Investigation on Control of Power Flow in Transmission Line Using SSSC

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Abstract : This paper discusses a Static Synchronous Series Compensator which is constructed with a six-pulse inverter. Extensive simulation studies are carried out to verify the proper operation of the mentioned Flexible AC Transmission Systems (FACTS) device. In MATLAB simulation environment the designed device is connected to a power system that is comprised of three phase power source, transmission line, line inductance and load. The system parameters such as line voltage, line current, reactive power Q and real power P transmissions are observed when the Static Synchronous Series Compensator is connected and disconnected from the power system. The compensation achieved by the SSSC and its effects on the line voltage, line current, phase angle and real/reactive power flow are investigated in detail. The motivation of modeling a Static Synchronous Series Compensator from a six-pulse inverter is to enhance the voltage waveform. The SSSC injects almost sinusoidal voltage of variable magnitude in series with the transmission line. The injected voltage is almost in-quadrature with the line current thereby emulating an inductive or a capacitive reactance in series with the transmission line. The emulated variable reactance, inserted by the injected voltage source, influences the electric power flow in the transmission line.

***IndexTerms* - FACTS, H-bridge Inverter, Multi-pulse, Power flow control, Power line compensation, PWM inverter.**

I. INTRODUCTION

Electric power flow through an alternating current transmission line is a function of the line impedance, the magnitude of the sending-end and receiving-end voltages, and the phase angle between these voltages [1]. The power flow can be decreased by inserting an additional inductive reactance in series with the transmission line, thereby increasing the effective reactance of the transmission line between its two ends. Also, the power flow can be increased by inserting an additional capacitive reactance in series with the transmission line, thereby decreasing the effective reactance of the transmission line between its two ends [2].

Traditionally, in order to control the power flow of the transmission line, the effective line reactance is controlled by using fixed or thyristor-controlled series capacitors or inductors. Recently, a new power flow controller entitled Transmission Line Dynamic Impedance Compensation System, which uses solid-state switching converters, has been proposed. With the use of the impedance compensation controller, a Static Synchronous Series Compensator (SSSC), which is a solid-state voltage source inverter, injects an almost sinusoidal voltage, of variable magnitude, in series with a transmission line. This injected voltage is almost in quadrature with the line current. A small part of the injected voltage which is in phase with the line current provides the losses in the inverter. Most of the injected voltage which is in quadrature with the line current emulates an inductive or a capacitive reactance in series with the transmission line. This emulated variable reactance, inserted by the injected voltage source, influences the electric power flow in the transmission line [10].

An impedance compensation controller can compensate for the transmission line resistance if an SSSC is operated with an energy storage system. An impedance compensation controller, when used with an SSSC and no energy storage system, is essentially a reactance compensation controller. The reactance compensation controller is used to operate the inverter in such a way that the injected alternating voltage in series with the transmission line is proportional to the line current with the emulated reactance being the constant of proportionality [10]. When an SSSC injects an alternating voltage leading the line current, it emulates an inductive reactance in series with the transmission line causing the power flow as well as the line current to decrease as the level of compensation increases and the SSSC is considered to be operating in an inductive mode. When an SSSC injects an alternating voltage lagging the line current, it emulates a capacitive reactance in series with the transmission line causing the power flow as well as the line current to increase as the level of compensation increases and the SSSC is considered to be operating in a capacitive mode. This study is mainly concerned with the design of a SSSC with a six-pulse PWM inverter and the simulation of its compensation characteristics over a modeled power line [5]. The motivation in utilizing a multi-pulse inverter is to increase the quality of the output waveform. The compensation of the reactive power Q over the power lines and the allocation of a larger portion of the overall power transmission capacity to the real power P is the ultimate goal of the designed system.

II. SSSC CONTROL SCHEME

The main function of the SSSC as a series compensator is the control of transmission line power flow. This can be accomplished by either direct control of the line current (power) or alternatively by indirect control of either compensating series impedance, X_s, or injected series compensating voltage, V_c . The direct power flow control has the advantages of maintaining the transmitted power under a closed loop control defined by a power reference. However, under some network contingencies, the maintenance of this constant power flow may not be either possible or even desirable.

