Series Compensation and Stability Enhancement of Transmission Systems using Series FACTS device

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Abstract— **Power systems are always associated with a large number of disturbances which affect the system stability and distorts the normal system performance. The active power transfer in the system is heavily affected by faults which occur in the transmission systems. Maintaining stability of the system after a major disturbance and reducing power oscillations in the transmission system 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 investigated. SSSC can be used to reduce the equivalent line impedance and enhance the active power transfer capability of the transmission line to which it is connected. SSSC consists of a VSC, an insertion transformer and a suitable DC link supply. The efficiency of the device in providing reactive power compensation is studied along with the capability of SSSC to damp rotor oscillations during a disturbance in the power system. Particle swarm optimization (PSO) is used to optimize the PI controller parameters in order to obtain smooth settling of the power oscillations after a disturbance. Simulations are carried out in MATLAB/SIMULINK and the results are analyzed.**

Index Terms— **FACTS, VSC, SSSC, stability improvement**

I. INTRODUCTION

The primary objective of all power systems is to maintain the continuous power supply. But as the complexity of the systems increase, the chances for various disturbances in the systems also increase. Faults could happen in transmission systems as a result of natural events or accidents. When severe disturbances like short circuits occur in the system, the machines may fall out of synchronism. The whole system may head to instability. This affects the quality and quantity of power delivered to the end customers. Therefore methods have to be formulated to operate the transmission lines much more effectively, thereby increasing their utilization degree while maintaining system stability.

In view of the need for power flow control, one of the most important difficulties faced by power engineers of all times is compensation of reactive power[2]. Reactive power causes an increase in the transmission systems losses, decrease in power carrying capacity of the transmission lines and changes in the voltage amplitude at the end of the lines.

Therefore, it is necessary to provide reactive power compensation in order to increase transmittable power, decrease losses and provide voltage amplitude stability. 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 are used extensively for improving power system stability [3]. 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 [4], [5],[6].

Reducing the effective reactance of lines by series compensation is a direct approach to increase transmission capability[7]. Series compensation by series capacitors has been used on long distance transmission lines from earlier periods itself to increase power transfer and to improve system stability[8],[9]. 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.

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. The paper describes a hybrid compensation scheme with SSSC and series capacitor.

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 [10]. 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 [11]. The applications of SSSC for power oscillation damping, stability enhancement and reactive power compensation have been investigated by several authors [12],[13].

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 [14]. But as the single phase topology resulted in harmonics, a VSC based on three-level converter topology was proposed. This is investigated in [15].

Converters for FACTS devices may be classified as directly controlled or indirectly controlled. An indirectly controlled converter can be utilized for maintaining a quadrature relationship between the instantaneous converter voltage and line current vectors. This provides series compensation and handles Sub Synchronous Resonance (SSR). A hysteresis current controlled PWM is presented in the paper [16].

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 [17]. For determining the optimal values of PI controller methods like fuzzy control can be used. Particle Swarm Optimization(PSO)can also be used as a better tuning method for FACTS devices like SSSC and STATCOM [18].

SSSC can also be used in coordination with the Power system Stabilizer (PSS).Although PSS can damp the oscillations significantly, they are liable to cause wide variation in voltage profile when subjected to severe disturbances. So incorporating FACTS devices like SSSC along with PSS can compensate for variations in system voltage especially during disturbances in addition to improved damping characteristics when compared with PSS. Thus it can enhance System security and reliability to a greater extent[19]. Here, the MATLAB modelling of a multi machine power system is done and the simulation results are investigated.

II. Series Compensation Of transmission lines

Series compensation is primarily applied to solve the power flow problem. The main purpose of series compensation in a power system is virtual reduction of line reactance in order to enhance power system stability and increase the loadability of transmission corridors. The concept of series compensation derives its origin from the reactive power flow in a transmission line. 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 that balances a fraction of the lines transfer reactance.

