Power Quality Improvement Of Three Phase Four Wire Distribution System Using VSC With A Zig-Zag Transformer

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ABSTRACT

For the Improvement of power quality in the three-phase four wire distribution system a voltage-source converter (VSC) is proposed which acts as distribution static compensator (DSTATCOM). The proposed VSC as DSTATCOM is used for the mitigation of harmonic currents, neutral current and compensation of reactive power, load balancing, voltage regulation at the point of common coupling (PCC). The zig-zag transformer is connected to the phase which is used for providing the low resistance path for the zero-sequence current. The performance of the VSC as DSTATCOM with zig-zag transformer is validated through extensive simulations using MATLAB software with its simulink and power system tool boxes.
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Keywords—power-quality (PQ), distribution static compensator (DSTATCOM), point of common coupling (PCC), zig-zag transformer.

1. INTRODUCTION.

There are severe power-quality problems, such as poor voltage regulation, high reactive power and harmonics current burden, load unbalancing excessive neutral current, etc now-a-days distribution systems are facing. The source voltage in the distribution systems are also experiencing PQ problems, such as harmonics, unbalance, flicker, sag, swell, etc as mentioned in the paper [1]. In order to limit the PQ problems many standards are also proposed such as IEEE 519-1992, IEEE Std. 141-1993, etc. [2][3]. The remedial solutions to the PQ problems can be reduced by using custom power devices (CPDs).The distribution static compensator (DSTATCOM) is proposed for compensating PQ problems in the current and dynamic voltage regulator (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 unbalancing [4][5] neutral current compensation techniques have been patented [6].

Three-phase four wire distribution systems have been used to supply single-phase low-voltage loads. The typical loads may be the linear loads or non-linear loads. Some of the 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 survey on excessive neutral current in distribution system is cited [7]. There are different techniques for the mitigation of neutral current in the three-phase four-wire distribution systems [8]-[10]. The neutral current compensation using zig-zag transformer [8]; and using three-phase four-wire active compensators along with source harmonic current compensation [9]-[10] 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 load.

2. 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. Even balanced three-phase currents produce excessive neutral current with computer loads in the systems. The source voltage distortions in systems with computer loads can cause excessive neutral current [7].

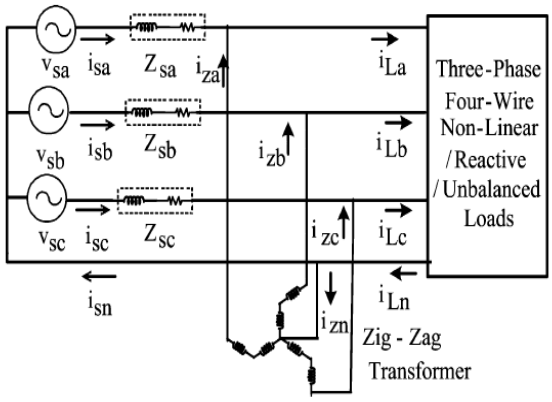

Fig 1. system configuration in a zig-zag transformer for neutral current compensation.

Various standards are proposed to mitigate PQ problems in the distribution system [3],[2]. 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 [3]. 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.

2.1 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 [8]. 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.

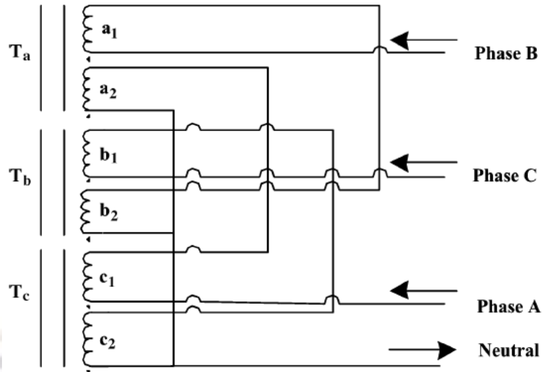

Fig 2. zig-zag transformer for neutral current compensation.

