Reduced Rating VSC With a Zig-Zag Transformer for Current Compensation in a Three-Phase Four-Wire Distribution System

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Abstract—A detailed investigation is made into the causes, standards, and remedies of the excessive neutral current. A reduced-rating voltage-source converter with a zig-zag transformer as a distribution static compensator is proposed for power-quality improvement in the three-phase four-wire distribution system. The proposed DSTATCOM is employed for the compensation of reactive power, harmonics currents, neutral current, load balancing and the voltage regulation at the point of common coupling. The zig-zag transformer is used for providing a path to the zero-sequence current. The performance of the DSTATCOM is validated through extensive simulations using MATLAB software with its Simulink and power system blockset toolboxes.

Index Terms—Distribution static compensator (DSTATCOM), neutral current compensation, power quality (PQ), zig-zag transformer.

I. INTRODUCTION

Distribution systems are facing severe power-quality (PQ) problems, such as poor voltage regulation, high reactive power and harmonics current burden, load unbalancing, excessive neutral current, etc. The source voltages in the distribution systems are also experiencing PQ problems, such as harmonics, unbalance, flicker, sag, swell, etc. [1]–[11]. In order to limit the PQ problems, many standards are also proposed, such as IEEE 519-1992, IEEE Std. 141- 1993, IEC 1000-3-2, etc. [12]–[18]. The remedial solutions to the PQ problems are investigated and discussed in the literature [4]–[11] and the group of devices is known as custom power devices (CPDs). The distribution static compensator (DSTATCOM) is proposed for compensating PQ problems in the current, and the dynamic voltage restorer (DVR) is used for mitigating the PQ problems in the voltage while the unified power-quality conditioner (UPQC) is proposed for solving current and voltage PQ problems. There are many techniques reported for the elimination of harmonics from the source

current as well as the compensation of the neutral current and load balancing [19]–[23]. Some neutral current compensation techniques have been patented [24]–[27].

Three-phase four wire distribution systems have been used to supply single-phase low-voltage loads. The typical loads may be computer loads, office automation machines, lighting ballasts, adjustable speeds drives (ASDs) in small air conditioners, fans, refrigerators, and other domestic and commercial appliances, etc., and generally behave as nonlinear loads. These loads may create problems of high input current harmonics and excessive neutral current. The neutral current consists of mainly triplen harmonics currents. The zero-sequence neutral current obtains a path through the neutral conductor. Moreover, the unbalanced single-phase loads also result in serious zero-sequence fundamental current. The total neutral current is the sum of the zero-sequence harmonic component and the zero-sequence fundamental component of the unbalanced load current, and this may overload the neutral conductor of the three-phase four-wire distribution system.

A number of surveys have been cited about the causes of excessive neutral current in the distribution system [31]–[35]. There are different techniques for the mitigation of neutral current in the three-phase four-wire distribution systems [35]–[54]. The neutral current compensation using a zig-zag transformer [35]–[38]; using a star/delta transformer [39], [40]; using a single-phase active compensator in the neutral path [41]–[43]; and using three-phase four-wire active compensators along with source harmonic current compensation [44]–[54] are reported in the literature. In this investigation, the causes, standards, and remedial solutions for PQ problems due to the excessive neutral current are analyzed and a technique using a zig-zag transformer along with a reduced rating VSC as a DSTATCOM is designed to mitigate these PQ problems. Moreover, the voltage regulation is also achieved at the point of common coupling (PCC) across the loads.

II. NEUTRAL CURRENT COMPENSATION TECHNIQUES

The major causes of neutral current in three-phase distribution systems are the phase current unbalance, third harmonic currents produced by single-phase rectifier loads, and the third harmonics due to source voltage third harmonics [28]. Even balanced three-phase currents produce excessive neutral current with computer loads in the systems. A study reveals that 22.6% of the sites have a neutral current in excess of 100% [29]–[31]. The source voltage distortions in systems with computer loads

Fig. 1. System configuration with a zig-zag transformer for neutral current compensation.
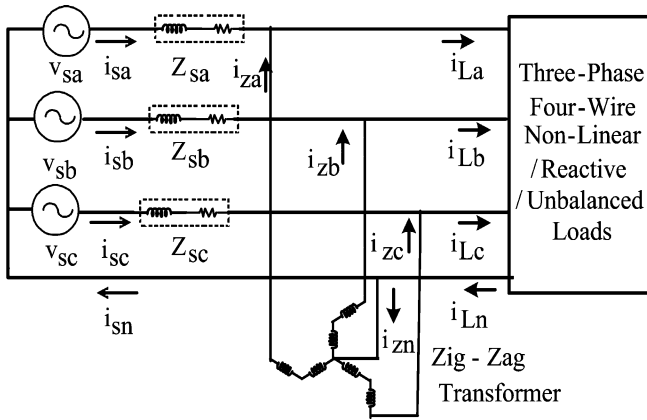

Fig. 2. Zig-zag transformer for neutral current compensation.

can cause excessive neutral current [32], [33]. The nonlinear loads are classified into harmonic current source loads and harmonic voltage-source loads [34].

Various standards are proposed to mitigate PQ problems in the distribution system [12]–[18]. The planning for a distribution system, the voltage considerations, calculation of short-circuit capacities, power factor improvement techniques, protective devices, surge protection, and grounding aspects are proposed in IEEE Standard 141-1993 [12]. It is a complete guide for an industrial plant power system. The recommended practice for electrical power systems in commercial buildings [13], the recommendation for harmonic control in power systems [14], the reference on shunt capacitor design, installation guidelines of improvement of power factor and other applications [15], the practices for monitoring electrical PQ [16], and the guide for the application and specification of harmonic filters [17] are available in the literature. In light of the various standards, there are many techniques proposed for the compensation of neutral current in the three-phase four-wire distribution system. These are discussed in the following sections.

