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NEUTRALCURRENTCOMPENSATIONUSING ZIG-ZAG TRANSFROMERWITH D-STATCOM

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ABSTRACT: 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

Three-phase four-wire distribution systems are facing severe power quality problems such as poor voltage regulation, high reactive power and harmonics current burden, load unbalancing, excessive neutral current etc. [1- 6]. Three -phase four-wire distribution systems are used in commercial buildings, office buildings, hospitals etc. Most of the loads in these locations are non-linear loads and are mostly unbalanced load in the distribution system. This creates excessive neutral current both of fundamental and harmonic frequency and the neutral conductor gets overloaded. The voltage regulation is also poor in the distribution system due to the unplanned expansion and the installation of different types of loads in the existing distribution system. In order to control the power quality problems, many standards are proposed such as IEER-519 standard [1].

The most common loads connected to the three-phase four-wire electrical distribution system in commercial and residential buildings are nonlinear and include PC, UPS, electronic and magnetic ballasts, photocopiers, etc. Nonlinear loads result in significant neutral current in the three-phase four-wire system since triplen-odd harmonics in phase currents do not cancel each other even under balanced condition and are added up in the neutral line. Under the worst case, the neutral current could be 1.73 times the phase current [1]. Excessive neutral currents could cause wiring failure of the neutral conductor, overloading of the distribution transformer, and a voltage drop between the neutral and the ground

There are mitigation techniques for power quality problems in the distribution system and the group of devices is known by the generic name of custom power devices (CPD) [1]. The DSTATCOM (distribution static compensator) is a shunt connected CPD capable of compensating power quality problems in the load current. These non-linear 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.

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

II. NEUTRAL CURRENT COMPENSATION TECHNIQUE

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 [7]. 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% [8]–[10]. The source voltage distortions in systems with computer loads can cause excessive neutral current [11], [12]. The nonlinear loads are classified into harmonic current source loads and harmonic voltage-source loads [13].

(i) *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 [14], [15].

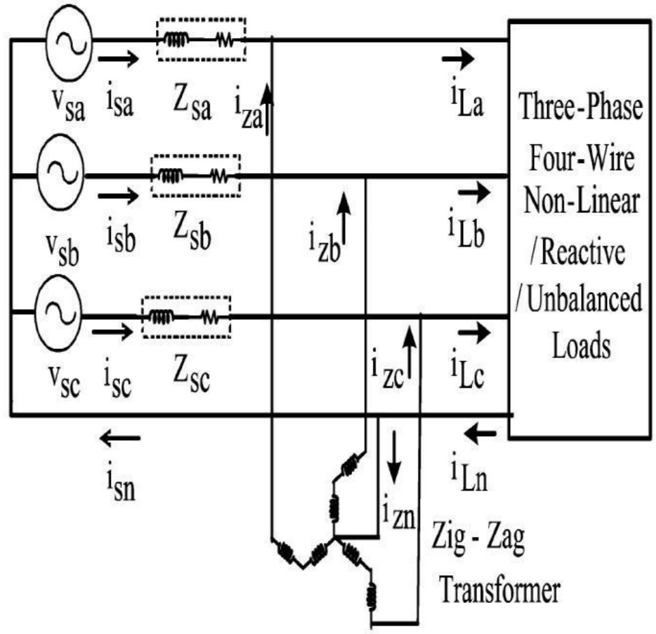

Fig. 1. System configuration with a zig-zag transformer for neutral current compensation.

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.

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.

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

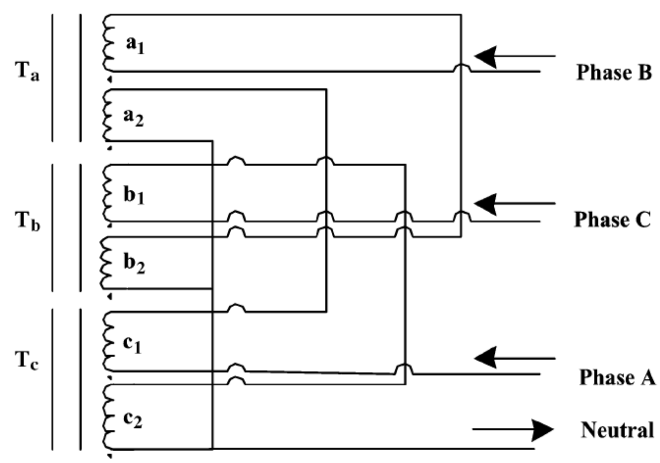

Fig. 2. Zig-zag transformer for neutral current compensation.