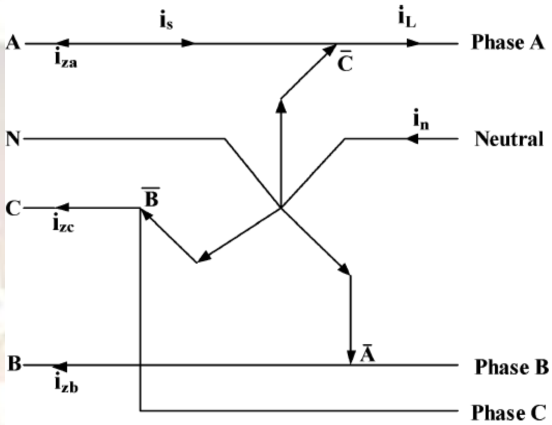

Fig 3. diagram showing the flow of current of zig-zag transformer for neutral current compensation.

Then the current flowing through the zig-zag transformer is only the zero-sequence component.

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.

2.2 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 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 [8] is shown in Fig. 5.

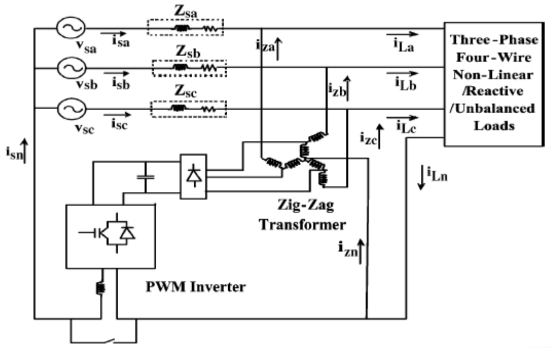

Fig 4. reduced rating single phase inverter with a zig-zag transformer for neutral current compensation.

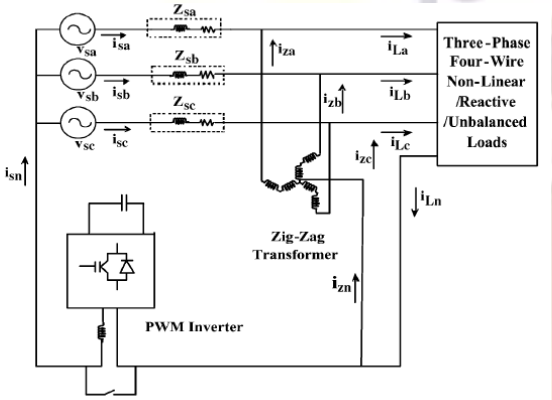

Fig 5. hybrid neutral current compensator using a single phase inverter and zig-zag transformer.

2.3 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 [9],[10]. Fig. 6 shows a four-leg DSTATCOM, split capacitor-based three-leg Fig.6. Three-phase four-leg DSTATCOM for neutral current compensation. DSTATCOM is shown in Fig. 8, and Fig. 9 shows three single-phase VSC-based DSTATCOMs.

There are different control techniques reported for deriving the reference control signals for the DSTATCOM. The instantaneous reactive power theory (p-q theory) , synchronous reference frame (SRF) theory or d-q theory [10], power balance theory, etc., have been proposed to control the DSTATCOM for three-phase four-wire systems. 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.

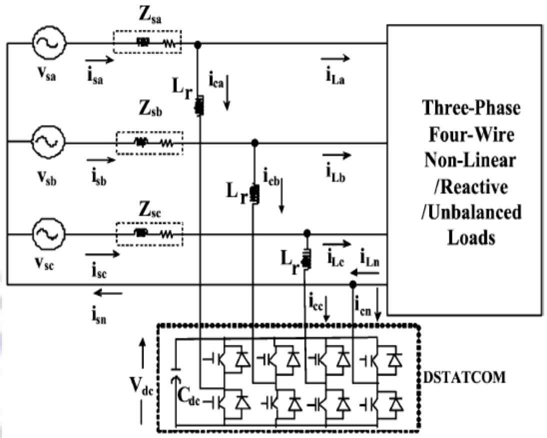

Fig 6. three phase four leg DSTATCOM for neutral current compensation.

