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Research Article

Sliding Mode Control of H Bridge Inverter Based DSTATCOM for Reactive Power Compensation

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Abstract: Reactive power compensation plays a key role in reducing distribution losses by improving power factor. A three phase three wire DSTATCOM consisting of a five level H-bridge Voltage Source Converter (VSC) is proposed for improving power factor in the distribution system at the Point of Common Coupling (PCC) when the load is continuously changing. The sliding mode control algorithm is used for reactive power compensation and achieve unity power factor. To accomplish this DSTATCOM is controlled to supply or absorb reactive power at PCC. Sinusoidal PWM method is used for obtaining the switching pulses for the cascaded H-bridge converter. The performance of the DSTATCOM controlled distribution system is validated by simulations using MATLAB/Simulink software and Power System block set toolboxes.

Keywords: Multi level inverter, power quality, power factor, reactive power compensation, sine PWM, voltage source converter

INTRODUCTION

In the recent years, there has been a considerable interest in power quality. This is mainly due to the increase in nonlinear loads such as power electronic converter based adjustable speed drives, electronic ballasts etc., which have deteriorated the power quality. The power quality problems mainly include load unbalance, excessive neutral current, high reactive power burden and larger harmonic currents, apart from voltage sag and swell (Akagi *et al*., 2007; Lin and Ou, 2004). Therefore, reactive power compensation of change in inductive load plays a significant issue in the modern power distribution systems. The distribution static compensator (DSTATCOM) has been used extensively for power factor improvement, balancing of load current and harmonic mitigation in the distribution systems (Chen and Hsu, 2008). The main function of the VSC based DSTATCOM is to either injects or absorbs reactive power from the grid for improving power factor and to maintain zero voltage regulation. By a suitable control approach, the DSTATCOM can be used as an active filter and a dynamic uninterruptable power source. It may be noted that the active filter in this context does the work of filtering the lower order harmonics apart from reactive power compensation. The power quality in distribution systems can be improved by eliminating harmonic content of load, balancing source currents when the loads are unbalanced apart from improving poor load power factor (Ghosh and Ledwich, 2003; Hurng-Liahng *et al*., 2008; IEEE Std. 519, 1993). To increase the power rating of DSTATCOM, high voltage switching devices have to be connected in series to reduce the current rating of individual switches. Several new inverter topologies have been used in high voltage FACTS, custom power equipment and industrial drives. Multilevel inverter has drawn attention of many researchers. Multilevel converters based on neutral point clamped philosophy and cascaded H-Bridge converters are widely used for high power conditioning applications (Ledwich and Ghosh, 2002). A cascaded five level H bridge inverter based DSTATCOM has been proposed for reactive power compensation. The implementation of H-bridge converters for DSTATCOM leads to reduced harmonics currents and a decrease in cost. The major advantages of the H-bridge converters are an improvement in power rating, modularity and cost effective compared to other topologies. The output voltage of the cascaded H-bridge converter is the summation of the output voltage of the individual H-bridges (Montero *et al*., 2007). By connecting a number of H-bridge converters in series, the output voltage of the VSC based DSTATCOM can be increased. To achieve the quality of output waveform in the cascaded H bridge converters same as its individual counterpart, the switching frequency of the converters can be decreased. The decreased switching frequency results in reduction of switching losses as well.

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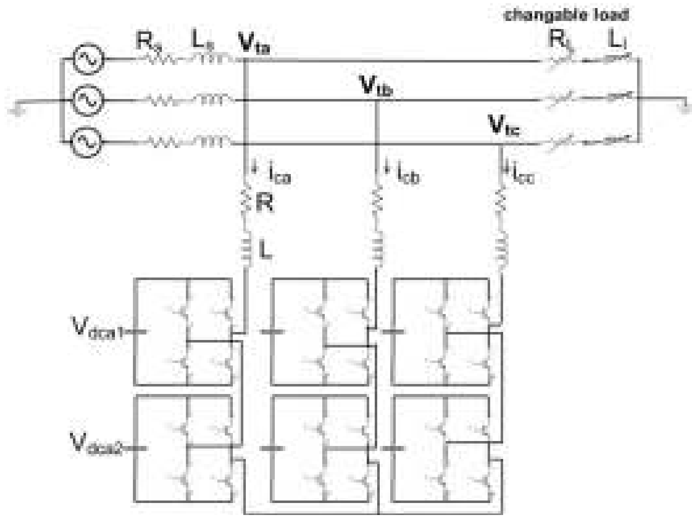