A .Reactance control

In power system applications the equivalent impedance control that maintains the equivalent impedance of the transmission line may be the preferred method from the operating standpoint. Fig. 3 shows a single line diagram of a simple transmission line with an inductive transmission reactance, XL, connecting a sending end (S.E.) voltage source, Vs and a receiving end (R.E.) voltage source, Vr, respectively. The real and reactive power (P and Q) flow at the receiving end voltage source is given by expressions:

$$P = \frac{V_s V_r}{X_L}\sin(\delta_s - \delta_r) = \frac{V^2}{X_L}\sin\delta \qquad (1)$$

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

$$\delta = \delta_s - \delta_r \qquad (3)$$

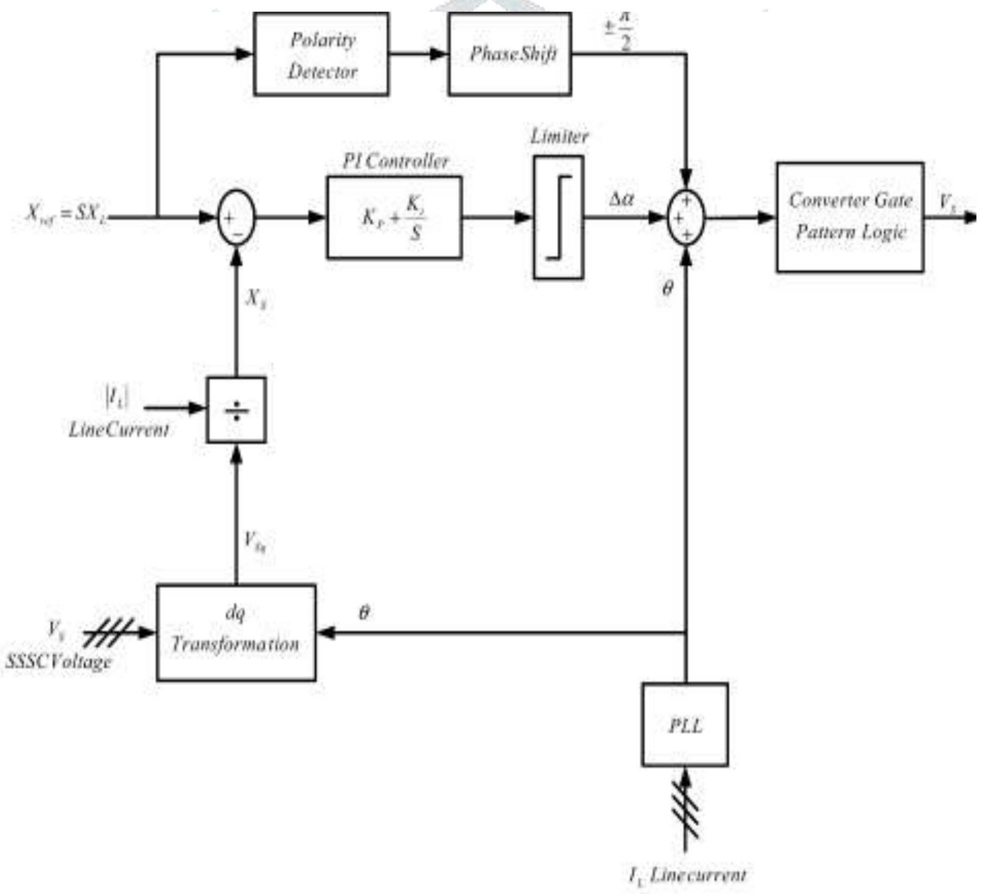

Fig.1 Control structure of the SSSC FACTS device.

Where V_s and V_r are the magnitudes and δ_s and δ_r are the phase angles of the voltage sources V_s and V_r, respectively, for simplicity, the voltage magnitudes are chosen such that $V_s = V_r = V$ and the difference between the phase angles is $\delta = \delta_s - \delta_r$. A SSSC, limited by its voltage and current ratings, is capable of emulating a compensating reactance, X_q (both inductive and capacitive) in series with transmission line inductive reactance, X_L. Therefore the expressions for power flow given in Eqs. (1) and (2) become

$$P_q = \frac{V^2}{X_{eff}}\sin\delta = \frac{V^2}{X_L\left(1 - \left(\frac{X_q}{X_L}\right)\right)}sin\delta \qquad (4)$$

and

$$Q_q = \frac{V^2}{X_{eff}}(1 - cos\delta) = \frac{V^2}{X_L\left(1 - \left(\frac{X_q}{X_L}\right)\right)}(1 - cos\delta) \qquad (5)$$