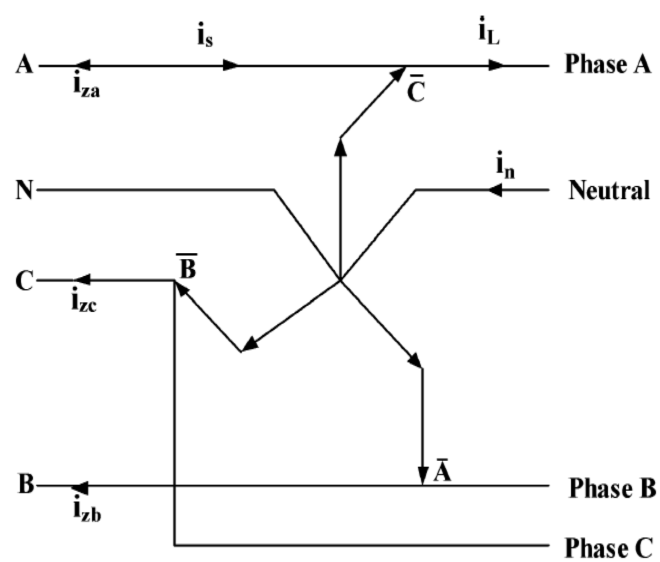

Fig. 3. Diagram showing the flow of currents of zig-zag transformer for neutral current compensation.

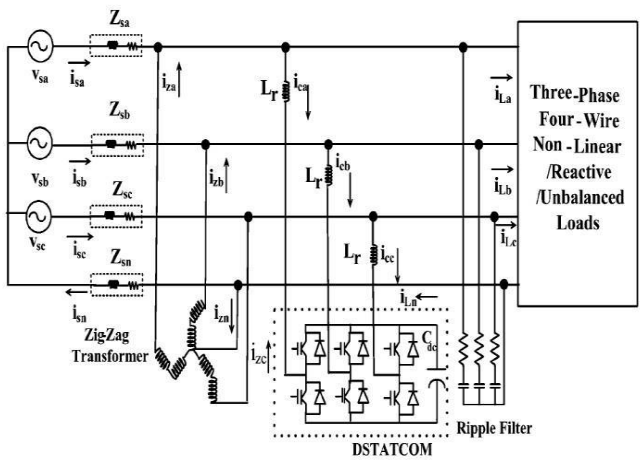

Fig.4. Proposed three phase three leg DSTATCOM with ZIG-ZAG transformer for neutral current compensation.

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_{L-L} 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} as

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

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 is considered as 350 µs. considering V_{dc}=680V, V_{dc1}= 670v, V=415/√3 V, α=1.2, the calculated value of C_{dc} is as 2600µf.So C_{dc} is chosen to be 3000µF.

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

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

Considering 5% current ripple, the switching frequency f_s=10 kHz, modulation index m=1, dc bus voltage of V_{dc}=680V and overload factor a=1.2, the value L_f is calculated to be 5.45 mH. And this L_f is been selected as 5.5 mH .

4) Ripple Filter: A high pass 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=20ms, considering C_f=5µf, R_f is chosen as 5Ω. This combination offers a low impedance of 8.1Ω for the harmonic voltage at a frequency of 5 kHz and 637Ω 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 150V, 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 [16]–[17] 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.5. 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)

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

A three-phase phase-locked loop (PLL) is used to synchronize these signals with the source voltage. The – components are then passed through low pass 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.