A. Zig-Zag Transformer-Based Compensation

The application of a zig-zag transformer for the reduction of neutral current is advantageous due to passive compensation, rugged, and less complex over the active compensation techniques [35], [37]. Fig. 1 shows the connection of a zig-zag transformer in the system and the zig-zag transformer is shown in Fig. 2. A zig-zag transformer is a special connection of three single-phase transformer windings or a three-phase transformer's windings. The zig-zag transformer in the past has been used to create neutral and to convert a three-phase three-wire system into a three-phase four-wire system. The new application of a zig-zag transformer is to connect in parallel to the load for filtering the zero-sequence components of the load currents. The phasor diagram of the zig-zag transformer is shown in Fig. 3. The currents flowing through the utility side of these three transformers are equal. Hence, the zig-zag transformer can be regarded as open-circuit for the positive-sequence and the negative-sequence currents. Then, the current flowing through the zig-zag transformer is only the zero-sequence component.
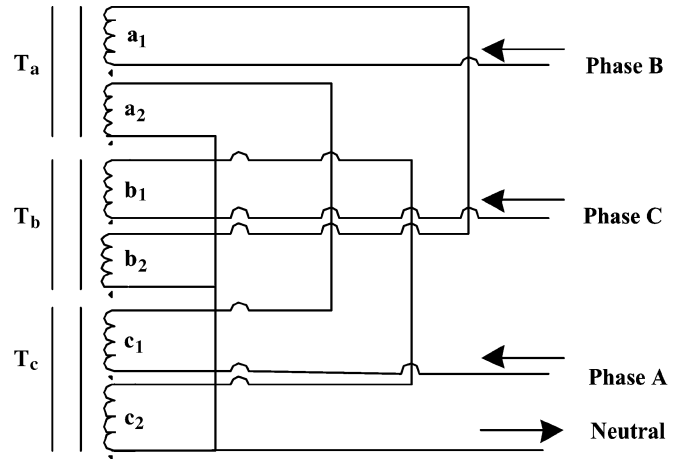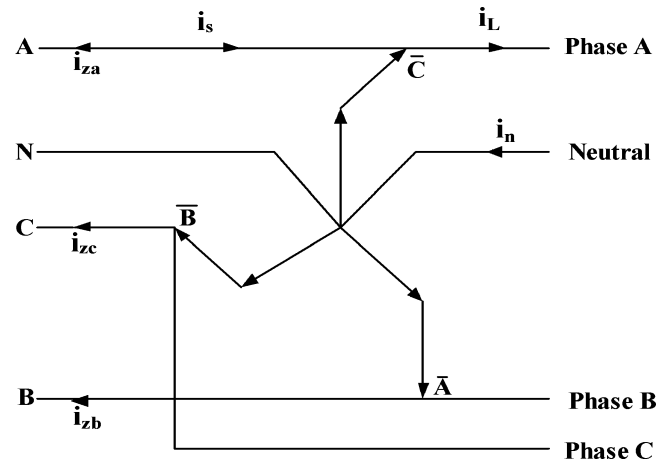

Fig. 3. Diagram showing the flow of currents of zig-zag transformer for neutral current compensation.

An application of a zig-zag transformer alone in a three-phase, four-wire system has the advantages of reduction in load unbalance and reducing the neutral current on the source side. But there are inherent disadvantages such as the performance being dependent on the location of the zig-zag transformer close to the load. Moreover, when the source voltage is distorted or unbalanced, the performance of reducing the neutral current on the source side is affected to an extent.

B. Zig-Zag Transformer With Active Filter-Based Compensation

A hybrid filter consisting of a single-phase VSC and a zig-zag transformer is also efficient in neutral current compensation [36], [38] and the topology is shown in Fig. 4. A different topology for a single-phase VSC with a self-supporting dc bus and zig-zag transformer-based neutral current compensation system [37] is shown in Fig. 5.

C. Star/Delta Transformer-Based Compensation

A star-delta transformer and an active filter are used for harmonic current reduction in the neutral conductor [26]. A filter is
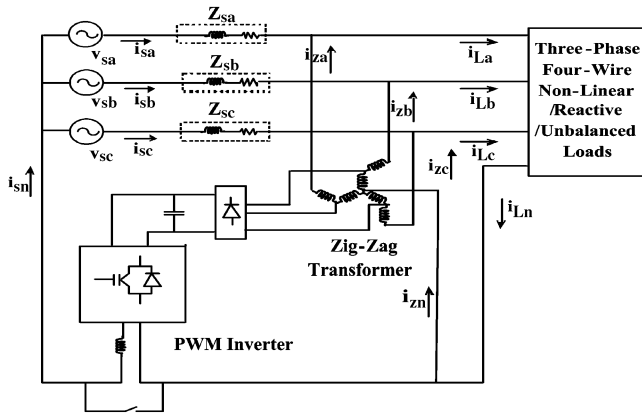
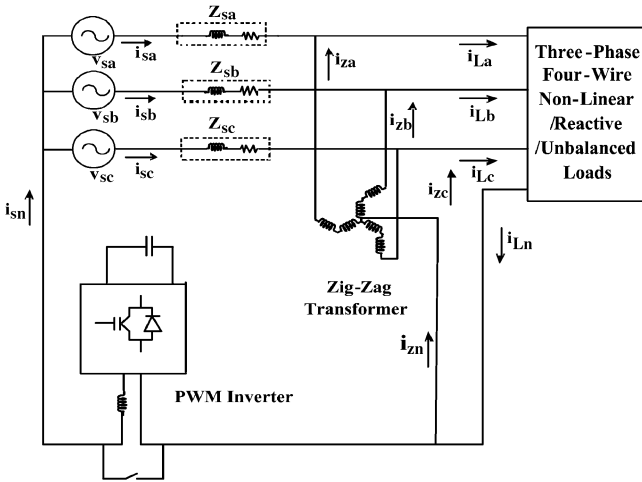Fig. 4. Reduced rating single-phase inverter with a zig-zag transformer for neutral current compensation.

