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Power Line Compensation Study of a Static Synchronous Series Compensator (SSSC) Based on Soft Switching 48-pulse PWM Inverter

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Abstract: This paper discusses a Static Synchronous Series Compensator which is constructed with a 48-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 both when the Static Synchronous Series Compensator is connected to 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 examined in detail. The motivation of modeling a Static Synchronous Series Compensator from a multi-pulse inverter is to enhance the voltage waveform of the device and this is observed in total harmonic distortion (THD) analysis performed in the end. The results of the study shows that the voltage injection is successfully achieved by the new device and the power flow and phase angle can be controlled. Also the THD analysis assures that this is accomplished without comprising from the quality of the line voltage and current.

Key words: multi-pulse, FACTS, Matlab simulation, power line compensation, power flow control, PWM inverter, H-bridge Inverter, quasi-resonant

Biography:

Taha Selim USTUN received his Bachelors degree in Electrical and Electronics Engineering from Middle East Technical University, TURKEY in 2007. He is currently an M. S. candidate in the Department of Electrical Engineering, University Malaya, Malaysia. His research interests are Power electronics, Power Systems and FACTS devices.

INTRODUCTION

The electric energy supply systems of the contemporary world, as usually dubbed as interconnected systems, are interconnected on a wide scale growing radially from intra-utility connections in their respective regions to inter-utility connections with other utilities and finally to international connections that bonds the energy systems of different countries. The motivation behind this idea is to pool the power plants and load centers in order to minimize the total power generation capacity along with the generation costs and improve the reliability of the grid since the transmission interconnections can take advantage of different types of load, source availabilities and fuel prices. (Hingorani, N., L. Gyugyi, 1999)

Although the amount of the power transmitted over power lines, power demand of the loads, access by the third parties to the lines and the bulk power transfers are increasing with every single day, due to a variety of environmental, land-use and regulatory pressures and high costs of new power line construction the growth of electric power transmission facilities in many parts of the world is restricted.(Asare, P., T. Diez, 1994) In order to meet the ever-growing power demand, utilities prefer to rely on already existing generation and power export/import arrangements instead of building new transmission lines that are subject to environmental and regulatory policies. This in turn loads the lines heavier than ever before. This can also be justified in the sense that transmission lines operate way below their thermal limits. In the past, before the appearing of semi-

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conductor based switches, the dynamic changes occurring on the line cannot be compensated immediately as there was no device which switches fast enough for this purpose. Instead the transients occurring due to dynamic changes on the line were suppressed and/or compensated by large operating margins on the line. (Hingorani, N., L. Gyugyi, 1999) (Asare, P., T. Diez, 1994; Ying, X., Y.H. Song, 2003) However, with the latest technology incorporating solid state switches much faster and reliable control of the lines is possible. This in turn opens the way for loading the interconnected systems heavier and thus utilizing them close to their full capacity. (Ying, X., Y.H. Song, 2003)

Furthermore, with increasing power transfer and heavier loading, the power systems becomes gradually more complex to operate and the system may become less secure for riding through the major outages. (Asare, P., T. Diez, 1994; Paserba, J., 2003) As a result not only large power flows with inadequate control may be observed but also excessive reactive power and large dynamic swings may be experienced in different parts of the system which prevent the transmission interconnections to be fully utilized. (Hingorani, N., L. Gyugyi, 1999)

In order to meet these issues an extensive method of power flow control over the interconnected systems is needed. Flexible AC Transmission Systems, or FACTS in short, are the devices that respond do these needs by significantly altering the way transmission systems are developed and controlled together with improvements in asset utilization, system flexibility and system performance. (Habur, K., D.O. Leary, 2005) Various FACTS devices are used to control dynamically the voltage, impedance and phase angle of high voltage AC transmission lines which in turn makes it possible to operate a transmission line more closely to its thermal capacity thus increasing its transmission capacity, to change the impedance of transmission lines and thus control the power flow and to damp and filter undesired transients over the transmission system. (Paserba, J., 2003) (Singer, A., W. Hoffman, 2007)

Due to its significance wide range of research on FACTS devices is performed. The optimal location of FACTS devices (Mahdad, B., T. Barek, 2006), control strategies (Lin, Z., C. Zexiang, 2008), their impacts on power systems (Galiana, F.D., K. Almeida, 1996) and connection of renewable energy systems to the grid with the help of FACTS device (Molinas, M., J. Kondoh, 2006) are all can be counted as general research topics in this field. The Static Synchronous Series Compensator, or SSSC in short, which is a specific type of FACTS devices and the main focus of this paper, is also popular in research projects. Analysis of different topologies such as 12-pulse (Padiyar, K.R., N. Prabhu, 2003) or 48-pulse inverter (Geethalaksmi, B., T. Hajmunnisa, 2007), based on voltage source converter (Han, B., S. Moon, 2000) or current source converter (Ye, Y., M. Kazerani, 2001) and their dynamic characteristics is performed on different topologies and the literature is very rich in this field. Furthermore the controller implementation for stabilization and better performance is also a very dynamic research field with proposed enhanced controllers for different kind of topologies or utilization purposes. (Zhao, Y., X. Xiao, 2008; El-Moursi, M.S., A.M. Sharaf, 2005)

This study is mainly composed of design of the SSSC with a 48-pulse PWM inverter and the simulation of its compensation characteristics over a modeled power line. The motivation in utilizing a multi-pulse inverter is to increase the quality of the output waveform. The compensation of the reactive power over Q the power line and allocation of larger portion of the overall power transmission capacity to the real power P is the ultimate goal of the designed system.

System Configuration:

A power system, which is shown in Figure 1, is modeled with a three phase source, a line inductance characterizing the power lines and three phase load at the receiving end. Bus B1, connecting the three phase source to the power line measures the voltage supplied by the source and current drawn from it whereas bus B2 connecting the three phase load to the power line measures the voltage and current supplied to the load. From these measured values 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 static synchronous series compensator are calculated. The position of the buses B1 and B2 are important in the sense that they are placed before and after, respectively, the transmission line inductances and the transformer connecting the static synchronous series compensator to the power system and thus the affect of the compensation can be observed.

The power source is set to generate 230 kV three phase voltages with 50 Hz. This value is selected so that the simulated power system emulates a long transmission line or high voltage transmission line (Wildi, T., 1991) depending on the classification method used. A purely resistive load is used in this example with the concern of observing the change in the line current due to compensation more easily. The line inductance value is also exaggerated for the same objective.