Xq = compensating reactance,
X_L = Line reactance and
X_{eff} = Effective reactance of the transmission line

The compensating reactance, Xq, is defined to be negative when SSSC is operating in an inductive mode and positive when the SSSC is operating in a capacitive mode. The degree of the series compensation, S, is usually expressed as the ratio of the series reactance, Xq, to the transmission line reactance XL, where Xq = SX_L. Similarly, for an inductive series compensation, the line series reactance is $X_{line} = X_L + X$q, where Xq = SXL. Therefore, the basic function of the effective control system is to keep the SSSC voltage, Vc, in quadrature with the transmission line current, I_L and only control the magnitude of injected series reactance to meet the desired reactance compensation level. The control Scheme for the SSSC is shown in Fig. 1.

The basic synchronization signal, θ, is the phase angle of the transmission line current. The SSSC equivalent injected reactance Xq is measured as the ratio of the q-axis voltage of the SSSC device, Vsq, to the magnitude of transmission line current, I_L. This equivalent inserted or equivalent (positive/negative) impedance is then compared with the reference level of the compensation impedance, (SXL).A proportional plus integral PI controller parameters are selected based on the off-line guided trial and error J_0-minimization method to generate the required small phase displacement angle, $\Delta\alpha$ of few electric degrees, in order to charge or discharge the dc capacitor (C), while a positive $\Delta\alpha$ discharges the dc side capacitor. When Xref is negative, Vs lags I_L by 90° (capacitive compensation) and when Vs leads I_L by 90° (inductive compensation). The final output of the control system is the desired phase angle of the SSSC device output voltage, $\theta^* = \pm(\pi/2) \pm \Delta\alpha + \theta$.

B. Constant injected quadrature voltage control

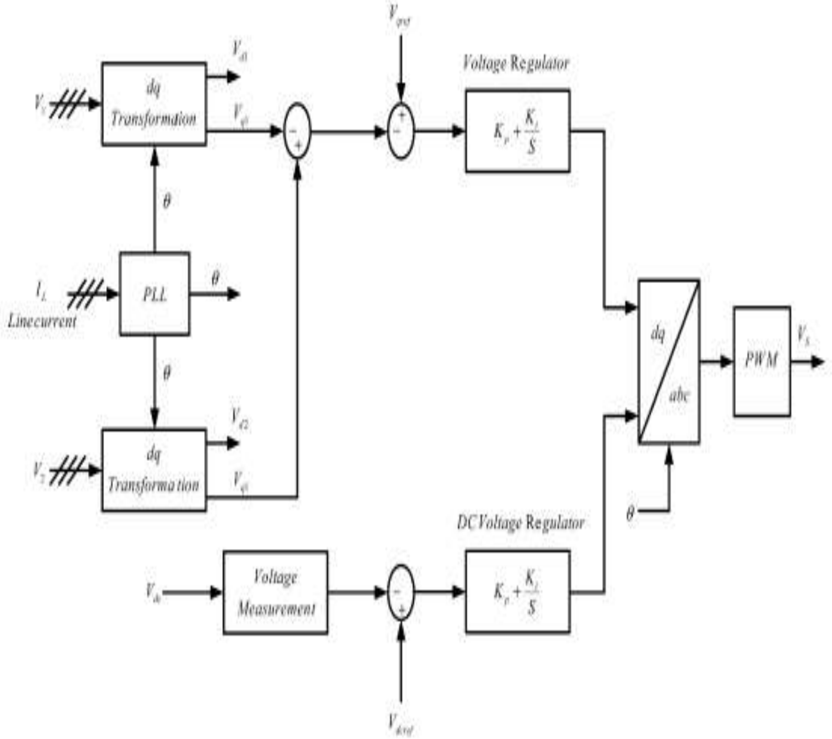

Fig. 2 The direct injected quadrature voltage control using PWM.

F

ig. 2 shows a constant injected quadrature voltage control. The injected quadrature voltage is independent of the line current and controlled by using the pulse width modulation switching techniques. The voltage source converter uses PWM switching techniques to ensure fast response and to generate a sinusoidal waveform from a capacitor dc voltage with considering a typical chopping frequency of a few kilohertz. Harmonics are cancelled due the phase shifting patterns of the Zigzag phase shifting transformer with considering the connection on Y or Δ. The constant injected voltage is implemented as shown in Fig. 2. A phase locked loop (PLL) which synchronizes on the positive sequence component of the line current. The output of the PLL is angle, θ, which is used to transform the direct axis and quadrature axis components of the ac three phase voltages and current. The voltage drop across the leakage reactance of the series coupling transformer is measured to compute the injected quadrature voltage with respect to the line current.