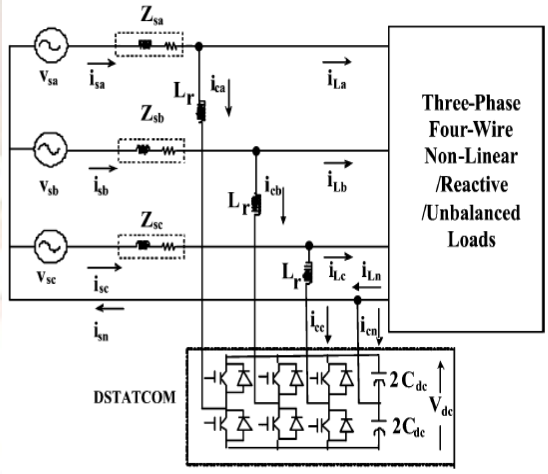

Fig 7. three-phase three-leg and split capacitor-based DSTATCOM for neutral current compensation.

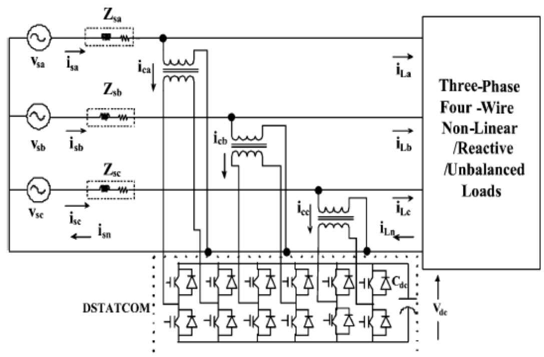

Fig 8. three single-phase VSC-based DSTATCOM for neutral current compensation.

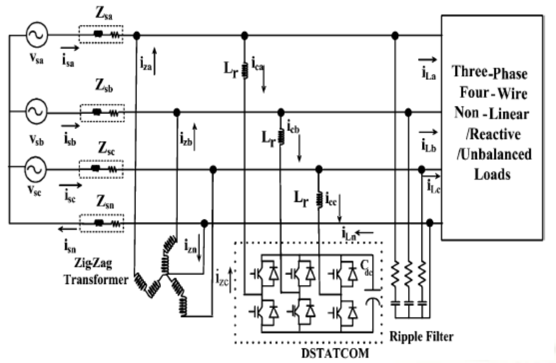

Fig 9. three-leg VSC-based DSTATCOM and zig-zag transformer for neutral current compensation.

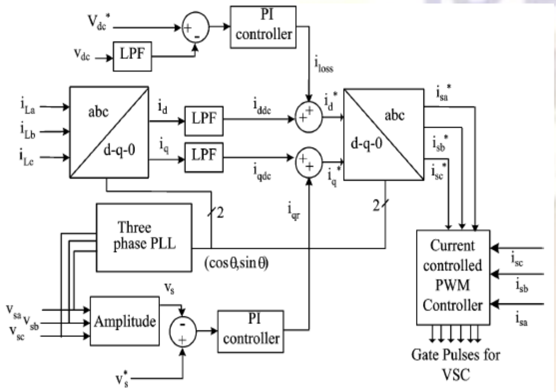

Fig 10. synchronous reference frame theory (SRFT)-based control of DSTATCOM.

A three-phase three-leg shunt compensator and a zig-zag transformer for neutral current compensation [11] are shown in Fig. 9.

3. 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. 9. The zig-zag transformer connected at the load terminal provides a circulating path for zero-sequence harmonic and fundamental currents.

3.1 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

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

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.

Using the principle of energy conservation, the equation governing C_{dc} is as [12]

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

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 350μs. 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 F. So C_{dc} is chosen to be 3000 F.

