Application of Static Synchronous Series Compensator(SSSC) for stability enhancement of a Multimachine Power System

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***Abstract*—Power systems are always associated with a large number of disturbances which affect the system stability and distorts the current and voltage profiles. The active power transfer in the system is heavily affected by faults which occur in the transmission systems. Maintaining the voltage profile during the fault and attaining stability of the system after a major disturbance is a challenge faced by power system engineers of all times. FACTS devices play a prominent role in modern power systems as these are the best options for increasing transmission capacity of lines while maintaining system stability. In this work, a series FACTS device, static synchronous series compensator (SSSC) is used to improve voltage profile of a system during a major three phase fault. A suitable controller is designed for the system and the operation of the device is tested in a two machine system. Also an algorithm based on PSO is applied to the SSSC power oscillation damping controller for fast damping of the oscillations.The MATLAB/SIMULINKmodeling of the system is done and the simulation results are obtained.**

Keywords— FACTS,VSC,SSSC, stability improvement

I. INTRODUCTION

One of the major problems faced by today's utility engineersis the need for transmitting large blocks of power over long distances. Transmission bottlenecks,non-uniform utilization of facilities and unwanted parallel path or loop flows are common. The factors that hinder transmission system expansion include a variety of environmental, land-use and regulatory requirements.As a result, utilities need to operate their power transmission system much more effectively, increasing their utilization degree.

Transient and steady state stability limits of a power system can be improved by the use of series capacitors.This also effectively improves the power transfer capability of transmission system. Because of the power electronic switching capabilities in terms of control and high speed, Flexible AC

Transmission Systems (FACTS) devices areused extensively for improving power system stability [4]. The bus voltages, line impedance and phase angles in the power system can be regulated rapidly and flexibly using FACTS devices. These devices can be used to increase the transmission capacity and minimize the power loss. It also assists in maintaining stability and controlling power flow[8],[9],[10].

Reducing the effective reactance of lines by series compensation is a direct approach to increase transmission capability [2], [3]. Series compensation by series capacitors has been usedon long distance transmission lines from earlier periods itself to increase power transfer and to improve system stability[5]. This method increases transmission capacity and improves transient stability of the transmission grid. This increases angular stability of the power corridor and improves voltage stability [6],[7].The effectiveness of using series capacitive compensation schemes in damping inter-area oscillations have been investigated in [1]. The paper also describes the use of Static Synchronous Series Compensator (SSSC) as an effective series compensation device.

SSSC is one of the important series compensation devices of FACTS family which is installed in series with transmission systems. The fundamental principle, characteristics and benefits of SSSC are thoroughly explored in [11]. SSSC is a solid-state voltage source inverter, which injects an almost sinusoidal voltage, of variable magnitude, in series with the transmission line. It can operate in both inductive mode and capacitive mode [12]. The applications of SSSC for power oscillation damping, stability enhancement and reactive power compensation have been investigated by several authors [13],[14].

SSSC for power transmission systems can be implemented using various semiconductor switching devices of suitable rating and characteristics. Commercial availability of GTOs and IGBTs have led to the development of fast controllable reactive power sources utilizing new electronic switching and converter technology. A single phase SSSC model is discussed in [15]. But as the single phase topology resulted in harmonics, a VSC based on three-level converter topology was proposed. This is investigated in [16].

Converters for FACTS devices may be classified as directly controlled or indirectly controlled. An indirectly controlledconverter can be utilized for maintaining a quadrature relationship between the instantaneous converter voltage and line current vectors. This providesseries compensation and handles Sub SynchronousResonance (SSR). A hysteresis current controlled PWM is presented in the paper[17].

In many STATCOM and SSSC models, the control logic is implemented with the conventional PI controllers. The controller gains are mostly determined by trial and error methods, but it is it is not feasible for utility engineers to perform trial-and-error studies to find suitable parameters when a new compensator is connected to a system. Therefore intelligent control schemes have to be formulated as mentioned in [18].

Here, the MATLAB modelling of a multi machine power system is done and the simulation results are investigated.

