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THREE-LEG VSC AND A T-CONNECTED TRANSFORMER BASED THREE PHASE FOUR WIRE DSTATCOM FOR DISTRIBUTION SYSTEM

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ABSTRACT:-
The distribution with three-phase four-wire systems are used in commercial buildings, organization buildings, hospitals, etc. Most of these loads used in these locations are nonlinear and unbalanced loads. This creates excessive neutral current wih the frequency of both harmonic and fundamental. Also the neutral conductor gets overloaded. The voltage regulation is also poor in the distribution system due to the unexpected expansion and the installation of different types of loads in the obtainable distribution system.

In this thesis, a new three-phase four-wire distribution static compensator (Distributed-STATCOM) based on a T-connected transformer and a three-leg voltage source converter (VSC) is proposed in order to improve the power quality. Two single-phase transformers are connected in T-configuration for interfacing to a three-phase four-wire distribution system. The Scott-*T* transformer connection mitigates the neutral current and the three-leg VSC compensates harmonic current and balances the load. The insulated gate bipolar transistor (IGBT) based VSC is supported by a capacitor is used to control the required compensation of the load current. The dc bus voltage of the voltage source converter is regulated during varying load conditions. The DSTATCOM is tested for harmonic elimination, neutral current is compensated along with voltage regulation, and balancing of linear loads as well as nonlinear loads.Here the theory of synchronous reference frame is used for the control of the proposed Didtributed -STATCOM .The performance of the distributed-STATCOM is validated using MATLAB software with Simulink and power system blockset toolboxes.

I INTRODUCTION

Electric power distribution network becomes gradually more important and plays an vital role in power system planning. This distribution power system has been widely used for supplying low-level voltage to office building , commercial and manufacturing amenities, etc. The loads connected distribution power system may be either the single-phase or the three-phase loads. Non-linear loads draw current that are non-sinusoidal and as a result voltage drops occurs in distribution conductors that are non-sinusoidal in nature. Most of these loads have the nonlinear input characteristic, which creates high input current harmonics. The harmonic current will infect the power system and result in the problems such as transformer overheating, vibration of rotary machine, voltage quality degradation, damaging of electric power components, malfunction of medical facilities, etc. In order to meet up the increasing reactive power demands, reactive power compensation has been recognized as an efficient and economic means of growing power transmission capability. To complete this confront, it requires cautious design for power network planning. However, consider an additional device to be installed somewhere in the network. Such devices are capacitor bank, series reactors, shunt reactor, automatic voltage regulators,dynamic voltage restorers, distribution STATCOM (our focus) and combination of them.

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At present, an extensive range of very flexible controllers, which is advantageous of newly available power electronics components and for emerging custom power applications. Among these, the Distributd-STATCOM and dynamic voltage restorer are most effective devices and both works based on VSC principle. A DVR injects a voltage and a D-STATCOM injects a current into the system respectively in order to correct the voltage sag, swell and interruption. The DSTATCOM has ample of applications in low voltage distribution systems designed to improve the quality and reliability of the power supplied to the consumer.It can be used to prevent non-linear loads from polluting the rest of the distribution system. The fast response of the DSTATCOM makes it possible to provide continuous and dynamic control of the power supply together with voltage and reactive power compensation, harmonic mitigation and elimination of voltage sags and swells.

II CONTROL ALGORITHM OF DSTATCOM

There are many control schemes available for control of shunt active compensators. The control approaches available for the generation of reference source currents for the control of VSC of DSTATCOM for three-phase four-wire system are instantaneous reactive power theory (IRPT)/PQ theory, synchronous reference frame theory (SRFT), power balance theory, instantaneous symmetrical components based, etc. They are described as follows:

Synchronous Reference Frame Theory

As the application of ac machines has continued to increase over this century, new techniques have been developed to assist in their analysis. Most of the analysis has been carried out for the treatment of the well-known induction machine. The significant advance in the analysis of three-phase ac machines was the development of reference frame theory. Using these techniques, it is feasible to transform the phase variable machine description to another reference frame. By astute choice of the reference frame, it proves possible to simplify considerably the complexity of the mathematical machine model.

