Three-Phase Four-Wire DSTATCOM with Reduced Switches for Power Quality Improvement

Bhim Singh[1] P. Jayaprakash[2] D.P. Kothari[3]

Abstract – In this paper, a two-leg VSC (voltage source converter) integrated with a star/hexagon transformer is used for the power quality improvement in three-phase four-wire distribution system. The primary winding of the transformer is star connected and it provides a path to the zero sequence fundamental as well as harmonics neutral currents. The secondary windings of the transformer are connected in hexagon manner and it provides isolation to the two-leg VSC. In order to optimise the voltage rating of the two-leg VSC, the secondary winding of the transformer is suitably designed. The proposed DSTATCOM (Distribution Static Compensator) provides the voltage regulation or power factor correction by reactive power compensation, harmonics elimination, load balancing and neutral current compensation in three-phase four-wire distribution system. This topology has the advantages of the use of 'off the shelf' two-leg VSC, reduced size and cost. The rating of the transformer remains same when it is compensating the neutral current due to unabalance in the load. The performance of the proposed DSTATCOM system is validated through simulations using MATLAB software with its Simulink and Power System Blockset (PSB) toolboxes.

Keywords - Power quality, DSTATCOM, H-bridge VSC, star/hexagon transformer, neutral current compensation

I. INTRODUCTION

The power quality problems in the three-phase four-wire distribution systems are severe mainly due to the proliferation of different types of non-linear loads, unplanned expansion of the distribution system etc. These power quality problems include high reactive power burden, harmonic currents, load unbalance and excessive neutral current [1-4]. The power quality aspects are governed by the various standards such as the IEEE-519 standard [5]. Some remedies to these power quality problems are reported in the literature [2-4] and the group of controllers used in the distribution system is known as custom power devices (CPD) which include the DSTATCOM (distribution static compensator), DVR (dynamic voltage restorer) and UPQC (unified power quality conditioner). These are used for compensating the power quality problems in the current, voltage and both current and voltage respectively. The DSTATCOM is developed and installed in the distribution system for power quality improvement [6].

Three-phase four-wire distribution systems are used to supply single-phase low voltage loads. The typical loads may be computer loads, lighting ballasts, small rating adjustable speeds drives (ASD) in air conditioners, fans, refrigerators and other domestic and commercial appliances etc. These loads may create problems of harmonics in the supply current as well as excessive neutral current. The neutral current consists of mainly third harmonics currents [3]. The zero- sequence neutral current gets a path through the neutral conductor. The unbalanced single-phase loads result in high neutral current. Three-phase four-wire shunt compensators are reported in the literarure [7-8] for neutral current compensation along with harmonic elimination and load balancing. The use of split capacitors with 2-leg VSC (voltage source converter) is used for compensation in three-phase three-wire system [9-10]. Some of the topologies of three-phase four-wire DSTATCOM for the mitigation of the neutral current along with power quality compensation in the supply current are four-leg VSC (voltage source converter), three single phase VSC, three-leg VSC with split capacitors [3], three-leg VSC with zig-zag transformer [7], three-leg VSC with neutral terminal at the positive or negative terminal of dc bus [8]. The application of a zig-zag transformer for reduction of the neutral current has the advantages due to passive compensation, rugged and less complex over the active compensation techniques [7].

In this paper, a new topology of DSTATCOM is proposed in which a two-leg VSC along with a star/hexagon transformer is able to perform required compensations for a three phase four wire system. Moreover, the star/hexagon transformer is suitably designed for mmf (magnetic motive force) balance. The star/hexagon transformer mitigates the neutral current and the H-bridge VSC compensates harmonic current, reactive power and balances the load. In order to optimize the voltage rating of the H-bridge VSC, the star/hexagon transformer is designed for integrating the DSTATCOM with the secondary winding of the transformer. The dynamic performance is studied for voltage regulation and power factor correction mode of the DSTATCOM using MATLAB software with its Simulink and PSB (power system blockset) tool boxes.