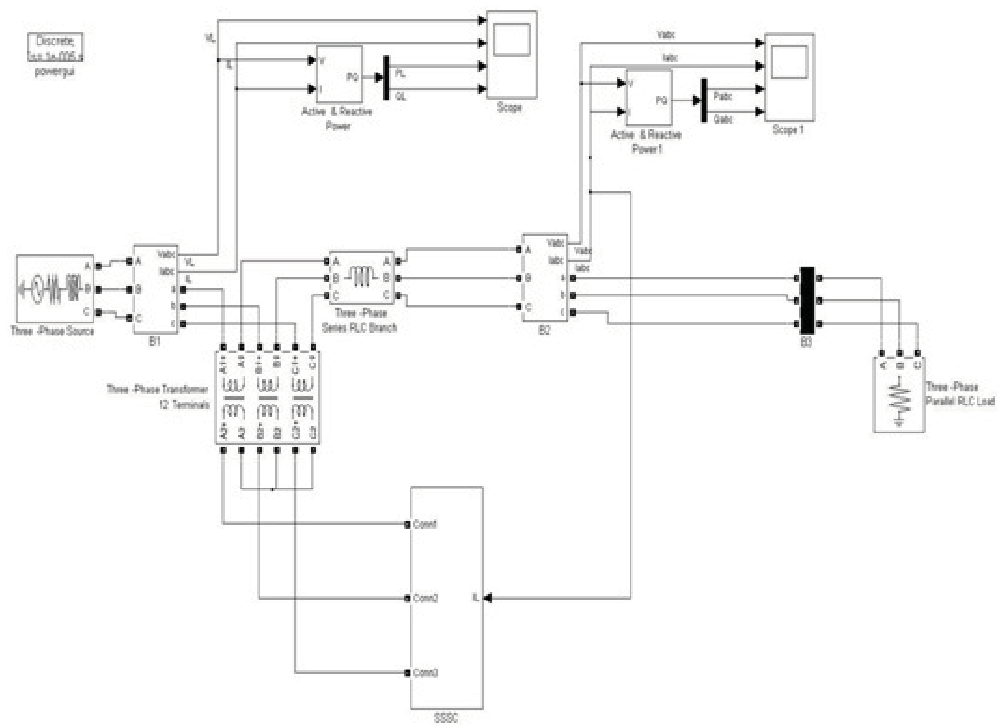

Fig. 1: Simulated Power Line and SSSC

Static Synchronous Series Compensator used in the simulation is given in Figure 2. Following the hierarchy of SSSC there are two sub-blocks which are quasi-resonant dc supply, shown in Figure 3, to provide soft switching and closed loop control, shown in Figure 4, for synchronization, compensation and PWM signal generation.

Figure 3 shows the quasi-resonant topology used in the system which is a deviated DC supply in the sense that the output of this supply is not a constant dc value but rather a dc value that occasionally goes down to zero whenever the resonance is triggered. This is useful in realization of zero voltage switching technique to reduce switching losses over the semi-conductor switches. The topology has been designed exclusively for quasi-resonance purposes (Hui, S.Y.R., *et al*., 1996) and its compatibility with H-bridge IGBT multi-pulse inverters have also been investigated in detail. (Ustun, T.S., S. Mekhilef, 2008)

The closed loop control shown above is used to determine phase angle of the line current flowing over the transmission line, then a phase shift of pi/2 radians is applied and then the PWM signals triggering the inverters used in multi-pulse inverter are generated from these data by the designed PWM generator. The PWM generator generates the sine waves with the angle given and generates the PWM signals by comparing this signal with the carrier frequency according to the value of the modulation index.

The section that is enclosed by the broken lines is an optional control which can be utilized to enhance the control of Q-flow over the line. However it is not indispensible as far as the implementation of static synchronous series compensator is concerned since the ultimate target of 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 whole of the injected voltage is capacitive. Throughout the simulation studies the idealized control loop is used to decrease the calculation load on the computer.

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. However, due to the transmission line inductance there is an amount of reactive power Q demanded. The simulations are performed to see the power demands, voltage and current supplied by the