Fig. 5. Hybrid neutral current compensator using a single-phase inverter and zig-zag transformer.

Fig. 6. Star-delta transformer-based neutral current compensator.

Fig. 7. Three-phase four-leg DSTATCOM for neutral current compensation.

used for removing harmonic current from the neutral conductor employing three single-phase transformers with a capacitor, and it has been patented [27]. A scheme using two transformers connected in antiphase, providing a six-phase system, cancels third harmonic currents along a common neutral conductor [28]. Fig. 6 shows the star-delta transformer connection for compensating the neutral current [40]. It consists of a star-delta transformer, a diode rectifier, and a half-bridge PWM inverter. The active power filter generates compensating currents that result in effective cancellation of harmonic currents flowing in the neutral conductor. The advantage of such a scheme is that it does not require a special designed transformer and its effectiveness does not depend on the location of installation.

D. Three-Phase Four-Wire Active Compensators

The neutral current along with harmonics, reactive power compensation, and load balancing are achieved using three phase four-wire DSTATCOM-based compensators. Three different topologies for three-phase four-wire DSTATCOMs, such as a voltage-source converter (VSC), with four leg, three single-phase VSC, and three-leg VSC with split capacitors are reported in the literature [44]–[52]. Fig. 7 shows a four-leg DSTATCOM, split capacitor-based three-leg DSTATCOM is
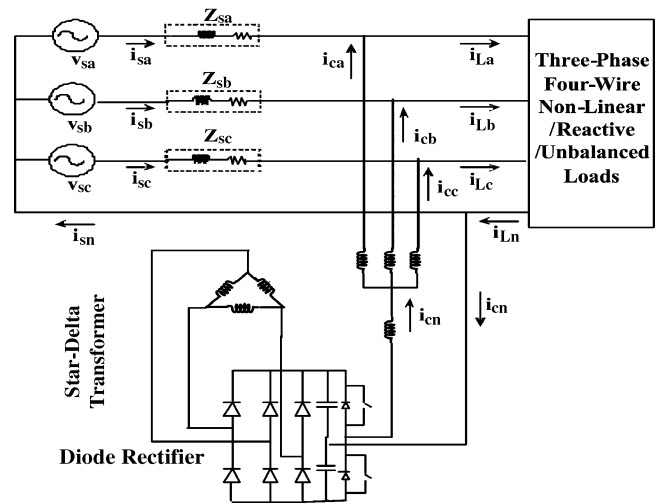
shown in Fig. 8, and Fig. 9 shows three single-phase VSC-based DSTATCOMs. Some researchers select the four-leg converter topology [44] as the best alternative compared to others considering the number of switching devices, complexity of control, etc.

There are different control techniques reported for deriving the reference control signals for the DSTATCOM. The instantaneous reactive power theory (p–q theory) [10], synchronous reference frame (SRF) theory or d–q theory [50], power balance theory [51], etc., have been proposed to control the DSTATCOM for three-phase four-wire systems. The control of the three-phase four-wire compensation under nonsinusoidal source conditions is verified to be satisfactory in [52] and the method is based on p–q theory. The instantaneous active and reactive powers are calculated after filtering out the harmonics in voltage and the theory is evaluated for a three-phase four-wire four-leg VSC-based system. The three-phase four-wire DSTATCOM-based systems are reported as very effective for the compensation, including neutral current. But this configuration has the disadvantages of a greater number of semiconductor switches, complexity of control, etc. A three-phase three-leg shunt compensator and a zig-zag
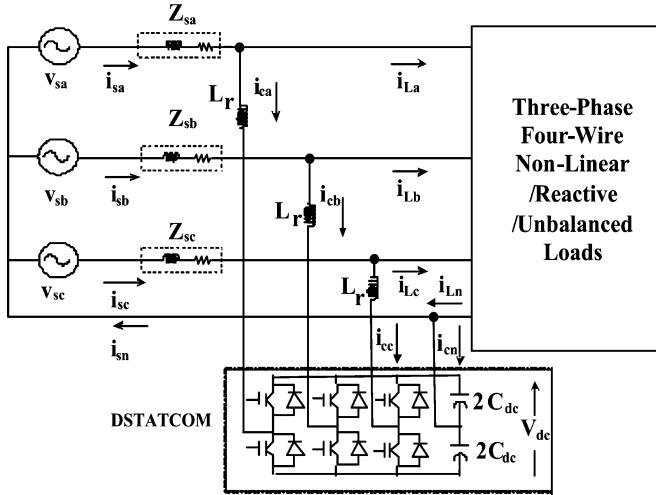
Fig. 8. Three-phase three-leg and split capacitor-based STATCOM for neutral current compensation.
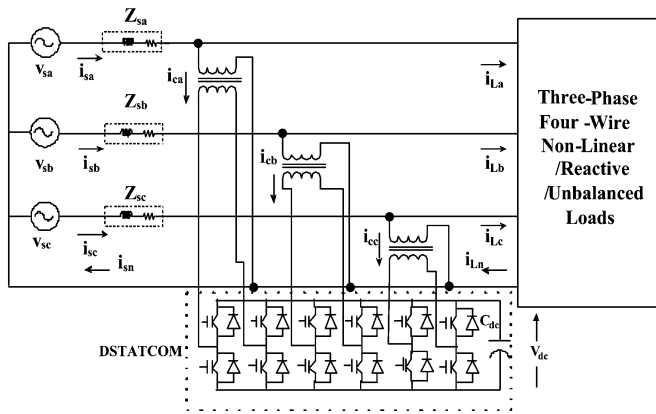

