Static Synchronous Series Compensator (SSSC): An approach for reactive power compensation for the transmission system.

Chintan R Patel, Sanjay N Patel and Dr. Axay J Mehta

Abstract— ***A transmission line needs controllable compensation for power flow control and voltage regulation. This can be achieved by FACTS controllers. Static Synchronous Series Compensator (SSSC) is a series connected FACTS controller, which is capable of providing reactive power compensation to a power system. The output of an SSSC is series injected voltage, which leads or lags line current by 90°, thus emulating a controllable inductive or capacitive reactance. SSSC can be used to reduce the equivalent line impedance and enhance the active power transfer capability of the line. In this paper, series compensation provided by an SSSC is considered.***

Index Terms—Compensation, FACTS Controllers, Reactive Power, SSSC.

1 INTRODUCTION

The rapid development of power electronics technology provides exciting opportunities to develop new power systems equipment for better utilization of existing systems. During the last decade a number of control devices under the term Flexible AC Transmission Systems (FACTS) technology have been proposed and implemented. The FACTS devices can be used for power flow control, loop flow control, load sharing among parallel corridors, voltage regulation, and enhancement of transient stability and mitigation of system oscillations. FACTS have become an essential and integral part of modern power systems. Modeling and digital simulation plays an important role in the analysis, design, testing and commissioning of such controllers.

Static Synchronous Series Compensator (SSSC) is a series compensator of FACTS family. It injects an almost sinusoidal voltage with variable amplitude. It is equivalent to an inductive or a capacitive reactance in series with the transmission line. The heart of SSSC is a VSI (voltage source inverter) that is supplied by a DC storage capacitor. With no external DC link, the injected voltage has two parts: the main part is in quadrature with the line current and emulates an inductive or capacitive reactance in series with the transmission line, and a small part of the injected voltage is in phase with the line current to cover the losses of the inverter. When the injected voltage is leading the line current, it will emulate a capacitive reactance in series with the line, causing the line current as well as power flow through the line to increase. When the injected voltage is lagging the line current, it will emulate an inductive reactance in series with the line, causing the line current as well as power flow through the line to decrease.
SSSC is superior to other FACTS equipment and the benefits of using SSSC are:

- Elimination of bulky passive components - 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.

2 THE SSSC

An SSSC comprises a voltage source inverter and a coupling transformer that is used to insert the ac output voltage of the inverter in series with the transmission line. The magnitude and phase of this inserted ac compensating voltage can be rapidly adjusted by the SSSC controls.

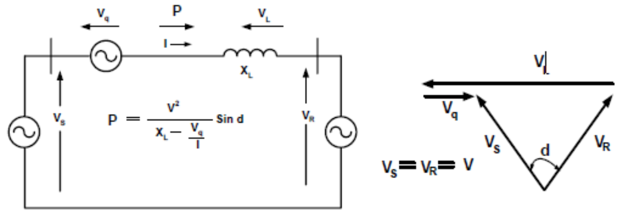

Fig.1. Elementary two-machine system with an SSSC and the associated phasor diagram

The SSSC injects the compensating voltage in series with the line irrespective of the line current. The transmitted power P_q, therefore becomes a parametric function of the injected voltage, and can be expressed as follows:

Chintan R Patel is pursuing M.E. in Electrical Power System at BVM Engineering College, Vallabh Vidyanagar. (k_chintan@yahoo.co.in)
Sanjay N Patel is pursuing M.E. in Electrical Power System at BVM Engineering College, Vallabh Vidyanagar. (sanjaychaitali@ yahoo.co.in)
Dr. Axay J Mehta is with G.H.Patel College of Engineering & Technology, Vallabh Vidyanagar.(draxaymehta@gmail.com)

.

$$P_q = \frac{V^2}{X_L} Sin\delta + \frac{V}{X_L} V_q Cos\left(\frac{\delta}{2}\right) \ldots\ldots\ldots\ldots(1)$$

The SSSC, therefore can increase the transmittable power, and also decrease it, simply by reversing the polarity of the injected ac voltage. The reversed (180° phase-shifted) voltage adds directly to the reactive voltage drop of the line as if the reactive line impedance was increased. Furthermore, if the injected voltage is made larger than the voltage impressed across the uncompensated line by the sending- and receiving end systems, that is if $|V_q| > |V_1 - V_2|$, then the power flow can reverse. Apart from the stable operation of the system with both positive and negative power flows, it can also be observed that the SSSC has an excellent (sub-cycle) response time and that the transition from positive to negative power flow through zero voltage injection is perfectly smooth and continuous.

