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Star/Hexagon Transformer Based Three-Phase Four-Wire DSTATCOM for Power Quality Improvement

Bhim Singh, Jayaprakash Pychadathil, and Dwarkadas Pralhaddas Kothari

Abstract

A new topology of DSTATCOM (distribution static compensator) is proposed for power quality improvement in three-phase four-wire distribution systems. A three-leg VSC (Voltage Source Converter) is integrated with a star/hexagon transformer for the compensation of reactive power for voltage regulation or for power factor correction along with load balancing, elimination of harmonics currents and neutral current compensation. The star/hexagon connected transformer provides a path to the zero sequence current in a three-phase four-wire distribution system. In order to optimize the voltage rating of the VSC, the star/hexagon transformer is designed to have a suitable voltage rating for the secondary windings for integrating the three-leg VSC. This transformer connection provides the selection of 'off the shelf' VSC for this application and it also provides isolation for the VSC system. The performance of the proposed DSTATCOM system is validated through simulations using MATLAB software with its Simulink and Power System Block set (PSB) toolboxes.

KEYWORDS: power quality improvement, DSTATCOM, voltage source converter, star/polygon transformer, neutral current compensation

I. INTRODUCTION

The AC distribution system is facing severe power quality problems such as high reactive power burden, harmonic currents, load unbalance, excessive neutral current etc. [1-7]. The power quality at the distribution system is governed by various standards such as IEEE-519 standard [1]. The remedies to power quality problems are reported in the literature and are known by the generic name of custom power devices (CPD) [2]. These custom power devices include the DSTATCOM (distribution static compensator), DVR (dynamic voltage restorer) and UPQC (unified power quality conditioner). The DSTATCOM is a shunt-connected device, which takes care of the power quality problems in the currents, where as the DVR is connected in series with the supply and can mitigate the power quality problems in the voltage and the UPQC can compensate power quality problems both in the current and voltage [3-7].

Three-phase four-wire distribution system is facing power quality problems such as excessive neutral current, unbalanced load, harmonics in current etc. due to various reasons such as single phase loads, non-linear loads etc. [7]. Three-phase four-wire compensators are used for neutral current compensation along with voltage regulation or power factor correction, harmonic elimination and load balancing in a three-phase four-wire system with linear and non-linear loads [8-12]. There are many different topologies reported in the literature for three-phase four-wire DSTATCOM such as a VSC (Voltage Source Converter) with four leg, three single-phase VSC, three leg VSC with split capacitors [6] and three leg VSC with a zig-zag transformer [8]. The application of a zig-zag transformer for reduction of neutral current is advantageous due to passive compensation, ruggedness and less complexity over the active compensation techniques. There are many control schemes reported in the literature for control of shunt compensators such as instantaneous reactive power theory, power balance theory, synchronous reference frame theory etc.[11-12]. The DSTATCOM is normally connected using a star/delta transformer in the distribution system for electrical isolation [13]. The DSTATCOM is tested for improved performance when both voltage regulation and elimination of harmonics currents are performed in the distribution system [14].

In this paper, a new topology of DSTATCOM is proposed in which a three-phase three-leg VSC is integrated with a star/hexagon transformer and is able to perform all the compensations required for a three-phase four-wire system. Star/hexagon transformer is reported in the literature [15-16] for different applications. In order to optimize the voltage rating of the three-leg VSC, the transformer secondary is designed for low voltage. The dynamic performance is studied for voltage regulation and power factor correction modes of the DSTATCOM. The load harmonic currents compensation and load balancing are

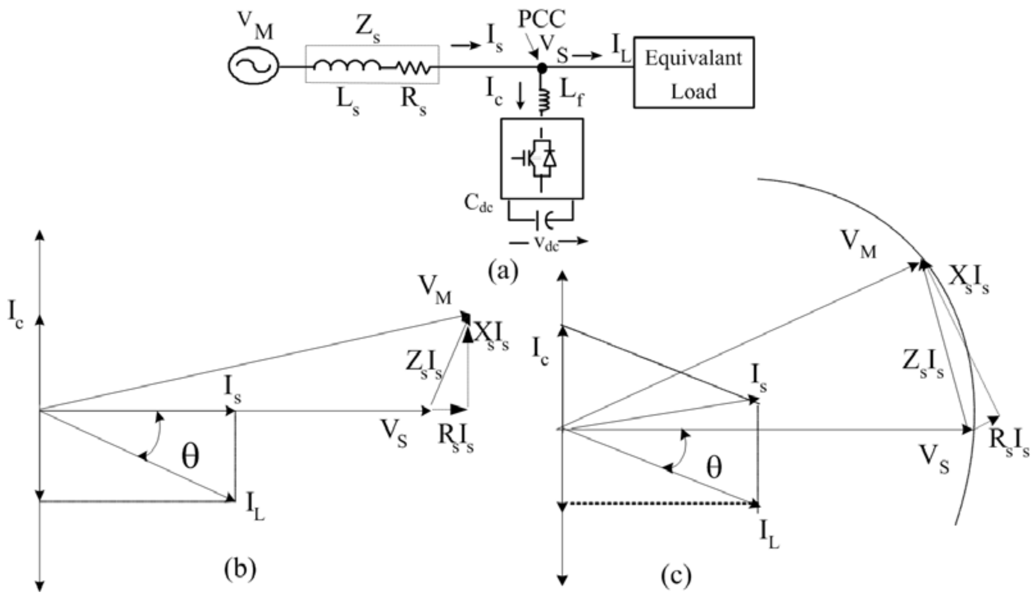

Fig.1 (a) Single line diagram of DSTATCOM system, (b) Phasor diagram for UPF operation, (c) ZVR operation.

also obtained along with voltage regulation or power factor correction. The DSTATCOM features the following characteristics.

a) Use of readily available 3-phase three-leg VSC as DSTATCOM for 3-phase four-wire system.
b) Neutral current compensation with linear and non linear loads using the star/hexagon connected transformer.
c) Isolated operation of three-leg VSC as it is integrated with the star/hexagon connected transformer.
d) Harmonic current compensation and load balancing.
e) Reactive current compensation for unity power factor (UPF) or the zero voltage regulation (ZVR) at the point of common coupling (PCC).
f) Capacitor supported operation of DSTATCOM.