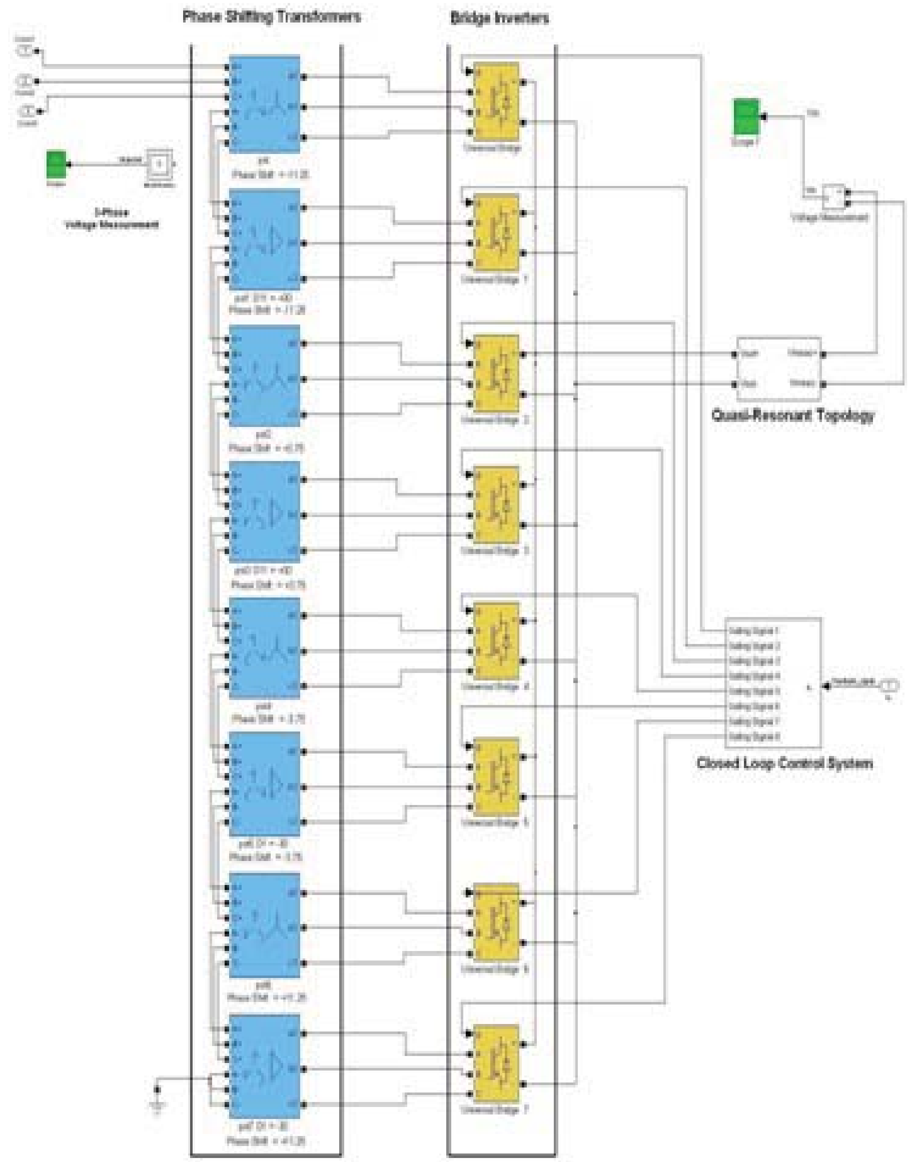

Fig. 2: Static Synchronous Series Compensator (SSSC) in MATLAB

source, transmitted by the line and received by the load. Following these observations Static Synchronous Series Compensator (SSSC) is operated to decrease the Q-flow over the line by compensating the reactive power demanded by the line inductance.

Firstly simulations were carried out when the Synchronous Series Compensator (SSSC) is switched off. The three phase source and load voltage, current waveforms along with the real and reactive power flow are obtained as shown in Figure 5 and Figure 6, respectively. The same parameters are observed after switching on the SSSC and the waveforms shown in Figure 7, Figure 8 and Figure 9 are obtained. The signal over the feedback loop and control signals for the closed loop control are given in Figure 10 whereas the output voltage of the multi-pulse inverter, which is the voltage that is injected to the line, is given in Figure 11.

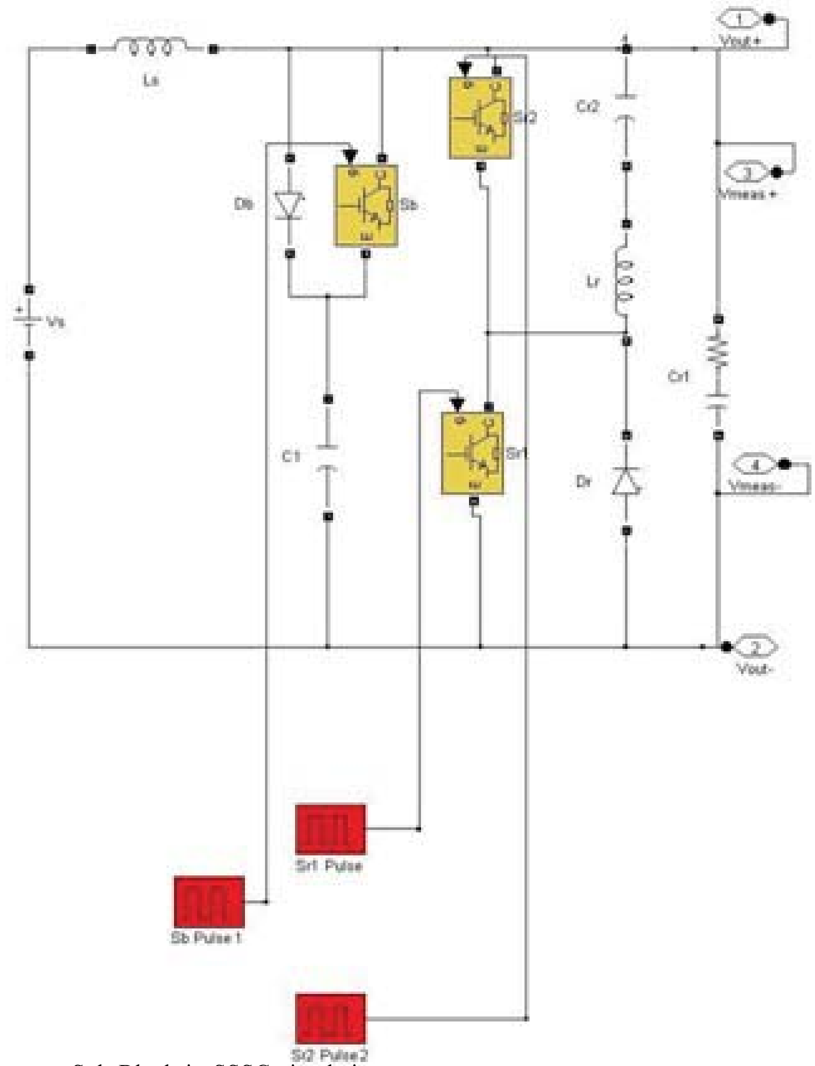

Fig. 3: Quasi-Resonant Sub-Block in SSSC simulation

Analyzing the results and the waveforms it can be said at ease that the synchronization and compensation are performed satisfactorily by the designed Static Synchronous Series Compensator (SSSC). The feedback signal which is generated from the line current flowing over the power line is used to generate the PWM signals and this way both synchronization and 90 degrees phase difference with the line current are achieved.

In order to interpret the result a comparative approach would be appropriate for the waveforms obtained before and after the SSSC is operated. The line voltage and current shown in Figure 5 clearly depict the phase difference between them induced by the inductive current drawn by the line inductance. Accordingly the reactive power Q drawn from the source reaches considerable values. The level of the real power P, which is delivered to the three phase load, should also be noted here in order to compare with the value under compensation conditions.

After turning on the SSSC the effect of the compensation is evident from the decreasing phase difference between the three phase line voltage and 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 used to be under non-compensation circumstances, the reactive power flow Q over the line reduces considerably. This 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 of the line inductance is met by the output voltage of Static Synchronous Series Compensator.