II.SERIES COMPENSATION OF TRANSMISSION LINES

In AC transmission, when both voltage and current changes polarity at the same time, only real power is transmitted. Both active and reactive power are transmittedonly when there is a time shift between voltage and current. In resistive loads, current produces heat energy which produces the desired output but in case of inductive loads, current creates magnetic field which further produces the desired work. Therefore, reactive power is the non-workingpower caused by the magnetic current to operate and sustain magnetism in the device.It is the circulating power which results from the energy storage elements (mainly inductors and capacitors) that does no useful work.

Reactive power (vars) is required to maintain the voltage to deliver active power (watts) through transmission lines. In the absence of reactive power, the voltage sags down and it is not possible to deliver the required power to the load via the transmission lines. It has a strong effect on the power factor and system voltages. Reactive power causes an increase in the transmission systems losses, decreases the power carried by the transmission lines and changes the voltage amplitude at the end of the lines.

Increasing or decreasing the inductive impedance of a line will greatly affect the active power flow. Thus, impedance control is the most cost effective means of controlling the power flow.The connection of a series compensating device generates reactive power thatbalances a fraction of the lines transfer reactance.

Hence it is necessary to provide series compensation in order to increase transmittable power, decrease losses and provide voltage stability. The power flow equations of a transmission line can be represented by Fig.1

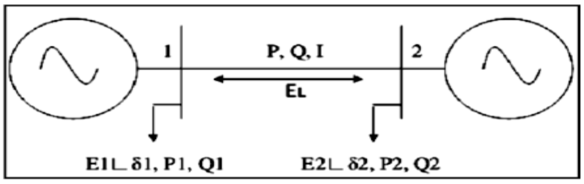

Fig. 1. A two machine system representing AC power flow control of the transmission lines

Active components of the current at the two ends of the transmission line at E_1 and E_2 is given by[2]:

$$I_{P1} = E_2 \sin \delta / x \quad (1)$$

$$I_{P2} = E_1 \sin \delta / x \quad (2)$$

Active power at the two ends at E_1 and E_2 is given by:

$$P_1 = E_1 (E_2 \sin \delta) / x \quad (3)$$

$$P_2 = E_2 (E_1 \sin \delta) / x \quad (4)$$

Reactive components of current at two ends of the transmission line at E_1 and E_2 are:

$$Iq_1 = (E_1 - E_2 \cos \delta) / x \quad (5)$$

$$Iq_2 = (E_2 - E_1 \cos \delta) / x \quad (6)$$

Reactive power at the two ends at E1 and E2 are:

$$Q_1 = E_1 (E_1 - E_2 \cos \delta) / x \quad (7)$$

$$Q_2 = E_2 (E_2 - E_1 \cos \delta) / x \quad (8)$$

Naturally, P 1 and P 2 are the same:

$$P_1 = E_1 E_2 \sin \delta / x \quad (9)$$

Where, x is the impedance of the line, E_1, E_2 are the voltages at bus1 and bus2 respectively and δ is the angular difference between the bus voltages. Thus, according to the above equations, varying the value of x will vary P, Q_1, and Q_2.

This shows that series compensation can be used as a highly effective means for up keeping and increasing voltage stability in a heavily loaded transmission system.It increases the voltage across impedance of the given physical line, which in turn increases the corresponding line current and the transmitted power.

TCSC and SSSC are the commonly used series controllers in the FACTS family. SSSC is superior to other FACTS equipment and the benefits of using SSSC are:

- Elimination of bulky passive components like capacitors and reactors
- Symmetric capability in both inductive and capacitive operating modes,
- Possibility of connecting an energy source on the DC side to exchange real power with the AC network.

III. STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

SSSC is one of the most recent series FACTS devices. It is a synchronous voltage source (SVS) in series with the system. It can inject an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line. The injected voltage is almost in quadrature with the line current. A large portion of the injected voltage is in quadrature with the line current. It emulates an inductive or capacitive reactance in series with the transmission line. A small part of the injected voltage that is in phase with the line current provides the losses in the inverter.The SSSC can be operated with or without an energy storage system. It can compensate for the transmission line resistance if operated with an energy storage system. With no energy storage system it acts essentially as a reactance compensation controller.

When SSSC injects an alternating voltage leading the line current, it is considered to be operating in an inductive mode.It emulates an inductive reactance in series with the transmission line, causing the power flow as well as the line current to decrease. When SSSC injects an alternating voltage lagging the line current, it emulates a capacitive reactance in series with the transmission line. The power flow as well as the line current increases, as the level of compensation increases.Now SSSC is considered to be operating in a capacitive mode.