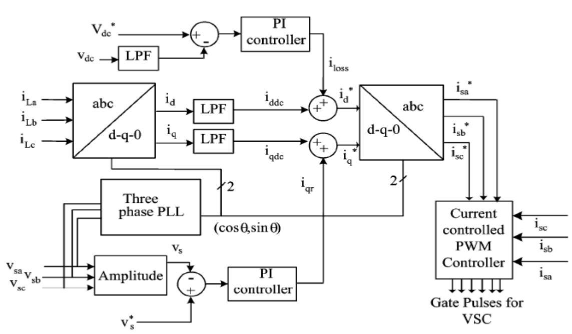

Fig.5.SRF theory based control of DSTATCOM

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.6. 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 (V_{dc}) of DSTATCOM. 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.

V. RESULTS AND DISCUSSION

The performance of voltage regulation, along with neutral current compensation and load balancing of a three-phase fourwireload using the proposed three-phase three-leg VSC and a zig-zag transformer as DSTATCOM, is depicted in Fig.7. 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_L), and dc bus voltage (V_{dc}) are demonstrated under unbalanced linear loads 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 load balancing along with neutral current compensation is shown in Fig.8. The voltages (V_s), balanced source currents (is), 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_L), and dc bus voltage (V_{dc}) are demonstrated under various changing nonlinear loads. The dc bus voltage of the VSC of DSTATCOM is regulated by the controller.

VI. Conclusion

The performance of a new topology of three-phase four-wire DSTATCOM consisting of three-leg VSC with a Zig-Zag transformer has been demonstrated for neutral current compensation along with reactive power compensation, harmonic compensation and voltage regulation for linear and nonlinear load under unbalanced condition. 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=0.01Ω, L_s=1mH ,
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=25Ωand c=470μF.
Ripple filter: R_f=5Ω, C=5μ F.
DC bus capacitance: 3000μF.
DC bus voltage: 680 V.
AC line voltage: 415 V, 50 Hz.
Zig-zag transformer: three numbers of single-phase transformers of 5 kVA, 150/150 V.