II. PROPOSED DSTATCOM

The three-phase four-wire DSTATCOM is used for reactive power and harmonics currents compensation along with load balancing and neutral current elimination. Fig. 1 shows the power circuit of proposed H-bridge VSC integrated with star/hexagon transformer as DSTATCOM. The linear and non-linear, balanced and unbalanced loads are connected at the PCC. The star/hexagon transformer connected at the load terminal provides a path for zero sequence harmonics and fundamental currents. A set of

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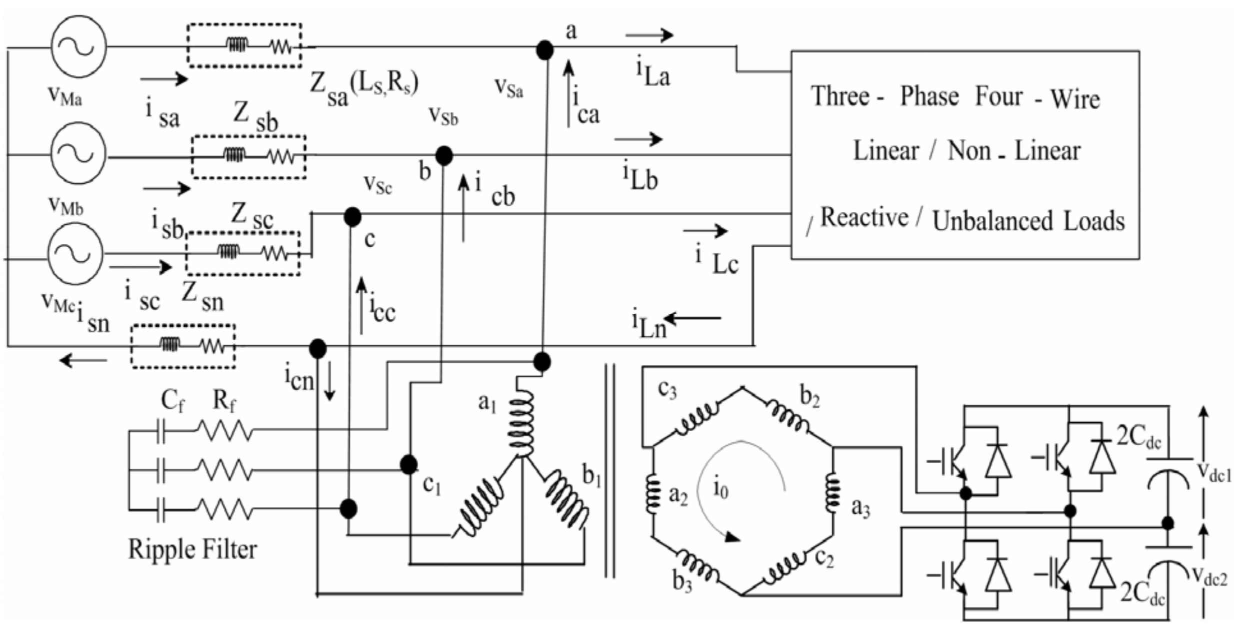

Fig. 1: Proposed Integrated 3-leg VSC with star/hexagon transformer based DSTATCOM in the distribution system.

secondary windings are designed in the star/hexagon transformer for connecting the H-bridge VSC. The VSC consists of four insulated-gate bipolar transistors (IGBTs) and two dc capacitors.

This transformer provides an isolation to the VSC as well as the suitability of selecting an 'off the shelf' H-bridge VSC for this application. In the zero voltage regulation (ZVR) mode of operation, DSTATCOM injects a current I_c, such that the voltage at PCC (V_S) and the source voltage (V_M) are in the locus of same circle.

A. *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. The voltage across each primary winding is the phase voltage and the H-bridge VSC is connected to this transformer as shown in Fig. 2(a). The volatge rating of the star/hexagon transformer windings are designed [11] as shown below.

The phasor diagram shown in Fig. 2(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

$$V_{ca} = K_1 V_a - K_2 V_c \tag{1}$$

where K_1 and K_2 are the fraction of winding in the phases. Considering $V_a = V\angle 0°$ and $V_{ca} = \sqrt{3}V\angle 30°$, then from (1),

$$\sqrt{3}V\angle 30° = K_1 V\angle 0° - K_2 V\angle -120° \tag{2}$$

one gets, $K_1 = 1$, $K_2 = 1$

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

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

Hence, three numbers of single-phase transformers of each of rating 5kVA, 240V/120V/120V are selected.