3. IMMUNITY TO RESONANCE

A series capacitor is also used to provide series compensation in power systems so far. However, the impedance of the series capacitor is a function of frequency and thus it may cause resonances at various frequencies with other reactive impedances present in the network. The resonance of greatest concern is that occurring with the series reactive impedance of the system at a frequency below the fundamental. At this frequency the electrical system may reinforce one of the mechanical resonances of certain turbine generators, causing the well-understood phenomenon of Sub-Synchronous Resonance (SSR), which may result in serious damage to the generator. In contrast to a series capacitor or to the combination of a series capacitor and a Thyristor Controlled Reactor (TCR), the static synchronous series compensator is essentially an ac voltage source which, with fixed control inputs, would operate only at the selected (fundamental) output frequency, and its output impedance at other frequencies would theoretically be zero. In practice, the SSSC does have relatively small inductive output impedance provided by the leakage inductance of the series insertion transformer. The voltage drop across this impedance is automatically compensated at the fundamental frequency when the SSSC provides capacitive line compensation. Thus, the effective output impedance versus frequency characteristic of the SSSC remains that of a small inductor at all but its fundamental operating frequency.

Consequently, the SSSC is unable to form a classical series resonant circuit with the inductive line impedance to initiate subsynchronous system oscillations. On the other hand, the SSSC has a very fast (almost instantaneous) response and thus it can be very effective in the damping of subsynchronous oscillations (which may be present due to existing series capacitors) if the electronic control is structured to provide this function. (In discussing dynamic interactions, it is of course true that the SSSC, like all actively controlled equipment, could under abnormal conditions exhibit instability or oscillatory interaction with the ac system if, for example, its closed-loop gains, providing automatic power flow control or other regulative functions, are improperly set, or if the electronic control itself malfunctions. However, these considerations are generic to all actively controlled systems and involve other subjects like control robustness, control redundancy, and protection, which are out of scope of this paper.)

4. RATING OF THE SSSC

The SSSC can provide capacitive or inductive compensating voltage independent of the line current. The VA rating of the SSSC (solid-state inverter and coupling transformer) is simply the product of the maximum line current (at which compensation is still desired) and the maximum series compensating voltage: $VA = I_{max}V_{max}$. An SSSC of 1 p.u. VA rating covers a control range corresponding to 2 p.u. compensating VARs, that is the control range is continuous from -1 p.u. (inductive) VARs to +1 p.u. (capacitive) VARs.

5. INTERNAL CONTROLS

From the standpoint of output voltage control, converters may be categorized as “directly” and “indirectly” controlled. For directly controlled converters both the angular position and the magnitude of the output voltage are controllable by appropriate valve (on and off) gating. For indirectly controlled converters only the angular position of the output voltage is controllable by valve gating; the magnitude remains proportional to the dc terminal voltage. The control method of maintaining a quadrature relationship between the instantaneous converter voltage and line current vectors, to provide reactive series compensation and handle SSR, can be implemented with an indirectly controlled converter. The method of maintaining a single frequency synchronous (i.e. fundamental) output independent of dc terminal voltage variation requires a directly controlled converter. Although high power directly controlled converters are more difficult and costly to implement than indirectly controlled converters (because their greater control flexibility is usually associated with some penalty in terms of increased losses, greater circuit complexity, and/or increased harmonic content in the output), nevertheless they can be realized to meet practical utility requirements.

6. CONTROL SCHEME OF SSSC

The basic system of SSSC is shown in Fig.2. The system consists of two generating machines along with transmission line and load as shown in figure. The compensator is provided with a DC voltage source which helps in feeding or absorbing the active and reactive power from the system.

The control circuit is shown in Fig. 3 below. The line voltage and current are sensed and from that measurement actual active power P_{act} and reactive power Q_{act} are calculated.

These P_{act} and Q_{act} 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 to generate error signals E_p and E_q. These error signals are processed in the controller.