II. Principle Of Operation

The basic circuit of a DSTATCOM connected system is shown in Fig.1. The DSTATCOM is connected in shunt with the load at the point of common coupling (PCC). The inductor (L_s) corresponds to line inductance and the resistor (R_s) corresponds to the effective resistance of the line. The current injected by the DSTATCOM is controlled based on the required compensation. Fig. 1(b) shows

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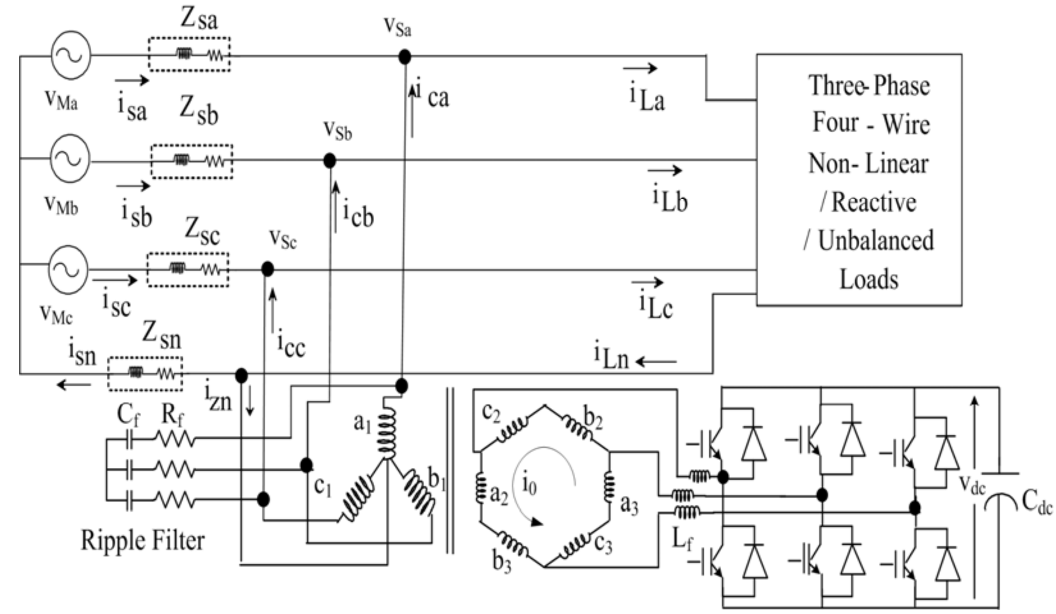

Fig. 2. Schematics of proposed Integrated 3-leg VSC with star/hexagon transformer based DSTATCOM connected in the distribution system.

the phasor diagram for power factor correction mode of the compensator. The reactive current (I_c) injected by the DSTATCOM is to cancel the reactive power component of the load current so that the source current is reduced to active power component of current only (I_s). Fig. 1(c) shows the phasor diagram for zero voltage regulation (ZVR) operation. In this mode, DSTATCOM injects a current I_c, such that the voltage at PCC (V_S) and source voltage (V_M) are in the locus of same circle. The DSTATCOM currents are adjusted dynamically under varying load conditions.

Fig. 2 shows the proposed star/hexagon transformer based three-phase four-wire DSTATCOM for power quality improvement. A three-leg VSC is connected to the secondary of the transformer, which is hexagon connected winding. The neutral current compensation is also achieved because this hexagon winding provides a circulating path for the zero sequence component of the load currents. The star connected primary winding of the transformer is connected to the PCC. The DSTATCOM consists of a three-phase pulse width modulated (PWM) voltage-source converter (VSC) using six insulated-gate bipolar transistors (IGBTs), three interface inductors, and one dc capacitor. This star/hexagon connected transformer provides isolation to the DSTATCOM as well as the suitability of selecting an off the shelf three-leg VSC. The DSTATCOM provides neutral current compensation, harmonic elimination and load balancing along with power factor correction or line voltage regulation. The detailed design of the DSTATCOM, star/hexagon transformer, control of the DSTATCOM are given in the following sections.

A. Design of Three-Phase DSTATCOM

A three-leg, PWM controlled voltage source converter (VSC) is used as a DSTATCOM and it has six insulated-gate bipolar transistors (IGBTs), three interface inductors, and one dc capacitor. The voltage rating of the secondary of the transformer is used for using an off the shelf three-leg VSC. The line voltage of the VSC is considered as 200V and the rating required for meeting the reactive power compensation of the load considered is found to be 12kVA. The ac inductor, dc capacitor and the ripple filter selection are as below.

(i) DC Capacitor Voltage

The minimum dc bus voltage should be greater than twice of the peak of the phase voltage of the system [17]. The dc bus voltage is calculated as

$$V_{dc} = 2\sqrt{2}V_{LL} /(\sqrt{3}m) \tag{1}$$

where, m is the modulation index and is considered as 1 and V_{LL} is the ac line output voltage of DSTATCOM. Thus V_{dc} is obtained as 326.54V for V_{LL} of 200V and it is selected as 400V.

(ii) DC Bus Capacitor

The value of dc capacitor (C_{dc}) depends on the instantaneous energy available to the DSTATCOM during transients [17]. The principle of energy conservation is applied as,

$$\frac{1}{2}C_{dc}[\left(V_{dc}^2\right)-\left(V_{dc1}^2\right)] = 3V\left(aI\right)t \tag{2}$$

where, V_{dc} is the reference dc voltage and V_{dc1} is the minimum voltage level of dc bus, a is the over loading factor, V is the phase voltage, I is the phase current and t is time by which the dc bus voltage is to be recovered.

Considering, a 2.5% (10 V) reduction in dc bus voltage during transients, V_{dc}= 400V, V_{dc1}= 390V, V= 239.60V, I= 27.82A, t= 350 μs, a= 1.2, the calculated value of C_{dc} is 2176 μF and it is selected as 2200 μF.

(iii) AC Inductor

The selection of the ac inductance (L_f) depends on the current ripple, $i_{cr,p-p}$, switching frequency f_s, dc bus voltage (V_{dc}) and the L_f is given as,

$$L_f = \left(\sqrt{3}mV_{dc}\right)/(12af_s i_{cr(p-p)}) \tag{3}$$

where m is the modulation index and a is the over-load factor. Considering, $i_{cr,p-p}$ = 5%, f_s= 10 kHz, m =1, V_{dc} = 400V, a=1.2, the L_f value is calculated to be 3.44 mH. The round off value of L_f of 3.5 mH is selected in this investigation.

(iv) Ripple Filter

A low- pass first order filter tuned at half the switching frequency is used to filter the high frequency noise from the voltage at the PCC. Considering a low impedance of 8 Ω for the harmonic voltage at a frequency of 5 kHz, the ripple filter capacitor is designed as C_f = 5 μF and a series resistance (R_f) of 5 Ω is included in series with the capacitor (C_f). The impedance is found to be 637 Ω at fundamental frequency, which is sufficiently large and hence the ripple filter draws negligible fundamental current.

B. Design of Star /Hexagon Transformer

The hexagon-connected secondary winding of the transformer provides a path for the zero sequence fundamental current and harmonic currents and hence offers a path for the neutral current when connected in shunt at PCC. Under single-phase load, the zero sequence load neutral current circulates in the hexagon windings of the star/hexagon transformer. The voltage across each primary winding is the phase voltage. The 3-leg VSC is connected to this transformer, as shown in Fig. 3. The voltage rating of the star/hexagon transformer windings are designed as shown below.

