

Performance Evaluation of Three Single Phase Voltage Source Inverter Based Configuration of DSTATCOM

Alka Adya¹ Bhim Singh² A.P. Mittal³

Abstract – This paper deals with the detailed modeling and simulation of a three-phase four-wire Distribution Static Compensator (DSTATCOM) used as a shunt compensator. This DSTATCOM configuration consists of three single-phase voltage source inverter (VSI) bridges having a common dc link. The model is developed using MATLAB/Simulink and tested for a variety of linear as well as non-linear loads. The ability of this compensator is demonstrated in improving various facets of power quality viz. power factor correction, voltage regulation and harmonic reduction. Comparisons with existing and well known DSTATCOM configurations are made and analyzed in detail.

Keywords – DSTATCOM, power quality, voltage regulation, harmonic reduction

I. INTRODUCTION

There has been a rapid rise in the development of power electronic based compensators. This has led to the development of FACTS as well as custom power devices for transmission as well as distribution systems [1-3]. Power quality issues have been a major concern for power engineers worldwide [4-8]. As a result, development of custom power devices is increasing for load compensation in distribution systems [9-13]. DSTATCOM is a popular shunt compensator having the ability to provide reactive power compensation. Both three-phase and single-phase DSTATCOMs can be designed for compensation of different load configuration. One of the most commonly used configurations of DSTATCOM is the three-leg VSI based configuration for three-phase, three-wire system. A three-phase, four-wire system also has an additional conductor. In the presence of neutral conductor, possible DSTATCOM configurations are four-leg VSI or a three-single phase VSI. This paper deals with the modeling and simulation of a three-single phase VSIs based DSTATCOM which has a number of advantages over its four-leg VSI counterpart. Each single-phase VSI has lower kVA rating and the cost of components such as DC capacitor, Insulated Gate Bipolar Transistor (IGBT) switches having low voltage and the current rating can also be effectively reduced. Moreover, modular approach involving three single-phase VSIs gives better flexibility and enhanced control.

II. STYLE INFORMATION

The DSTATCOM system configuration considered here consists of a three-phase, four-wire ac source feeding a variety of loads. A three-phase, four-wire ac source with supply impedance (L_s , R_s) feeds power to balanced/unbalanced linear/non-linear loads. Fig. 1 shows the basic diagram of DSTATCOM connected as shunt compensator to the distribution system via three single phase transformers. The DSTATCOM configuration considered here consists of three independent single-phase voltage source inverters having a common dc bus. Three-VSI bridges are connected together at the dc link at which a dc bus capacitor (C_{dc}) provides a self-supporting dc bus. This scheme requires three single-phase transformers or a three-phase transformer with access to individual windings. The control scheme consists of providing gating pulses to the three VSI bridges. The control algorithm is suitably modified to improve various power quality features. Another advantage of this DSTATCOM configuration is that the current in neutral wire is controlled to zero value.

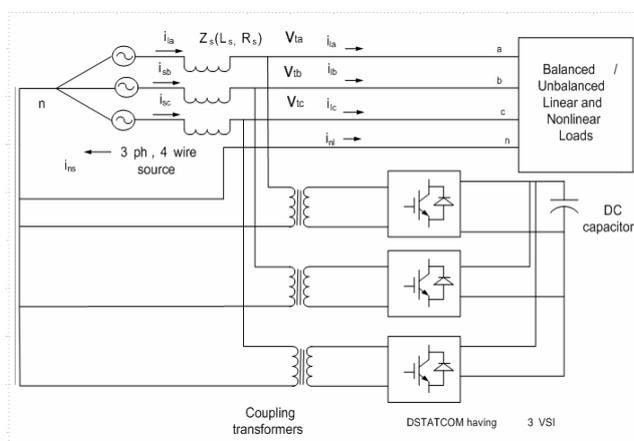


Fig. 1: Schematic diagram of DSTATCOM (3 VSI configuration) connected to a three-phase, four-wire distribution system.