The synchronous reference frame theory(SRFT) is based on the determination of the instantaneous active and reactive currents(id and iq).The SRFT creates a reference frame of orthogonal axes that rotates at the supply frequency(d-q system),which is a synchronous reference. This synchronism with the supply can be achieved by a phase locked loop (PLL) connected to the supply voltages and/or currents. In some situations only the supply frequency is necessary for applying the synchronous reference frame theory, so that, the supply phase is not required. In this rotating reference, the fundamental stator current becomes dc value in the id-iq currents that can be determined by some type of low-pass filter.and the id and iq currents are calculated.The Clarke transformation is applied to the stator currents, followed by the Park transformation. So that, the stator currents at the a-b-c system are transferred to the α-β-0 system and from the α-β-0 system to the d-q-0 system. Eqns (1) and (2) show the Park and the invariant power Clarke transformations, respectively

.

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

Where θ is the phase angle of the phase voltage; and the fundamental frequency unit vectors, sin(θ) and cos (θ), are determined by the phas locked loop.

The id and iq components can be both divided into alternating (ac) and constant parts(dc),as shown below.

$$i_d = i_{\bar{d}} + i_{\tilde{d}}$$
$$i_q = i_{\bar{q}} + i_{\tilde{q}} \quad (3)$$

After the Park transformation the fundamental stator currents becomes the dc parts of the id and iq currents(id¯ and iq¯)and all the rest of the harmonics become the ac parts of them(id˜ and iq˜) with a frequency offset equal to the supply frequency. Therefore, eliminating the ac parts of id and iq, that is, id˜ and iq˜, the fundamental currents at the d-q-0 system, that is , id¯ and iq¯, will last. The elimination of ac parts of id and iq can be done by some kind of low pass filter.

Once the id¯ and iq¯ currents were determined, they must be transformed to the α-β-0 system by the inverse invariant power Clarke transformation as in following equation (4).

$$\begin{bmatrix} i_\alpha^- \\ i_\beta^- \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} i_d^- \\ i_q^- \end{bmatrix} \quad (4)$$

And, so to the a-b-c system by the inverse invariant power Clarke transformation in equation (5)

$$\begin{bmatrix} i_a^- \\ i_b^- \\ i_c^- \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_0 \\ i_\alpha^- \\ i_\beta^- \end{bmatrix}$$

(5)

III SYSTEM CONFIGURATION AND DESIGN

The schematic diagram of three-phase four-wire compensated system is shown in Figure 4.1. The compensator and the load are connected at a point called as point of common coupling (PCC). The load may be unbalanced and non-linear.

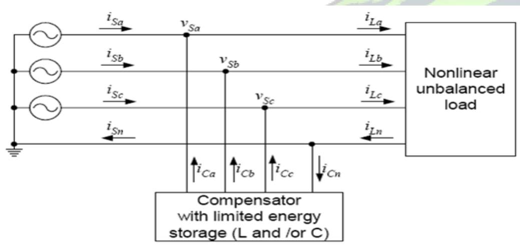

Figure.Schematic diagram of three-phase four-wire compensated system

COMPENSATOR STRUCTURE AND MODELING

The proposed DSTATCOM consisting of a T-connected transformer and a three-leg VSC is shown in Fig, where the T-connected transformer is responsible for compensating the neutral current. The windings of the T-connected transformer are designed in such a way that the mmf is balanced properly in the transformer. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and with the ac system and coupled through the reactance of the coupling transformer. A suitable adjustment of the phase and magnitude of the output voltages from D-STATCOM allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power.

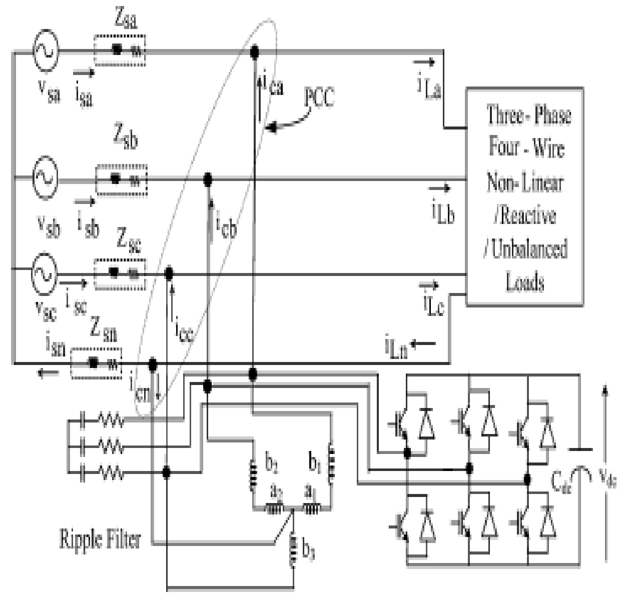

Figure.Schematic diagram of VSC and T-transformer Based DSTATCOM in Distribution System

In the present work neutral clamped converter topology is used to track the reference currents using two-level voltage source converter as shown in Figure4.2. The structure of two-level VSC consists of six IGBT switches, each with anti-parallel diodes and a dc storage capacitor.