A. *Configuration of SSSC*

SSSC is a power electronic-based VSC that generates a nearly sinusoidal three phase voltage which is in quadrature with the line current. The heart of SSSC is the voltage source converter (VSC). The converter block is connected in series with the transmission line by a series coupling transformer. It can be operated with or without an external energy source.The configuration of an SSSC is shown in Fig.2.

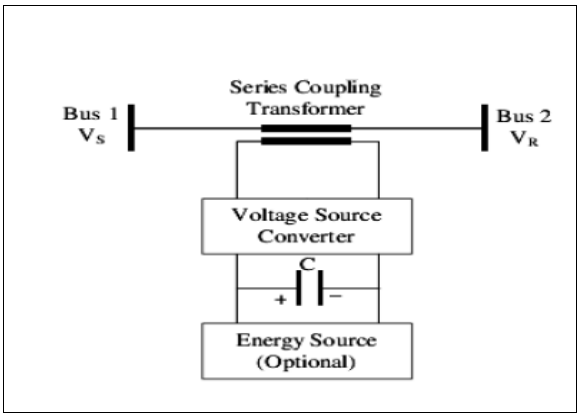

Fig. 2. Configuration of SSSC

The equivalent circuit diagram of SSSC is shown in Fig.3

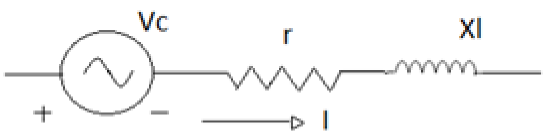

Fig. 3. Equivalent circuit of SSSC

The magnitude of Vc can be controlled to regulate the power flow. The winding resistance and leakages reactance of the connecting transformer appears is series with the voltage source Vc

B. *Operating principle of SSSC*

Consider a simple transmission line with an inductive reactance, X, connecting a sending-end voltage source, V_S, and a receiving-end voltage source, V_r, respectively.

The real and reactive power (P and Q) flow at the receiving-end voltage source are given by the expressions:

$$P = \frac{V_S V_r}{X_L}\sin(\delta_s - \delta_r) = \frac{V^2}{X_L}\, sin\delta \qquad (9)$$

$$Q=\frac{V_S V_r}{X_L}(1-\cos(\delta_s - \delta_r)) = \frac{V^2}{X_L}\,(1 - cos\delta) \qquad (10)$$

V_S and V_r are the magnitudes of the sending end and receiving end voltage sources respectively. δ_S and $\delta_r$are the phase angles of the voltage sources V_S and V_r , respectively.
For simplicity, the voltages are represented as $V_S = V_r = V$ and the difference between the phase angles as $\delta_S - \delta_r = \delta$

An SSSC, can emulate a compensating reactance, X_q, (both inductive and capacitive) in series with the transmission line inductive reactance, X. Therefore, the expressions for power flow given above becomes:

$$P_q = \frac{V^2}{X_{eff}} sin\delta = \frac{V^2}{X_L\,(1 - Xq/X_L)}\; sin\delta \qquad (11)$$

$$Q_q = \frac{V^2}{X_{eff}}(1-\cos\delta) = \frac{V^2}{X_L(1-Xq/X_L)}\,(1 - cos\delta) \qquad (12)$$

between its two ends, including the variable reactance inserted by the injected voltage source of the SSSC.

SSSC injects a compensating voltage in series with the line irrespective of the line current. The compensation capability of SSSC is twice the VA rating of the voltage source converter. This means that by changing or reversing the polarity of the injected ac voltage,the SSSC can increase or decrease the power flow to the same degree in either direction simply.

IV. MODELLING OF THE CONTROL SCHEME

The basic system configuration is shown in Fig.2. The power grid consists of two power generation substations and one major load center at bus B3. The first substation has a rating of 2100 MVA, representing 6 machines of 350 MVA and the other one has a rating of 1400 MVA, representing 4 machines of 350 VA. The load center of approximately 2200 MW is modeled using a dynamic load model where the active & reactive power absorbed by the load is a function of the system voltage.The generation substation M1 is connected to this load by two transmission lines L1 and L2. L1 is 280-km long and L2 is split in two segments of 150 km in order to simulate a three-phase fault (using a fault breaker) at the midpoint of the line. The generation substation M2 is also connected to the load bya 50-km line L3. The system with SSSC introduced is shown in Fig.5.