3) AC Inductor*:* The selection of the ac inductance depends on the current ripple $i_{cr,p-p}$. The ac inductance is given as [12]

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

Considering 5% current ripple, the switching frequency (f_s) = $10kHz$, modulation index (m) = 1, dc bus voltage (V_{dc}) of 680V, 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).

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

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

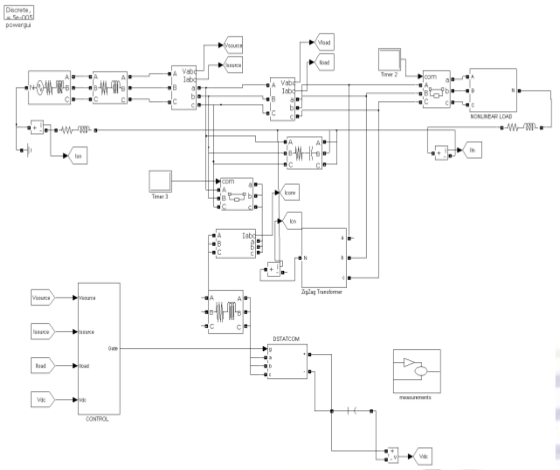

Fig 11. MATLAB model of the three-phase four-leg DSTATCOM and zig-zag transformer for neutral current compensation.

3.2. 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 150V, 10 A, and hence, three single-phase transformers of 5-kVA capacity each are selected in this investigation.

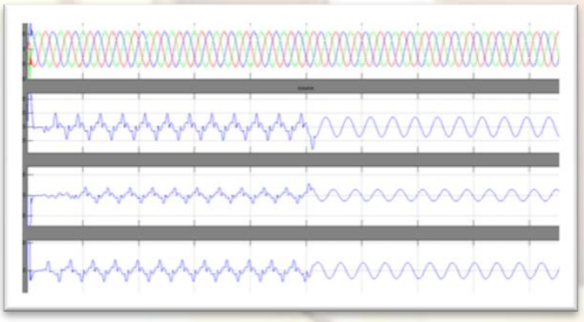

Fig 12. source voltage (V_s) and source current (i_s) with zig-zag transformer.

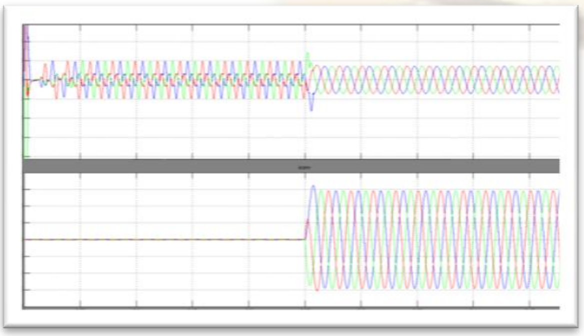

Fig 13. three phase source current and converter current (i_{conv}).

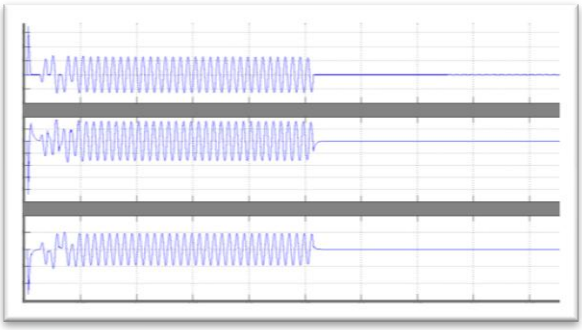

Fig 14.wave form for load neutral current(i_{ln}), source neutral current (i_{sn}), converter neutral current(i_{cn}).