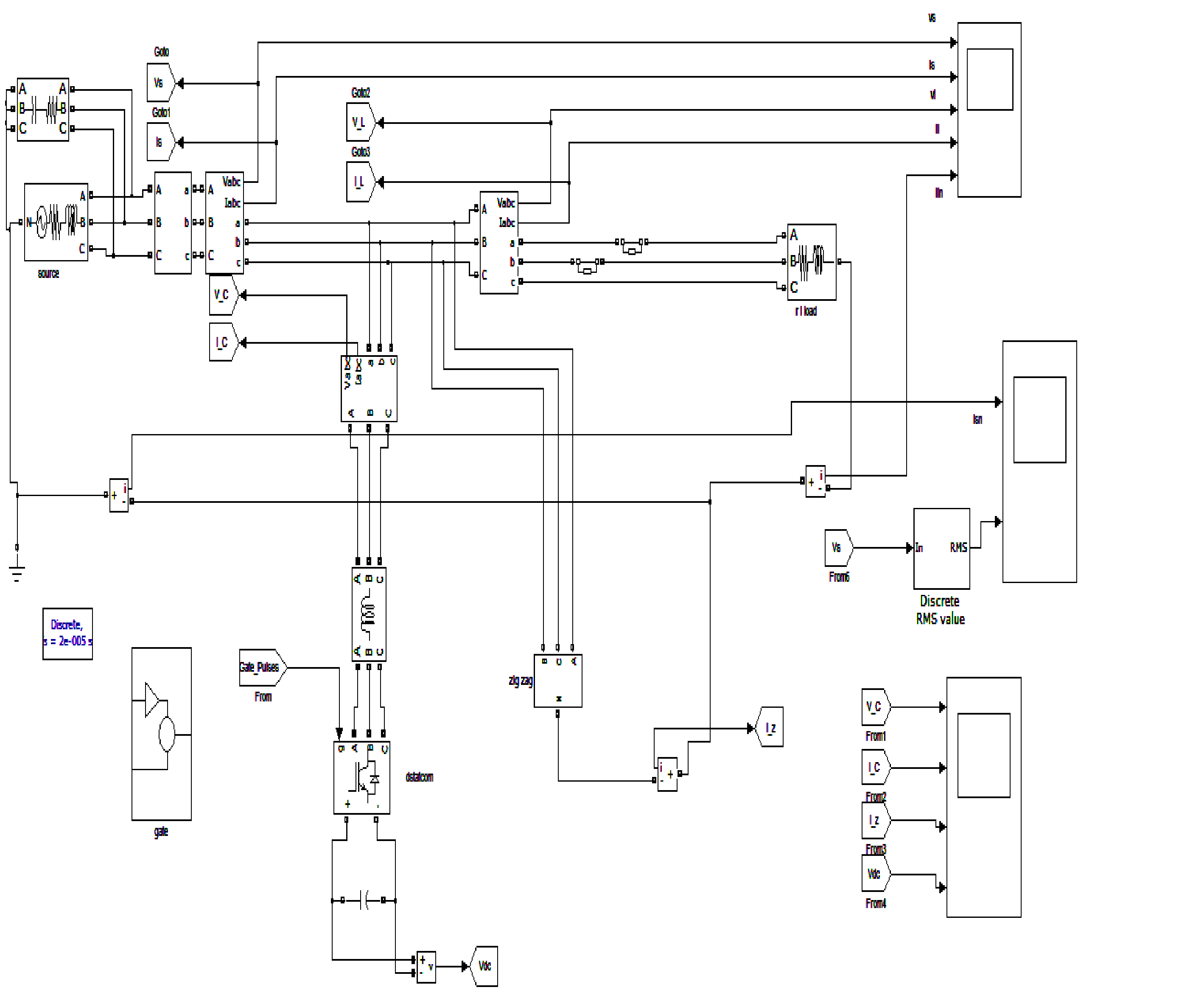

Fig.6. MATLAB model of three phase three leg DSTATCOM and ZIG-ZAG transformer for neutral current compensation.