Fig. 1: Model of the DSTATCOM controlled distributions system

PI controllers are widely used control schemes for the control of the DSTATCOM (Muni *et al*., 2003). The PI controller with decoupled control algorithm is used in Singh and Solanki (2009). However the DSTATCOM is nonlinear and the linear control approach does not give the required steady state response. Several nonlinear control algorithms are proposed to design the DSTATCOM controller. A discontinuous feedback control is used in Singh *et al*. (1999, 2000). Passivity sliding mode control is proposed in Hung-Chi and Chia-Chi (2006) and Mingchao and Yanhui (2013) with a three level inverter. In this study sliding mode control technique is applied to a cascaded five level multilevel inverter based DSTATCOM for compensating reactive power. Sliding Mode Control (SMC) approach is used for designing non linear DSTATCOM controller for reactive power compensation. In designing the model, a changing load condition is considered. In designing SMC two control loops are used. The inner control loop is used for generating the PWM pulses for the H bridge inverter based DSTATCOM. The outer loop which is cascaded to the inner loop is designed to maintain the dc capacitor voltage as constant and achieve the required reactive power compensation at PCC.

Proposed DSTATCOM: The schematic diagram of the proposed system with the three phase three wire VSC based DSTATCOM is shown in Fig. 1. The changing load is connected at the Point of Common Coupling (PCC). The DSTATCOM can be operated in reactive power compensation (power factor correction) mode at the PCC to the reference value. When operated in the power factor correction mode the source current is controlled to be in-phase with the PCC voltage. For reactive power compensation of the load, the DSTATCOM has to supply reactive power of the load with same magnitude, but of opposite sign. Thus, the reactive power drawn from the source is zero. If the reactive power supplied by the source is monitored and controlled in closed-loop fashion to maintain it at

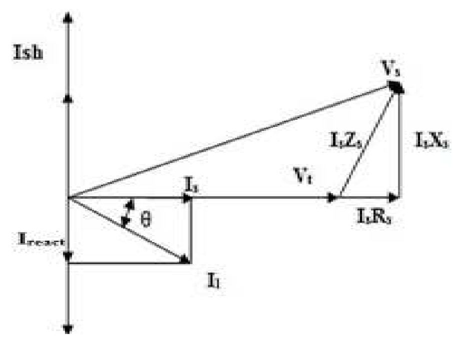

Fig. 2: Phasor diagram for UPF operation

zero value, then the objective of reactive compensation/power factor improvement can be achieved as shown in Fig. 2 with the aid of the phasor diagram. In Fig. 2 the reactive component I_{react} of the load current I_l is exactly out of phase with DSTATCOM current I_{sh} for UPF operation. In the phasor diagram V_t represents the terminal voltage at PCC, I_s is the source current and R_s, X_s are the line parameters of the system and θ is the angle between terminal voltage V_t and source current.

The mathematical model of the DSTATCOM in three phase coordinates are given by:

$$L\frac{di_{ca}}{dt} = V_{ta}(t) - V_{ca}(t) - Ri_{ca}(t) \quad (1)$$

$$L\frac{di_{cb}}{dt} = V_{tb}(t) - V_{cb}(t) - Ri_{cb}(t) \quad (2)$$

$$L\frac{di_{cc}}{dt} = V_{tc}(t) - V_{cb}(t) - Ri_{cc}(t) \quad (3)$$

In the above equations $V_{ta,b,c}$ represents the PCC voltages, $V_{ca,b,c}$, $i_{ca,b,c}$ the DSTATCOM voltage and currents and R, L are the inverter loss components. The dq transformations are used for the analysis of DSTATCOM. For reactive power compensation the dq transformations are given by:

$$\begin{bmatrix} L\dfrac{di_d}{dt} \\ L\dfrac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} V_d \\ V_q \end{bmatrix} + \begin{bmatrix} -R & \omega L & -M\cos\delta \\ -\omega L & -R & -M\sin\delta \end{bmatrix} * \begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} \quad (4)$$

Here i_d and i_q are the dq components of the DSTATCOM currents, V_d and V_q are the dq components of PCC voltages and M represents the modulation index; δ is the angle between PCC voltage and DSTATCOM voltages and V_{dc} is the cumulative dc voltages of the H bridge inverter.

