TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 15, No. 1, July 2015, pp. 71 ~ 77
DOI: 10.11591/telkomnika.v15i1.8075

Power Flow and Transient Stability Improvement by Static Synchronous Series Compensator

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Abstract

In the present world, modern power system networks, being a complicated combination of generators, transmission lines, transformers, circuit breakers and other devices, are more vulnerable to various types of faults causing stability problems. Among these faults, transient fault is believed to be a major disturbance as it causes large damage to a sound system within a certain period of time. Therefore, the protection against transient faults, better known as transient stability control, is one of the major considerations for the power system engineers. This paper presents the control approach in the transmission line during transient faults by means of Static Synchronous Series Compensator (SSSC) in order to stabilize Single Machine Infinite Bus (SMIB) system. In this paper, SSSC is represented by variable voltage injection associated with the transformer leakage reactance and the voltage source. The comparative results depict that the swing curve of a system increases monotonically after the occurrence of transient faults. However, SSSC is effective enough to make it stable after a while.

Keyword: *SMIB, power angle curve, transient stability, SSSC, swing curve*

1. Introduction

With the passage of time, the demand of electricity, being considered as a vital source of energy, has been leapt due to the fact that the number of consumers is growing day by day. This situation urges the necessity of adding more transformers, transmission lines, switchgear equipment and distribution lines indicating a complex power system. It is needless to say that the possibility of his power system network to be affected by the faults is very high. As a result, stability problem is a key concern as far as modern power system network goes [1-3].

Stability refers to the tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium. Stability problem is concerned with the behavior of the synchronous machines after a disturbance. For convenience of analysis, stability problems are generally divided into two major categories steady state stability and transient stability. Steady state stability is the ability of the power system to regain synchronism after small and slow disturbance, such as gradual power changes. An extension of the steady state stability is known as the dynamic stability which is concerned with small disturbances lasting for a long time with the inclusion of automatic control devices. Transient stability studies deal with the effect of large, sudden disturbances, such as the occurrence of a fault, the sudden outage of a line or the sudden application or removal of loads [4]. Since, the transient stability has a role to play in case of major disturbances, the improvement of this stability is important. Many researchers and power system engineers have worked and proposed different methods and techniques to control the stability problem [5-8]. One of these technologies is Flexible AC Transmission System (FACTS) that is a family of several power electronic products [9-11].

FACTS devices are essential to change the power system parameters in order to obtain a better system operation in a faster and more effective way [12]. The voltage source converter based series compensator, called Static Synchronous Series Compensator (SSSC) is a part of FACTS devices family which is connected in series with the power system and was firstly proposed in 1989 [13]. SSSC provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line. The virtual reactance inserted by the injected voltage source influences electric power flow in the transmission lines

Received March 14, 2015; Revised May 13, 2015; Accepted May 28, 2015

independent of the magnitude of the line current. The ability of SSSC to operate in capacitive as well as inductive mode makes it very effective in controlling the power flow of the system. Apart from the stable operation of the system with bidirectional power flows, the SSSC has an excellent response time and the transition from positive to negative power flow through zero voltage injection is perfectly smooth and continuous [14-16]. Moreover, the reactive power or current of SSSC can be adjusted by controlling the magnitude and phase angle of the output voltage of the shunt converter [17-18]. The contribution of this paper lies in handling of electrical power flow and stability by connecting SSSC in the network in a proper manner.

2. Research Method

The input mechanical power from the prime mover of the generator, P_m is assumed as a constant quantity and the electrical power output, P_e will determine whether the machine be in synchronism or not indicating whether the rotor decelerates, accelerates, or remains at the synchronous speed. Until P_e equals P_m the machine maintains synchronism. But if P_e changes from P_m, the rotor consequently deviates from the steady state synchronous speed. Any electrical disturbance due to faults, sudden load change or circuit breaker operations would change the electrical output, P_e in a rapid way resulting in a transient stability problem. This change in P_e depends on the transmission and distribution network and also on the loads to which the machine supplies power [19].