Fig. 9. Three single-phase VSC-based DSTATCOM for neutral current compensation.
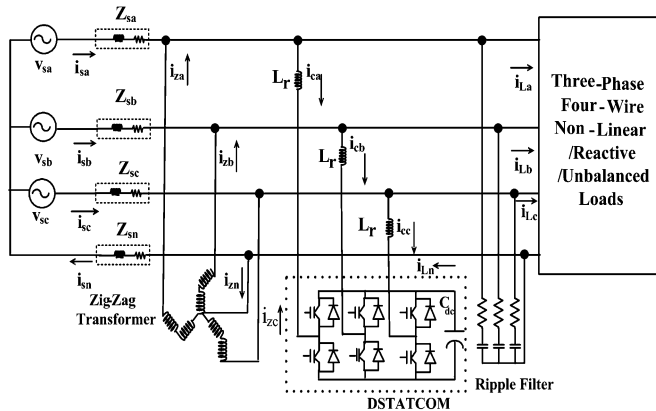

Fig. 10. Three-leg VSC-based DSTATCOM and zig-zag transformer for neutral current compensation.

transformer for neutral current compensation [54] are shown in Fig. 10.
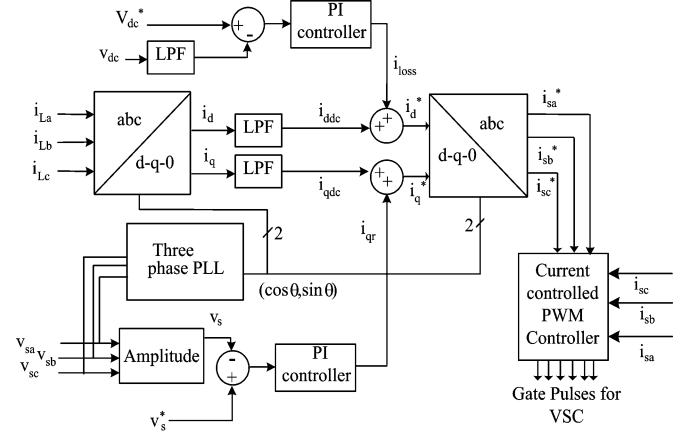

Fig. 11. Synchronous reference frame theory (SRFT)-based control of DSTATCOM.

III. PROPOSED REDUCED RATING COMPENSATOR

The proposed compensator is a hybrid of a three-phase, three-wire VSC and a zig-zag transformer as a DSTATCOM. The DSTATCOM rating is reduced due to the elimination of a fourth leg compared to a three-phase four-leg VSC-based DSTATCOM. It compensates for neutral current along with the load voltage regulation, harmonics currents elimination, reactive power compensation, and load balancing. The considered configuration of the proposed system is shown in Fig. 10. The zig-zag transformer connected at the load terminal provides a circulating path for zero-sequence harmonic and fundamental currents.

A. Design of the DSTATCOM VSC

The VSC used as a DSTATCOM in this configuration is a three-leg pulse-width modulated (PWM) insulated-gate bipolar transistor (IGBT)-based VSC. The PWM signals are generated by the control scheme for which the reference source currents and the sensed source currents are the input signals. The rating of the switches is based on the voltage and current rating of the compensation system. For the considered load mentioned in the Appendix, the rating of the VSC is 12 kVA. The selection of the dc bus voltage, dc bus capacitor, ac inductor, and the ripple filter will be given.

1) DC Bus Voltage: The value of the dc bus voltage V_{dc} depends on the instantaneous energy available to the DSTATCOM. For a VSC, the dc bus voltage is defined as

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

where m is the modulation index and is considered as 1.

Thus, one may obtain the value of V_{dc} as 677 V for V_{LL} of 415 V. Thus, V_{dc} of the value of 680 V is selected.

2) DC Bus Capacitor: The design of the dc capacitor is governed by the reduction in the dc bus voltage upon the application of load and rise in the dc bus voltage on removal of the load.

Fig. 12. MATLAB model of the three-phase three-leg DSTATCOM and zig-zag transformer for neutral current compensation.

Fig. 13. Performance of the zig-zag transformer for harmonic neutral current compensation.

Fig. 14. Performance of the zig-zag transformer for fundamental neutral current compensation.

Using the principle of energy conservation, the equation governing C_{dc} is as [53]

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

where V_{dc} is the reference and V_{dc1} is the minimum voltage level of the dc bus voltage, a is the over loading factor, V is the phase voltage, I is the phase current of the VSC, and t is the response time of the DSTATCOM and t is considered as 350 μs.

Considering $V_{dc} = 680$ V, $V_{dc1} = 670$ V, V $= 415/\sqrt{3}$ V, a $= 1.2$, the calculated value of C_{dc} is 2600 μF. So C_{dc} is chosen to be 3000 μF.

3) AC Inductor: The selection of the ac inductance depends on the current ripple $i_{cr,p-p}$. The ac inductance is given as [53]

$$L_f = \left(\sqrt{3} m V_{dc} \right) / \left(12 a f_s i_{cr(p-p)} \right). \tag{3}$$

Considering 5% current ripple, the switching frequency $(f_s) = 10$ kHz, modulation index (m) $= 1$, dc bus voltage (V_{dc}) of

Fig. 15. Performance of the three-phase four-leg DSTATCOM for neutral current compensation, load balancing, and voltage regulation.

680 V, and overload factor $a = 1.2$, the L_f value is calculated to be 5.45 mH. The value of L_f of 5.5 mH is selected in this investigation.

4) Ripple Filter: A highpass first-order filter tuned at half the switching frequency is used to filter out the noise from the voltage at the PCC. The time constant of the filter should be very small compared to the fundamental time period (T)

$$R_f C_f \ll T/10 \qquad (4)$$

when $T = 20$ ms, considering $C_f = 5 \ \mu F$, R_f is chosen as $5 \ \Omega$. This combination offers a low impedance of 8.1 Ω for the harmonic voltage at a frequency of 5 kHz and 637 Ω for fundamental voltage.