The phasor diagram shown in Fig. 3(b) gives the following relations to find the turns ratio of windings. If V_a, V_b and V_c are the per phase voltages across each winding and V_{ca} is the resultant voltage, then

$$V_{ca} = K_1 V_a - K_2 V_c \tag{4}$$

where K_1 and K_2 are the fraction of winding in the phases. Considering $V_a = V\angle 0^\circ$ and $V_{ca} = \sqrt{3}V\angle 30^\circ$, then from (4),

$$\sqrt{3}V\angle 30^\circ = K_1 V\angle 0^\circ - K_2 V\angle -120^\circ \tag{5}$$

One gets, $K_1 = 1$, $K_2 = 1$

The line voltage is, $V_{ca} = 200V$, then

$$V_a = V_b = V_c = 200/\sqrt{3} = 115.50V \tag{6}$$

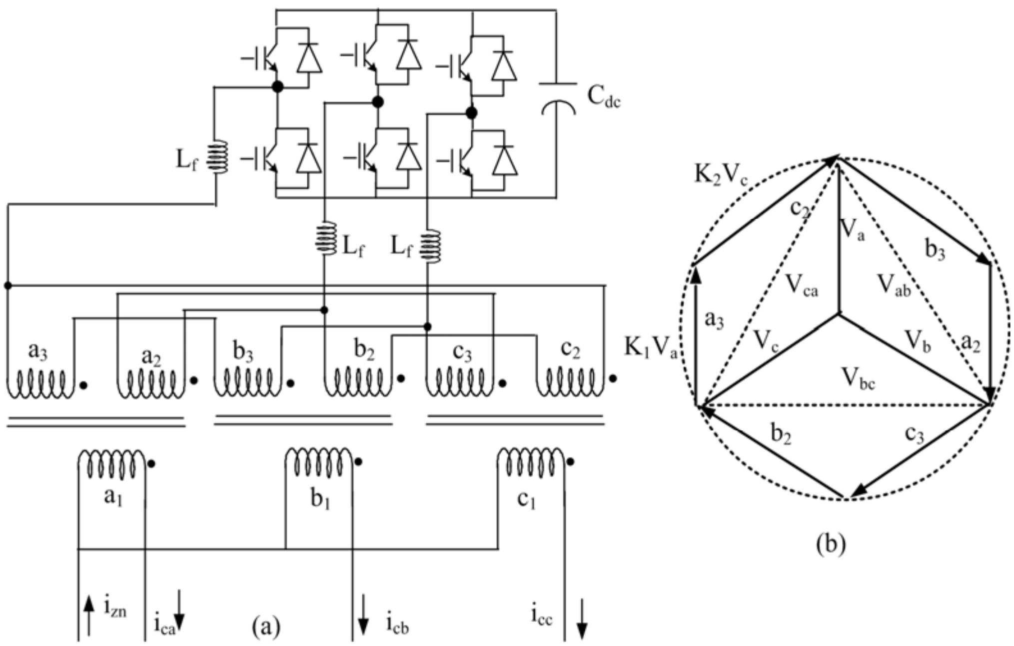

Fig. 3. Star/Hexagon transformer and the three-leg VSC for operation as DSTATCOM (b) Phasor diagram

Hence, three numbers of single-phase transformers of each of rating 5kVA, 240V/116V/116V are selected.

C. *Control of DSTATCOM*

The control approaches available for the generation of reference source currents for the control of VSC of DSTATCOM for three-phase, four-wire system are instantaneous reactive power theory (IRPT), synchronous reference frame theory (SRFT), unity power factor (UPF) based, instantaneous symmetrical components (ISC) based etc. [11-12]. The synchronous reference frame theory is used for the control of three-phase three-leg VSC of the DSTATCOM. A block diagram of the control scheme is shown in Fig. 4. The load currents (i_{La}, i_{Lb}, i_{Lc}), the PCC voltages (v_{Sa}, v_{Sb}, v_{Sc}) and dc bus voltage (v_{dc}) of DSTATCOM are sensed as feedback signals. The load currents (i_{La}, i_{Lb}, i_{Lc}) from the a-b-c frame are converted to the d-q-o frame as,

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$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (7)$$

where the unit vectors, $\cos\theta$ and $\sin\theta$ are obtained using a three-phase phase locked loop (PLL). The d-axis and q-axis currents consists of fundamental and harmonic components as,

$$i_{Ld} = i_{d\,dc} + i_{d\,ac} \quad (8)$$

$$i_{Lq} = i_{qdc} + i_{qac} \quad (9)$$

The oscillatory components (ac components) are eliminated using low pass filter (LPF) and the dc component is the fundamental frequency part of the load current.

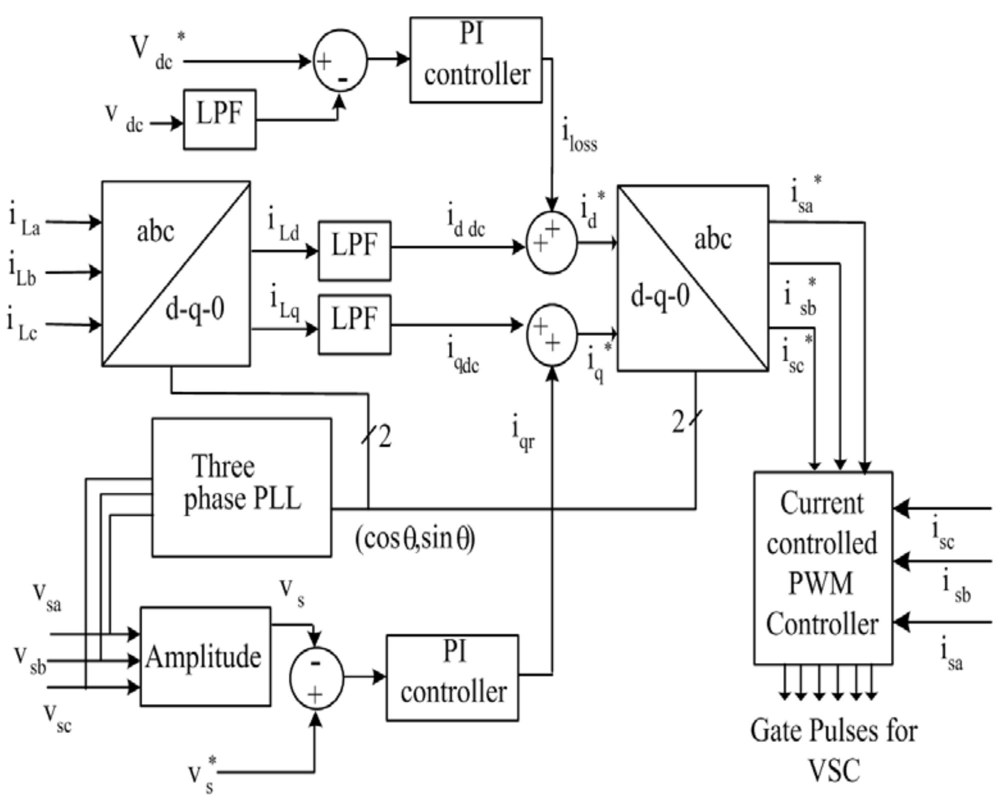

Fig. 4. Control algorithm for the three-leg VSC based DSTATCOM in a three phase 4-wire system

(i) Unity Power Factor (UPF) Operation of DSTATCOM

The compensating strategy for reactive power compensation for UPF operation considers that the source must deliver the mean value of the direct-axis component of the load current (i_{ddc}) along with the active power component current for maintaining the dc bus and meeting the losses (i_{loss}) in DSTATCOM. The output of PI (proportional-integral) controller at the dc bus voltage of DSTATCOM is considered as the current (i_{loss}) for meeting its losses.

$$i_{loss(n)} = i_{loss(n-1)} + K_{pd}(v_{de(n)} - v_{de(n-1)}) + K_{id} v_{de(n)} \qquad (10)$$

where, $v_{de(n)} = v_{dc}^* - v_{dc(n)}$ is the error between the reference (v_{dc}*) and sensed (v_{dc}) dc voltage at the nth sampling instant. K_{pd} and K_{id} are the proportional and the integral gains of the dc bus voltage PI controller.