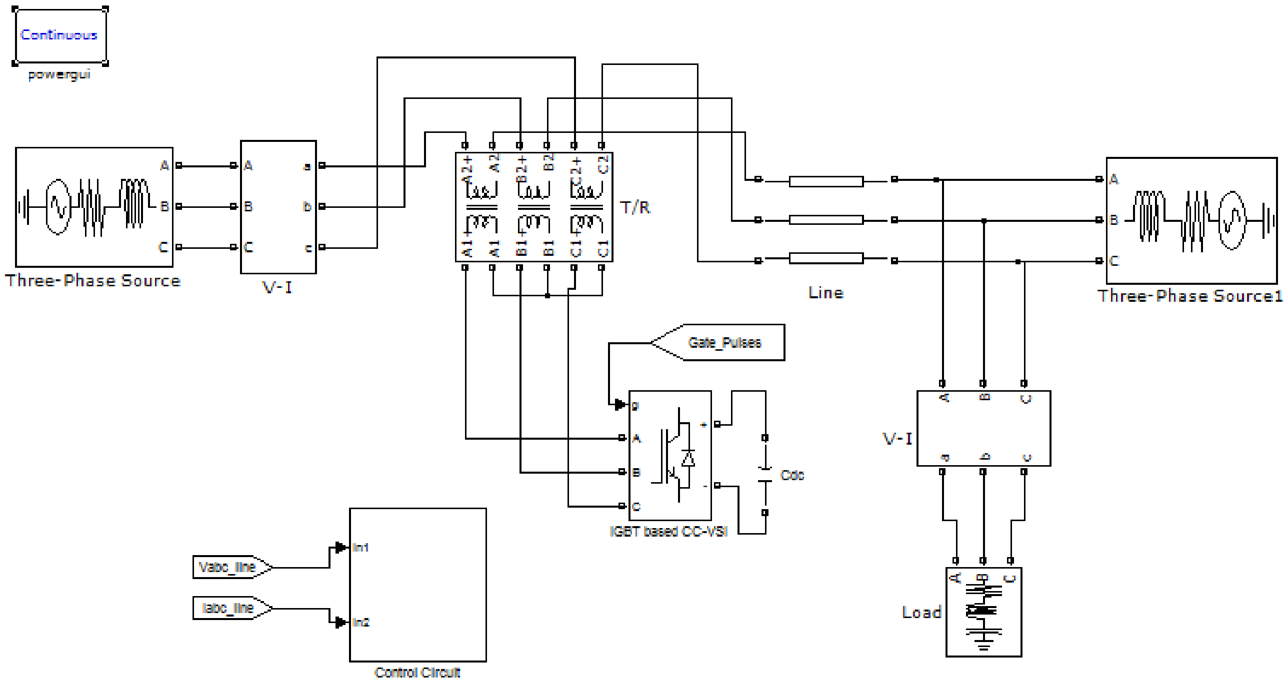

Fig.2 Schematic System with SSSC

The output s of the controllers Vp and Vq 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 (Z_e). These currents (I_{pqa}^*,I_{pqb}^*,I_{pqc}^*) are compared with the three-phase currents (I_{pqa},I_{pqb},I_{pqc}) measured at the output of the inverter. The PWM current controller based on hysteresis control is used to generate the gate pulses for the inverter switches. According to the switching signals, inverter generates the three-phase voltages (V_{pqa},V_{pqb},V_{pqc}) at its output terminals and these voltages are injected in the series with the transmission line. This injected voltage insures that P_{act} remains same as P_{ref} and Q_{act} remains same as Q_{ref}.

7. MODELING OF THE SYSTEM

The control scheme of the SSSC is shown in Fig. 3. It consists of two control loops. One is for reactive power controlvand other is for active power control.

Computation of power: The active and reactive power of the line are calculated with help of V_{abc} and I_{abc} measured from the line.

$$P_{act} = Re[V_{abc}I_{abc}^*] \qquad Q_{act} = Im[V_{abc}I_{abc}^*] \;\ldots\ldots(2)$$

Where I_{abc}^* is the conjugate of line current.

The calculated powers P_{act} and Q_{act} work as feedback signals and they are compared with the reference values P_{ref} and Q_{ref} respectively. The errors are given by

$$E_p = P_{ref} - P_{act} \qquad E_q = Q_{ref} - Q_{act} \;\ldots\ldots\ldots\ldots(3)$$

Controller: The good response can be obtained with help of a fine tuned PI controller.