The power flow equations of a transmission line can be represented by Fig.1

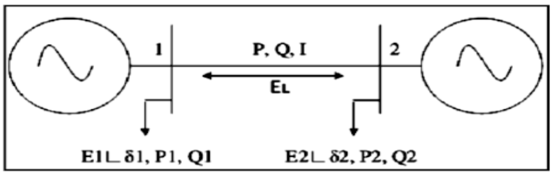

Fig. 1. A two machine system representing AC power flow control of the transmission lines

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

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

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

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

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

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

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

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

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

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

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

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

Naturally, P 1 and P 2 are the same:

$P_1 = E_1 E_2 \sin \delta / x$ (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 makes series compensation a highly effective means for up keeping or even increasing voltage stability in a heavily loaded transmission circuit and likewise, it allows additional power transmission over the circuit without upsetting voltage stability. Series controllers are used to inject voltage in series with the line, and can be a variable capacitive or inductive reactance, or a power electronics based variable source of main frequency. Examples for series controllers in the FACTS family are Static synchronous series compensator (SSSC) and Thyristor-Controlled Series Capacitor (TCSC).

III. Static Synchronous Series Compensator (SSSC)

The Static Synchronous series Compensator (SSSC) is one of the most recent FACTS devices which has attracted the attention of many researchers. The IEEE PES Task Force of The FACTS working group has defined terms and conditions for FACTS and FACTS controllers [4]. The definition for SSSC given by this IEEE team is *"A static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the* *purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behaviour of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line".* 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

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.

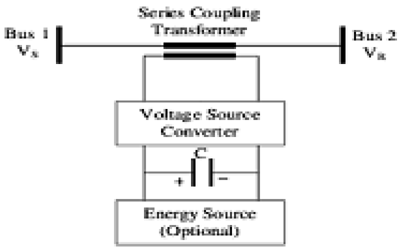

Fig. 2. Configuration of SSSC

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.

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:

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

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

V_S and V_r are the magnitudes of the sending end and receiving end voltage sources respectively. δ_S and δ_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 $\delta_S - \delta_r = \delta$

A 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:

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

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

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 TEST SYSTEM AND CONTROL SCHEME

The power system consists of two synchronous machines and one major load center at bus B3. The first machine(M1) has a rating of 2100 MVA and the other one (M2) has a rating of 1400 MVA. The second generator operates as a swing bus inorder to balance the voltage. 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 other resistive loads are also placed at different locations in the transmission lines as shown in Fig.3.It shows the Simulink model of the system.

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 by a 50-km line (L3). The system with SSSC introduced is shown in Fig.4.

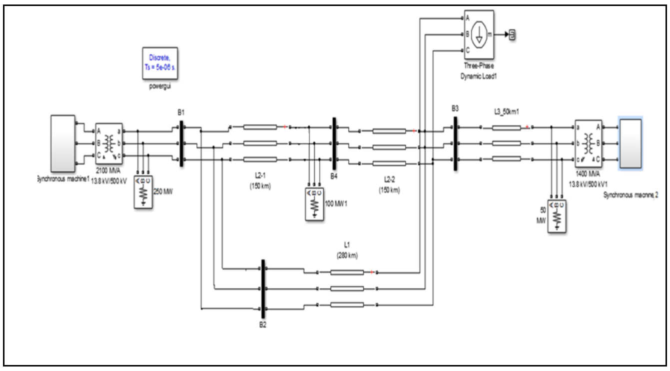

Fig. 3. Study system

In the control circuit, the gate pulses for the converter are developed. A heuristic vector based direct control method is used here. As a fault is simulated in the transmission system, the controller is designed in such a way to provide voltage and power compensation during the fault time so that the voltage and power are maintained within the nominal limits. The 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].