III. PROBLEMS ASSOCIATED WITH NEUTRAL CURRENT

In three-phase, four-wire system, the current in the neutral conductor is the sum of three line currents. If the system is perfectly balanced, the neutral current is zero. However, practical distribution system is never perfectly balanced and the neutral current mitigation always becomes an important issue for power system engineers [7, 11-13]. The main cause of neutral conductor current is load unbalancing and presence of non-linear loads. Moreover, under certain conditions, even perfectly balanced single-phase loads could result in significant neutral currents. The presence of non-linear loads having non-sinusoidal

The paper first received 26 Apr 2008 and in revised form 24 Oct 2008.
Digital ref: A170401196

¹ Department of Electrical Engineering Maharaja Agrasen Institute of Technology New Delhi-110016, India. E-mail: alkaadya@gmail.com

² Department of Electrical Engineering, Indian Institute of Technology, New Delhi-110016, India. E-mail: bhimsinghr@gmail.com

³ Department of Instrumentation & Control Engg. Div, Netaji Subhas Institute of Technology, New Delhi-110016, India. E-mail: mittalapa@yahoo.com

$$v_{sb} = i_{sb}R_s + L_s p i_{sb} + n v_{tb} \quad (17)$$

$$v_{sc} = i_{sc}R_s + L_s p i_{sc} + n v_{tc} \quad (18)$$

where p denotes the time differential operator (d/dt). v_{sa} , v_{sb} and v_{sc} are the three-phase supply voltages. v_{ta} , v_{tb} and v_{tc} are the three-phase voltages at point of common coupling (PCC), n is the turns ratio of the transformer. i_{sa} , i_{sb} , i_{sc} are three-phase supply currents, R_s and L_s are the supply resistance and inductance parameters.

B. Modeling of DSTATCOM

The DSTATCOM configuration with three-single phase VSIs is connected in shunt configuration to the system. Each single phase VSI has two legs and it is connected to each phase and neutral. The dc link of three VSIs is held in common by a single dc bus capacitor as represented in Fig. 3. The control of each VSI is independent. The model equations for three-legged DSTATCOM can be written as:

$$v_{ta} = i_{ca}R_c + L_c p i_{ca} + v_{ca} \quad (19)$$

$$v_{tb} = i_{cb}R_c + L_c p i_{cb} + v_{cb} \quad (20)$$

$$v_{tc} = i_{cc}R_c + L_c p i_{cc} + v_{cc} \quad (21)$$

where v_{ta} , v_{tb} and v_{tc} are the three-phase ac voltages at the PCC, i_{ca} , i_{cb} , i_{cc} are the DSTATCOM currents, R_c and L_c are the DSTATCOM resistance and inductance parameters. The first order differential equation for DC link voltage (v_{dc}) can be written as:

$$p v_{dc} = (i_{cad} + i_{cbd} + i_{ccd}) / C_{dc} \quad (22)$$

where v_{dc} denotes the DC link voltage at the DSTATCOM terminals and SA_1 , SA_2 , SB_1 , SB_2 , SC_1 , SC_2 are the switching functions decided by switching logic of the three phases of DSTATCOM. The three-phase ac voltages at the terminals of DSTATCOM (v_{ca} , v_{cb} and v_{cc}) are calculated as:

$$v_{ca} = (SA_1 - SA_2) v_{dc} \quad (23)$$

$$v_{cb} = (SB_1 - SB_2) v_{dc} \quad (24)$$

$$v_{cc} = (SC_1 - SC_2) v_{dc} \quad (25)$$

The charging currents i_{cad} , i_{cbd} , i_{ccd} are expressed as:

$$i_{cad} = i_{ca}(SA_1 - SA_2) \quad (26)$$

$$i_{cbd} = i_{cb}(SB_1 - SB_2) \quad (27)$$

$$i_{ccd} = i_{cc}(SC_1 - SC_2) \quad (28)$$

C. Modeling of Loads

Different nature of load (linear, nonlinear) are modeled here.

1) Linear Load

Three-phase balanced and unbalanced star connected resistive inductive loads (Z_{1a} , Z_{1b} , Z_{1c}) are connected on a three-phase, four-wire system (Fig. 4a) with switches to disconnect any phase of the loads. These inductive-resistive three phase loads may be modeled by the following equations:

$$v_{ta} = R_l i_{ta} + L_l p i_{ta} \quad (29)$$

$$v_{tb} = R_l i_{tb} + L_l p i_{tb} \quad (30)$$

$$v_{tc} = R_l i_{tc} + L_l p i_{tc} \quad (31)$$

where i_{ta} , i_{tb} and i_{tc} are the three-phase load currents, R_l and L_l are the load resistance and inductance parameters.