Control of DSTATCOM: A sliding mode control is used for designing the DSTATCOM controller. In Fig. 3 the controller is divided into inner loop and an outer loop. The outer loop is designed to generate the direct and quadrature axis currents which are fed to the inner loop. The sliding mode controlled inner loop will generate the required switching functions for generating the switching pulses for the H bridge inverter. The control strategy for reactive power compensation is given below. Let the state variables be $X = [x_1\ x_2]^T = [i_d\ i_q]^T$; the control variables $U = [u_1\ u_2]^T$. From equation 4 the output equation can be derived as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \dfrac{-R}{L}x_1 + \omega x_2 + \dfrac{V_{ds}}{L} \\ -\omega x_1 - \dfrac{R}{L}x_2 \end{bmatrix} + \begin{bmatrix} \dfrac{-V_{dc}}{L} & 0 \\ 0 & \dfrac{-V_{dc}}{L} \end{bmatrix} * \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (5)$$

Let $A = \begin{bmatrix} \dfrac{-R}{L}x_1 + \omega x_2 + \dfrac{V_{ds}}{L} \\ -\omega x_1 - \dfrac{R}{L}x_2 \end{bmatrix}$ and $B = \begin{bmatrix} \dfrac{-V_{dc}}{L} & 0 \\ 0 & \dfrac{-V_{dc}}{L} \end{bmatrix}$ (6)

$$\dot{X} = A + BU \quad (7)$$

$$U = B^{-1}(\dot{X} - A) \quad (8)$$

There will be two sliding mode controllers one for regulating dc voltage and another for maintaining reactive power to zero at PCC. In the dc voltage control loop, the error e_{dc} is given by:

$$e_{dc} = V_{dcref} - V_{dc} \quad (9)$$

The sliding surface is given by:

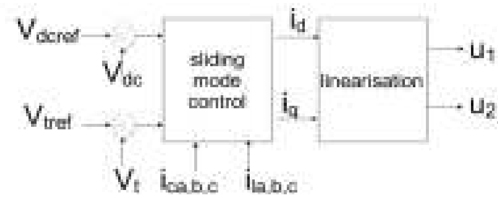

Fig. 3: Sliding mode control algorithm block diagram

$$S_1 = C_1 e_{dc} + C_2 e_{dc} \quad (10)$$

The d axis current is given by:

$$i_d = C_3 e_{dc} sign(S_1 e_{dc}) + C_4 \dot{e}_{dc}\, sign(S_1 \dot{e}_{dc}) \quad (11)$$

The reactive component of the load current of the i_{qload} is compared against the reference value i_{qref} to obtain the error in reactive current for reactive power compensation:

$$e_{rr} = i_{qref} - i_{qload} \quad (12)$$

The sliding surface is given by:

$$S_2 = C_5 e_{rr} + C_6 e_{rr} \quad (13)$$

The d axis current is given by:

$$i_q = C_7 e_{rr} sign(S_2 e_{rr}) + C_8 \dot{e}_{rr}\, sign(S_8 \dot{e}_{rr}) \quad (14)$$

Using Eq. (11) and (14) I_d and I_q currents are calculated and substituting this in Eq. (5), (6) and (7), the control variables u_1 and u_2 are calculated and the switching functions are calculated using sine PWM technique.

SIMULATION RESULTS AND ANALYSIS

The Simulink model of DSTATCOM controlled distribution system is built for the power circuit shown in Fig. 1 and system parameters are AC source voltage V_t = 400V(RMS); Line resistance R_s = 0.00010 Ω, line inductance L_s = 3 mH, DSTATCOM resistance R = 0.0001Ω, L = 0.1 mH, load resistance = 50 Ω, load inductance = 3 mH, single capacitor in the dc side = 60.2 mF. As depicted in Fig. 1 each phase of the DSTATCOM consists of two H-Bridge inverter connected in series. The DSTATCOM is controlled in such a way that the source current I_s should be in phase with the PCC voltage V_t. To accomplish this, the load current is continuously monitored and the H Bridge VSC has to supply or absorb reactive power based on the requirement of the load.