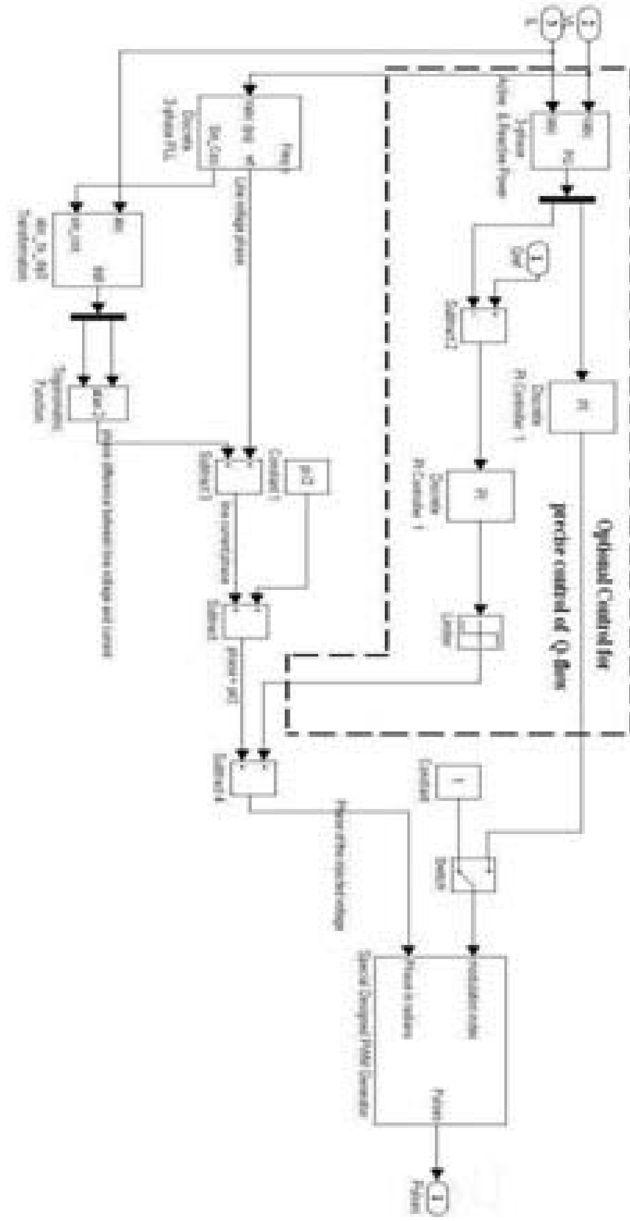

Fig. 4: Closed Loop Control of SSSC

Returning back to the fundamental motivations of series compensation it is out of question that reactive power flow Q over the transmission line is desired to be as low as possible so that the transmission capacity is allocated to the power demand of the load. Considering the figures 6 and 9 the rise in the real power transmission P to the same load with the same source settings and same line voltage waveform can be observed.

The effects of the compensation are summarized in Table 3.2 where it can be clearly seen that the real power P transmission from the source to the load becomes five times larger whereas the reactive power Q demanded from it is reduced to one third of its previous value. These changes are obviously the results of the phase difference that is caused by the compensation which reduces that 45^0 of line current lagging to a mere 5^0. Looking at the overall real and reactive power ratio it is observed that the ratio has improved ten times. When the apparent power is calculated from the equation;

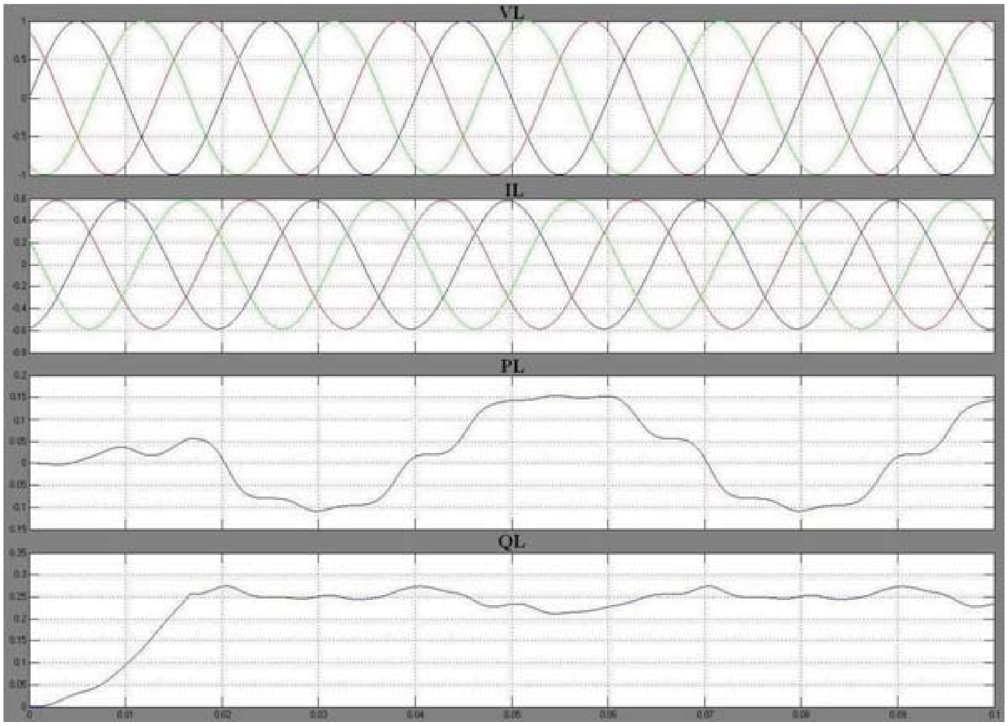

Fig. 5: Three phase Source Voltage, Current, Real and Reactive Powers (SSSC OFF)