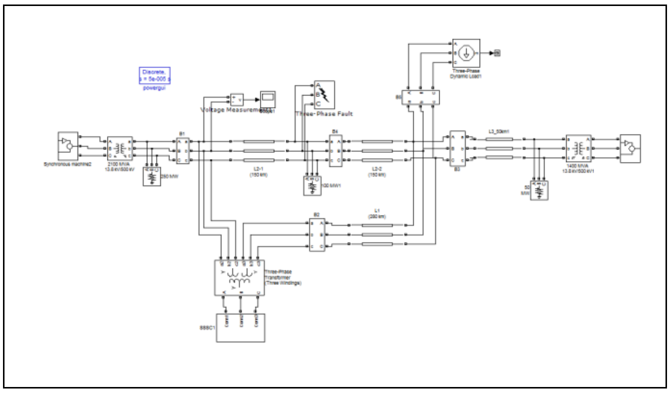

Fig. 4. Study system with SSSC

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. A schematic of the control scheme is shown in Fig.5.

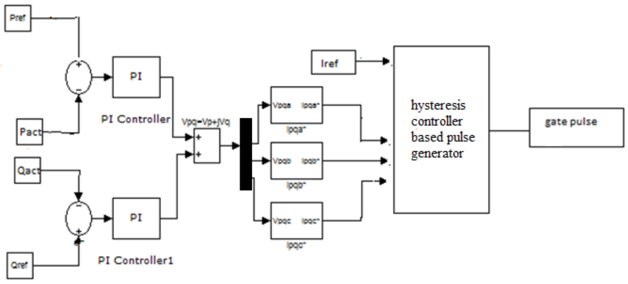

Fig.5: Schematic of the control scheme

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. Pso algorithm is used to tune the PI controllers.

V. SIMULATION AND RESULTS

Using MATLAB/SIMULINK, the model of the study system is established. The active and reactive powers injected by power plants 1 and 2 to the power system are presented in per unit by using base parameters Sb =100MVA and Vb=500KV. The basic system shown in figure 3 is simulated in MATLAB environment, and then powers and voltages in the transmission line sections are measured at the four buses B1, B2, B3 and B4. The results are given in Table 1.

Bus No.	Voltage	Current	Active power	Reactive power
1	1 pu	13.5 pu	20.06 pu	-3.77 pu
2	1 pu	6.7 pu	9.96 pu	1.82 pu
3	1 pu	10 pu	14.84 pu	-0.49
4	1 pu	5.55 pu	8.45 pu	-0.59

Table1: Obtained results from simulations

From the obtained results it can be seen that the reactive power demand is more for transmission line L1.This is why the reactive power measured at bus 2 is positive. The simulation of active and reactive power flow during this condition is shown in figure 6:

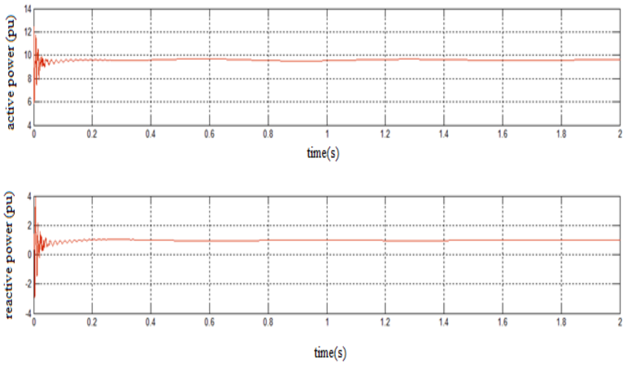

Fig 6: Active and reactive power flow at bus2

Here both the parallel transmission lines are sharing the power transmitted to the load. In transmission systems, symmetrical faults results in a loss of service and may require manual involvement for clearing such faults. During such severe faults temporary isolation of the faulted line is necessary which can be done by the protective relays and circuit breakers. In this case, since the reactive power of the lower transmission line L1 is more, the amount of real power which it can carry is affected considerably.

Therefore, the compensating device SSSC is installed in that transmission line to meet the reactive power requirement and hence control the power flow. The simulation results are concentrated at bus 2 where the measurements are done for L1. A three phase to ground fault (LLLG) is simulated from 0.2 to 0.25 seconds in the upper transmission line L1. The system configuration in simulink during the faulted condition is shown in figure 4. The active and reactive power flow of the transmission line L2 is obtained as shown in figure7.