The measured quadrature voltage is compared with the desired reference constant quadrature voltage to the input of the ac voltage regulator which is a PI controller. Thus the voltage regulator provides the quadrature component of the converter voltage. Also the measured capacitor dc voltage is compared with the reference dc voltage; this driven error is an input to the dc voltage regulator which is a PI controller to compute the direct component of the converter voltage. The PI control parameters, proportional and integral gains are selected based on the off-line guided trial and error J_0 minimization method. Both direct and quadrature components of the converter voltage are used to determine the modulation index which is varied ($0 < M < 1$), thus it controls the injected quadrature series voltage based on the desired dc voltage and injected voltage, V_{qref}.

III. SYSTEM CONFIGURATION

IV. A three phase source, a line inductance characterizing the power lines and a three phase load at the receiving end are used to model a power system, as shown in Fig. 4. The bus B1, connecting the three phase source to the power line measures the voltage supplied by the source and the current demanded by the system. From these measured values the instantaneous real (P) and reactive (Q) power flows are worked out and thus the power flow over the power system and the compensation, if any, by the SSSC are calculated. The positions of the buses B1 and B2 are important. Because they are placed before and after, respectively, the transmission line inductances and the transformer connecting the SSSC to the power system the affect of the compensation can be observed.

V. The power source is set to generate a 440 kV three phase voltage at 50 Hz. This value is selected so that the simulated power system emulates a long transmission line or a high voltage transmission line depending on the classification method used. A purely inductive load is used in this example since most of the industrial loads, such as electrical machines, can be characterized with inductive loads.

VI. The closed loop control shown in Fig. 5 is used to determine the phase angle of the line current flowing over the transmission line. Then a phase shift of pi/2 radians is applied and the PWM signals triggering the inverters used in the six pulse inverter are generated from these data by the designed PWM generator. The PWM generator generates sine waves with the angle given and it then generates the PWM signals by comparing these signals with the carrier frequency according to the value of the modulation index. This closed loop control operates SSSC in “compensation for power flow” mode, a classification put forth by Hingorani and Gyugi.

The section that is enclosed by the broken line is an optional control which can be utilized to enhance the control of the Q-flow over the line. However, it is not indispensable as far as the implementation of a SSSC is concerned since the ultimate target of the compensation is to decrease the reactive power flow over the line and thus increase the real power flow capacity. The ideal case for a purely inductive load, which necessitates capacitive compensation, is attained when the former is minimized so as to maximize the latter. This ideal case can be achieved when the phase shift is 90 degrees and all of the injected voltage is capacitive. Throughout the simulation studies this idealized control loop is used to decrease the calculation load on the computer.

IV. SIMULATION RESULTS

The circuit is simulated to observe the free (uncontrolled) power flow over the line. The real power P demanded by the load is supplied by the three phase source and transmitted by the transmission line between B1 and B2. The simulations were performed to see the power demands, voltage and current supplied by the source, transmitted by the line and received by the load. Following these observations a Static Synchronous Series Compensator (SSSC) is operated to decrease the Q-flow over the line by compensating the reactive power demanded by the system