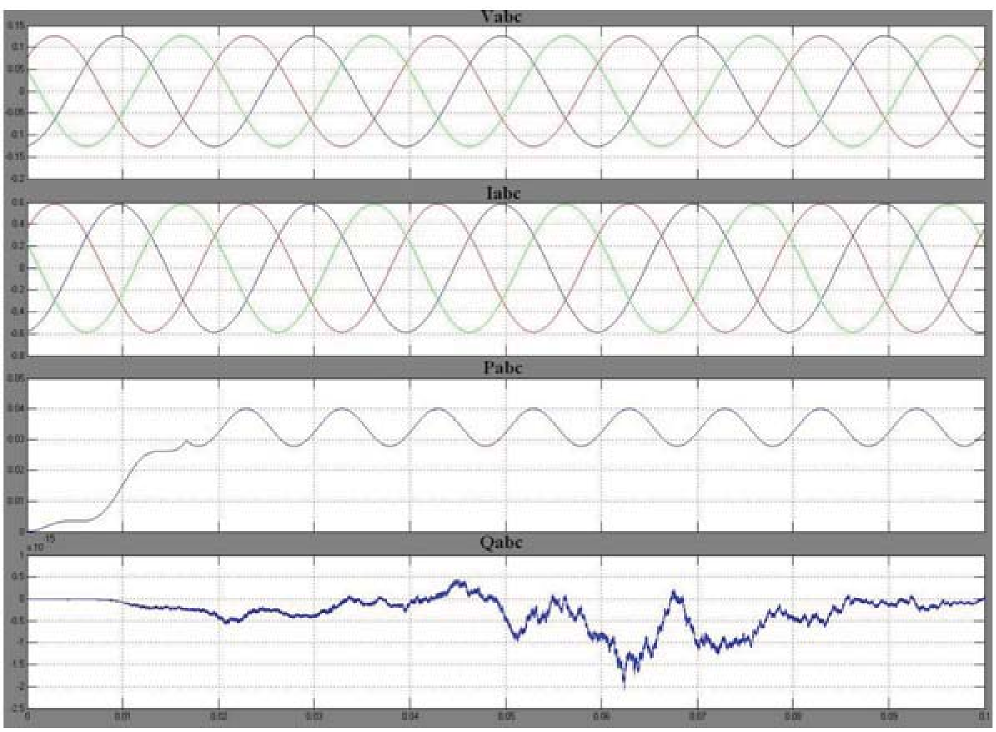

Fig. 6: Three phase Load Voltage, Current, Real and Reactive Powers (SSSC OFF)

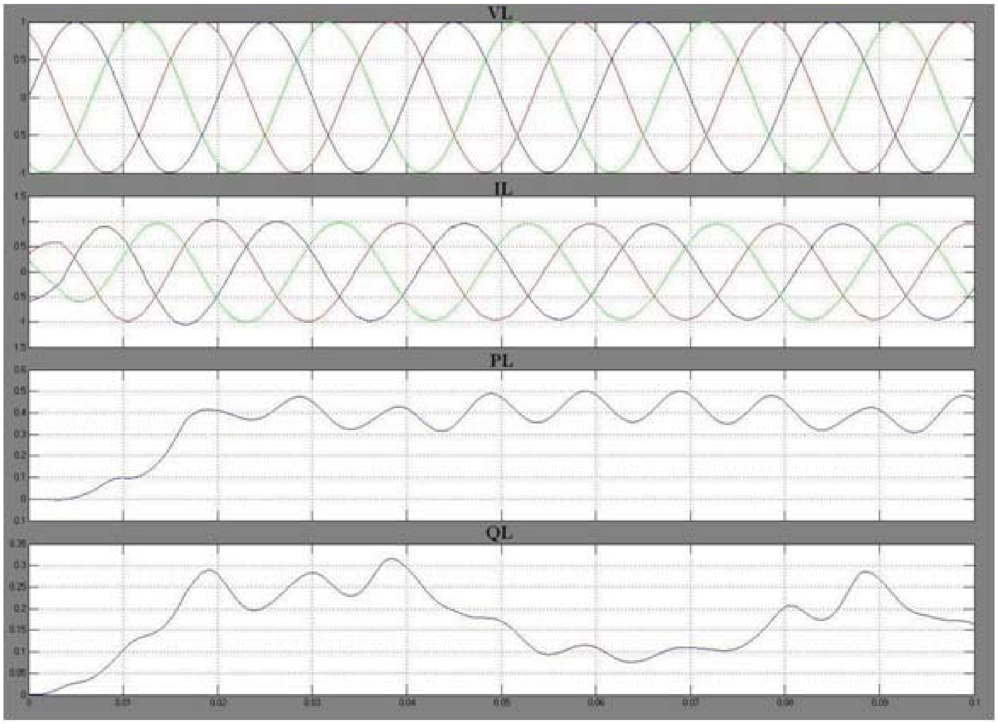

Fig. 7: Three phase Source Voltage, Current, Real and Reactive Powers (SSSC ON)

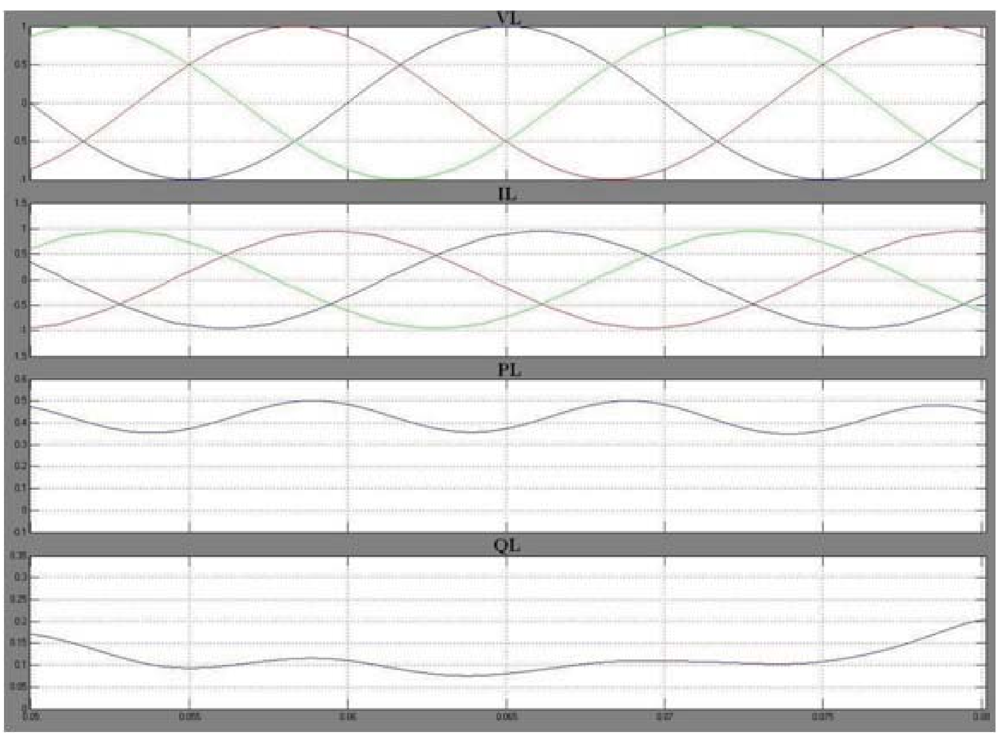

Fig. 8: Three phase Source Voltage, Current, Real and Reactive Powers (SSSC ON – close up)