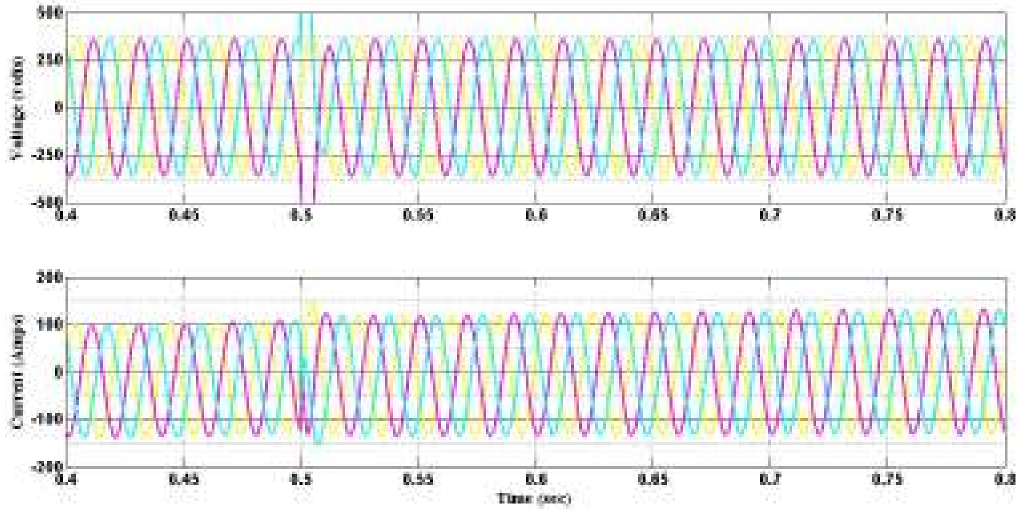

Fig. 4: Three phase voltages and currents at PCC

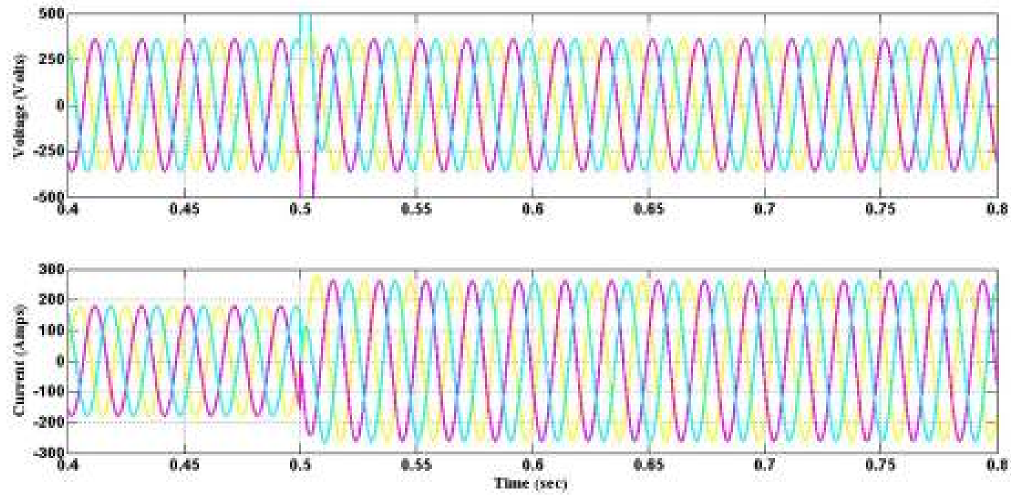

Fig. 5: Three phase load voltage and current

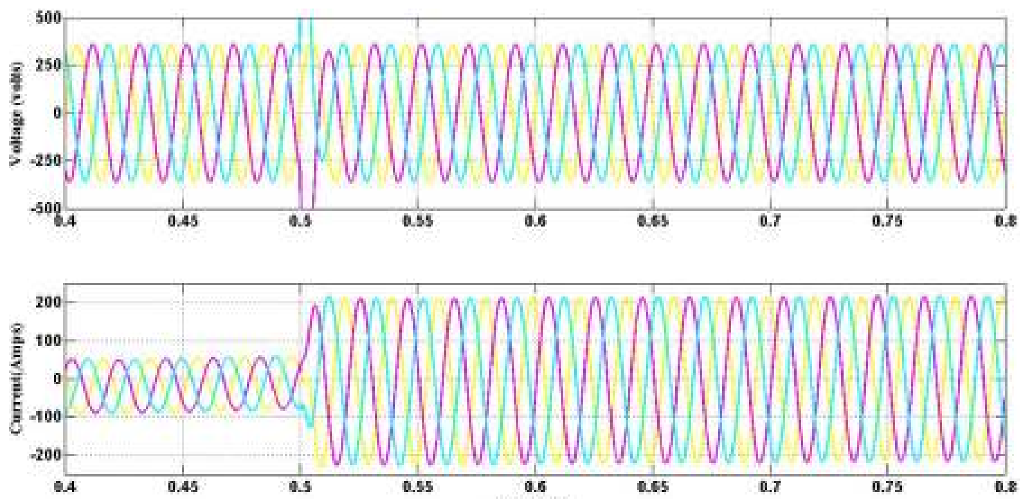

Fig. 6: Three phase DSTATCOM voltage and current

Simulation results have been obtained to validate that the sliding mode controlled DSTATCOM employed with Sine PWM switching pattern technique which operates in UPF mode. The load is modeled as a dynamic load and in simulation the load changes to a high inductive load at 0.5 sec. With this condition, Fig. 4 illustrates the three phase voltages and currents at PCC and Fig. 5 depicts the load voltages and currents. From Fig. 4 and 5 it can be seen that the PCC and load voltage remains constant at 400V (RMS) before and after the load change and the source current increase from 85A to 90A; the load current rises from 127A to 185A, respectively. The voltage and the compensating currents supplied by the DSTATCOM are shown in Fig. 6. The load real and reactive powers are shown in Fig. 7 and the real and reactive power supplied by the source is shown in Fig. 8. From Fig. 7 the real power supplied to the load is 96 KW and the reactive power increases from zero to 100 KVAR, respectively. The real power supplied by the source remains changes to 68 KW with the addition of the load at 0.5 sec. The power factor of the load changes from unity to 0.707 at the instant of 0.5 sec, but the power factor at PCC remains at unity irrespective of the load change as illustrated in Fig. 8 and 9. The details of the source, load and the DSTATCOM performance parameters are