2) Non-Linear Load

A set of three single-phase nonlinear loads is connected to three-phase, four-wire grid system (Fig. 4b). Each phase load consists of a single-phase uncontrolled bridge rectifier with an AC input impedance and DC link

capacitive-resistive (R-C) loading. When the diodes are conducting, AC supply mains is connected to the load. The basic equations for the three phase loads are written as:

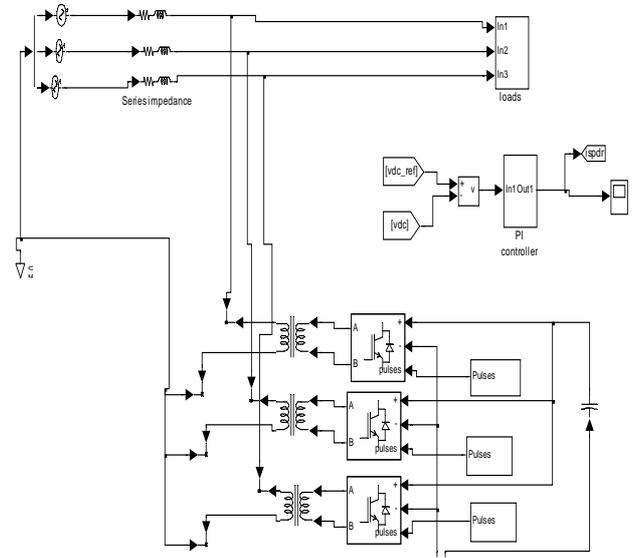


Fig. 3: MATLAB based model for the DSTATCOM configuration.

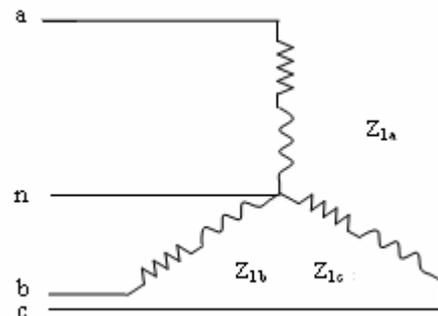


Fig. 4a: Linear load connected in star configuration.

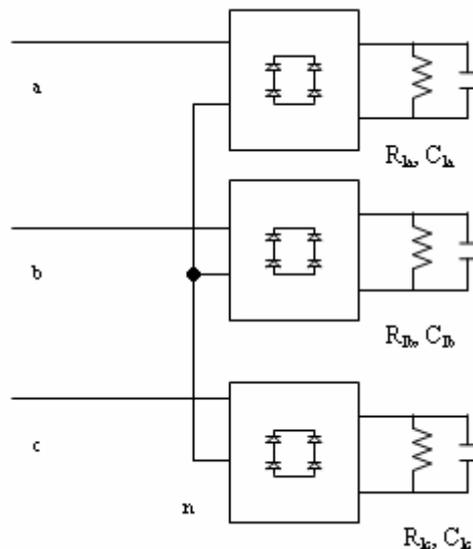


Fig. 4b: Non-Linear load connected for four-wire system.

$$v_{sa} = v_{la} + i_{la}R_s + L_s p i_{la} \quad (32)$$

$$v_{sb} = v_{lb} + i_{lb}R_s + L_s p i_{lb} \quad (33)$$

$$v_{sc} = v_{lc} + i_{lc}R_s + L_s p i_{lc} \quad (34)$$

where v_{sa} , v_{sb} , v_{sc} are three-phase ac voltages, R_s , L_s are supply impedance, v_{la} , v_{lb} , v_{lc} are voltages across load capacitors C_{la} , C_{lb} , C_{lc} . The load capacitor equations can be written as:

$$p v_{la} = (i_{da} - i_{ra}) / C_{la} \quad (35)$$

$$p v_{lb} = (i_{db} - i_{rb}) / C_{lb} \quad (36)$$

$$p v_{lc} = (i_{dc} - i_{rc}) / C_{lc} \quad (37)$$

where currents i_{la} , i_{lb} , i_{lc} are the load currents drawn from ac mains and i_{da} , i_{db} , i_{dc} are their magnitudes. The currents i_{ra} , i_{rb} , i_{rc} are dc load currents (v_{la}/R_{la}), (v_{lb}/R_{lb}) and (v_{lc}/R_{lc}) respectively. The load neutral current (i_{nl}) can be calculated from three-phase load currents i_{la} , i_{lb} , i_{lc} as:

$$i_{nl} = -(i_{la} + i_{lb} + i_{lc}) \quad (38)$$

VI. RESULTS AND DISCUSSION

The developed model for DSTATCOM is tested over a variety of linear and non-linear loads for power quality improvement.

A. Performance of DSTATCOM with Linear Loads

The performance of DSTATCOM with linear loads is considered here for a variety of power quality improvement features viz. power factor correction and voltage regulation.