The reference d-axis source current is therefore as,

$$i_d^* = i_{ddc} + i_{loss} \qquad (11)$$

The reference source currents (i_{sa}^*, i_{sb}^*, i_{sc}^*) must be in phase with the voltage at the PCC but with no zero-sequence component. It is therefore obtained by the following reverse Park's transformation with the i_d^* as in (11) and i_q^* and i_0^* as zero.

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \\ i_0^* \end{bmatrix} \qquad (12)$$

(ii) Zero Voltage Regulation (ZVR) Operation of DSTATCOM

The compensating strategy for ZVR operation considers that the source must deliver the same direct axis component, i_d* as mentioned in eqn. (11) along with the sum of quadrature axis current (i_{qdc}) and the component obtained from the PI controller (i_{qr}) used for regulating the voltage at PCC. The amplitude of ac terminal voltage (V_S) at the PCC is controlled to its reference voltage (V_S^*) using the PI controller. The output of PI controller is considered as the reactive component of current (i_{qr}) for zero voltage regulation of ac voltage at PCC. The amplitude of AC voltage (V_S) at PCC is calculated from the ac voltages (v_{sa}, v_{sb}, v_{sc}) as,

$$V_S = (2/3)^{1/2}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)^{1/2} \qquad (13)$$

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Then, a PI controller is used to regulate this to a reference value as,

$$i_{qr(n)} = i_{qr(n-1)} + K_{pq}(v_{te(n)} - v_{te(n-1)}) + K_{iq} v_{te(n)} \quad (14)$$

where, $v_{te(n)} = V_S^* - V_{S(n)}$ denotes the error between reference (V_S*) and actual ($V_{S(n)}$) terminal voltage amplitudes at the n^{th} sampling instant. K_{pq} and K_{iq} are the proportional and the integral gains of the AC voltage PI controller. The reference q-axis source current is as,

$$i_q^* = i_{qdc} + i_{qr} \quad (15)$$

The reference source currents in *abc* reference frame (i_{sa}^*, i_{sb}^*, i_{sc}^*) from the *dq0* frame (i_d^*, i_q^*, i_0^*) is obtained by reverse Park's transformation using eqn.(12) with the i_d^* as in (11) and i_q^* as in (15) and i_0^* as zero.

(iii) Current Controlled PWM Generator

In a current controller, the sensed source currents (i_{sa}, i_{sb}, i_{sc}) and reference source currents (i_{sa}^*, i_{sb}^*, i_{sc}^*) are compared and a proportional controller is used for amplifying current error in each phase. Then, the amplified current error is compared with a triangular carrier signal of switching frequency to generate the gating signals for six IGBT switches of VSC of DSTATCOM. The gate signals are PWM controlled so that sensed source currents follows the reference source currents precisely.

III. MATLAB Modeling And Simulation

The three-leg VSC integrated with the star/hexagon transformer is used as DSTATCOM, connected to a three-phase four-wire system and it is modeled and simulated using the MATLAB with its Simulink and Power System Block set toolboxes. The ripple filter is connected to the DSTATCOM for filtering the ripple in the PCC voltage. The system data are given in Appendix. The MATLAB based model of the three-phase four-wire DSTATCOM shown in Fig. 2 is modeled and is shown in Fig.5. The available model of linear transformers, which includes losses, is used for modeling the star/hexagon transformer.

The control algorithm for the DSTATCOM shown in Fig. 4 is also modeled in MATLAB and the model of the control scheme is shown in Fig. 6. The system parameters are included in the Appendix. The reference source currents are derived from the sensed PCC voltages (v_{sa}, v_{sb}, $v_{sc.}$), load currents (i_{La}, i_{Lb}, i_{Lc}) and the dc bus voltage of DSTATCOM (v_{dc}). A pulse width modulated (PWM) current controller is used over the reference (i_{sa}^*, i_{sb}^*, i_{sc}^*) and

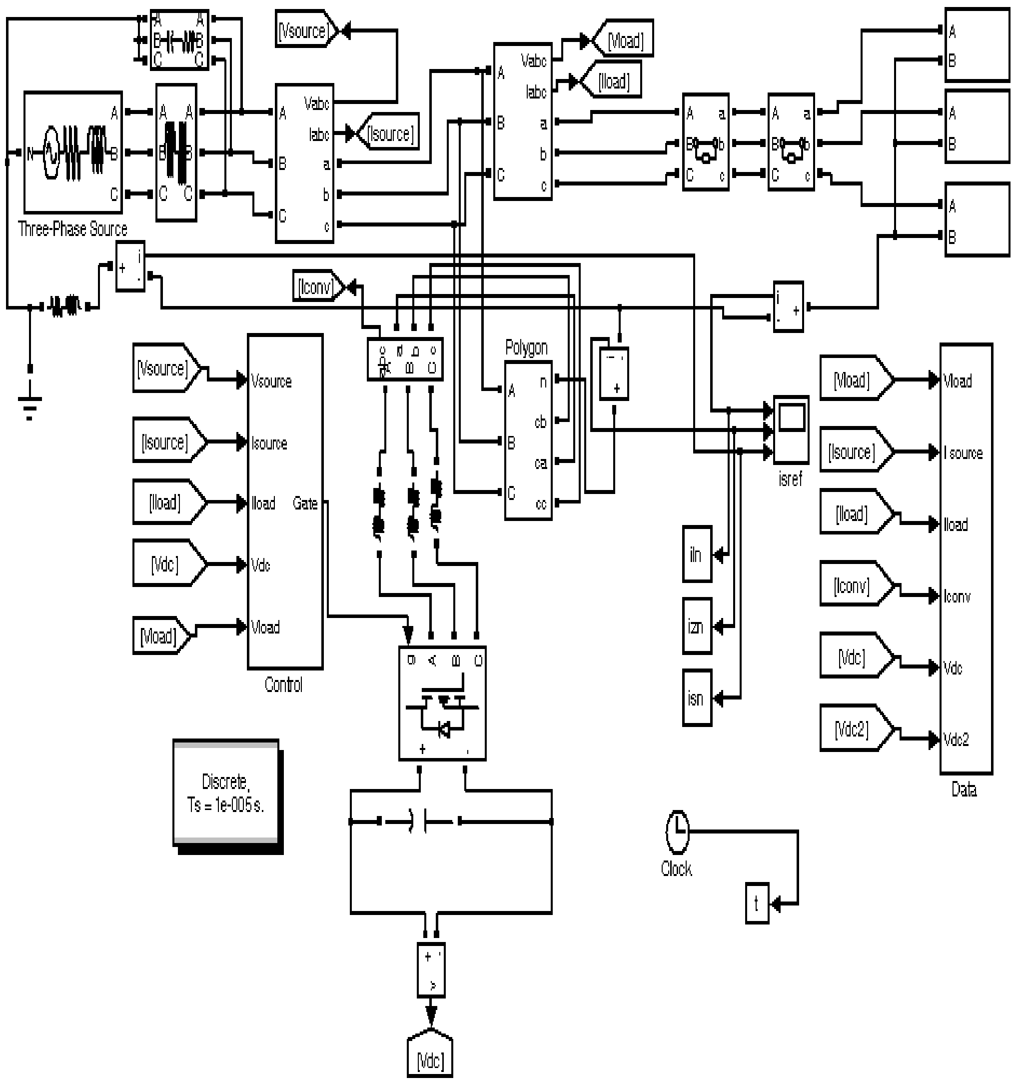

Fig. 5. MATLAB model of proposed three-phase four-wire DSTATCOM connected system

sensed (i_{sa}, i_{sb}, i_{sc}) source currents to generate the gating signals for the IGBTs of the VSC of the DSTATCOM.