In the present work neutral clamped converter topology is used to track the reference currents using two-level VSC as shown in Figure.4.2. The structure of two-level VSC consists of six IGBT switches, each with anti-parallel diodes and a dc storage capacitor.

In two-level inverter six IGBT switches are used each with the dc storage capacitors are used for VSC operation, they will discharge in due course of time, due to switching losses in the compensator. The dc capacitor connected at the dc bus acts as an energy buffer and establishes a dc voltage for the normal operation of the DSTATCOM system. If the voltage across any of these capacitors falls below the peak of system voltage, then the inverter will not follow the reference currents properly. Therefore for proper operation of compensator, the total voltage across the capacitor is to be maintained at the reference voltage level. The ripple filter at the point of common coupling

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(PCC) is for reducing the high frequency ripples. The high frequency ripple voltage is due to the presence of switching current of the VSC of the DSTATCOM.The required compensation to be provided by the DSTATCOM decides the rating of the components in VSC. The data of DSTATCOM system considered for analysis is shown in the Appendix.

The T-connected transformer mitigate the neutral current and the three-leg VSC compensates the harmonic current ,reactive power and balances the load. The insulated gate bipolar transistor (IGBT) based VSC is self-supported with a dc bus capacitor and is controlled for the required compensation of the load current. The selection of interfacing inductor, dc capacitor, and the ripple filter are given in the following sections.

CapacitorVoltage

The minimum dc bus voltage of VSC of DSTATCOM should be greater than twice the peak of the phase voltage of the system. The dc bus voltage is calculated as

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

where m is the modulation index and is considered as 1, and $V_{LL}$is the ac line output voltage of DSTATCOM. Thus, V_{dc} is obtained as 677.69 V for $V_{LL}$of 415 V and is selected as 700 V.

DC Bus Capacitor

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

$$\tfrac{1}{2} C_{dc} [(v^2_{dc})-(V^2_{dc1})]= 3V (a I) t \quad (2)$$

where the reference dc voltage is V_{dc} and the minimum voltage level of dc bus is V_{dc1}, the overloading factor a, the phase voltage V, the phase current I, and t is the time by which the dc bus voltage is to be recovered. Considering the minimum voltage level of the dc bus, V_{dc1} =690 V, V_{dc} = 700 V, V = 239.60 V, I = 27.82 A, t = 350 μs, a = 1.2, the calculated value of C_{dc} is 2600 μF and is selected as 3000 μF.

AC Inductor

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

$$L_f = \frac{\sqrt{3}mV_{dc}}{12a\, f_s\, i_{cr,p-p}} \quad (3)$$

where m is modulation index and a is the overload factor. Considering, $i_{cr,p-p}$ = 5%, f_s= 10 kHz, m = 1, Vdc = 700 V, a = 1.2, the$L_f$value is calculated to be 2.44 mH. A round-off value of $L_f$of 2.5 mH is selected in this investigation.

Ripple Filter

A first-order low-pass filter tuned at half the switching frequency is used to filter the high-frequency noise from the voltage occurs at PCC. Considering a low impedance of 8.1 Ω for the harmonic voltage at a frequency of 5 kHz, the ripple filter capacitor is designed as C_f= 5 μF. A series resistance (R_f) of 5 Ω is included in series with the capacitor (C_f). The impedance is found to be 637 Ω at fundamental frequency, which is sufficiently large, and hence, the ripple filter draws negligible fundamental current.

Design of the T-connected Transformer

The T-connected transformer is used in the three-phase distribution system for different applications. But the application of T-connected transformer for neutral current compensation is demonstrated for the first time. Moreover, the T-connected transformer is suitably designed for magnetic motive force (mmf) balance. The T-connected transformer mitigates the neutral current and the three-leg VSC compensates the harmonic current and reactive power, and balances the load.