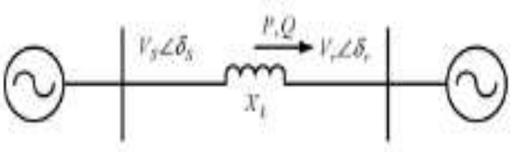

Fig. 3 Twobus Transmission System

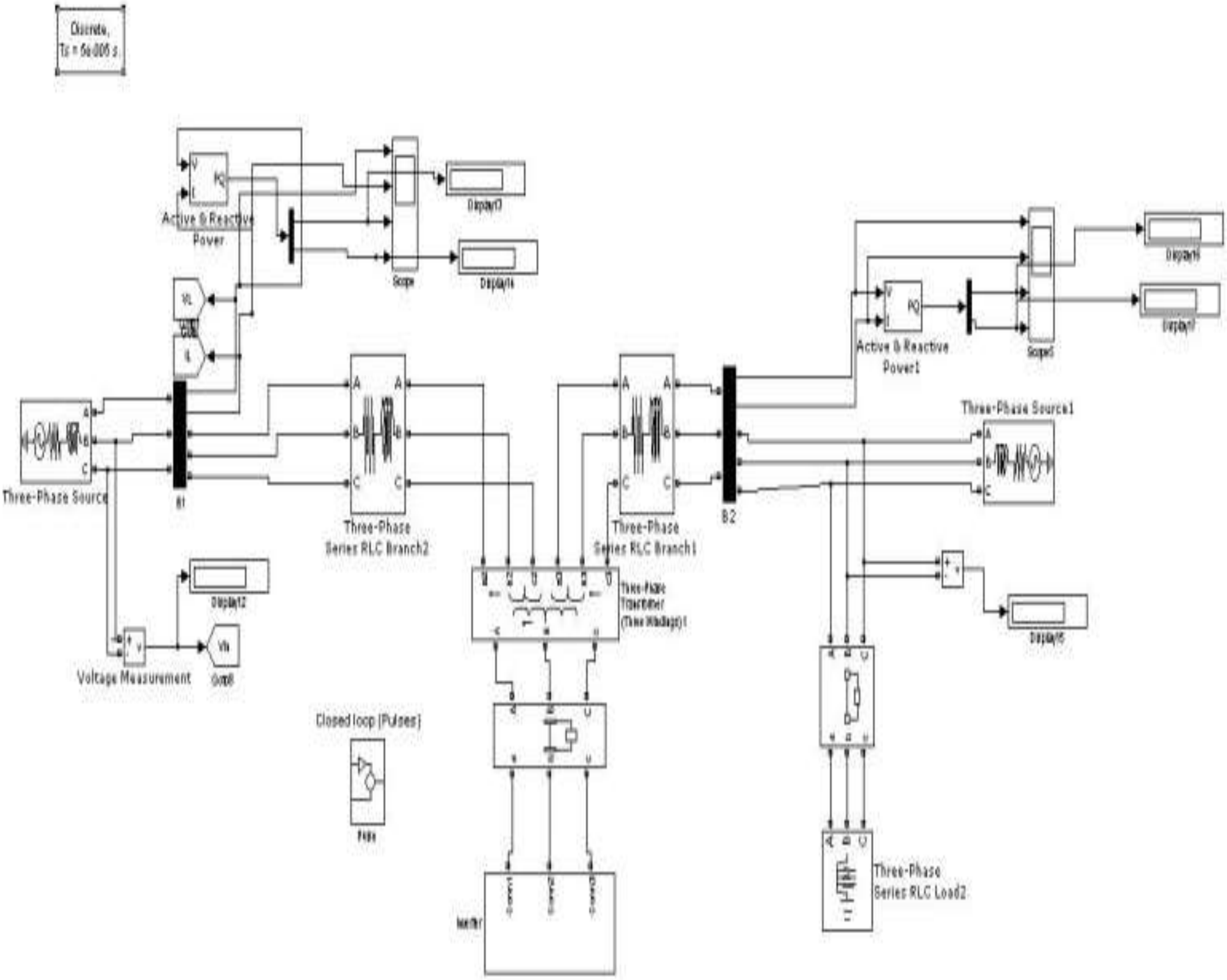

Fig. 4 Simulation Diagram

First the simulations were carried out when the SSSC was disconnected from the transmission line. The three phase source voltage and current waveforms along with the real and reactive power flows were obtained as shown in Fig. 6. The same parameters were observed after connecting the SSSC with the transmission line and the waveforms shown in Fig. 7 were obtained. The output voltage of the six-pulse inverter, which is the voltage that is injected into the line, is given in Fig.8.