1) Power factor correction and Load balancing

Fig. 5 shows the performance of DSTATCOM for power-factor correction with R-L lagging load (20.5kW, 0.8pf). A PI controller is realized over the dc bus to regulate the dc link voltage to a value of 550V. The dynamic performance of variables like supply voltage (v_s), supply currents (i_s), load currents (i_l), compensator currents (i_c) and sensed and reference values of dc link voltage (v_{dc}) are shown to demonstrate the performance of DSTATCOM. It is observed that DSTATCOM improves the supply power-factor to unity. The supply currents are balanced, sinusoidal and in-phase with the voltages. For dynamic performance of DSTATCOM, load unbalancing is introduced at $t=0.66$ sec, one phase of load ('a' phase) is switched off (13.67 kW) and at $t=0.76$ sec, the load is put back to 20.5kW. The control action provides a self-supporting dc bus.

2) Voltage regulation and Load balancing

Fig. 6 shows the response of the DSTATCOM for ac voltage regulation at PCC with 20.5kW, 0.8 lagging power-factor linear (R-L) load. The transient response for the various performance variables are shown for load changing from three-phase (30kW) to two-phase (20kW) at $t=0.57$ sec. The dynamic performance of variables like supply voltage (v_s), terminal voltage at PCC (v_t), supply currents (i_s), load currents (i_l), DSTATCOM currents (i_c), sensed and reference values of dc link voltages (v_{dc}) and sensed and reference values of ac terminal voltage (v_m) is observed in this figure. At $t=0.57$ sec, when one phase (phase 'a') of the load is thrown off, dc link voltage tends to increase. This reflects in the form of an overshoot in

DC link voltage. However, by controller action, the dc bus voltage of DSTATCOM and ac terminal voltage at PCC are regulated at their reference values. The supply currents are sinusoidal, balanced and slightly leading with respect to supply voltages. DSTATCOM maintains ac terminal voltage without any abnormal surge. The supply currents are sinusoidal, balanced and reduced in magnitude for transient period after $t=0.57$ sec when the load currents are unbalanced.

B. Performance of DSTATCOM with Non-Linear Loads

Here a balanced three-phase nonlinear load is represented in the form of three single-phase uncontrolled diode bridge rectifiers feeding resistive load with parallel capacitor filter.

(1) Power Factor Correction and Harmonic Reduction

Fig. 7 shows the transient response of the DSTATCOM for power-factor correction and harmonic reduction with nonlinear loads. The response for the various performance variables are shown in this figure for $R=25\Omega$ and $C=500\mu F$ (14.5kW) connected at end of diode rectifier. The load on the system is changed from 14.5kW to 19.8kW at $t=0.4$ sec and back at $t=0.6$ sec. The reference dc link voltage is set to 550V. It is observed that at $t=0.4$ sec, the dc link voltage dips a little but the DSTATCOM regulates V_{dc} to reference value. It is observed that the supply neutral conductor has negligible current even though the load and DSTATCOM neutral conductors carry large currents. The waveform and Total Harmonic Distortion (THD) for supply current and load current are shown in Fig. 8 and Fig. 9. It is observed that THD of load current 63.88% is reduced to 3.88% in supply current.