IV. RESULTS AND DISCUSSION

The performance of the star-hexagon connected transformer based three-phase four-wire DSTATCOM is demonstrated for power factor correction and voltage regulation along with harmonic reduction, load balancing and neutral current compensation. The model is analysed under varying loads.

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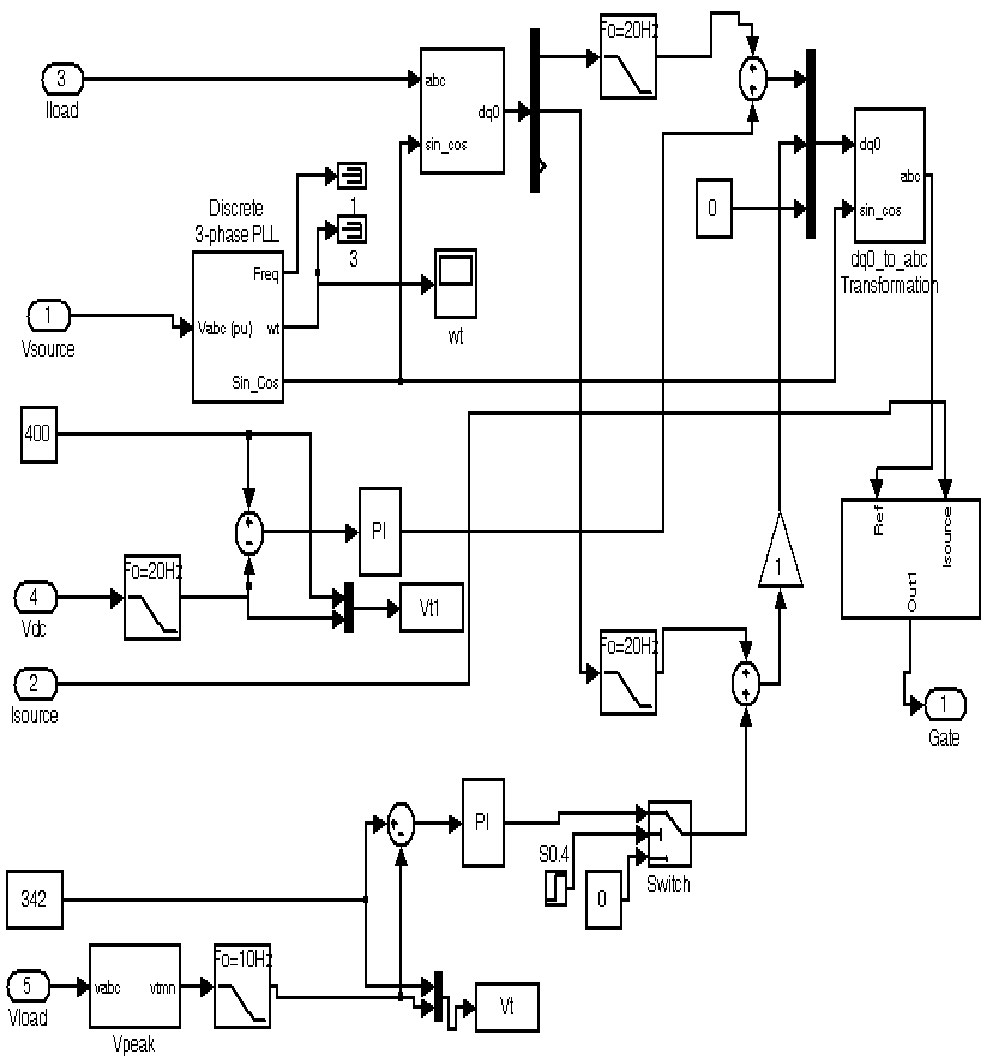

Fig. 6. MATLAB model of the control scheme of the three-phase four-wire DSTATCOM

A. Performance of DSTATCOM with Linear Load for Neutral Current Compensation, Load Balancing and ZVR Operation

The dynamic performance of the DSTATCOM under linear lagging power factor unbalanced load condition is shown in Fig. 7. The source currents are balanced and sinusoidal. At 0.6 sec, the load is changed to two-phase load and to single-phase load at 0.7 sec. These loads are applied at 0.8 sec and 0.9 sec respectively. The PCC voltages (v_S), source currents (i_S), load currents (i_L),compensator currents (i_C), source neutral current (i_{Sn}), load neutral current (i_{Ln}), compensator neutral current (i_{Zn}), dc bus voltage (v_{dc}) and amplitude of voltage (V_S) at PCC are also depicted in Fig. 7. The source neutral current is observed as nearly zero and this verifies the proper compensation. It is also observed that the dc bus voltage of DSTATCOM is able to maintain close to the reference value under all disturbances. The amplitude of PCC voltage is maintained at the reference value under various load disturbances, which shows the ZVR mode of operation of DSTATCOM.