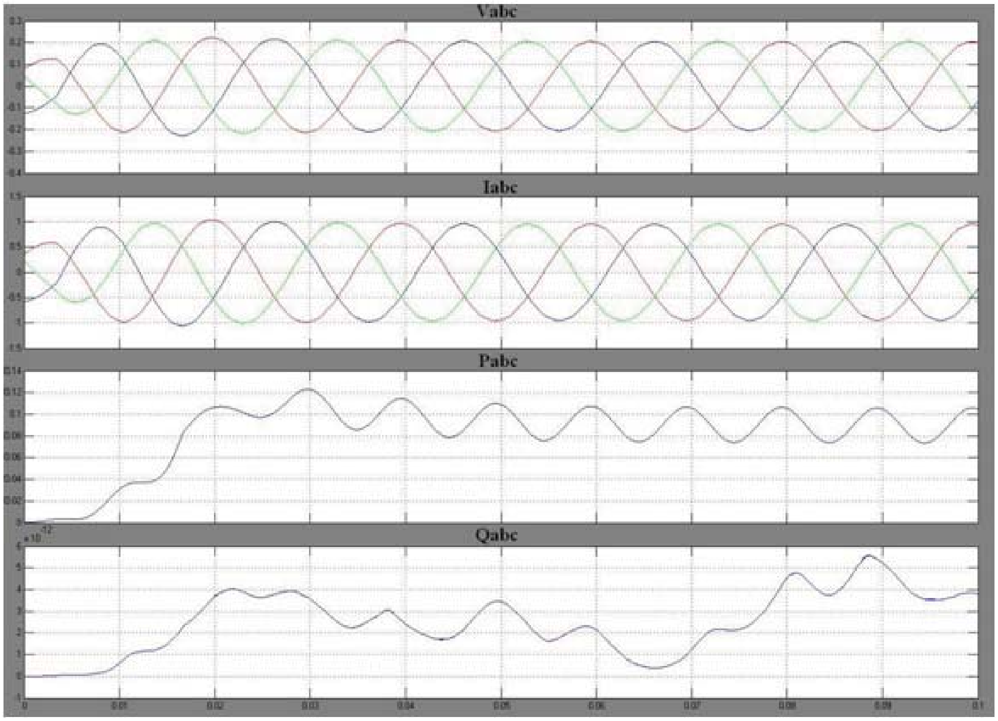

Fig. 9: Three phase Load Voltage, Current, Real and Reactive Powers (SSSC ON)

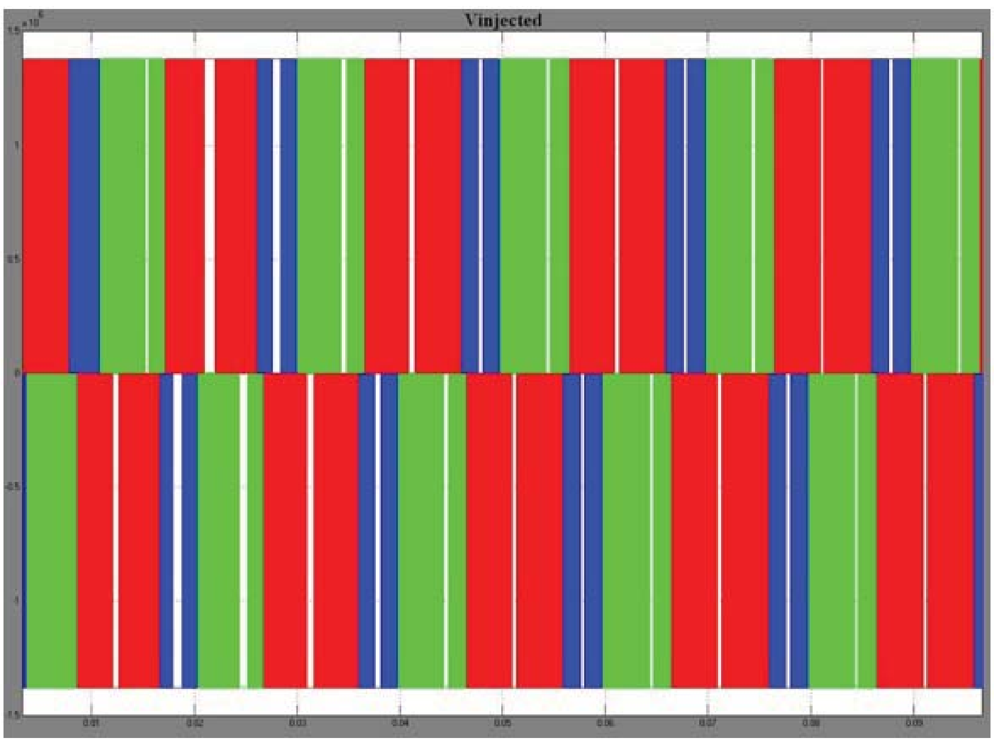

Fig. 10: Injected Voltage by the SSSC (Inverter Output Voltage)