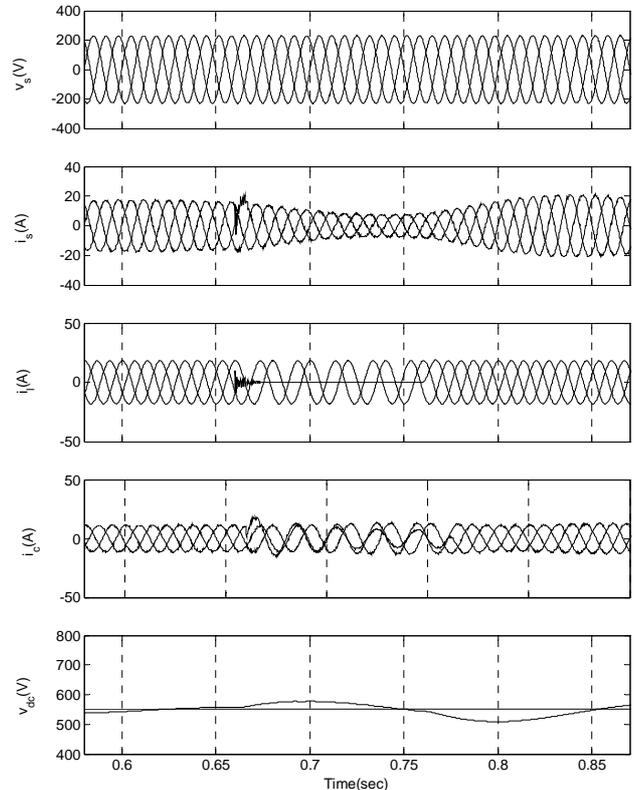


Fig. 5: Performance of DSTATCOM with linear loads for power factor correction

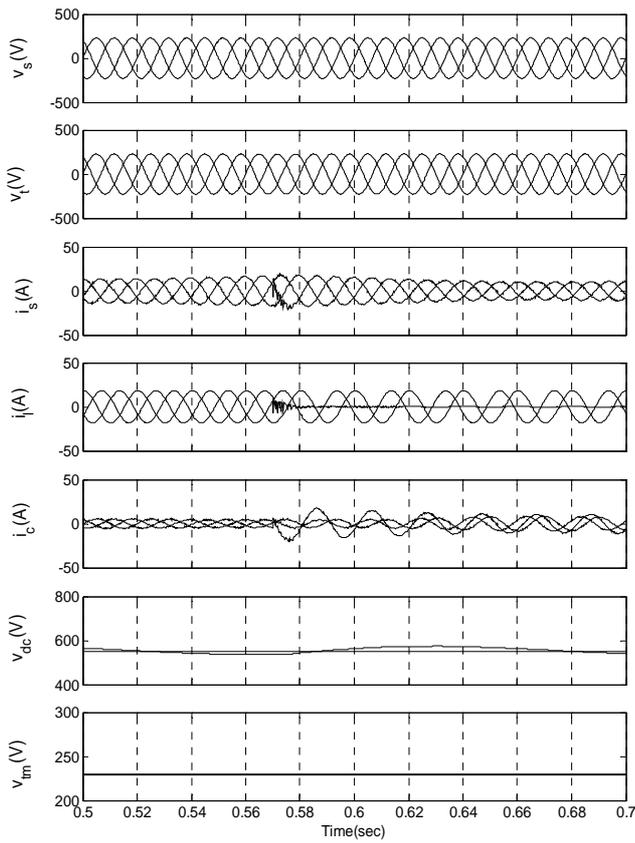


Fig. 6: Performance of DSTATCOM with linear loads for voltage regulation.

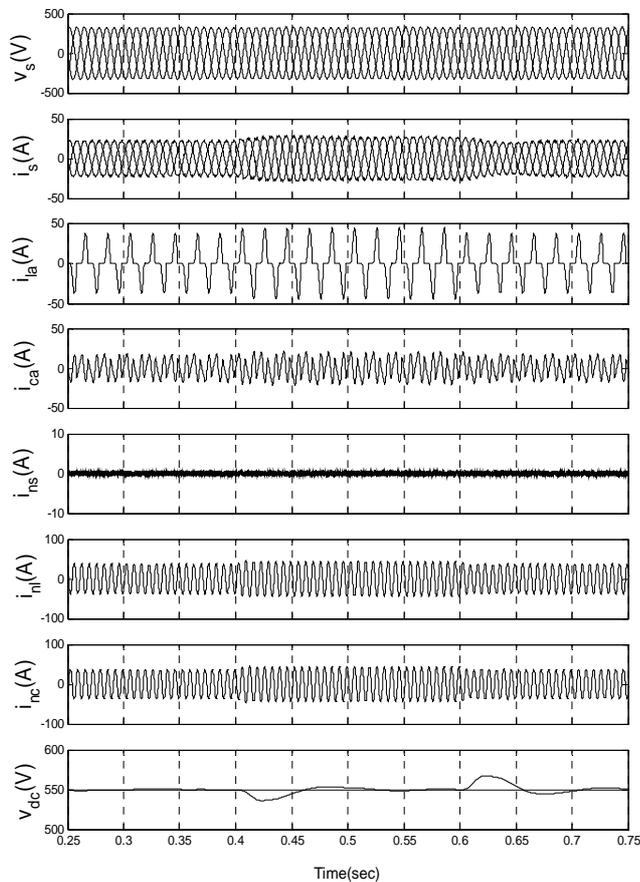


Fig. 7: Performance of DSTATCOM with non-linear load for power factor correction and harmonic reduction.