B. Design of the Zig-Zag Transformer

The zig-zag transformer provides a low impedance path for the zero-sequence currents and, hence, offers a path for the neutral current when connected in shunt and, hence, attenuates the neutral current on the source side. When a zig-zag transformer is used alone as a neutral current compensator, the rating of the zig-zag transformer depends on the amount of imbalance and harmonic content. Under the single-phase load, nearly half of the load current flows through the zig-zag windings. All six windings (two windings each of three phases) are rated as 150 V, 10 A, and hence, three single-phase transformers of 5-kVA capacity each are selected in this investigation.

C. Control of DSTATCOM

There are many theories available for the generation of reference source currents in the literature [50]–[52] viz. instantaneous reactive power theory (*p–q* theory), synchronous reference frame theory, power balance theory, etc. The synchronous reference frame theory-based method is used for the control of DSTATCOM. A block diagram of the control scheme is shown in Fig. 11. The load currents (i_L), the source voltages, (v_s) and dc bus voltage (v_{dc}) 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 (5)

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix}. \qquad (5)$$

A three-phase phase-locked loop (PLL) is used to synchronize these signals with the source voltage. The *d–q* components are then passed through lowpass filters to extract the dc 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 proportional-integral (PI) controller whose output is considered the loss component of the current and is added to the dc component of i_d. Similarly, a second PI controller is used to regulate the load terminal voltage. The amplitude of the load terminal voltage and its reference value are fed to a PI controller

Fig. 16.   Performance of the three-phase three-leg VSC and zig-zag transformer as DSTATCOM for neutral current compensation, load balancing, and voltage regulation.
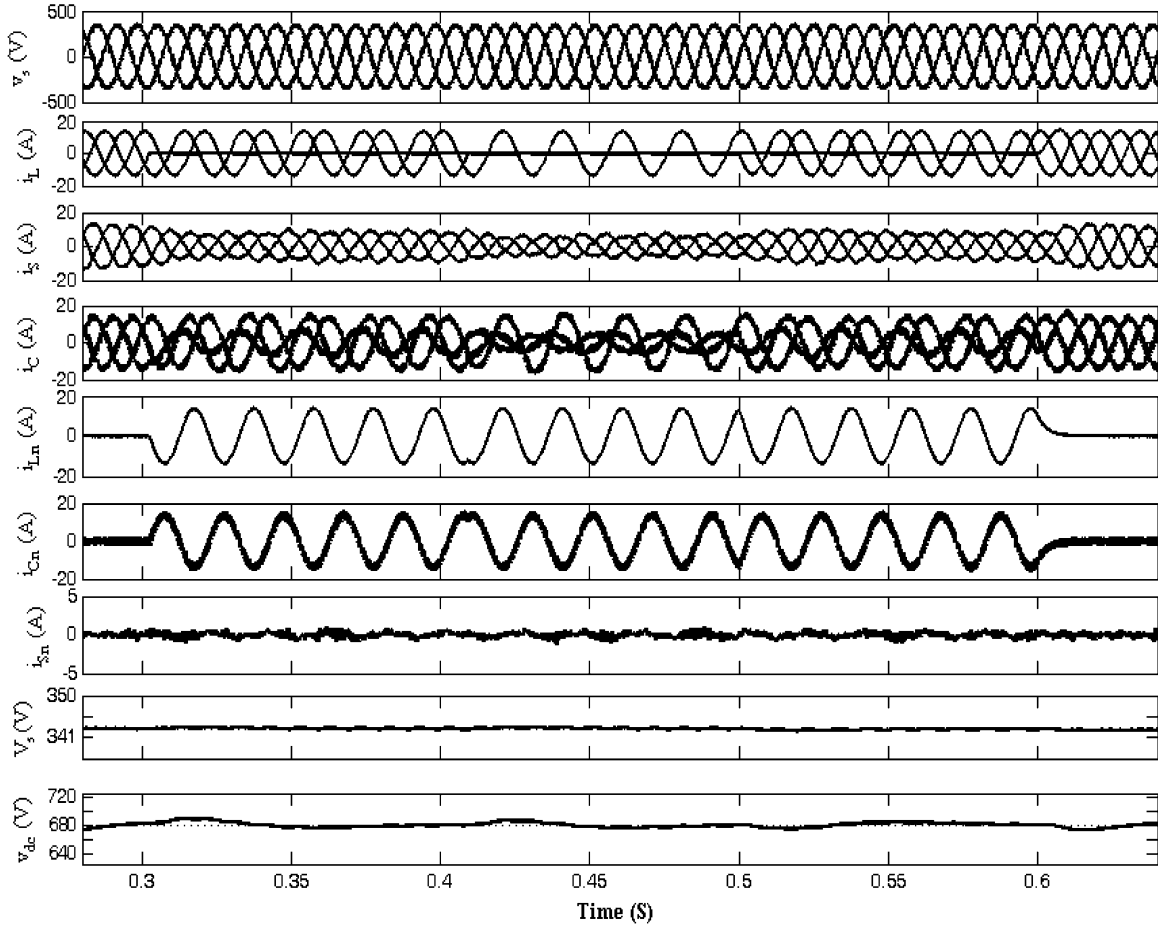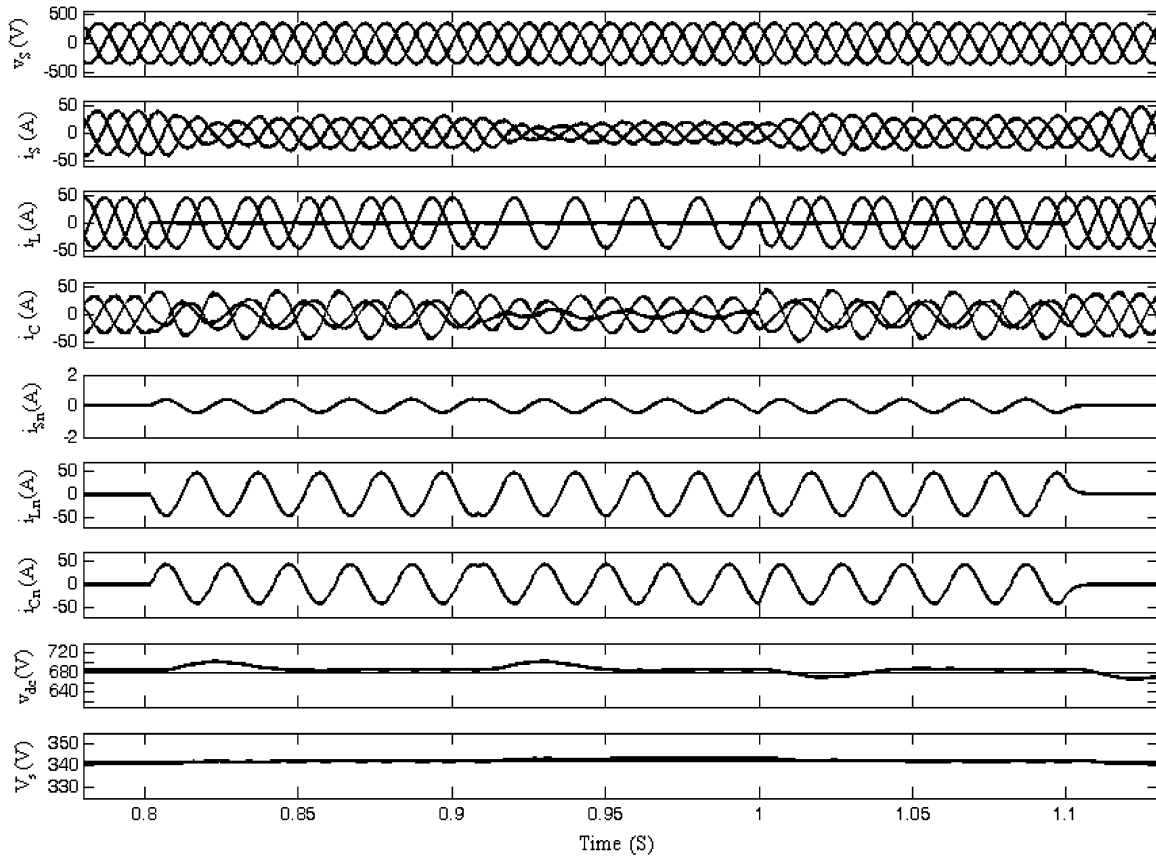
and the output of the PI controller is added with the dc component of i_q. The control strategy is to regulate the terminal voltage and the elimination of harmonics in the load current and load unbalance. The resulting currents are again converted into the reference source currents using the reverse Park's transformation. The reference source currents and the sensed source currents are used in the PWM current controller to generate gating pulses for the switches. For the power factor correction, only the dc bus voltage PI controller is used in the control algorithm.