B. *H-Bridge VSC*

The DSTATCOM uses a two- leg, H-bridge, PWM controlled *IGBTs* based VSC. The rating of the switches is based on the voltage and current rating of the compensation system. For the considered load given in Appendix, the rating of the VSC for power factor correction by reactive power compensation is found to be 12 *kVA*. The selection of dc bus voltage, dc bus capacitor, ac inductor and the ripple filter are selected as per the design of VSC for the shunt compensator [12].

C. *Control of DSTATCOM*

There are many theories available for the generation of reference source currents for the control of VSC of DSTATCOM for three phase four wire system in the literature viz. instantaneous reactive power theory (p-q theory), synchronous reference frame theory, power balance theory etc [13]. The synchronous reference frame theory based method is used for the control of H-bridge VSC. A block diagram of the control scheme is shown in Fig. 3. The load currents (i_L), the PCC voltages (v_s) and dc bus voltage (v_{dc1}, v_{dc2}) of DSTATCOM are sensed as feedback signals. The loads currents in the three-phases are converted into the d-q-0 frame using the Park's transformation as in eqn. (4).

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \tag{4}$$

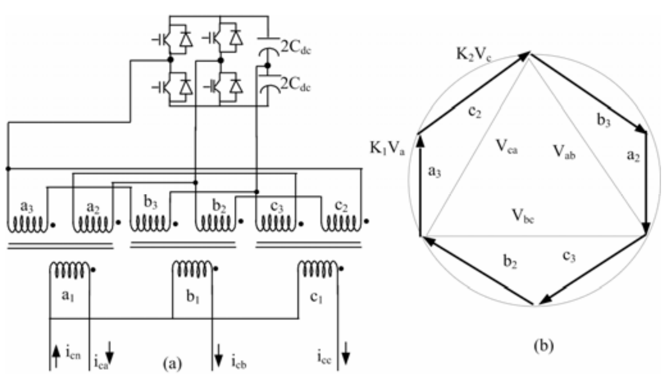

Fig. 2: (a)Star/hexagon transformer and the H-bridge VSC for operation as DSTATCOM (b) phasor diagram

A three-phase PLL (phase locked loop) is used to synchronise these signals with the PCC voltage. These d-q current components are then passed through low pass filters to extract the d_c components of i_d and i_q. The error between the reference dc capacitor voltage and the sensed dc bus voltage of DSTATCOM is given to a PI (proportional-integral) controller and its output voltage is considered as the loss component of the current (i_{loss}) and is added to the dc component of i_d.

$$i_{loss(n)} = i_{loss(n-1)} + K_{pd}\,(v_{de(n)} - v_{de(n-1)}) + K_{id}\,v_{de(n)} \quad (5)$$

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 error between the difference of the dc bus capacitors voltages and its reference zero value is given to another PI controller and the output (i_{equal}) is also added to the dc component of i_d.

The reference d-axis supply current is therefore as,

$$i_d^{*} = i_{d\,dc} + i_{loss} + i_{equal} \quad (6)$$

Similarly, a third PI controller is used to regulate the PCC voltage. The amplitude of PCC voltage and its reference value are fed to a PI controller and the output of the PI controller is added with the dc component of i_q because this is estimated as the quadrature component of current for regulating the ac voltage.

$$i_{qr(n)} = i_{qr(n-1)} + K_{pq}\,(v_{te(n)} - v_{te(n-1)}) + K_{iq}\,v_{te(n)} \quad (7)$$

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 nth sampling instant. K_{pq} and K_{iq} are the proportional and the integral gains of the PCC voltage PI controller. The reference q-axis supply current is as

$$i_q^{*} = i_{qdc} + i_{qr} \quad (8)$$

The control strategy is to regulate the PCC voltage, elimination of harmonics in load currents and the load balancing. The resultant d-q-0 currents are again converted into the reference three-phase supply currents using the reverse Park's transformation. The reference currrents in two phases are used for the control of the H-bridge VSC. The sensed and reference supply currents are compared in those two phases before comparing with a triangular carrier signal to generate the gating signals for four switches. For power factor correction of the load, the PCC voltage PI controller is set as zero in the control algorithm of DSTATCOM.