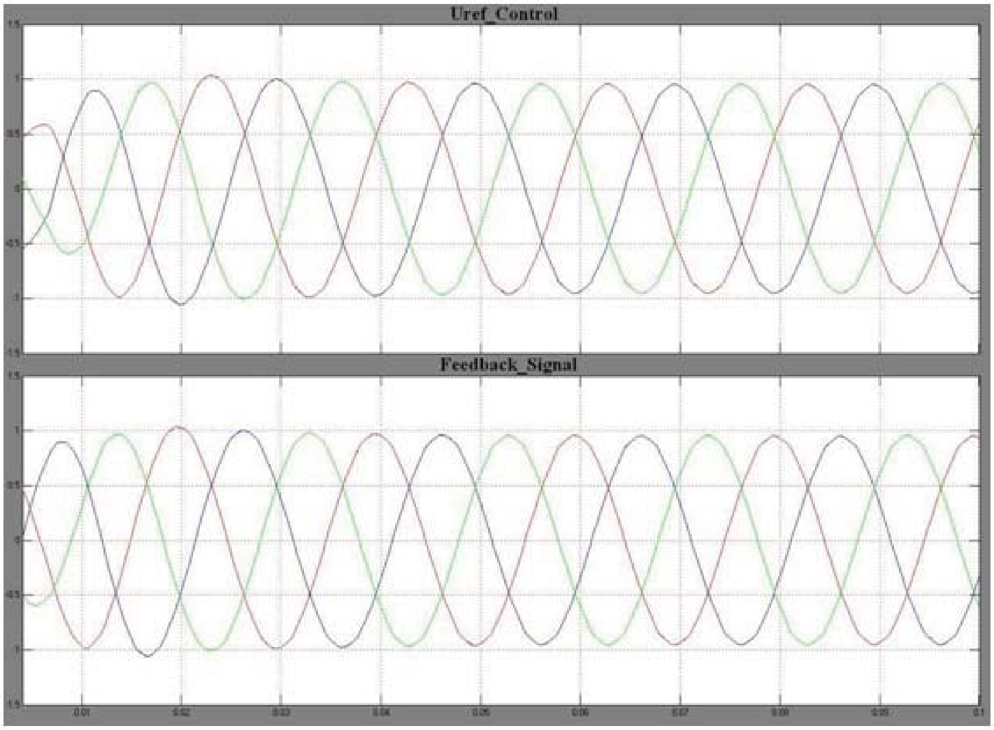

Fig. 11: Feedback Signal and Uref_control signal for PWM generation

Table 1: Effects of SSSC Compensation

SSSC STATUS	Phase difference	Psource (pu)	Qsource (pu)	Pload (pu)	P/Q ratio	% of capacity allocated for P
OFF	45^0	0.15	0.27	0.035	0.55	48.38
ON	5^0	0.5	0.1	0.1	5	98.03

$S^2 = P^2 + Q^2$

Mohan, N., T. Undeland, 1995 and calculating the ratio of the allocated real power transmission capacity to that of apparent power it is seen that the allocation percentage has almost doubled. Consequently another aspect of compensation is also realized and simulated with success.

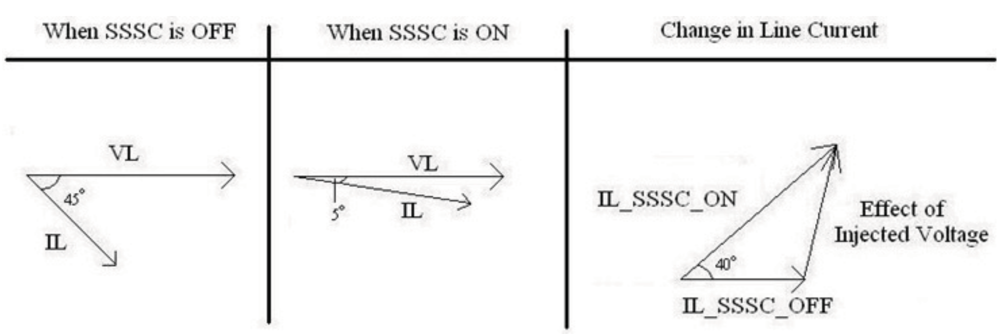

Fig. 12: Line Voltage and Current Phasor Diagrams

The phasor diagram given above in Figure 12 is a method of compensation and the effect of the injected voltage in a visual manner. It is not only descriptive but also lucid and thus is widely used in power system analysis. On the left the three phase voltage and current phasor diagram for non-compensated network is given. Due to the line inductance the current drawn from the source has a phase difference with the voltage supplied by it and as expected the phase difference is inductive, consequently the line current is lagging the line voltage. When the SSSC is turned on the compensation decreases the effect of the line inductance and as a result of this the phase difference between the line voltage and current decreases. This in turn, obviously, decreases the reactive power supplied by the source. Should it be desired it is possible to increase the amount of compensation and the line current flows in phase with the lie voltage which makes the reactive power flow zero, or even the compensation may be increased furthermore and a capacitive transmission line appears in front of the three phase source. In this simulation to be more realistic and to see the compensation total negation of inductive effect of the line inductance is not implemented.

One of the biggest challenges in inverter grid connection and voltage injection studies is the appearance of harmonic distortion due to the injected voltage and/or current. (Kisck, D.O., V. Navrapescu, 2007) In order to be able to assess the quality of the line current total harmonic distortion THD analysis of the line currents are performed both under compensated and non-compensated circumstances. The results for THD analysis are presented in Figure 13 to Figure 16.

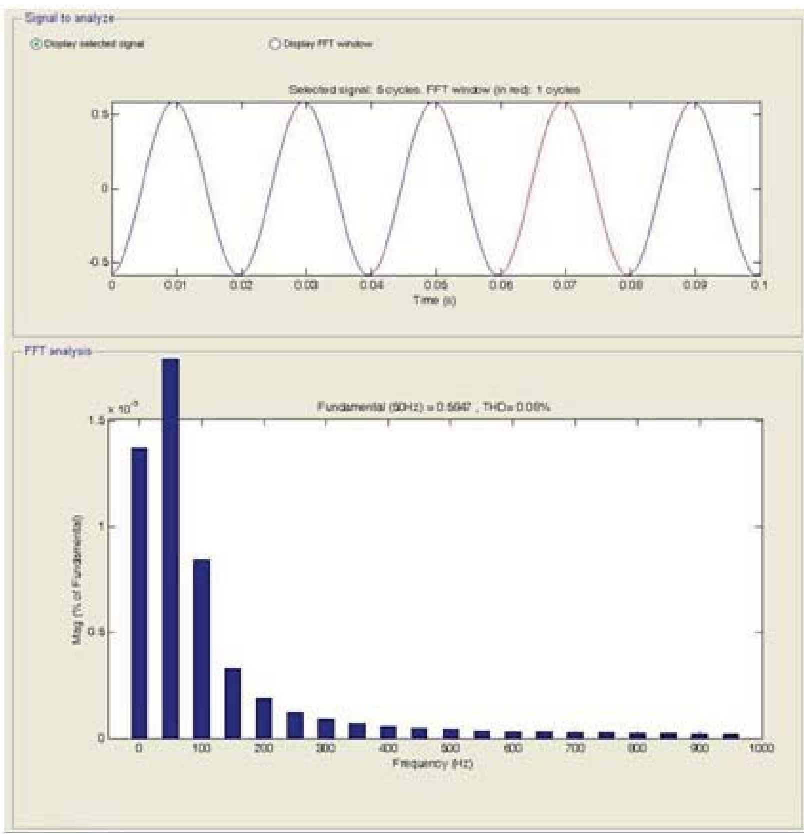

Fig. 13: Line Current THD Analysis (at Bus B1 – SSSC OFF)

The figures show that the injected voltage has a negative effect on the harmonic distortion of the line current. However, in spite of the change in THD value, the compensated current has a very low harmonic content and is acceptable according to harmonic rules and regulations. (IEEE, 2000)