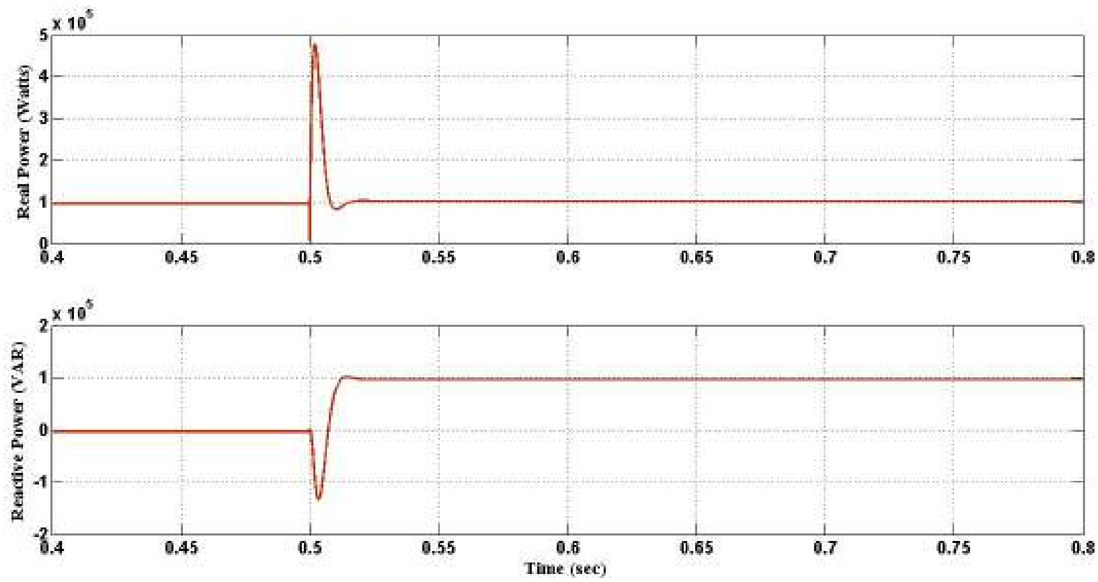

Fig. 7: Load real and reactive power

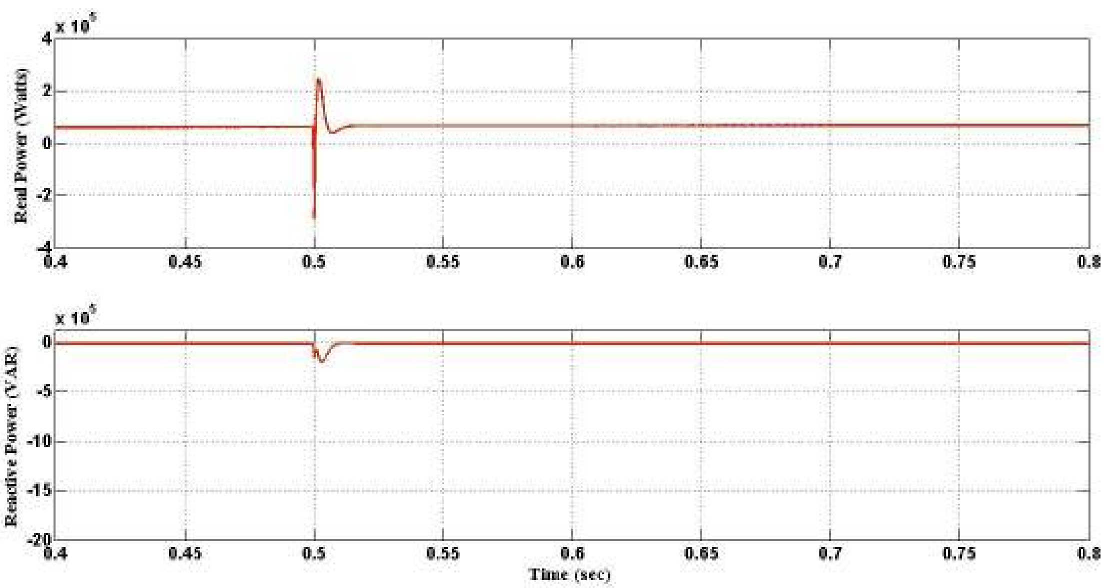

Fig. 8: Real and reactive powers at PCC

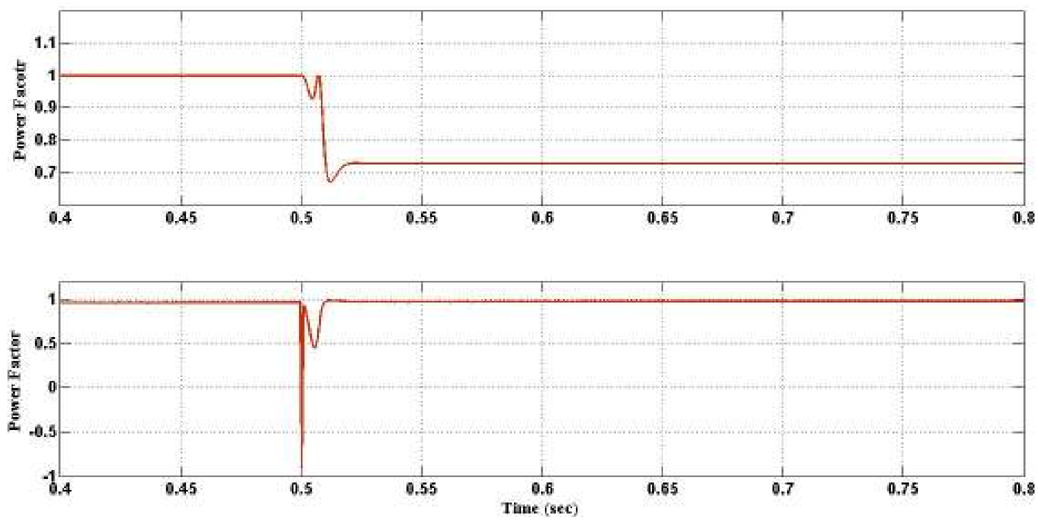

Fig. 9: Power factor at load and PCC

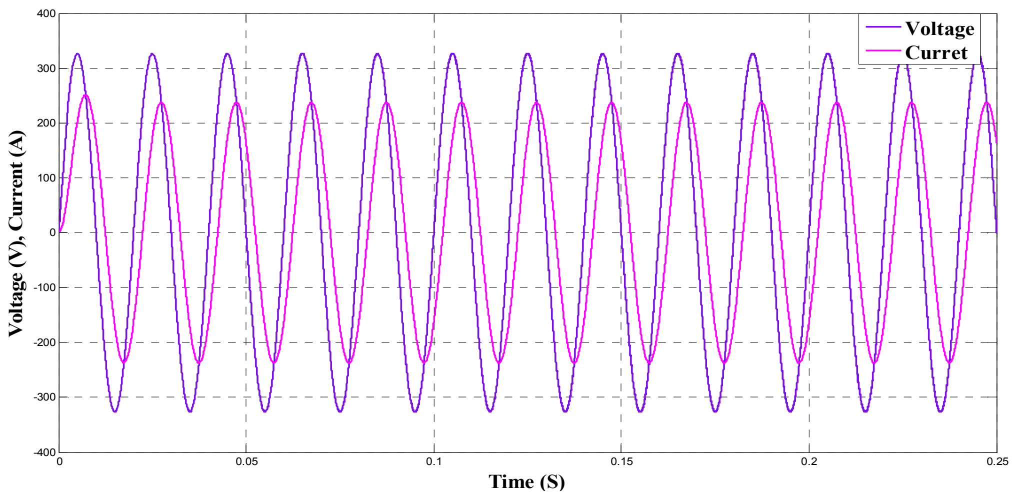

Fig. 10: Load voltage and load current

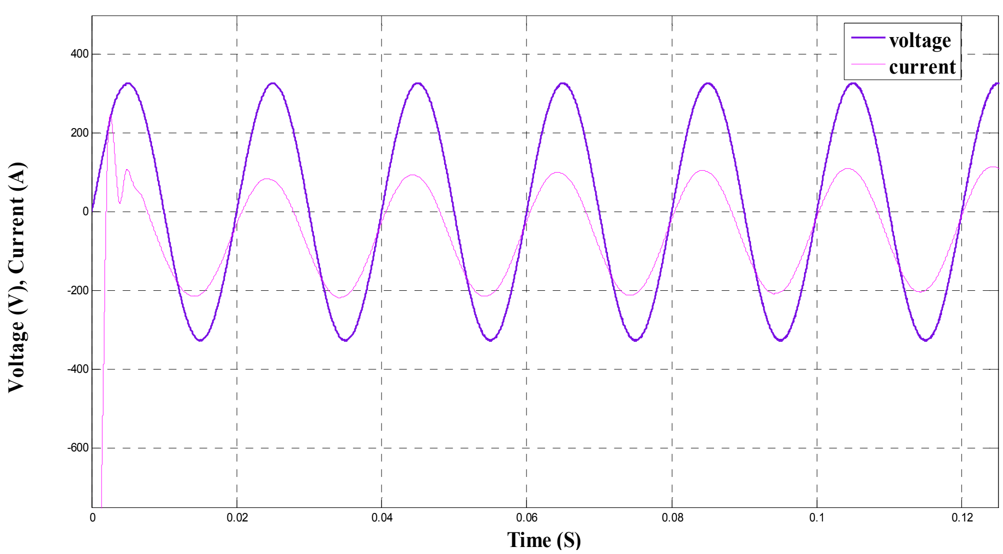

Fig. 11: PCC voltage and source current

Table 1: Power system performance with DSTATCOM

	PCC		Load		DSTATCOM	
Performance parameters	Before load change	After load change	Before load change	After load change	Before compensation	After compensation
Voltage (RMS)	400 V	400 V	400 V	400 V	400	400
Current (RMS)	85 A	90 A	127 A	185A	60 A	155 A
Real power	60 KW	68 KW	96 KW	102.5 KW	35 KW	35 KW
Reactive power	0	0	0	100 KVAR	0	-110 KVAR
Power factor	0.99	0.99	0.99	0.728 (Lag)	-	-

summarized in Table 1. Table 1 reveals that the entire reactive power demand of load is supplied by DSTATCOM. The wave forms of load voltage and currents, PCC voltages and currents are shown in Fig. 10 and 11. From Fig. 10, the load current is lagging behind the load voltage by 90o, but the source voltage and source current are in phase as shown in Fig. 11. Thus by using sliding mode control the objective of reactive power compensation is achieved.

CONCLUSION

In this study, the performance of sliding mode control of DSTATCOM employed with H-bridge VSC has been demonstrated for reactive power compensation in a three-phase, three-wire distribution system using MATLAB/SIMULINK. The simulation results exhibits that the DSTATCOM cater the entire reactive power needs of the load. Owing to this reason, with proposed DSTATCOM in the network, the power factor at PCC is unity. At the outset, it has been concluded that the sliding mode controlled DSTATCOM built with cascaded H bridge converter is a better option for the power factor correction in the distribution system.

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