B. Performance of DSTATCOM with Non-Linear Load for Harmonic Compensation, Load Balancing and ZVR Operation

The dynamic performance of the DSTATCOM with non-linear and unbalanced

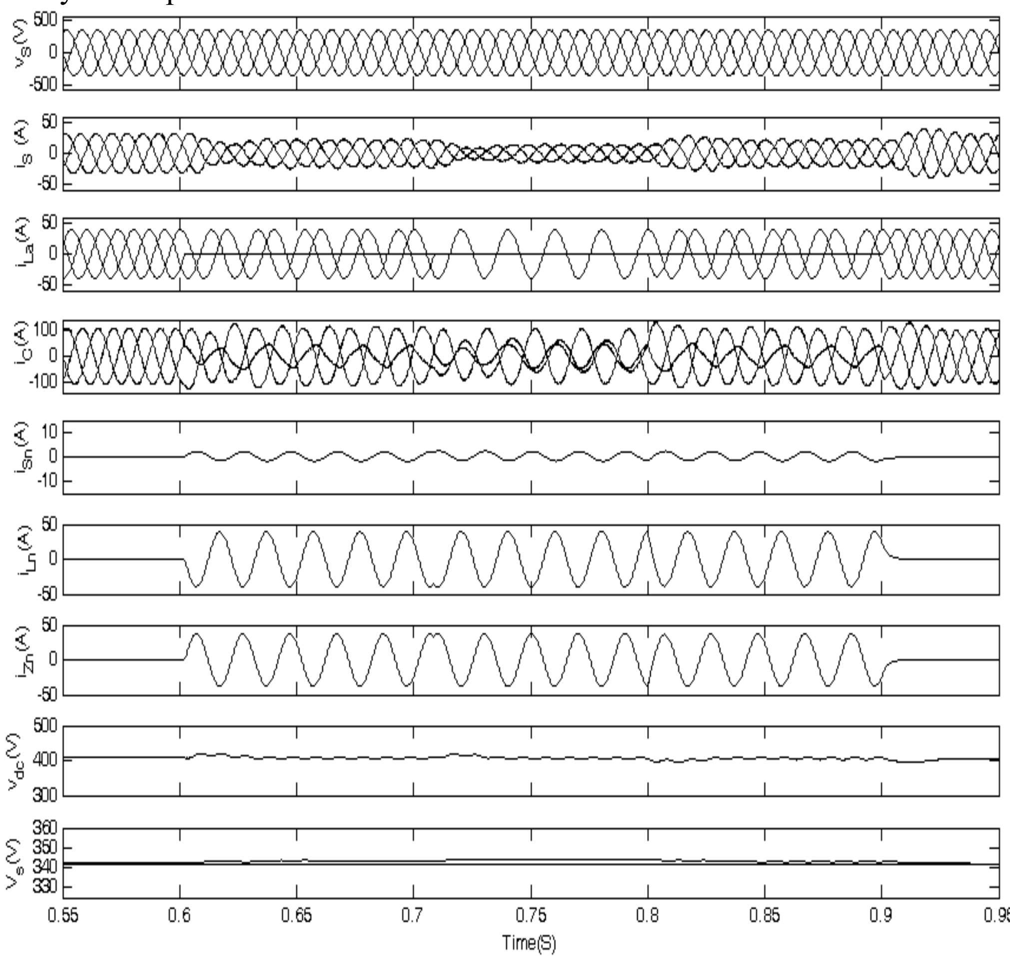

Fig. 7. Performance of 3-phase Three-leg VSC and star/hexagon transformer based DSTATCOM for neutral current compensation, load balancing and voltage regulation.

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load is given in Fig. 8. It is observed that the harmonic current is compensated and the source currents are balanced and sinusoidal. At 1.0 sec, the load is changed to two-phase load and to single-phase load at 1.1 sec. The loads are applied at 1.2 sec and 1.3 sec respectively. The source currents are still balanced and sinusoidal even when the current in a phase is zero. The dc bus voltage of DSTATCOM is maintained at nearly to its reference value under all disturbances.

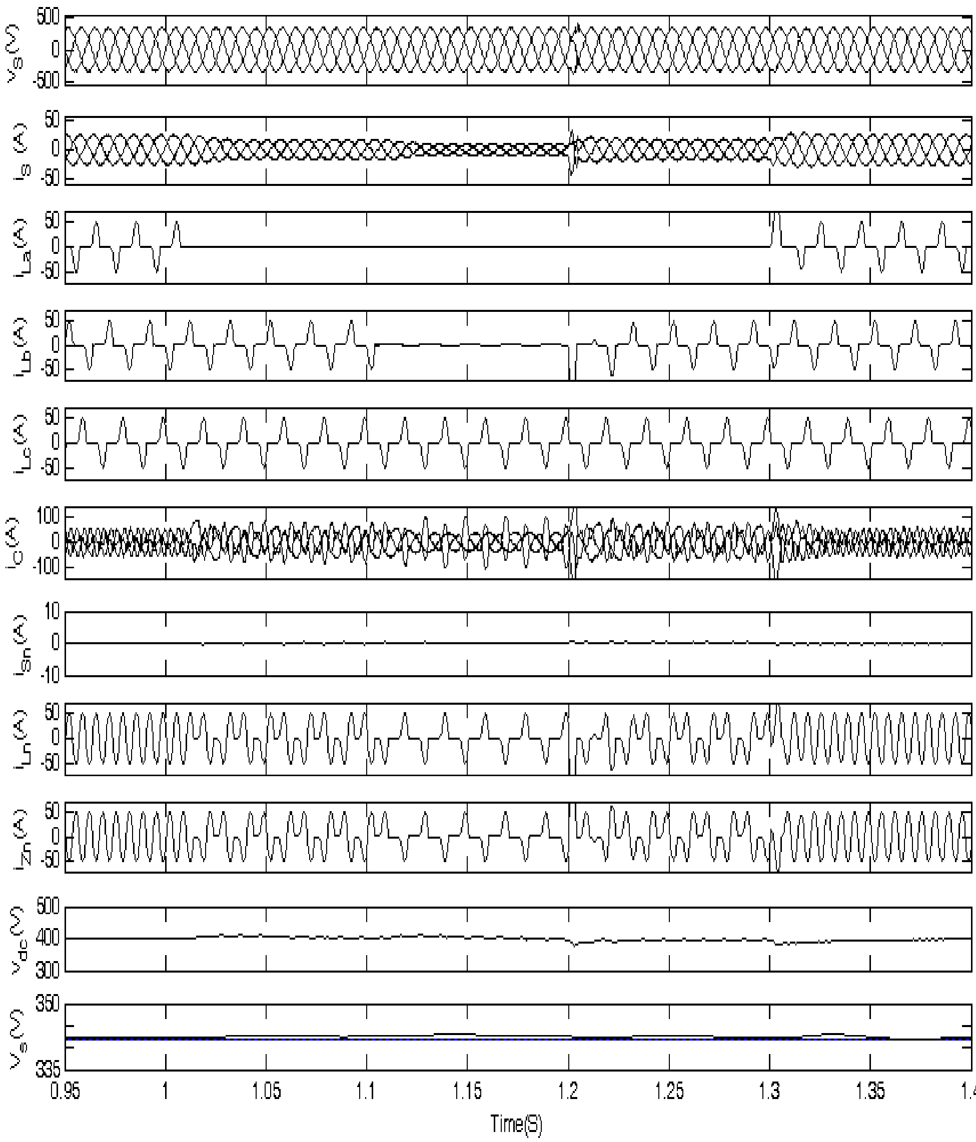

Fig. 8. Performance of 3-phase Three-leg VSC and star/hexagon transformer based DSTATCOM for neutral current compensation, load balancing, harmonic compensation and voltage regulation.

C. Performance of DSTATCOM with Linear Load for Neutral Current Compensation, Load Balancing and UPF Operation

The dynamic performance of the DSTATCOM during linear lagging power factor unbalanced load condition is depicted in Fig. 9. At 0.6 sec, the load is changed to two-phase load and to single-phase load at 0.7 sec. These loads are applied at 0.8 sec and 0.9 sec respectively. The PCC voltages (v_S), source currents (i_S), load currents (i_L), compensator currents (i_C), source neutral current (i_{Sn}), load neutral current (i_{Ln}), compensator neutral current (i_{Zn}), dc bus voltage (v_{dc}) and amplitude of voltage (V_S) at PCC are also depicted in Fig. 9. The reactive power is compensated for power factor correction and the source currents are balanced and sinusoidal. The source neutral current is nearly zero and it verifies the proper