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

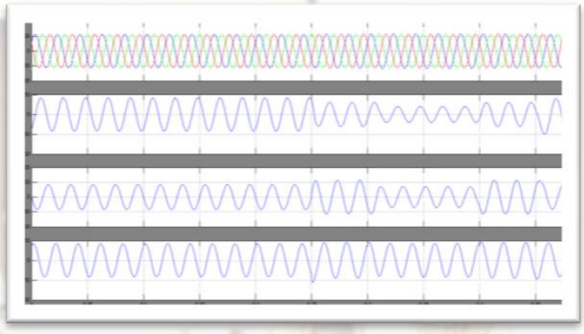

Fig 15.source voltage (V_s) and source current (i_s).

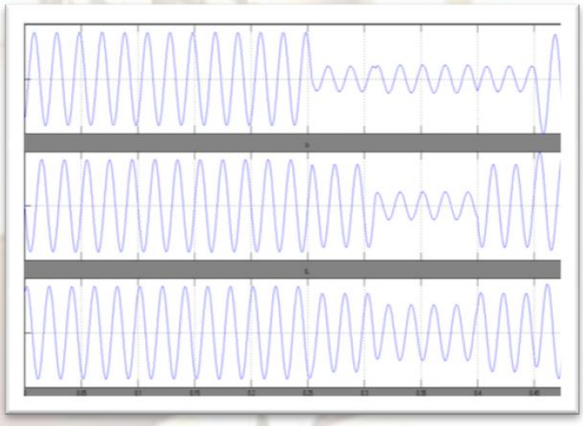

Fig 16. load current (i_L).

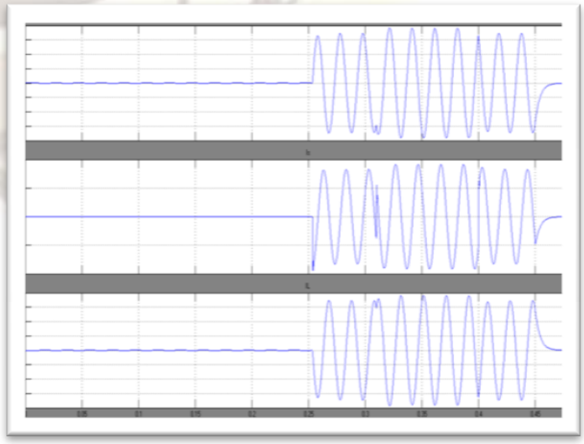

Fig17. wave form for load neutral current(i_{ln}),source neutral current (i_{sn}), converter neutral current(i_{cn}).

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

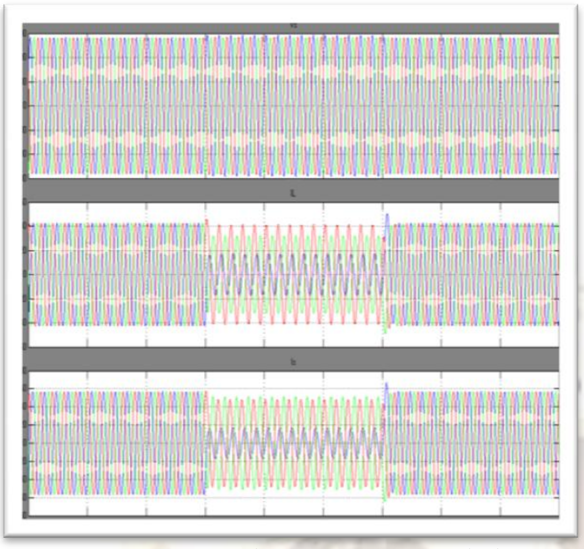

Fig18. *source voltage*(V_s), *load current*(i_L) and source current(i_s).

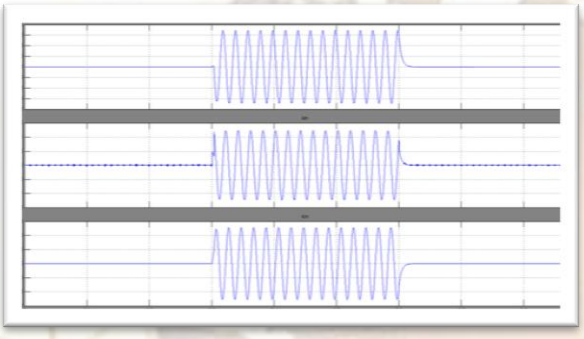

Fig 19. wave form for load neutral current(i_{ln}), source neutral current (i_{sn}), converter neutral current(i_{cn}).