III. MATLAB MODELLING OF DSTATCOM SYSTEM

The H-bridge VSC and the star/hexagon transformer based DSTATCOM interfaced to a three phase four wire system is modeled and simulated using the MATLAB and its Simulink and PSB toolboxes. The DSTATCOM system shown in Fig. 1 is modeled in MATLAB with its Simulink and PSB toolboxes. The load considered is a lagging power factor and non-linear loads. The ripple filter is connected to the VSC of the DSTATCOM for filtering the ripple in the terminal voltage. The system data are given in Appendix. The multi-winding transformer model avilable in the PSB is used for modelling the star/hexagon transformer.

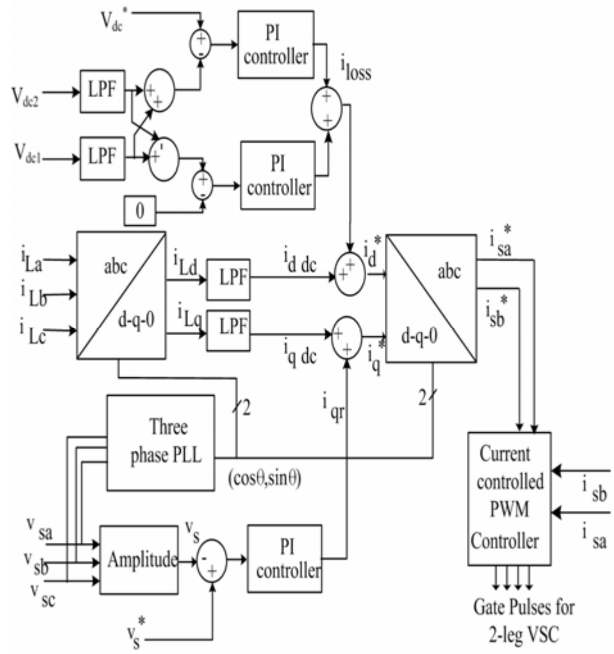

Fig. 3: Control algorithm for the H-bridge VSC

The control algorithm for the DSTATCOM is also modelled in MATLAB. The reference supply currents are derived from the sensed PCC voltages (v_s), load currents (i_L) and the dc bus voltages of DSTATCOM (v_{dc1}, v_{dc2}). A PWM current controller is used over the reference and sensed supply currents to generate the gating signals for the IGBT of the VSC of the DSTATCOM.

IV. RESULTS AND DISCUSSION

The performance of DSTATCOM consisting of H-bridge VSC and the star/hexagon transformer for PCC voltage regulation along with neutral current compensation and load balancing of a three-phase four–wire load is shown in Fig. 4. At 1.8 sec, the load is changed to two-phase load and again to single-phase load at 1.86 sec. These loads are applied again at 1.94 sec and 2.0 sec respectively. The voltages at PCC (v_s), balanced supply currents (i_s), load currents (i_{La}, i_{Lb}, i_{Lc}), compensator currents (i_C), supply neutral current (i_{sn}), load neutral current (i_{Ln}), compensator neutral current (i_{Cn}), dc bus voltages (v_{dc}) along with split capacitor voltages (v_{dc1}, v_{dc2}) and the amplitude of PCC voltage (V_S) are demonstrated under varying load conditions. It is observed that the amplitude of PCC voltage is regulated to the reference amplitude by the required reactive power compensation. The d_c bus voltages of two capacitors of the VSC of DSTATCOM are regulated to equal magnitude by the controller and the d_c bus voltage is maintained at the reference voltage under different load disturbances.

The dynamic performance of DSTATCOM with star/hexagon transformer for voltage regulation and harmonic elimination along with neutral current compensation is shown in Fig. 5. The PCC voltages (v_s), balanced supply currents (i_s), load currents (i_{La}, i_{Lb}, i_{Lc}), compensator currents (i_C), supply neutral current (i_{sn}), load neutral current (i_{Ln}), compensator neutral current (i_{Cn}), dc bus voltage *(v_{dc})* along with split capacitor voltages (v_{dc1}, v_{dc2}) and amplitude of PCC voltage (V_s) are demonstrated under varying loads. At 0.8 sec, the load is changed to two-phase load and to single-phase load at 0.9 sec. The loads are applied again at 1.0 sec. The PCC voltage is regulated to the reference amplitude value.