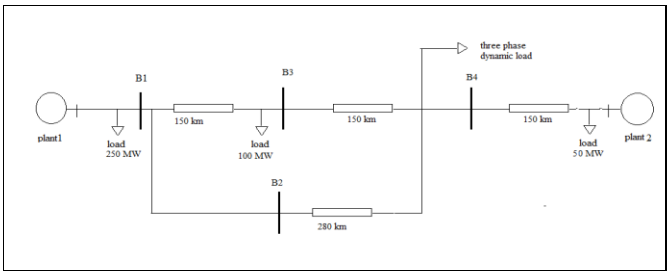

Fig. 4. Study system

A control circuit is used to sense the line voltage and current and from that measurement actual active power, P_{act} and reactive power, Q_{act} are calculated. These actual powers work as a feedback for the closed loop control system. The desired active and reactive power P_{ref} and Q_{ref} are compared with the P_{act} and Q_{act} respectively and error signals E_p and $E_q$are generated.These error signals are processed in the PI controller[18].

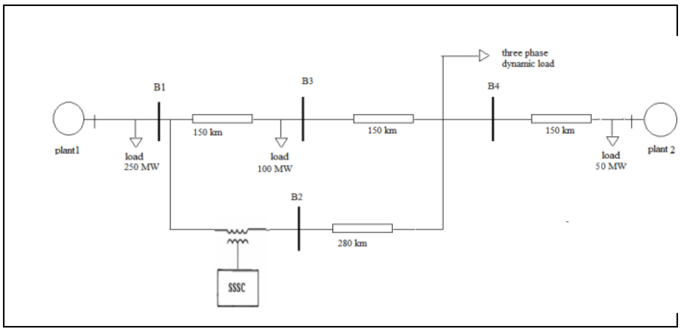

Fig. 5. Study system with SSSC

The outputs of the controllers V_p and $V_q$are used to generate three-phase reference voltages (V_{pqa}*,V_{pqb}*,V_{pqc}*) injected in the line through insertion transformer. The three-phase reference currents (I_{pqa}*,I_{pqb}*,I_{pqc}*) are calculated by knowing the impedance of insertion transformer (Ze). These currents are compared with the three-phase currents (I_{pqa}, I_{pqb}, I_{pqc}) measured at the output of the inverter. The gate pulses for the inverter switches are obtained from a PWM current controller based on hysteresis control. The inverter generates three-phase voltages (V_{pqa},V_{pqb},V_{pqc}) at its output terminals and these voltages are injected in series with the transmission line. This injected voltage insures that the error between P_{act}, P_{ref} and Q_{act}, $Q_{ref.}$ remains the same. Here, a three phase fault is applied to the transmission line and SSSC is used for providing compensation for the active and reactive power of the RL load.

The control scheme of the SSSC consists of two control loops. One is for reactive power control and other is for active power control.

The injected voltage V_{pq} is computed as follows

$$Vpq = Vp + jVq \tag{13}$$

The phase of the injected voltage is given by

$$\delta_{pq} = tan\left(\frac{Re[V_{pq}]}{Im[V_{pq}]}\right) \tag{14}$$

Three-phase reference values of the injected voltages are given by:

$$\begin{aligned} V_{pqa}^* &= \sqrt{2}V_{pq}Sin(\omega t + \delta_{pq}) \\ V_{pqb}^* &= \sqrt{2}V_{pq}Sin(\omega t + 2\frac{\pi}{3} + \delta_{pq}) \\ V_{pqc}^* &= \sqrt{2}V_{pq}Sin(\omega t - 2\frac{\pi}{3} + \delta_{pq}) \end{aligned} \tag{15}$$

The current-controlled pulse width modulated voltage source inverter is used to inject ac voltage in series in the line.

The current controlled VSI is based on the hysteresis current control.