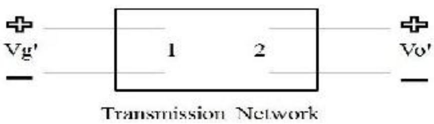

Figure 1. Schematic Diagram for Stability Studies

Figure 1 shows the reduced schematic diagram of a single machine infinite bus system where the generator at bus 1 is supplying power to the receiving end at bus 2 through the transmission system consisting of the various passive components including transmission line, transformers, circuit breakers, capacitors and the transient reactance of the generators. V_g' represents the transient internal voltage of generator at bus 1 and V_o' at the receiving end is regarded as that of an infinite bus or as the transient internal voltage of a synchronous motor. Now, the bus admittance matrix of the network can be considered as follows reducing to two nodes.

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \quad (1)$$

And for the complex power of any bus,

$$P_k - jQ_k = V_k^* \sum_{n=1}^{N} Y_{kn} V_n \quad (2)$$

In this case, K=1 and N=2 therefore,

$$P_1 + jQ_1 = V_g' (Y_{11} V_g')^* + V_g' (Y_{12} V_0')^* \quad (3)$$

Where, the parameters are defined as:

$$V_g' = |V_g'| \angle \delta_1 \quad ; \quad V_0 = |V_0'| \angle \delta_2 \quad and$$

$$Y_{11} = G_{11} + jB_{11} \quad ; \quad Y_{12} = |Y_{12}| \angle \theta_{12}$$

Now, from “(3)”,

$$P_1 = \left|V_g^{'}\right|^2 G_{11} + \left|V_g^{'}\right| \left|V_0^{'}\right| \left|Y_{12}\right| \cos\ (¢_1 - ¢_2 - ¯_{12}) \qquad (4)$$

$$Q_1 = -\left|V_g^{'}\right|^2 B_{11} + \left|V_g^{'}\right| \left|V_0^{'}\right| \left|Y_{12}\right| \sin\ (¢_1 - ¢_2 - ¯_{12}) \qquad (5)$$

If two new angles are defined as:

$$¢ = (¢_1 - ¢_2) \quad and \quad ¥ = (¯_{12} - \frac{®}{2})$$

“(4)”, and “(5)”, yield that:

$$P_1 = \left|V_g^{'}\right|^2 G_{11} + \left|V_g^{'}\right| \left|V_0^{'}\right| \left|Y_{12}\right| \sin\ (¢ - ¥) \qquad (6)$$

$$Q_1 = -\left|V_g^{'}\right|^2 B_{11} + \left|V_g^{'}\right| \left|V_0^{'}\right| \left|Y_{12}\right| \cos\ (¢ - ¥) \qquad (7)$$

“(6)”, can be rewritten in the following form:

$$P_e = P_c + P_{\max} \sin\ (¢ - ¥) \qquad (8)$$

Where,

$$P_c = \left|V_g^{'}\right|^2 G_{11} \quad and \quad P_{\max} = \left|V_g^{'}\right| \left|V_0^{'}\right| \left|Y_{12}\right|$$

Neglecting the armature copper loss, P_c “(8),” can be written as:

$$P_e = P_{\max} \sin ¢ \qquad (9)$$

Where, $P_{\max} = \frac{\left|V_g^{'}\right| \left|V_0^{'}\right|}{X}$

X is the transfer reactance between the voltages $V_g^{'}$ and V_o’. “(9)”, is known as the power angle equation.

A Single Machine Infinite Bus (SMIB) system is considered as shown in the Figure 2 with its equivalent single line diagram illustrated in Figure 3. The generator is being represented by a constant voltage source V_g’ with a transient reactance X_g’. And X_1, X_2, X_3 are the equivalent reactance between bus 1 and 2, bus 2 and 3 and bus 3 and 4 respectively, whereas bus 4 is considered as the infinite bus. The output electrical power of the SMIB transmission network can be evaluated by the power angle Equation “(9)”.