IV.   MATLAB-Based Modeling of DSTATCOM

The neutral current compensation using a zig-zag transformer is modeled and simulated using the MATLAB and its Simulink and Power System Blockset toolboxes. Fig. 12 shows the MATLAB model of the DSTATCOM and zig-zag transformer-connected system for neutral current compensation. The considered load is a lagging power factor load. 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 the Appendix.

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

Fig. 17.   Performance of the three-phase three-leg VSC and zig-zag transformer of the DSTATCOM for neutral current compensation, harmonic compensation, and voltage regulation.

V.   Results and Discussion

Some of the important neutral current mitigation techniques are analyzed and modeled using MATLAB. The performance of harmonic neutral current compensation using the zig-zag transformer for the nonlinear load and linear load are shown

Fig. 18.   Performance of the three-phase three-leg VSC and zig-zag transformer of the DSTATCOM for neutral current compensation, load balancing, and power factor correction.

in Figs. 13 and 14, respectively. The voltages (v_s), source currents (i_{sa}, i_{sb}, i_{sc}), load currents (i_{La}, i_{Lb}, i_{Lc}), zig-zag transformer currents (i_{Za}, i_{Zb}, i_{Zc}), load neutral current (i_{Ln}), source neutral current (i_{sn}), and zig-zag transformer neutral source neutral current (i_{Sn}) and zig-zag neutral current (i_{Zn}) are demonstrated. It is observed that the zig-zag transformer has compensated the load neutral current, resulting in a source neutral current of nearly zero.

The performance using a three-phase four-leg DSTATOM for voltage regulation along with neutral current compensation and load balancing of a three-phase four-wire load is shown in Fig. 15. The voltages (v_s), balanced source currents (i_s), load currents (i_L), compensator currents (i_C), load neutral current (i_{Ln}), compensator neutral current (i_{Zn}), source neutral current (i_{sn}), amplitude of the load terminal voltage (V_s), and dc bus voltage (v_{dc}) are demonstrated under changing load conditions. It is observed that the amplitude of the load voltage is regulated to the reference amplitude by the required reactive power compensation.

The performance of voltage regulation, along with neutral current compensation and load balancing of a three-phase four-wire load using the proposed three-phase three-leg VSC and a zig-zag transformer as DSTATCOM, is depicted in Fig. 16. The voltages (v_s), balanced 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}),

amplitude of the load terminal voltage (V_s), and dc bus voltage (v_{dc}) are demonstrated under changing load conditions. It is observed that the voltage amplitude is regulated to the reference value under all load disturbances. The source current is balanced, even though the load current is highly unbalanced and this is achieved by using the unbalanced fundamental current injection by the DSTATCOM. The zero-sequence fundamental current of the load neutral current resulting from the unbalanced load current is circulated in the zig-zag transformer, and hence, the source neutral current is maintained at nearly zero. The dc bus voltage of the VSC of DSTATCOM is regulated by the controller and the voltage is maintained near the reference voltage under all load disturbances.