The control law for active power is given by

$$V_{p(n)} = V_{p(n-1)} + K_{pp}\{E_{p(n)} - E_{p(n-1)}\} + K_{ip}E_{p(n)} \;\ldots\ldots(4)$$

Where K_{pp} and K_{ip} are proportional and integral gains of the PI controller. Similarly, the control law for the reactive power is also given. From the output of both the control loops, i.e. active power control loop and reactive power control loop, the injected voltage V_{pq} is computed as follows:

$$V_{pq} = \frac{V_p + jV_q}{I_{abc}*} \;\ldots\ldots\ldots\ldots(5)$$

The magnitude of the injected voltage is given by

$$V_{pq} = |V_{pq}| \;\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Whereas the phase of the injected voltage is given by

$$\delta_{pq} = \tan\left(\frac{\mathrm{Re}[V_{pq}]}{\mathrm{Im}[V_{pq}]}\right) \ldots\ldots\ldots\ldots\ldots(7)$$

For the control of the power-flow in the transmission line, following inequalities are followed:

$0 < V_{pq} < V_{pqmax}$ magnitude control

$0 < \delta_{pq} < 360^0$ phase control

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

$$V_{pqa}* = \sqrt{2}V_{pq}Sin(\omega t + \delta_{pq})$$
$$V_{pqb}* = \sqrt{2}V_{pq}Sin(\omega t + 2\prod/3 + \delta_{pq}) \;\ldots\ldots\ldots\ldots(8)$$
$$V_{pqc}* = \sqrt{2}V_{pq}Sin(\omega t - 2\prod/3 + \delta_{pq})$$

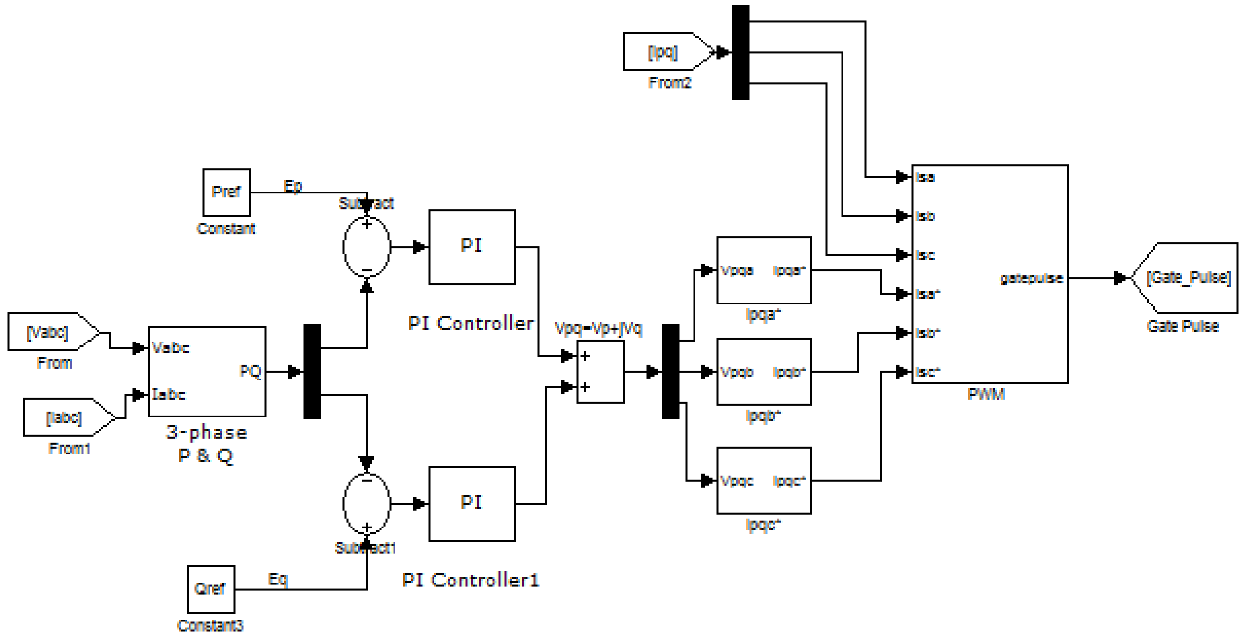

Fig.3 Schematic of the Control Scheme for the SSSC

CC-VSI: The current-controlled pulse width modulated voltage source inverter is used to inject ac voltage in series in the line. The three-phase reference currents of the compensator are calculated as follows:

$$I_{pqa}* = \frac{V_{pqa}*}{Z_e}$$

$$I_{pqb}* = \frac{V_{pqb}*}{Z_e} \quad \ldots\ldots\ldots\ldots\ldots(9)$$

$$I_{pqc}* = \frac{V_{pqc}*}{Z_e}$$

Where $Z_e = R_e + jX_e$

Switching of the VSI: The CC-VSI consists of six IGBT switches(S_1-S_6) with an anti-parallel diodes. This current-controlled VSI is based on the hysteresis current control. The schematic arrangement of this type of controller is shown in Fig.4 below.

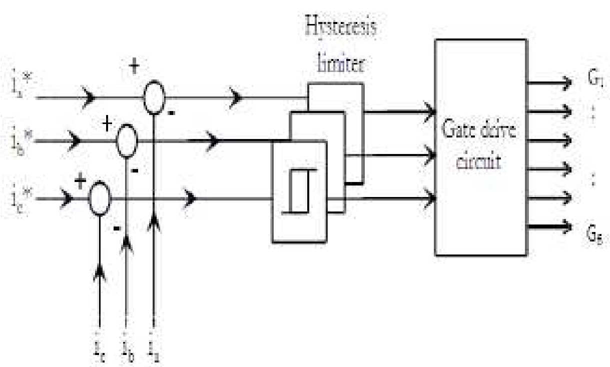

Fig.4 Schematic of current controlled PWM

The operation of switches in the leg of phase a is as follows:

If $I_{pqa} < (I_{pqa}^* - HB)$ S_1 is ON & S_4 is OFF

If $I_{pqa} > (I_{pqa}^* + HB)$ S_1 is OFF & S4 is ON

Here, HB is the hysteresis bandwidth around the reference currents. The similar switching law for other phases can also be described. The hysteresis current controller control structure is shown in Fig.5 below:

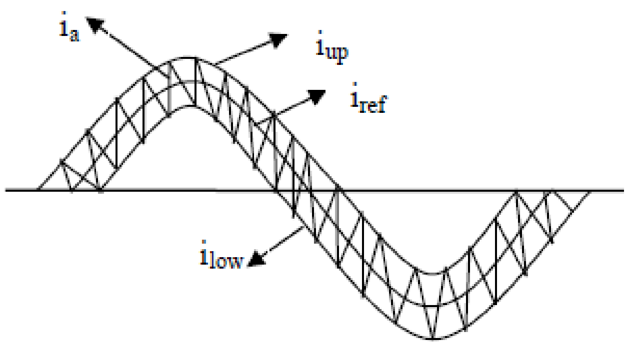

Fig.5 Hysteresis Controller Control Structure

8. CONCLUSION

It has been found that the SSSC is able to control the power flow in the transmission line. It can also injects fast changing voltage in series with the line irrespective of the magnitude and phase of the line current. The SSSC can also damp out the oscillations of the system.

9. REFERENCES

1. Hingorani,N.G.:"High power electronics and flexible ac transmission System",IEEE Power Eng. Rv., July 1998.

2. GYUGYI, L et el : " Static Synchronous Series Compensator: A solid state approach to the series compensation of the transmission line", IEEE Trans., 1997,PD-12.
3. HATZIADONIU,C.J. et el : " Development of control scheme for a series connected solid state synchronous voltage source.", IEEE Trans., 1996, PD-11.
4. SEN,K.K.: " SSSC-" Static Synchronous Series Compensator: Theory, Modeling and applications", IEEE Trans.,1997 PD-13.
5. SINGH,B.N. et el: " Performance of sliding-mode and fuzzy controllers for a " Static Synchronous Series Compensator" IEE Proc.-Gener. Transm. Distrib., Vol.146,No.2 March 1999.
6. REDDY, B.V. et el: " Hysteresis controller & delta modulator- A two viable schemes for current controlled voltage source inverter.
7. SHARAF, N et el: " A model of static synchronous series compensator for real time digital simulator".
8. HUANG, F.W. et el:" A static synchronous series compensator model for EMTDC", IEEE Africon 2002.