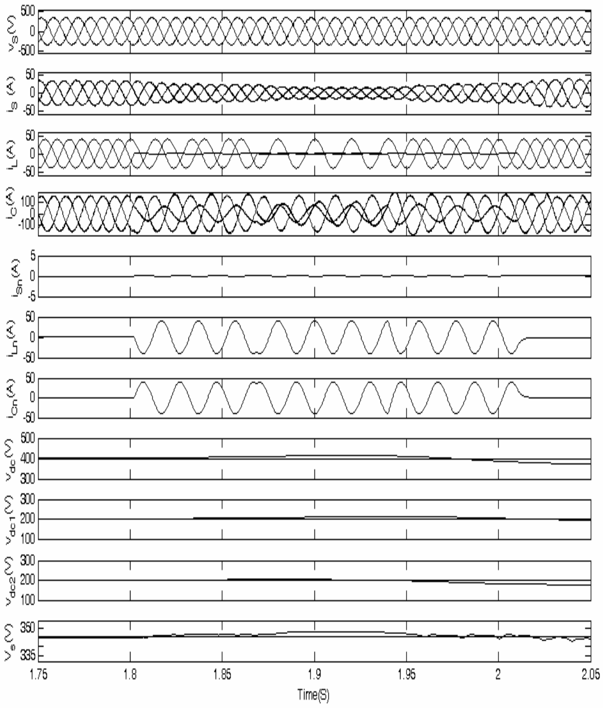

Fig. 4: Performance of proposed DSTATCOM for neutral current compensation, load balancing and voltage regulation.

The performance of the DSTATCOM system in the unity power factor (UPF) mode of operation is depicted in Fig. 6 and Fig. 7. The load balancing and neutral current compensation are demonstrated in Fig. 6 and the harmonic elimination, load balancing and neutral current compensation are demonstrated in Fig. 7. The PCC voltages (v_s), balanced sinusoidal supply currents *(i_s)*, load currents *(i_{La}, i_{Lb}, i_{Lc})*, compensator currents (i_C), supply neutral current *(i_{sn})*, load neutral current (i_{Ln}), compensator neutral current (i_{Cn}), dc bus voltage (v_{dc}) along with split capacitor voltages (v_{dc1}, v_{dc2}) and amplitude of PCC voltage (V_s) are shown in both these cases. It is also observed that the PCC voltage is not regulated in both these cases as the compensator is operated in the UPF mode. The waveform of the load current and its harmonic spectrum is shown in Fig. 8 and the compensated supply current with its harmonic spectrum is shown in Fig. 9. The voltage at the PCC with its harmonic spectrum is shown in Fig. 10. It may be observed that the THD (total harmonic distortion) of the supply current is reduced less than 5% thus meeting the requirement of IEEE-519 standard [5].

V. CONCLUSION

The performance of a new topology of three-phase four-wire DSTATCOM consisting of the H-bridge VSC integrated to a star/hexagon transformer has been demonstrated for neutral current compensation along with reactive power compensation, harmonic elimination and load balancing. The star/hexagon transformer has mitigated the supply neutral current and it has been found effective for compensating the zero sequence fundamental and harmonics currents. The voltage regulation and power factor correction modes of operation of the DSTATCOM have been observed as expected ones. The dc bus voltage of the DSTATCOM has been regulated to the reference dc bus voltage under all varying loads. Moreover, an off the shelf two-leg, H-bridge VSC has been controlled for power quality compensation in the three-phase four-wire distribution system. The star/hexagon transformer configuration requires three single phase transformers and this provides isolation to the VSC along with power quality improvement and neutral current compensation.