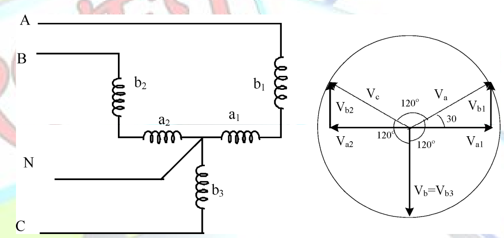

Figure. Winding diagram of T-Connected Transformer

The T-connected transformer in the three-phase distribution system is used for different applications, but the for neutral current compensation is demonstrated for the first time. It is suitably designed for magnetic motive force (mmf) balance. Moreover, this transformer mitigates the neutral current and the three-leg VSC compensates the harmonic current, reactive power and balances the load.

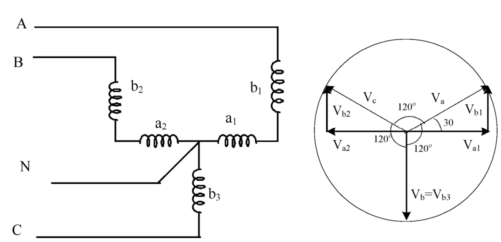

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Figure. Winding diagram of T-Connected Transformer

The T-connected windings not only provide a path for the zero-sequence fundamental and harmonic currents but also offer a path for the neutral current ,when connected in shunt at PCC. Under unbalanced load, the zero-sequence load-neutral current divides equally into three currents and takes a path through the T-connected windings of the transformer. The current rating of the windings is decided by the required neutral current compensation. The voltages across each winding are designed as follows.

The phasor diagram gives the following relations is to find the turn's ratio of windings. If $Va1$ and $Vb1$ are the voltages across each winding and $V_a$is the resultant voltage, then

$V_{a1} = K_1V_a$ (4)

$V_{b1} = K_2V_a$ (5)

where $K_1$and $K_2$are the fractions of winding in the phases. Considering $|V_a| = |V_b| = V$and $V_{a1} = V_a\cos 30°$, $V_{b1} = V_a\sin 30°$, then from (4) and (5), we gets, $K1 = 0.866$ and $K2 = 0.5$.

The line voltage is

$V_{ca}= 415$ V

$V_a= V_b= V_c=415/\sqrt{3}= 239.60$ V (6)

$V_{a1} = 207.49$ V, $V_{b1} = 119.80$ V. (7)

Hence, two single-phase transformers of rating 5 kVA, 240 V/120 V and 5 kVA, 208 V/208 V are selected.

SYNCHRONOUS REFERENCE FRAME IMPLEMENTATION

The control approaches available for reference source currents generation to the control of VSC of DSTATCOM for the distribution system are instantaneous reactive power theory (IRPT),unity power factor (UPF) based ,synchronous reference frame theory (SRFT), , instantaneous symmetrical components based, etc. The SRFT is used in here for the control of the proposed DSTATCOM.

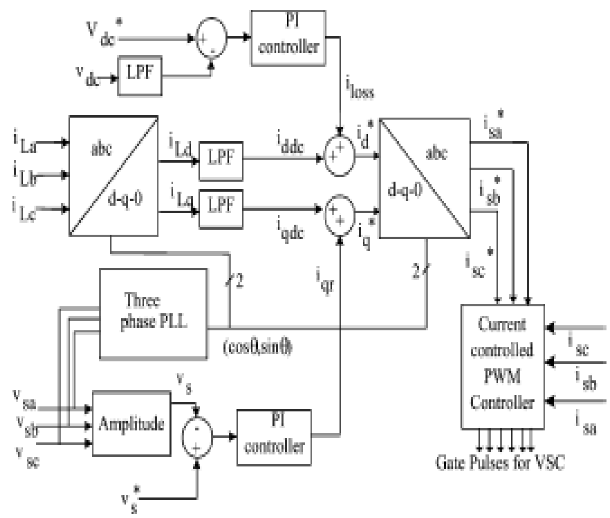

Figure .Control Block of DSTATCOM in Distribution System

A block diagram of the control scheme is shown in Fig. The load currents (i_{La}, i_{Lb}, i_{Lc}), the PCC voltages (v_{Sa}, v_{Sb}, v_{Sc}), and dc bus voltage (v_{dc}) of DSTATCOM are measured as feedback signals. The load currents from the *a–b–c* frame are first converted to the *α–β–o* frame and then to the *d–q–o* frame using

$$\begin{bmatrix} i_{Lq} \\ i_{Ld} \\ i_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (8)$$