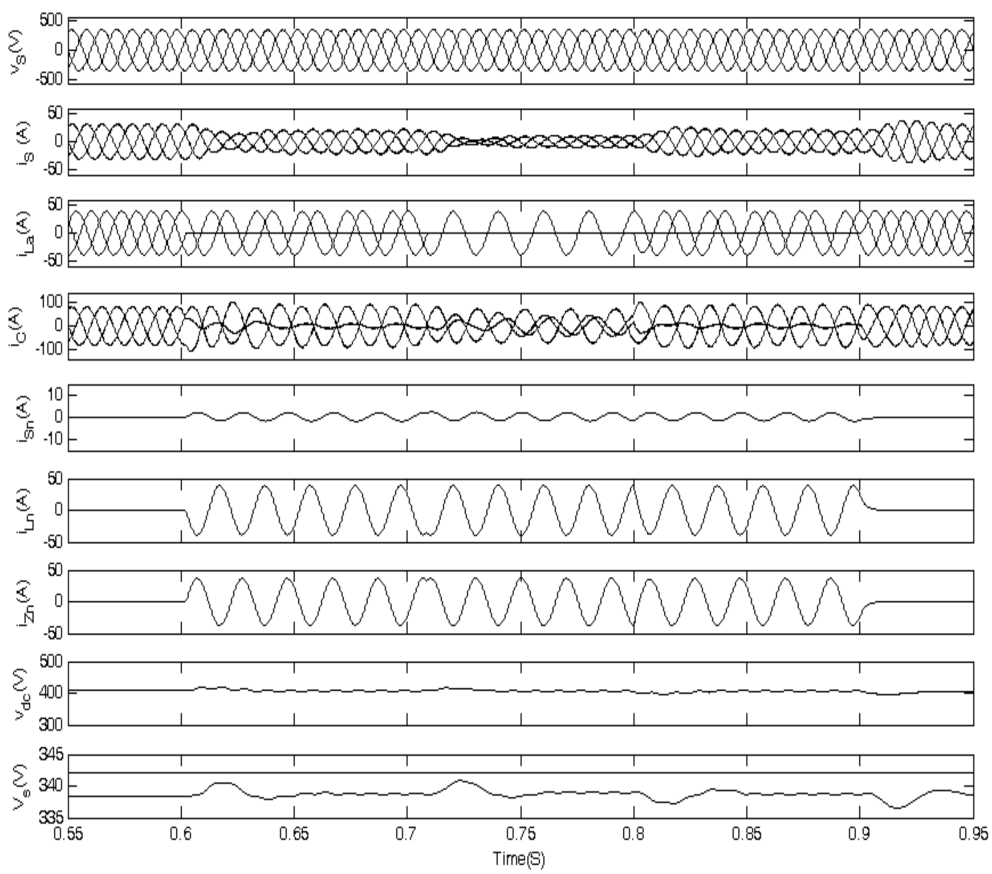

Fig. 9. Performance of 3-phase Three-leg VSC and star/hexagon transformer based DSTATCOM for neutral current compensation, load balancing and power factor correction.

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compensation. It is also observed that the dc bus voltage of DSTATCOM is maintained at the reference value under all disturbances.

D. Performance of DSTATCOM with Non-Linear Load for Harmonic Compensation, Load Balancing and UPF Operation

The dynamic performance of the DSTATCOM during non-linear, unbalanced load conditions is shown in Fig. 10. The source currents are observed as balanced and sinusoidal under all these conditions. At 1.0 sec, the load is changed to two-phase load and to single-phase load at 1.1 sec. These loads are applied again at 1.2 sec and 1.3 sec respectively. The PCC voltages (v_S), source currents (i_S), load currents (i_{La}, i_{Lb}, i_{Lc}), compensator currents (i_C), source neutral current (i_{Sn}), load neutral current (i_{Ln}), compensator neutral current (i_{Cn}), dc bus voltage (v_{dc}) and amplitude of voltage (V_S) at PCC are also depicted in Fig. 10. The dc bus voltage

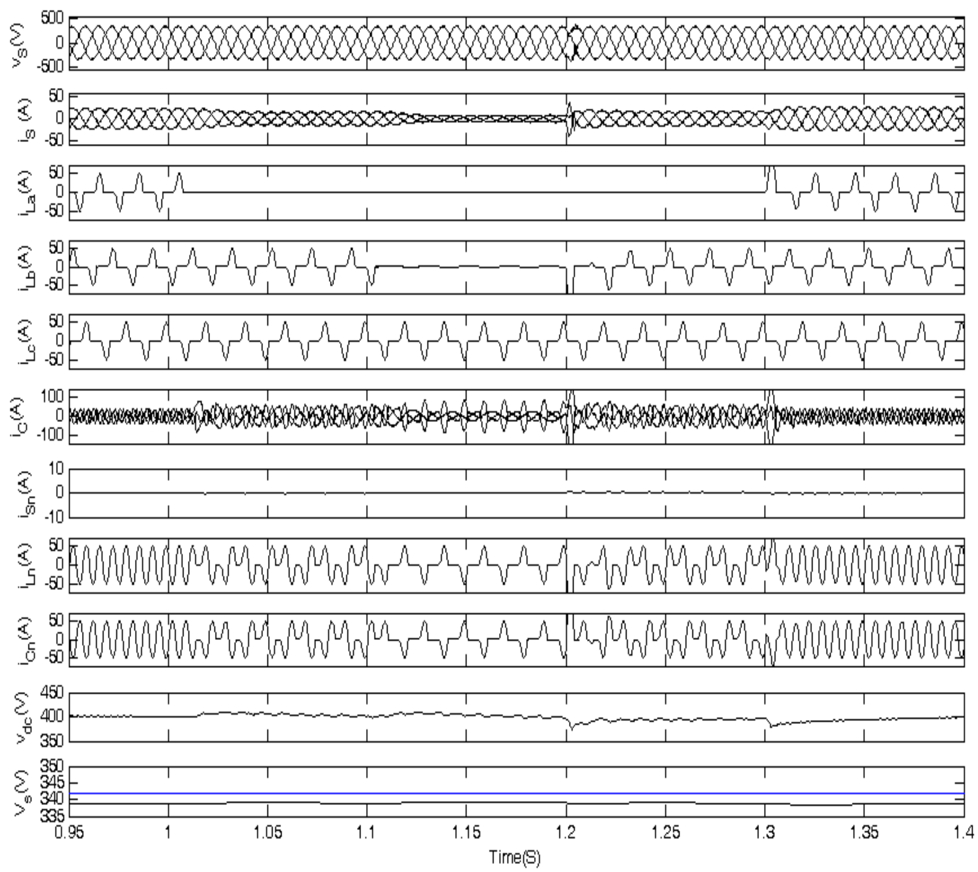

Fig. 10. Performance of 3-phase Three-leg VSC and star/hexagon transformer based DSTATCOM for neutral current compensation, load balancing, harmonic compensation and power factor correction.

of DSTATCOM is maintained at the reference value under all disturbances through proper control. The amplitude of PCC voltage is not regulated to the reference value under load disturbances. The waveform of the load current, source current and PCC voltage in one phase along with their harmonic spectra are demonstrated in Fig. 11, Fig. 12 and Fig. 13 respectively. The total harmonic distortion (THD) of the source current is 2.01%, where as that of load current is 77.31% and this shows the satisfactory performance of DSTATCOM for harmonic compensation as stipulated by IEEE-519 standard.