V. SIMULINK MODEL AND RESULTS

Using MATLAB/SIMULINK, the model of the study system is established. The fault is a three phase short circuit fault applied between the duration 0.1s to 0.2s.Load voltage, load current, active and reactive powers at the load is obtained as:

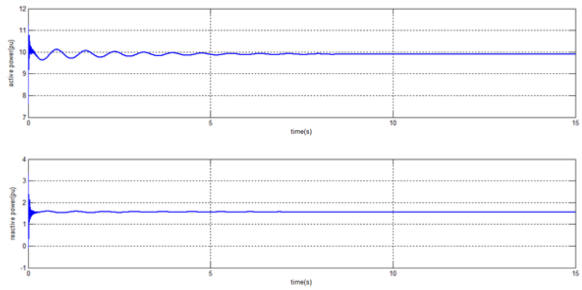

Fig 6: Real and reactive powers at bus 2 before the application of SSSC

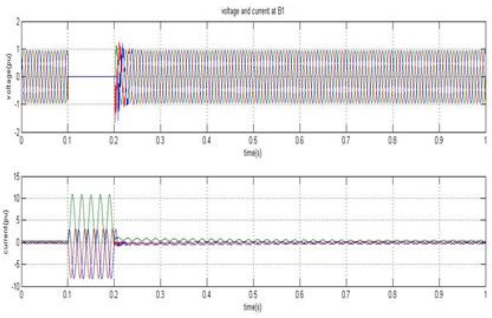

Fig. 7. Load voltage and current at the load without SSSC

When the three phase short circuit fault is applied, the source voltage reduces and the current increases.It is also observed from Fig.6that real and reactive power at the load falls in the duration of 0.1 to 0.2 seconds. Reactive power in the bus was positive earlier.

ThenSSSC is introduced to the system for series compensation. The control circuitry generates pulses at the time period of the fault and thus provides gate pulses for the 6 pulse Voltage source inverter. The VSI generates output voltage which acts as compensation. The Simulink model of the system is shown in Fig.8.

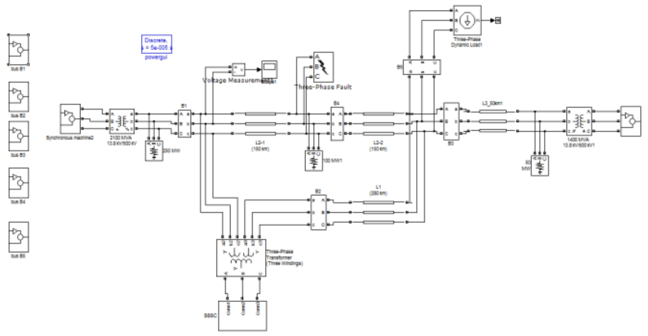

Fig. 8. Simulink model of the system with SSSC

Now. After the application of SSSC, the reactive power has reduced to a negative value. That means it has been compensated by the device.

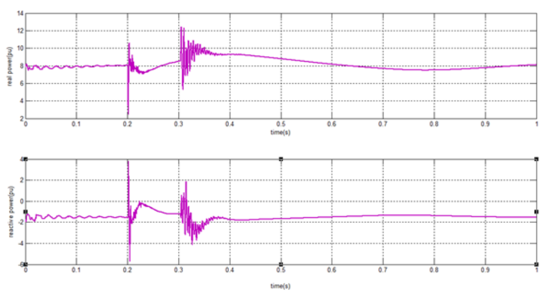

Fig. 9 Real and reactive powers after the application of SSSC

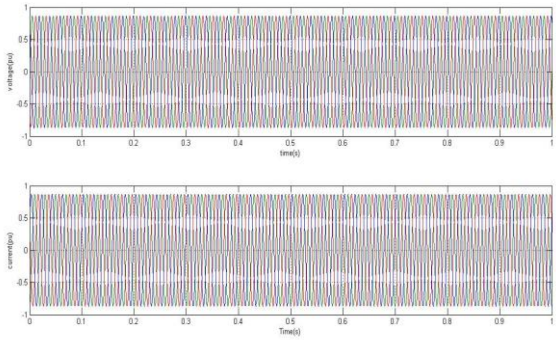

Fig. 10 Voltage and current at the load with SSSC

It can be seen from Fig.9 and Fig.10that the real and reactive power compensation has improved along with the voltage profile.

VI. Conclusion

SSSC provides series compensation and improves the active and reactive power profiles at the load. The voltage and current waveforms justify the voltage regulation.The damping effect of the SSSC can be investigated by implementing a PSO based damping control algorithm. The control of the gating pulse can be improved by using some intelligent control technique.

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