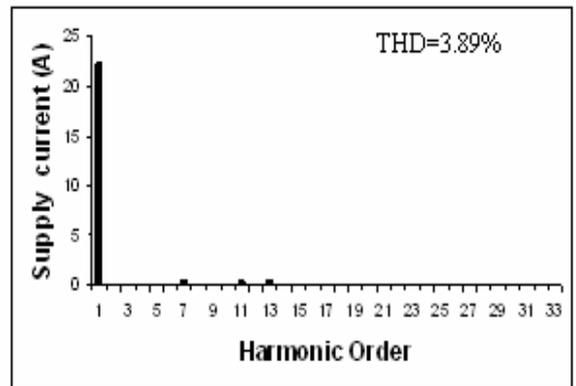
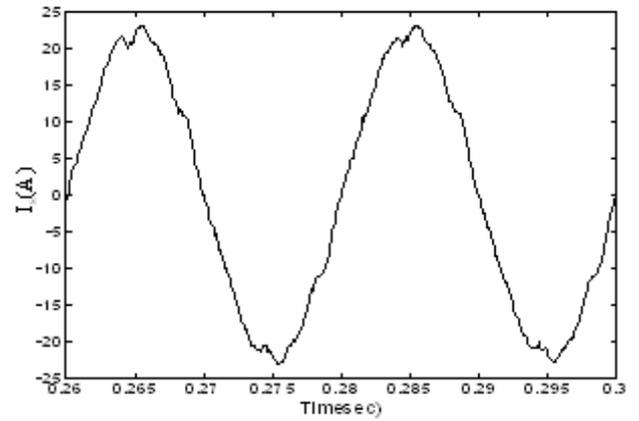


Fig. 8: Waveform and harmonic spectrum for supply current.

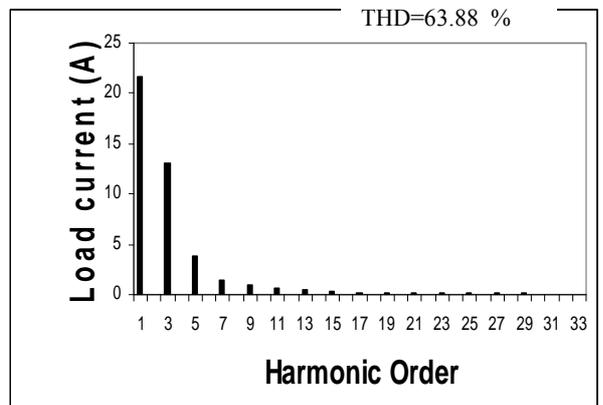
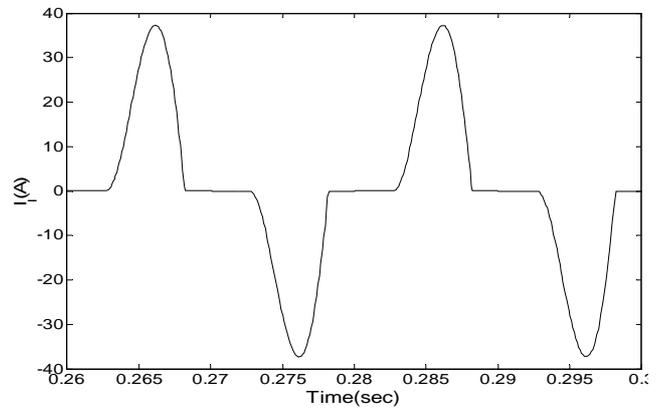


Fig. 9: Waveform and harmonic spectrum for load current I_l .

