability gets increase as the K is increased. With K = 50, the maximum and minimum machine angle are improved to 82.14 and 39.36, respectively.

CONCLUSION

This study presents the method of improving transient stability of power system using a SSSC. The mathematical model of power system equipped with a SSSC is systematically derived. It was found that the power flow of the system can be control a series injected voltage of a SSSC. The stability of the power system can be controlled by a SSSC. This study uses machine speed deviation to control parameter of a SSSC. The simulation results are tested on a Single Machine Infinite bus system. The effect of gain control of a SSSC on stability improvement is also investigated. From the simulation results, it indicates that a SSSC can improve transient stability of the system and the stability of system gets increase when the gain control is increased.

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