The performance of the DSTATCOM with a zig-zag transformer for voltage regulation and harmonic elimination along with neutral current compensation is shown in Fig. 17. The voltages (v_s), source currents (i_s), load currents (i_L), compensator currents (i_c), load neutral current (i_{Ln}), zig-zag transformer neutral current (i_{Zn}), source neutral current (i_{sn}), dc bus voltage (v_{dc}), and amplitude of the load terminal voltage (V_s) are demonstrated under various nonlinear loads. It is observed that the terminal voltage is regulated to the reference value.

The dynamic performances of the DSTATCOM system in the unity power factor (UPF) mode of operation are depicted in Figs. 18 and 19. The load balancing and neutral current compen-
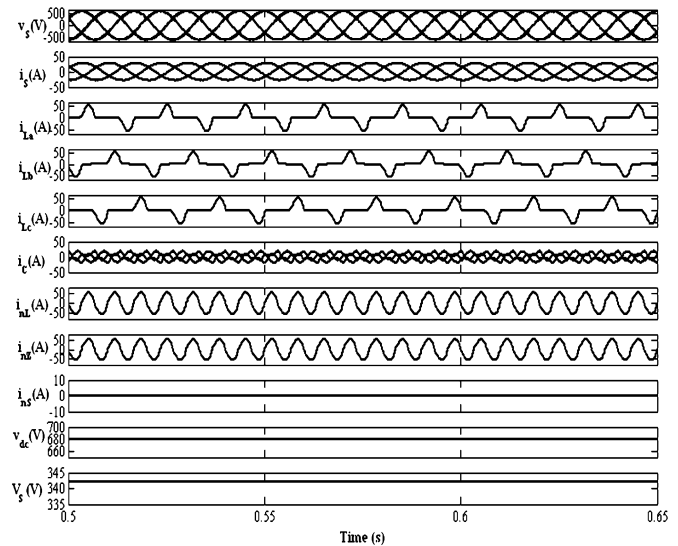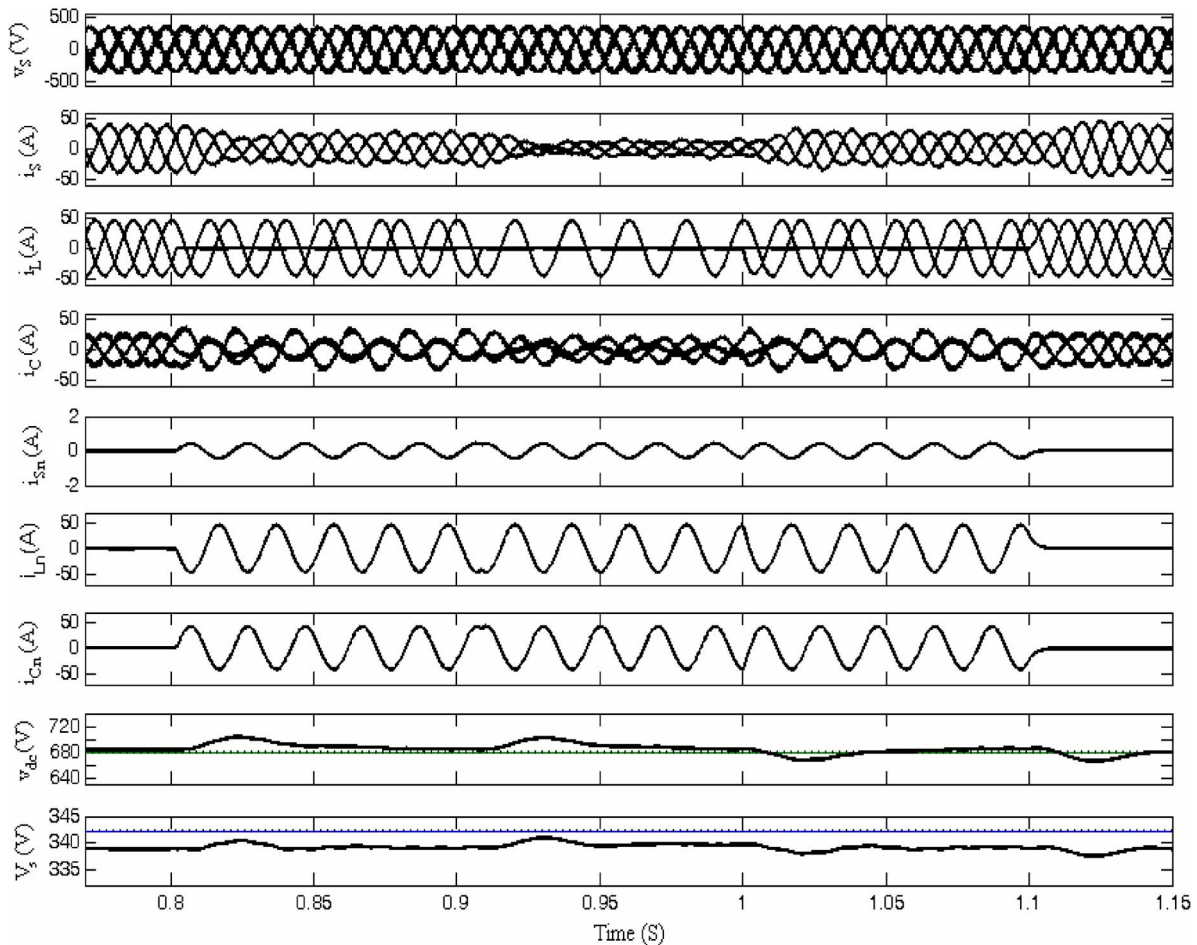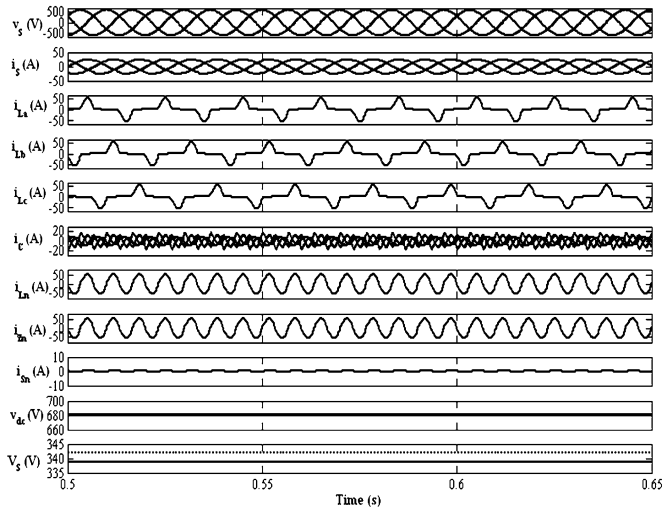
Fig. 19. Performance of the three-phase three-leg VSC and zig-zag transformer of the DSTATCOM for neutral current compensation, harmonic compensation, and power factor correction.