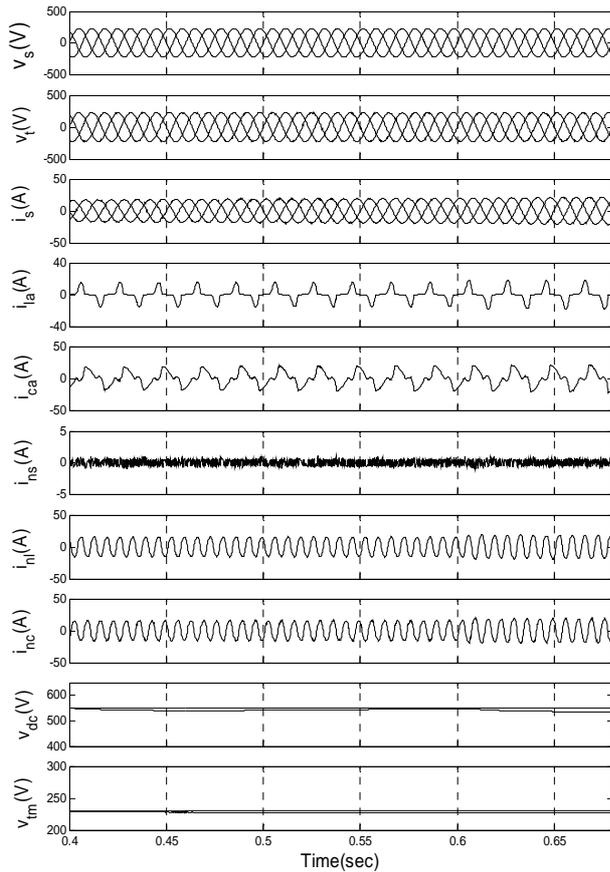


Fig. 10: Performance of DSTATCOM for voltage regulation and harmonic reduction

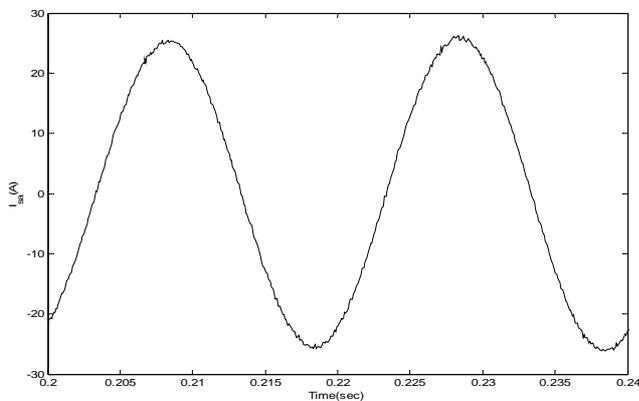


Fig. 11: Waveform and harmonic spectrum for supply current (I_s).

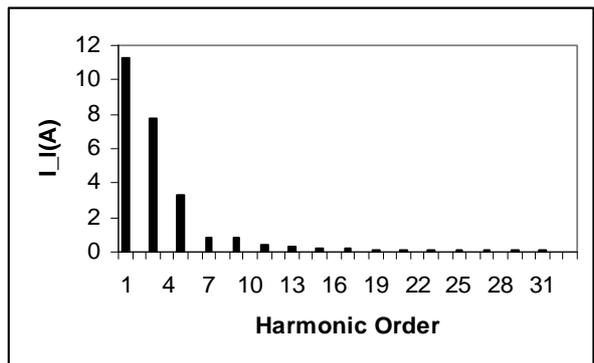
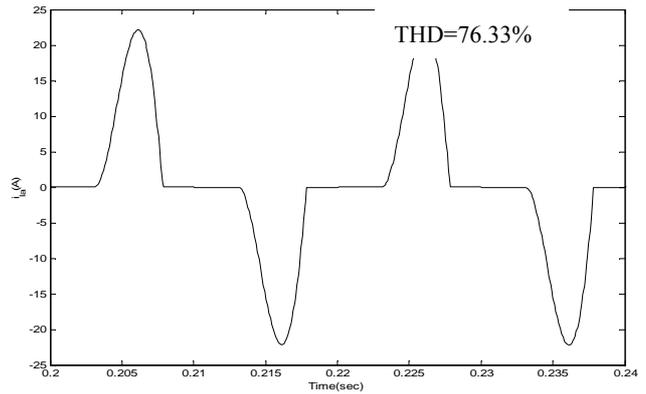


Fig. 12: Waveform and harmonic spectrum for load current (I_l)

(2) Voltage Regulation and Load Balancing

Fig. 10 shows the transient response under non-linear load for voltage regulation and harmonic elimination. Here, two PI controllers are used—one over V_{dc} and the other over V_{tm} . The dynamic response for the various performance variables are shown in this figure for $R=50 \Omega$ and $C= 500\mu F$ (17 kW). The load on the system is changed at $t=0.6\text{sec}$ (20kW). The supply currents are nearly sinusoidal, balanced and slightly leading with respect to supply voltages. Fig. 11 and Fig. 12 show the waveforms and harmonic spectra where THD of load current of 76.33% is reduced to 0.71% in supply current. The DSTATCOM controller has regulated DC bus voltage, ac terminal voltage at PCC under varying load conditions and also reduced THD of supply currents to less than the 5% limit.