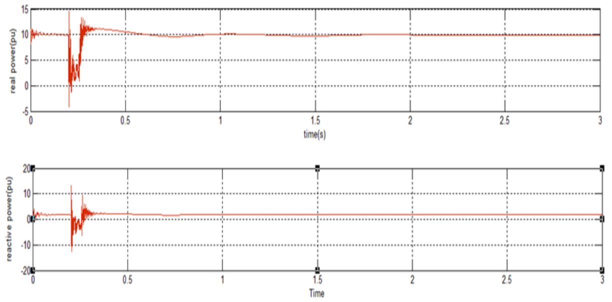

Fig. 7 Active and reactive powers at L1 during faulted condition

Speed of the machine M1 during the faulted situation is as shown in the figure 9.9. The speed deviates at the time of the fault and takes some time to reach steady state after the oscillations. Only after 10 seconds, the machine comes to stable equilibrium. This means the stability of the whole system is affected due to the fault.

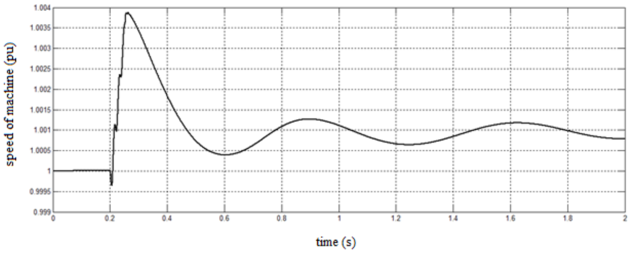

Fig. 8 Speed of the machine M1

A SSSC is installed at transmission line L1 and the voltage and current waveforms after the installation point is observed. The behaviour of SSSC to improve the power flow and providing power oscillation damping is obtained in the simulation. The positive value of reactive power has to be reduced with the aim of maintaining the active power constant and reactive power negative. When SSSC is introduced to the system, the control circuitry generates pulses at the time period of the fault and thus provides gate pulses for the Voltage source inverter. The active and reactive power are shown in Fig.9

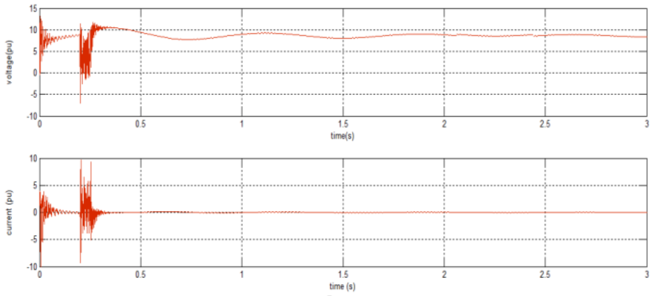

Fig.9 Real and reactive power of transmission line L1 after installing SSSC

After the installation of SSSC, the reactive power is now maintained at zero indicating that SSSC has provided the compensation during and after the fault. The machine speed after installation of SSSC based controller is shown in figure 10

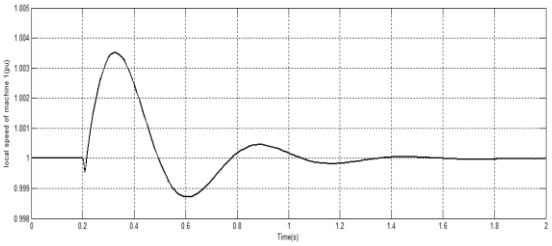

Fig.10 Speed of M1 after installation of SSSC

The speed settles down to 1 pu t 1.6s after the fault. This shows the system stability has been achieved and it has prevented the system from losing synchronism following a severe fault.

VI. CONCLUSION

The performance of Static Synchronous Series compensator (SSSC) is studied. It has been found that the closed loop control scheme enabled the SSSC to inject a series voltage of desired magnitude in order to maintain real power flow over the transmission line. Simulation results clearly depicts the enhancement of power transfer over the transmission line. Significant improvement in settling time in addition to improved damping during inter area disturbances is achieved. The transient stability of the system is also improved on the application of this series FACTS controller.

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