Analyzing the results and the waveforms it can be easily said that the synchronization and compensation are performed satisfactorily by the designed SSSC. The feedback signal

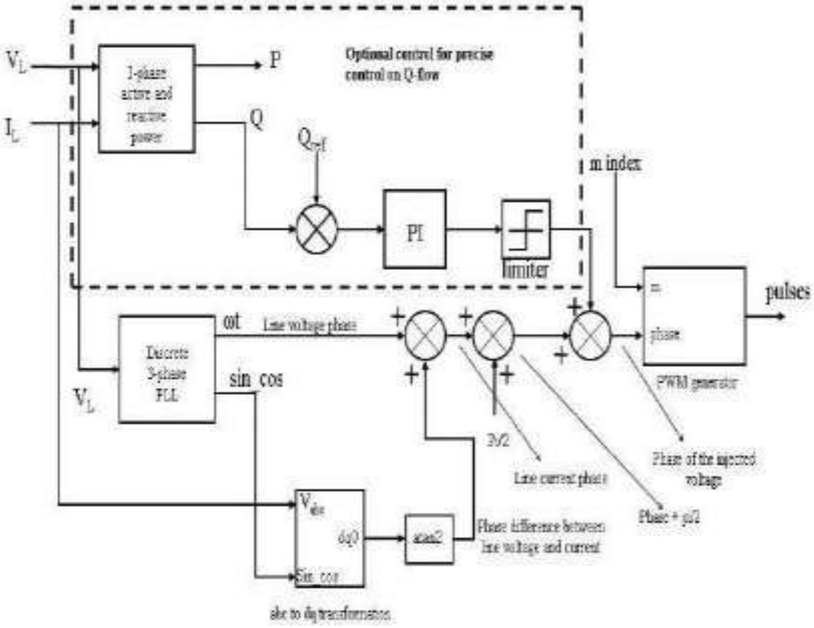

Fig. 5 Closed loop Control

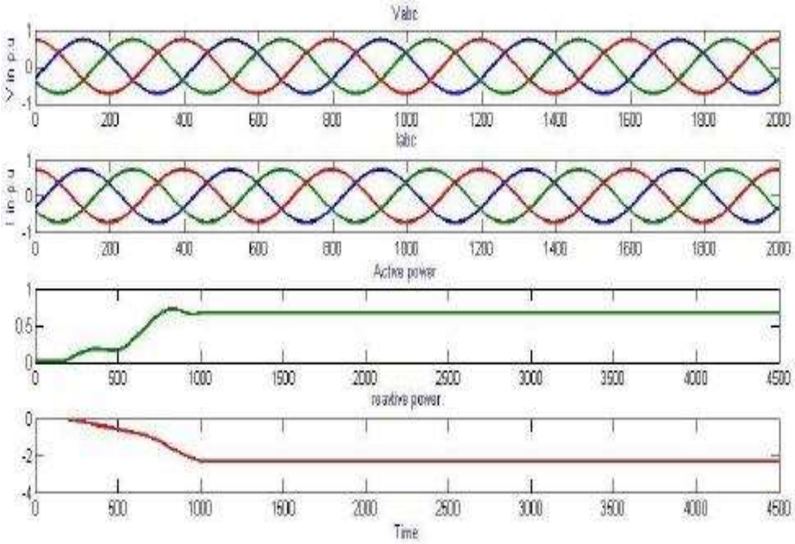

Fig. 6 Three phase voltage, current, real and reactive power (SSSC OFF)

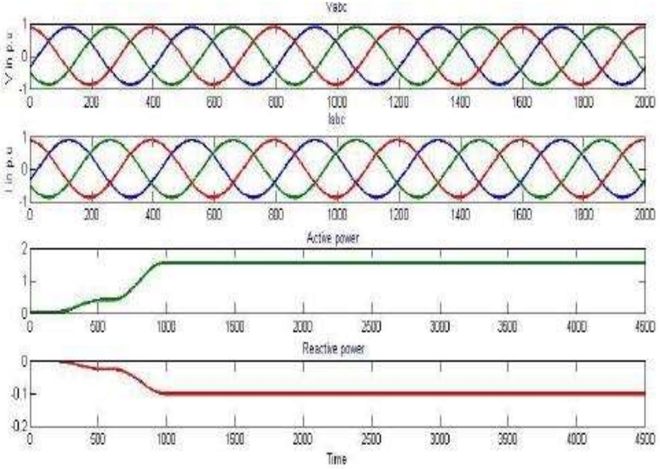

Fig. 7 Three phase voltage, current, real and reactive power (SSSC ON)