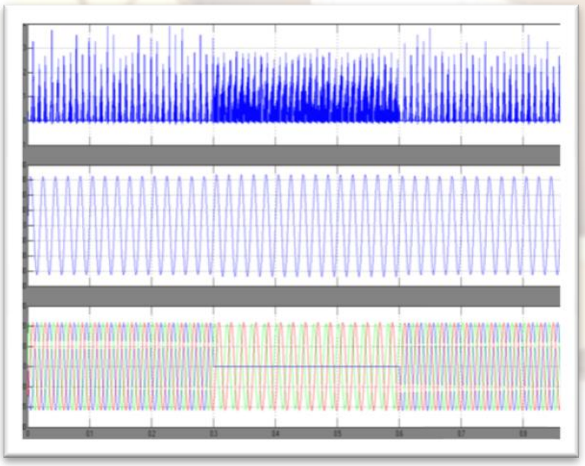

Fig 20. *dc bus voltage*(V_{dc}) , load voltage(V_{load}), converter current(i_{conv}).

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

3.3 Control of DSTATCOM

There are many theories available for the generation of reference source currents in the literature [10] 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. 10. The load currents, the source voltages, and dc bus voltage of DSTATCOM are sensed as feedback signals. The loads 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)

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

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 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.

4. 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. 11 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 modeled 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.

5. 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 non-linear loads are shown in Figs. 12, 13 and 14 respectively. The voltages, source currents, three phase source currents, converter current, load neutral current, source neutral current, and converter neutral current are demonstrated. The performance of fundamental neutral current compensation using the zig-zag transformer for non-linear loads are shown in Figs. 15, 16 and 17 respectively. 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 Figs. 18, 19 and 20respectively. The voltages, balanced source currents, load currents, load neutral current, converter neutral current, source neutral current, amplitude of the load terminal voltage , and dc bus voltage and converter currents 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.

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.

TABLE I
kVA Rating of Three-Phase Four Wire DSTATCOM

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

The rating of DSTATCOM and zig-zag transformer compensators is given in Table I. The rating of the VSC is 61kVA for a four leg DSTATCOM. The current magnitude and total harmonic distortion (THD) are shown in Table II.

TABLE II
Current and THD During Load Balancing, Harmonic Compensation, and Neutral Current Compensation.

Topo-logies / Para-meters	No Compensator	Four leg VSC	zig-zag transformer only
I_{sa}(A)	Open Circuit	10.04	5.718
THD of I_{sa}		3.15%	55.68%
I_{sb}(A)	17.06A	10.23	15.17
THD of I_{sb}	84.70%	3.22%	50.92%
I_{sc}(A)	17.09A	10.40	15.22
THD of I_{sc}	83.39%	3.15%	50.44%
I_{sn}(A)	Third harmonic 26.57	26.43	Third harmonic 0.18
I_{Ln}(A)	Third harmonic 26.57	26.31	Third harmonic 27.17
I_{Cn}(A)	No Compensator	1.40	Third harmonic 27

The 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.

6. Conclusion.

The causes, standards, and mitigation techniques of the excessive neutral current have been investigated in the three-phase four-wire distribution system. The modeling and simulation of the zig-zag transformer has been demonstrated for neutral current compensation. The performance of the proposed compensator is validated through extensive computer simulation.

Appendix

Line impedance R_s = 0.01 Ω,L_s = 1 mH Non linear load: a three single-phase bridge rectifier with an R-C load with $R = 5\ \Omega$ and $C = 470\ \mu$F.
Ripple filter: $R_f = 5\Omega$; C_f = 5 μF.
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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