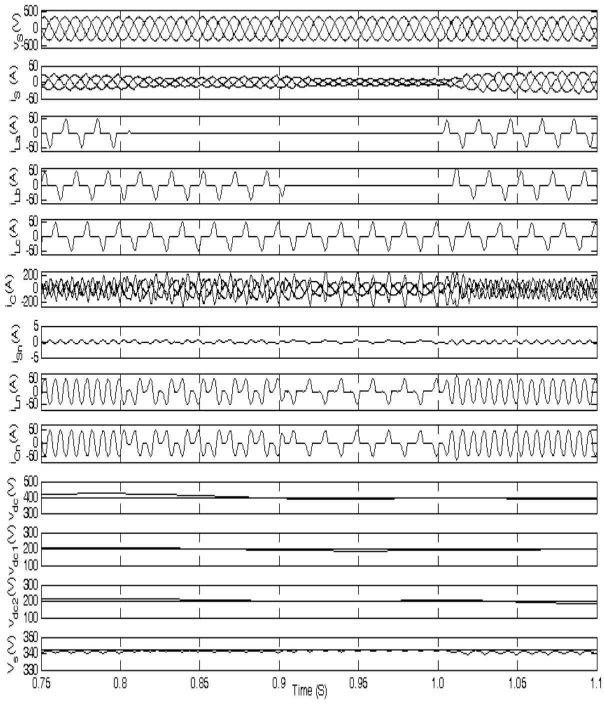

Fig. 5: Performance of proposed DSTATCOM for harmonic elimination, neutral current compensation, load balancing and voltage regulation.

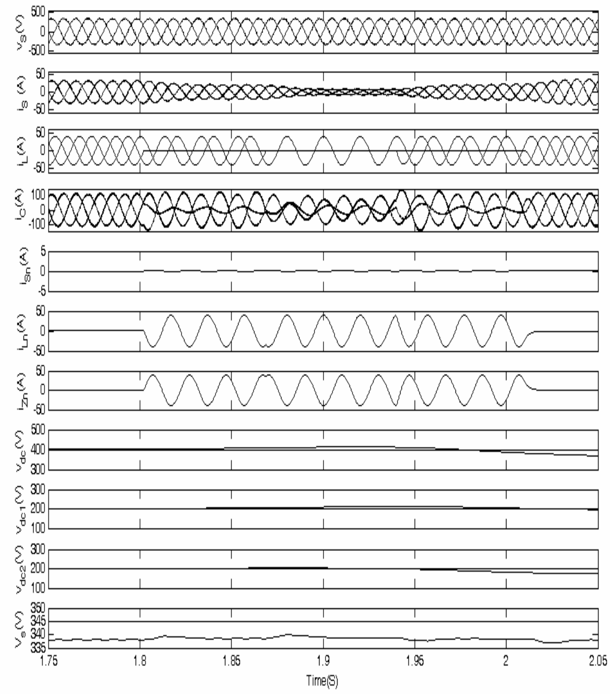

Fig. 6: Performance of proposed DSTATCOM for neutral current compensation, load balancing and power factor correction.

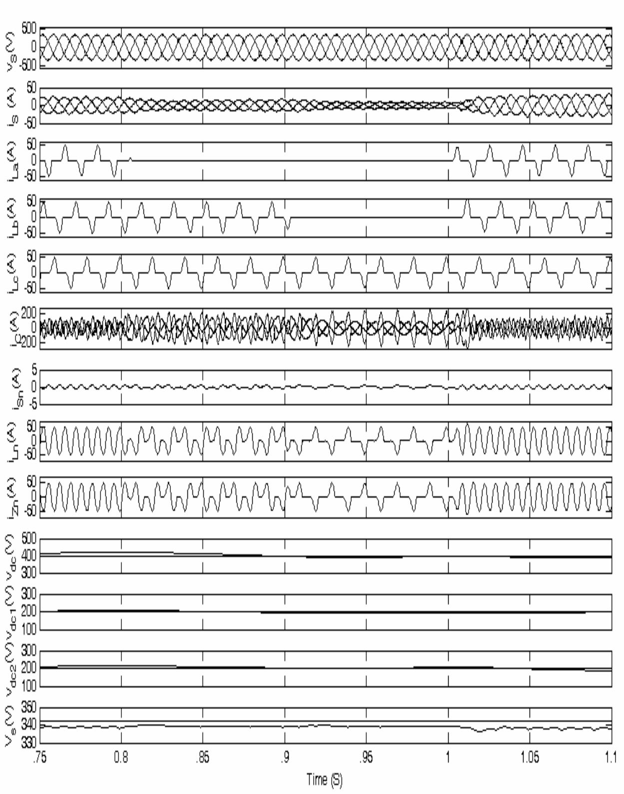

Fig. 7: Performance of proposed DSTATCOM for harmonic elimination, neutral current compensation, load balancing and power factor correction.