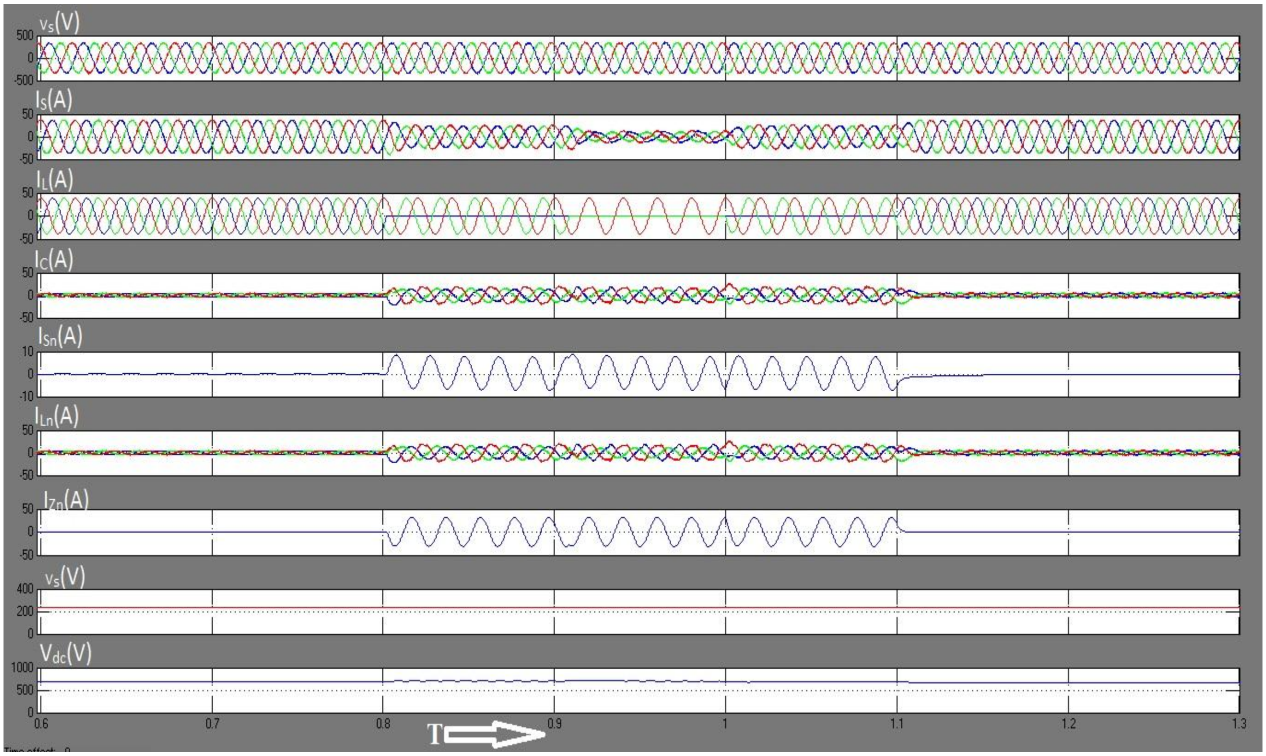

Fig.7. Performance of the three-phase three-leg VSC and zig-zag transformer of the DSTATCOM for neutral current compensation, load balancing and voltage regulation for linear unbalanced load.

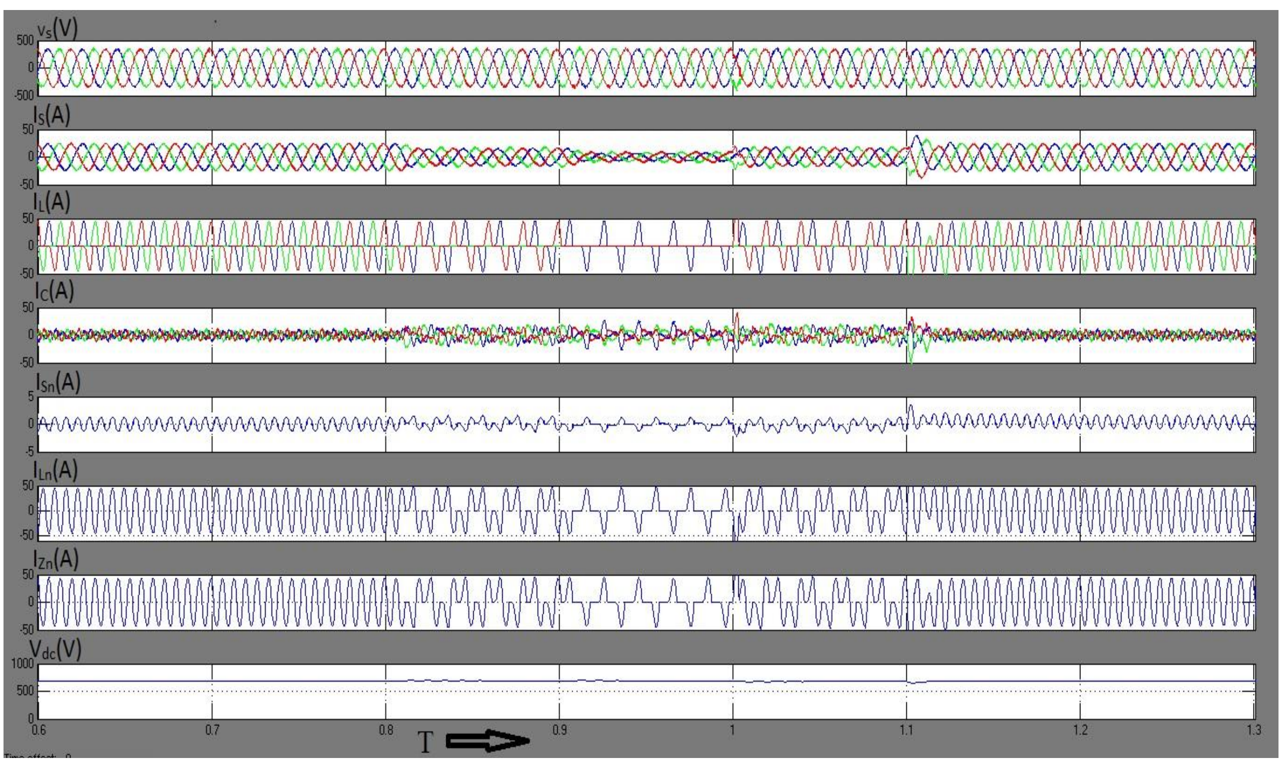

Fig.8. Performance of the three-phase three-leg VSC and zig-zag transformer as DSTATCOM for neutral current compensation, load balancing, harmonic compensation and voltage regulation for non linear unbalanced load.

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