TABLE I
COMPARISONS OF kVA RATING OF THREE METHODS
FOR A LOAD OF 20-kVA, 0.8-pf LAG

Zig-zag Transformer	Three-phase Four wire DSTATCOM	Three-phase three-wire DSTATCOM
Three-single-phase Transformers of 150V/150V, 1.5kVA each	600V, 50A IGBTs (8Nos) based VSC. KVA=16kVA	600V, 50A IGBTs (6Nos) based VSC. KVA=12kVA

sation are demonstrated in Fig. 18 and the harmonic elimination and neutral current compensation are demonstrated in Fig. 19. The 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}), zig-zag transformer neutral current (i_{Zn}), amplitude of load terminal voltage (V_s), and dc bus voltage (v_{dc}) are shown in both cases. It is also observed that the terminal voltage is not regulated in both cases as the compensator operates in the UPF mode.

These results show that the zig-zag transformer is able to compensate for the fundamental and harmonic neutral current. The rating of the transformer used for the zig-zag connection depends on the neutral current on the load side. The three-phase four-wire DSTATCOM compensates for the neutral current along with harmonic and reactive current compensation in the phase current. But additional IGBTs are required for neutral current compensation. A hybrid of a three-wire DSTATCOM and zig-zag transformer is also able to perform satisfactorily and the advantage is that it uses a readily available three-wire VSC as a DSTATCOM and a passive zig-zag transformer. The comparison of the rating of DSTATCOM and zig-zag transformer compensators during different compensation methods is given in Table I. The rating of the VSC is reduced to 12 kVA where as it is 16 kVA for a four-leg DSTATCOM. The current magnitude and total harmonic distortion (THD) are compared in the three cases and are shown in Table II. The

TABLE II
COMPARISON OF CURRENT AND THD DURING LOAD BALANCING, HARMONIC COMPENSATION, AND NEUTRAL CURRENT COMPENSATION

Topologies / Parameters	No Compensator	Four leg VSC	zig-zag transformer only	zig-zag transformer and 3-leg VSC
$I_{sa}(A)$	Open Circuit	10.04	5.718	11.51
THD of I_{sa}		3.15%	55.68%	4.2%
$I_{sb}(A)$	17.06A	10.23	15.17	11.48
THD of I_{sb}	84.70%	3.22%	50.92%	4.6%
$I_{sc}(A)$	17.09A	10.40	15.22	11.46
THD of I_{sc}	83.39%	3.15%	50.44%	4.9%
$I_{sn}(A)$	Third harmonic 26.57	26.43	Third harmonic 0.18	Third harmonic 0.16
$I_{Ln}(A)$	Third harmonic 26.57	26.31	Third harmonic 27.17	Third harmonic 24.46
$I_{Cn}(A)$	No Compensator	1.40	Third harmonic 27	Third harmonic 24.36

THD of unbalanced load currents is nearly 85%, when the load is a voltage-source rectifier. When a zig-zag transformer is employed, the source neutral current is reduced to 0.11 A, whereas the load neutral current is 16 A. But the source-phase currents are balanced and with reduced THD, when a DSTATCOM is also employed as a voltage regulator. The additional benefit of terminal voltage regulation is also demonstrated in Figs. 16 and 17.

VI. CONCLUSION

The causes, standards, and mitigation techniques of the excessive neutral current have been investigated in the three-phase four-wire distribution system. The modelling and simulation of the zig-zag transformer has been demonstrated for neutral current compensation. Moreover, a hybrid of zig-zag transformer with a three-phase three-leg DSTATCOM has been observed as an effective option for overall compensation. The performance of the proposed compensator is validated through extensive computer simulation.

APPENDIX

Line impedance $R_s = 0.01\ \Omega$, $L_s = 1$ mH
1) linear load: 20 kVA, 0.80-pf lag;
2) nonlinear load: a three single-phase bridge rectifier with an R-C load with $R = 25\ \Omega$ and $C = 470\ \mu F$.
Ripple filter: $R_f = 5\ \Omega$; $C_f = 5\ \mu F$.
DC bus capacitance: 3000 μF.
DC bus voltage: 680 V.
AC line voltage: 415 V, 50 Hz.
PWM switching frequency: 10 kHz.
Zig-zag transformer: three numbers of single-phase transformers of 5 kVA, 150/150 V.

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