VII. CONCLUSION

Detailed analysis of a three-phase, four-wire DSTATCOM has been carried out for a configuration realized from three-single phase VSIs. The advantages of this scheme are that independent control of the three VSI's is possible and a cost effective capacitor with lower voltage rating can be utilized. This in-turn reduces the cost and offers an economically viable option as compared to a four leg DSTATCOM. Power quality aspects such as pf correction, voltage regulation, the load balancing and harmonic reduction for linear as well as non-linear loads have been achieved using this DSTATCOM. The performance results have justified the load compensation of the proposed algorithm for DSTATCOM.

REFERENCES

- [1] E. Acha, V.G. Agelidis, O. Anaya-Lara and T.J.E Miller, *Power Electronic Control in Electrical Systems*, (Newnes Power Engineering Series, Oxford, Britain, 2002).
- [2] A. Ghosh and G. Ledwich, *Power Quality Enhancement Using Custom Power Devices*, (Kluwer Academic Publishers, 2002).
- [3] T.J.E. Miller, *Reactive Power Control in Electric Systems*, (John Willey Sons, Toronto, 1982).
- [4] M.J. Sullivan, T. Vardell and M. Johnson, "Power interruption costs to industrial and commercial consumers of electricity", *IEEE Transactions on Industry Applications*, Vol. 33, No. 6, 1997, pp. 1448-1458.
- [5] C.J. Melhorn, T.D. Davis and G.E. Beam, "Voltage sags: Their impact on utility and industrial customers", *IEEE Transactions on Industry Applications*, Vol. 34, No. 3, 1998, pp. 549-558.
- [6] W.E. Reid, "Power quality issues – standards and guidelines", *IEEE Transactions on Power Delivery*, Vol. 32, No. 3, May/ June 1996. pp. 625-632.
- [7] IEEE-519 "Recommended Practices and Requirements for Harmonic Control in Electric power System", October 1992.
- [8] N.G. Hingorani, "Introducing Custom power", *IEEE Spectrum*, Vol. 32, June 1995, pp. 41-48.
- [9] L. Xu, O.A. Lara, V.G. Agelidis and E. Acha, "Development of prototype custom power devices for power quality enhancement", *IEEE Conference on Harmonics and Quality of Power*, Vol. 3, 2000, pp.775 – 783.
- [10] A. Ghosh and A. Joshi, "The concept and operating principles of a mini custom park", *IEEE Transactions on Power Delivery*, Vol. 19, No. 4, Oct 2004, pp. 1766 – 1774.
- [11] B. Singh, K. Al-Haddad and A. Chandra, "Harmonic Elimination, Reactive Power Compensation and Load Balancing in 3-Phase, 4-wire Electric Distribution System Supplying Non-Linear Load", *Electric power Systems Research*, Vol. 44, 1998, pp. 93-100.
- [12] B.N. Singh, A. Chandra and K. Al-Haddad, "DSP-based indirect-current-controlled STATCOM. I. Evaluation of current control techniques", *IEE Proceedings-Electric Power Applications*, Vol. 147, No. 2, March 2000, pp. 107 – 112.
- [13] B.N. Singh, A. Chandra and K. Al-Haddad, "DSP-based indirect-current-controlled STATCOM. II. Multifunctional capabilities", *IEE Proceedings- Electric Power Applications*, Vol. 147, No. 2, March 2000, pp. 113 – 118.

BIOGRAPHIES

Alka Adya graduated from Delhi College of Engineering in 1996 with BE (Electrical), M.Tech. in Power Systems from IIT Delhi in 2001 and Ph.D from Delhi University, 2007. She is presently working as an Assistant Professor in the Department of Electrical and Electronics Engineering in Maharaja Agrasen Institute of Technology. Her research interests include FACTS, power systems and power quality.

Bhim Singh graduated from University of Roorkee in 1977 with BE (Electrical), M.Tech. in Power Apparatus and Systems from IIT Delhi in 1979 and PhD from IIT Delhi in 1983. He is currently working as a Professor in IIT Delhi. He is a Fellow of Institution of Engineers (India), Fellow of INAE and IETE, a Life Member of ISTE, SSI and NIQR and Senior Member IEEE. His research interests include power electronics, electrical machines, induction generator, active filters, static VAR compensator, analysis and digital control of electrical machines, FACTS, electric drives.

A.P. Mittal received his B.E. in 1978 from M.M.M Engg. College, Gorakhpur, M.E. in 1980 from University of Roorkee and PhD in 1991 from IIT Delhi. He has teaching experience of more than twenty years. He is presently Professor and Head of Instrumentation and Control Engineering Department in Netaji Subhas Institute of Technology. He is a Fellow of Institution of Engineers (India). His research interests include active filters, FACTS, electric machines and drives.