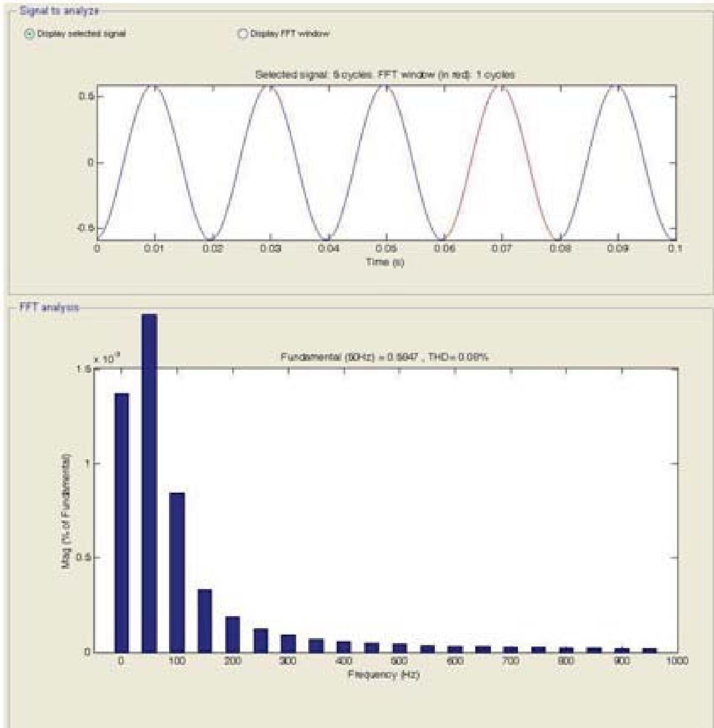

Fig. 14: Line Current THD Analysis (at Bus B2 – SSSC OFF)

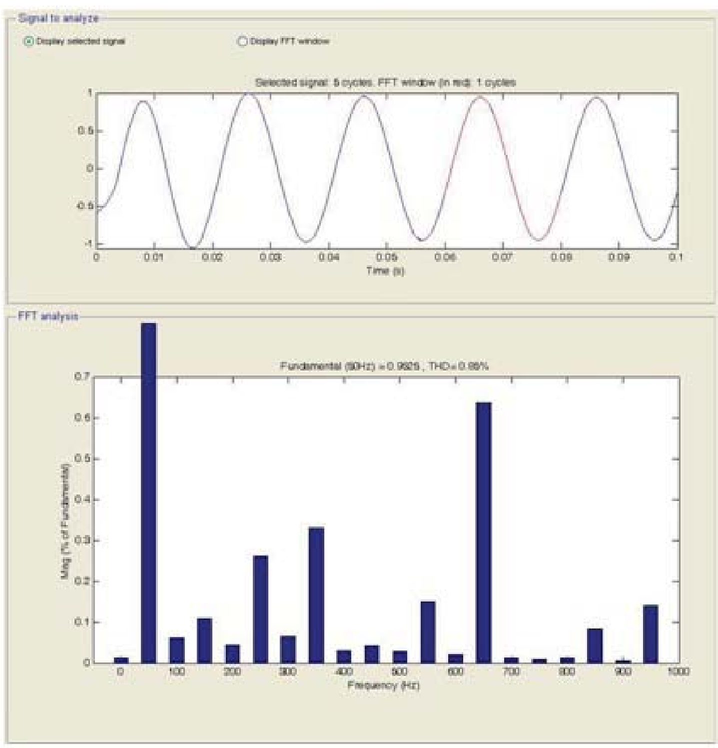

Fig. 15: Line Current THD Analysis (at Bus B1 – SSSC ON)

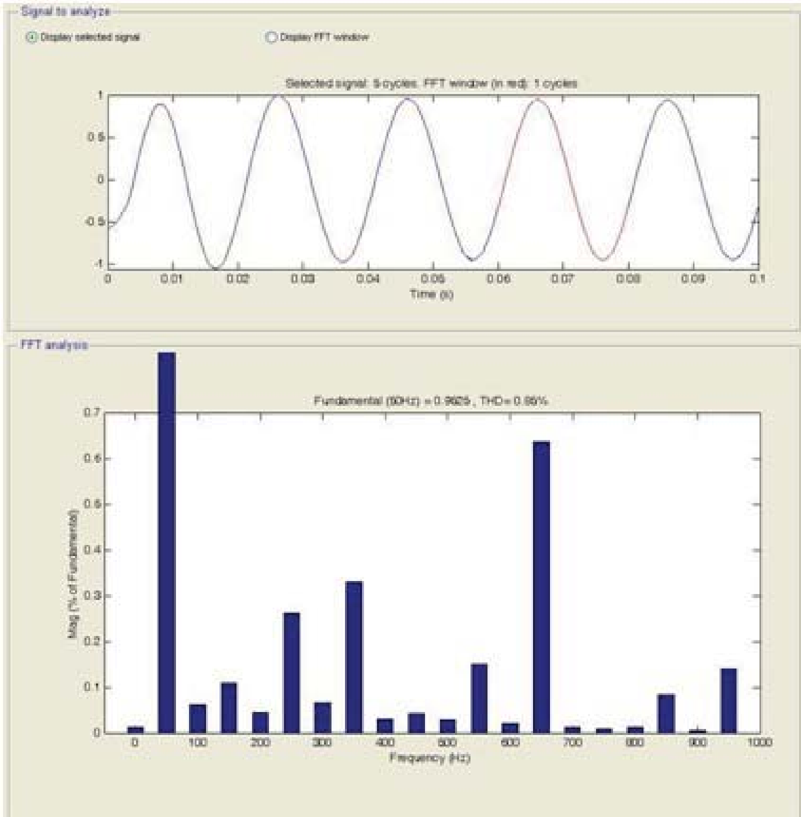

Fig. 16: Line Current THD Analysis (at Bus B2 – SSSC ON)

Conclusion:

In this paper a Static Synchronous Series Compensator (SSSC) is constructed from a conventional 48-pulse inverter. A detailed closed loop control is designed to control the power flows over the power line. The operation of the designed device is verified by a series of simulations in MATLAB environment and the obtained results proved to be satisfactory. The Total Harmonic Distortion (THD) studies performed both when SSSC is on and off shows that the harmonic content introduced to the line current is very low. This is due to the utilization of a multi-pulse inverter in the construction of the device, which inherently filters harmonics up to certain levels and thus enhances the output waveform quality.

The voltage and current waveforms along with the instantaneous active and reactive power calculations reveal that the designed topology works satisfactorily. The compensation of the reactive power flow over the power line due to the power line inductance is compensated with the help of series injected voltage. The balance or the stability of the system is not affected and the harmonic distortion is kept to reasonable levels thanks to the multi-pulse inverter used in the construction of the device.

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