$$P_e = \frac{\left|V_g^{'}\right| \left|V_0^{'}\right|}{X} \sin ¢ \qquad (10)$$

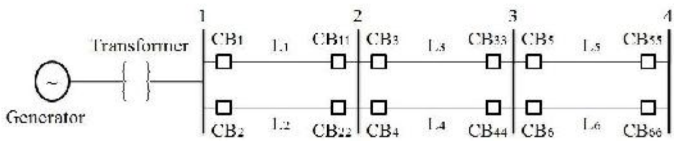

Figure 2. Schematic Diagram of SMIB

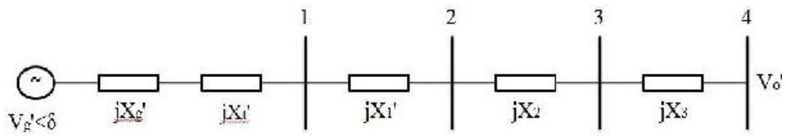

Figure 3. Single Line Diagram of SMIB

In order to control three parameters of line power flow such as line impedance, voltage and phase angle, a Static Synchronous Series Compensator (SSSC) that is a Voltage Source Inverter (VSI) is connected in series to the Single Machine Infinite Bus (SMIB) system through a series transformer and this can be seen from Figure 4. In practice, SSSC is connected by a common dc link including storage capacitor [20]. The series inverter can be applied to control the real and reactive line power flow and voltage with controllable magnitude and phase in series with the transmission line. Therefore, the SSSC can fulfill the responsibility of active and reactive series compensation and phase shifting. For this case, the output electrical power may be expressed as:

$$P_e^{ss} = P_e + \Delta P_e^{ss} \qquad (11)$$

For the capacitive mode V_{ss} is positive and the SSSC supplies a reactive power to the system.

With this mode, $\Delta P_e^{ss} = \frac{V_g' V_{ss}}{X} \sin(\delta - \theta_{ss}) \qquad (12)$

$$\theta_{ss} = \sin^{-1}\left(\frac{X_3}{V_s V_o}\right)$$

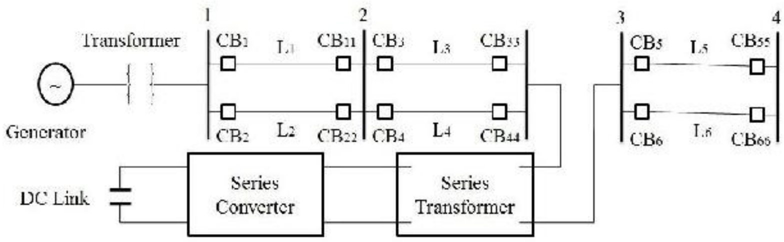

Figure 4. Schematic Diagram of SMIB with SSSC

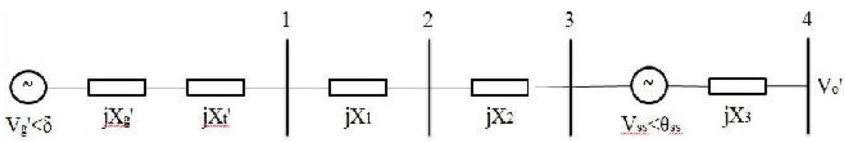

Figure 5. Single Line Diagram of SMIB with SSSC

3. Results and Analysis

3.1. Power Angle Curve

The curve of power angle equation as a function of δ is called power angle curve. Certain parameters are assumed deliberately to with a view to drawing a power angle curve of “Figure 2”, such as delivered power of the machine, P_m=1 per unit, transient internal voltage, V_g'=1.05 per unit, transient reactance of generator, X_g'=0.2, transient reactance of transformer, X_t'=0.1, line reactance are X_{L1}= X_{L2}=0.4, X_{L3}= X_{L4}=0.5 and X_{L5}= X_{L6}=0.3, infinite bus voltage is V_o'=1 per unit and constant H=5MJ/MVA.