V. Conclusion

A new three-phase four-wire DSTATCOM using a star/hexagon transformer has been proposed for three-phase four-wire distribution system to improve the power quality. The performance of DSTATCOM system has been demonstrated for neutral current compensation along with reactive power compensation, harmonic

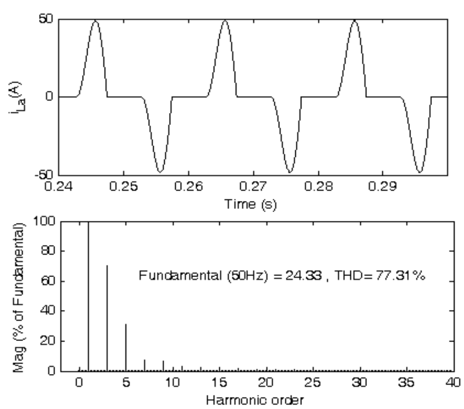

Fig. 11. Load current and harmonic spectrum.

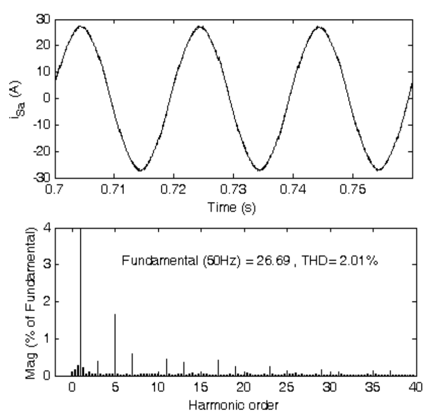

Fig. 12. Source current and harmonic spectrum.

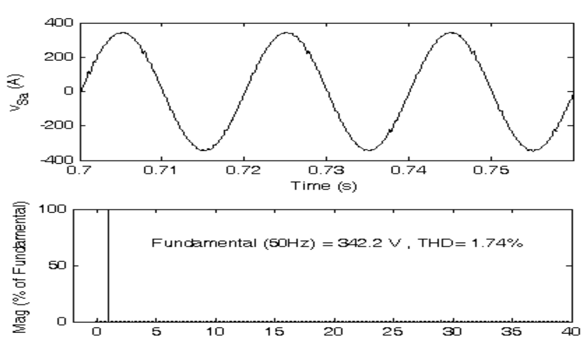

Fig. 13. Voltage at PCC and its harmonic spectrum.

elimination and load balancing for both linear and non-linear loads. The voltage regulation and power factor correction modes of operation of the DSTATCOM have been observed as expected ones. The star/hexagon transformer has been found effective for compensating the zero sequence fundamental and harmonics currents. The dc bus voltage of the DSTATCOM has been regulated to the reference dc bus voltage under all varying loads. The DSTATCOM has been found to meet IEEE 519-1992 standard recommendations of harmonic levels.

APPENDIX

Line Impedance: R_s=0.01 Ω, L_s= 2 mH.
Loads: (i) Linear: 20 kVA, 0.80 pf lag.
(ii) Non-linear: Three single-phase bridge rectifier with R = 25 Ω and C = 470μF.
Ripple filter: R_f= 5 Ω, C_f= 5 μF.
DSTATCOM:
Interfacing Inductance, L_f = 3.5 mH.
DC bus capacitance of DSTATCOM: 2200 μF.
DC bus voltage of DSTATCOM: 400 V.
DC voltage PI controller: K_{pd}=0.1, K_{id}=0.8.
PCC voltage PI controller: K_{pq} =0.2, K_{iq} =0.5.
AC line voltage: 415 V, 50 Hz.
PWM switching frequency: 10 kHz.
Star-Hexagon Transformer:
Three numbers of single-phase transformers of each of rating 5kVA, 240V/116V/116V.

REFERENCES

[1] *IEEE Recommended Practices and Requirements for Harmonics Control in Electric Power Systems*, IEEE Std. 519, 1992.
[2] A.Ghosh and G. Ledwich, *Power Quality Enhancement using Custom Power devices*, Kluwer Academic Publishers, London, 2002.
[3] E.Acha, V.G. Agelidis, O. Anaya-Lara, T J E. Miller, *Power Electronic Control in Electric Systems,* Newness Power engineering series, 1st Edition, Oxford, 2002.
[4] R. C. Dugan, M. F. McGranaghan and H. W. Beaty, *Electric Power Systems Quality*. 2ed Edition, New York, McGraw Hill, 2006.
[5] Antonio Moreno-Munoz, *Power Quality: Mitigation Technologies in a Distributed Environment*, Springer-Verlag London limited, London 2007.

[6] H. Akagi, E H Watanabe and M Aredes, *Instantaneous power theory and applications to power conditioning*, John Wiley & Sons, New Jersey, USA, 2007.

[7] Ewald F. Fuchs and Mohammad A. S. Mausoum, *Power Quality in Power Systems and Electrical Machines*, Elsevier Academic Press, London, UK, 2008.

[8] Hurng- Liahng Jou, Kuen- Der Wu, Jinn- Chang Wu and Wen- Jung Chiang, "A three-phase four- wire power filter comprising a three-phase three-wire active filter and a zig-zag transformer," *IEEE Trans. Power Electron.,* vol. 23, No. 1, pp. 252- 259, January 2008.

[9] Bhim Singh, Ambrish Chandra, Kamal Al-Haddad, Anuradha and D. P. Kothari, "Reactive power compensation and load balancing in electric power distribution systems," *International Journal of Electrical Power & Energy Systems*, vol. 20,no. 6, pp. 375-381, Aug. 1998.

[10] M. Tavakoli Bina, M.D. Eskandari and M. Panahlou, "Design and installation of a ±250 kVAr D-STATCOM for a distribution substation," *Electric Power Systems Research*, vol.73, no. 3, pp. 383-391, Mar 2005.

[11] M.C. Benhabib and S. Saadate, "New control approach for four-wire active power filter based on the use of synchronous reference frame," *Electric Power Systems Research*, vol. 73,no. 3, pp. 353-362, Mar 2005.

[12] María Isabel Milanés, Enrique Romero Cadaval and Fermín Barrero González, "Comparison of Control Strategies for Shunt Active Power Filters in Three-Phase Four-Wire Systems," *IEEE Trans. on Power Electronics*, vol. 22, no. 1, pp.229-236, Jan. 2007.

[13] M.G.Molina and P.E.Mercado, "Control Design and Simulation of DSTATCOM with Energy Storage for Power Quality Improvements," in *Proc. of TDC 06,* Aug 2006, pp. 1-7.

[14] H Fugita and H Akagi, "Voltage-regulation performance of a shunt active filter intended for installation on a power distribution system," *IEEE Trans. on Power Electronics*, vol. 22, no.1, pp. 1046-1053, May 2007.

[15] B Singh, S Gairola, B.N.Singh, A.Chandra and K. Al-Haddad, "Multipulse AC–DC Converters for Improving Power Quality: A Review," *IEEE Trans. on Power Electronics*, vol.23, no.1, pp.260 – 281, Jan.2008.

[16] Bhim Singh, Sanjay Gairola, Ambrish Chandra and Kamal Al-Haddad, "Power Quality Improvements in Isolated Twelve-Pulse AC-DC Converters Using Delta/Double-Polygon Transformer," in *Proc. of IEEE PESC*, June 2007, pp. 2848 – 2853.

[17] B.N.Singh, P.Rastgoufard, B.Singh, A.Chandra and K.Al.Haddad, "Design, simulation and implementation of three pole/ four pole topologies for active filters," *IEE Eletr. Power Appl.*, vol. 151, no. 4, pp. 467-476, July 2004.

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