APPENDIX

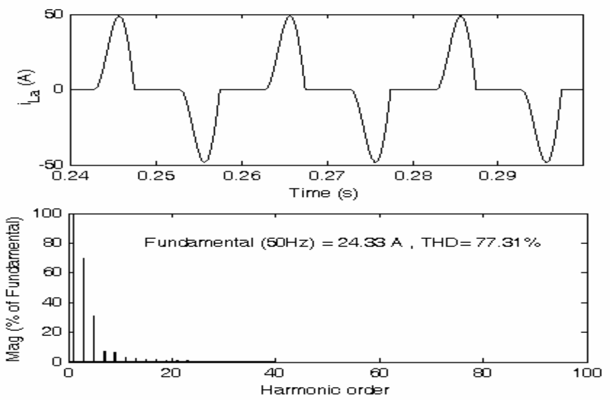

Fig. 8: Load voltage and harmonic spectrum

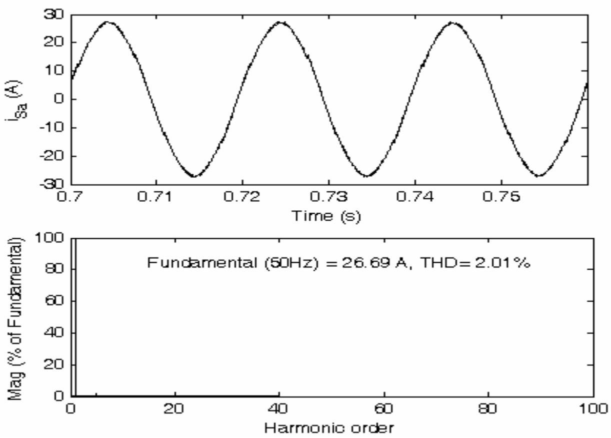

Fig. 9: Supply current and harmonic spectrum

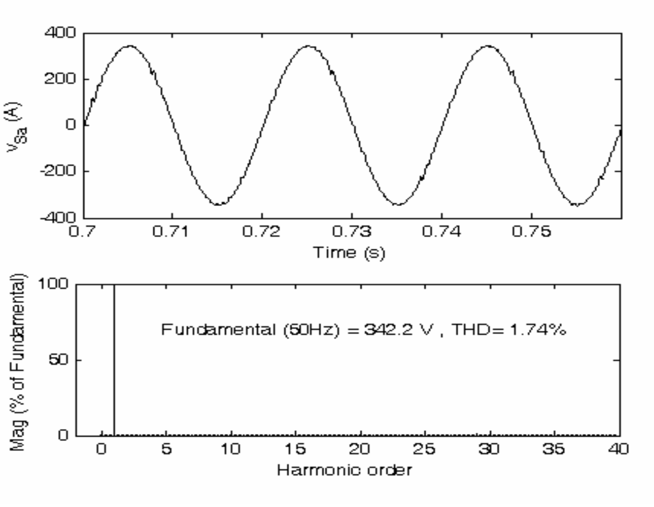

Fig. 10: PCC Voltage and harmonic spectrum

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 rectifiers with R = 25 Ω and C = 470 μF
Ripple filter: R_f= 5 Ω, C_f= 5 μF
DSTATCOM:
DC bus voltage of DSTATCOM: 400 V
Individual capacitor voltages: 200 V
DC bus capacitance of DSTATCOM:10000 μF
AC inductor: 4.2 mH
DC voltage PI controller: K_{pd}=0.19, K_{id}=6.25
DC equal bus voltages PI controller: K_p=0.09, K_i=2.5
PCC voltage PI controller: K_{pq} =0.9, K_{iq} =7.5
AC line voltage: 415V, 50 Hz
PWM switching frequency: 10 kHz
Star/Hexagon Transformer: Three 1-phase transformers of 5 kVA, 240V/120V/120V.

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BIOGRAPHIES

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Dr. Singh is a fellow of Indian National Academy of Engineering (INAE), the Institution of Engineers (India) (IE (I)), and the Institution of Electronics and Telecommunication Engineers (IETE), a life member of the Indian Society for Technical Education (ISTE), the System Society of India (SSI), and the National Institution of Quality and Reliability (NIQR) and Senior Member of Institute of Electrical and Electronics Engineers (IEEE)

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