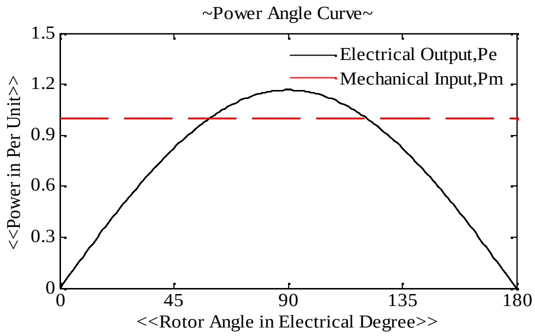

Figure 6. Power Angle Curve at Sound Condition

If it is considered that a three phase fault occurs on line, L_6. In this case, the output power drops to zero and in order to regain the sound operation SMIB system, it is required to open the faulted line L_6. This can be done by opening the circuit breakers. The clearing time of fault is 86ms that can be calculated from “(11)”.

$$t_{cr} = \frac{\sqrt{4H(\delta_{cr} - \delta)}}{w P_m} \qquad (13)$$

$$\delta_{cr} = \cos - [(\pi - 2\delta_0)\sin\delta_0 - \cos\delta_0]$$

and $\delta_0 = \sin - 1(\frac{P_m}{P_{max}})$

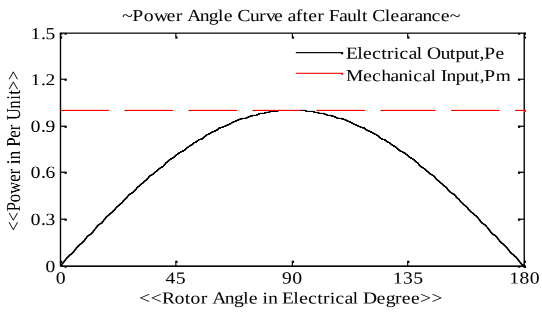

Figure 7. Power Angle Curve at Post Fault Condition

According to the expectation, after clearing fault, the electrical output power has been increased demonstrated in Figure 7 but this value is less than the output power if there is no fault.

3.2. Transient Stability Improvement

SSSC has a secondary function but important that is used to control stability for standing power system oscillations and therefore, SSSC has the capability of improving the transient stability of power system. The transient stability of SMIB system can be expressed by the swing Equation “(14)”, which describes the acceleration or de-acceleration of rotor with synchronously rotating air gap mmf during any disturbance and control strategy equation of SSSC “(15)”.

$$\frac{d^2\delta}{d^2 t} = \frac{w_s}{2H}(P_m - P_e) \qquad (14)$$

$$w_S = \frac{d\text{¢}}{dt} \quad and \quad V_{ss} = K\, w_S \qquad (15)$$

Where, *K* is a constant gain control specified as 100.

A curve that contains the solution of swing equation for the expression of δ as a function of time is called swing curve. It helps to determine whether the system remains in synchronism after the occurrence of disturbance or not [19]. As far as Figure 8, representing swing curve is concerned, it is evident that SMIB system is unstable and that can be made stable only a little time later if SSSC is inserted in it.

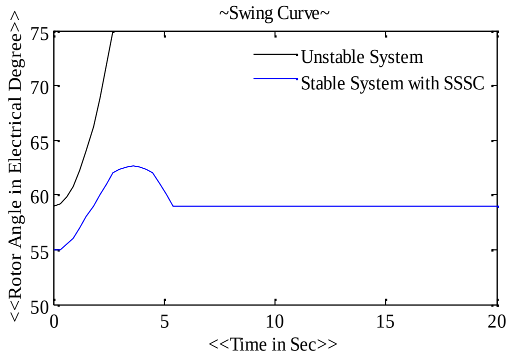

Figure 8. Transient Stability of SMIB System with and without SSSC

4. Conclusion

The proposed strategy of using a Static Synchronous Series Compensator (SSSC) in a Single Machine Infinite Bus (SMIB) system outlines that not only electrical power flow can be influenced but also stable operation can be achieved through it.

As the days are going, the power systems are becoming modernized requiring flexibility, high flow of power and stable operation. Because of having the capability of providing flexibility and rapidness of power flow in the power system network, the utilization of SSSC is expected to grow more and there is a great possibility that new realistic models of this controller will be appeared in the upcoming days.

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