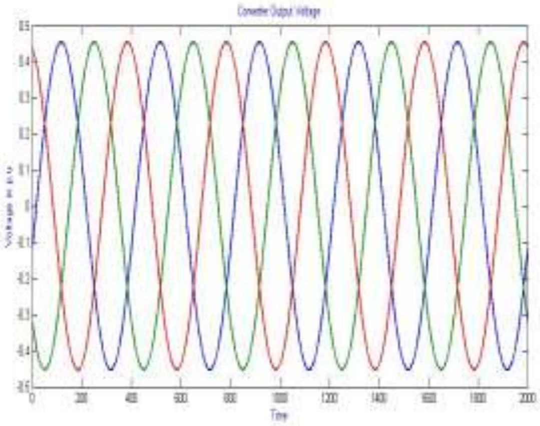

Fig. 8 Inverter Output Voltage

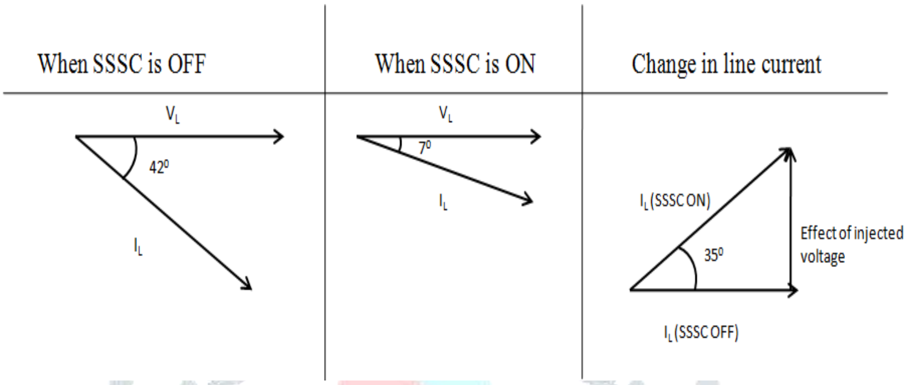

Fig. 9 Line Voltage and Current Phasor Diagram

which is generated from the line current flowing over the power line is used to generate the PWM signals. This way both synchronization and a 90 degree phase difference with the line current are achieved. In order to interpret the results, a comparative approach would be appropriate for the waveforms obtained before and after the SSSC is operated. The line voltage and current shown in Fig. 6 clearly depict the phase difference between them induced by the inductive current drawn by the system which decreases the power factor of the source side. Accordingly the reactive power Q drawn from the source reaches considerable values. The level of the real power P should also be noted here in order to compare it with the value obtained under the compensation condition. After turning on the SSSC the effect of the compensation is evident from the decreasing phase difference between the three phase line voltage and the current. The phase difference can be controlled with the relevant control on the SSSC by means of the control loop shown earlier. Since the line current is not lagging as much as it did under non-compensation condition, the reactive power flow Q over the line is reduced considerably. The flow of reactive power is not only decreased over the line but also from the overall power demanded from the three phase power source. In short the reactive power demand is met by the output voltage of the SSSC.

Returning to the fundamental motivation for series compensation, the reactive power flow Q over the transmission line is desired to be as low as possible so that the transmission capacity can be allocated to the power demand of the load. Considering Fig. 6 and Fig. 7 a rise in the real power transmission P to the same load with the same source settings and the same line voltage waveform can be observed.

The effects of the compensation are summarized in Table 1 where it can be clearly seen that the real power P transmission from the source to the load becomes three times larger whereas the reactive power Q demanded from it is compensated to its previous value. These changes are obviously the results of the phase difference that is caused by the compensation which reduces the 42^0 of line current lagging to a mere 7^0.

The phasor diagram given below in Fig. 9 is a method of depicting the compensation and the effect of the injected voltage in a visual manner. It is not only descriptive but also lucid and therefore it is widely used in power system analysis.

Table.1: Effect of SSSC Compensation

SSC Status	3-phase voltage in pu	3-phase current in pu	Real power in pu	Reactive power in pu
OFF	0.73	0.73	0.66	-2.308
ON	0.88	0.88	1.495	-0.098

V. CONCLUSION

A Static Synchronous Series Compensator (SSSC) is constructed from a conventional six-pulse inverter and a detailed closed loop control is designed to control the power flows over power lines. The designed device is connected to the receiving end of a modeled power system and its operation is verified by a series of simulations in the MATLAB environment. The obtained results proved to be satisfactory. The voltage and current waveforms along with the instantaneous active and reactive power calculations reveal that the designed topology works satisfactorily. The reactive power flow over the power line is compensated with the help of series injected voltage by the SSSC.

VI. REFERENCES

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