where cos θ and sin θ are obtained using a three-phase phase locked loop (PLL). A PLL signal is obtained from terminal voltages for the generation of fundamental unit vectors which converts sensed currents to the *d–q–o* reference frame. The SRF controller extracts dc quantities by a low-pass filter, and hence, the non-dc quantities (harmonics) are separated from the reference signal. The *d*-axis and *q*-axis currents consist of fundamental and harmonic components as

$$i_{Ld} = i_{d\,dc} + i_{d\,ac} \quad (9)$$

$$i_{Lq} = i_{q\,dc} + i_{q\,ac} \quad (10)$$

CONTROL OF DSTATCOM

UPF Operation of DSTATCOM

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

$$i_{\text{loss}\,(n)} = i_{\text{loss}\,(n-1)} + K_{pd}\,(v_{dc(n)} - v_{dc(n-1)}) + K_{id} v_{dc(n)} \qquad (11)$$

where $v_{dc(n)} = v^*_{\text{dc}} - v_{\text{dc}(n)}$ is the error between the reference(v^*_{dc}) and sensed (v_{dc}) dc voltages at the n^{th} sampling instant. $K_{pd}$and $K_{id}$are the proportional and integral gains of the dc bus voltage PI controller.
The reference source current is therefore

$$i^*_d = i_{d\,\text{dc}} + i_{\text{loss}} (12)$$

The reference source current must be in phase with the voltage at the PCC but with no zero-sequence component. It is therefore obtained by the following reverse Park's transformation with i^*_das in (12) and $i^*_q$and i^*_0 as zero

$$\begin{bmatrix} i^*_a \\ i^*_b \\ i^*_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i^*_d \\ i^*_q \\ i^*_0 \end{bmatrix}. \qquad (13)$$

Zero-Voltage Regulation (ZVR) Operation of DSTATCOM

The compensating strategy for ZVR operation considers that the source must deliver the same direct-axis component i^*d, as mentioned in (12) along with the sum of quadrature-axis current (iq dc) and the component obtained from the PI controller (i_{qr}) used for regulating the voltage at PCC. The amplitude of ac terminal voltage (V_S) at the PCC is controlled to its reference voltage (V^*_S) using the PI controller. The output of PI controller is considered as the reactive component of current (i_{qr}) for zero-voltage regulation of ac voltage at PCC. The amplitude of ac voltage (V_S) at PCC is calculated from the ac voltages (v_{sa}, v_{sb}, v_{sc}) as

$$V_S = (2/3)^{1/2}(V_{sa}^2+V_{sb}^2+V_{sc}^2)^{1/2} \qquad (14)$$

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

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

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 integral gains of the dc bus voltage PI controller. The reference source
quadrature - axis current is
$i^*_q = i_{qdc} + i_{qr}$.
The reference source current is obtained by reverse Park's transformation using (13) with i^*d as in (12) and i^*q as in (16) and i^*0 as zero

Current-Controlled pulse width modulation (PWM) Generator

In a current controller, the sensed and reference source currents are compared and a proportional controller is used for amplifying current error in each phase before comparing with a triangular carrier signal to generate the gating signals for six IGBT switches of VSC of DSTATCOM.

SIMULATION AND RESULTS

SIMULINK

SIMULINK is a companion program to MATLAB. It is an interactive system for simulating non linear dynamic systems. It is graphical mouse driven program that allows modeling of system by drawing a block diagram on the screen and manipulating it dynamically. It can work with linear, non-linear, continuous and discrete time, multivariable and multi rate system.

Block sets are add-ins to simulink that provides additional libraries of blocks for specialized applications like communications, signal processing and power systems.

SIMULATION OF DSTATCOM SYSTEM

The three-leg VSC and the T-transformer based DSTATCOM connected to a three-phase four-wire system is modeled and simulated using the MATLAB with its Simulink and Power System Blockset toolboxes. The system data are given in Appendix. The MATLAB based model of the three-phase four-wire DSTATCOM is developed.

The control algorithm for the DSTATCOM is also modeled in MATLAB. The reference source currents are derived from the sensed PCC voltages (v_{sa}, v_{sb}, v_{sc}), load currents (i_{La}, i_{Lb}, i_{Lc}) and the dc bus voltage of DSTATCOM (v_{dc}). A pulse width modulated (PWM) current controller is used over the reference and sensed source currents to generate the gating signals for the IGBTs of the VSC of the DSTATCOM.

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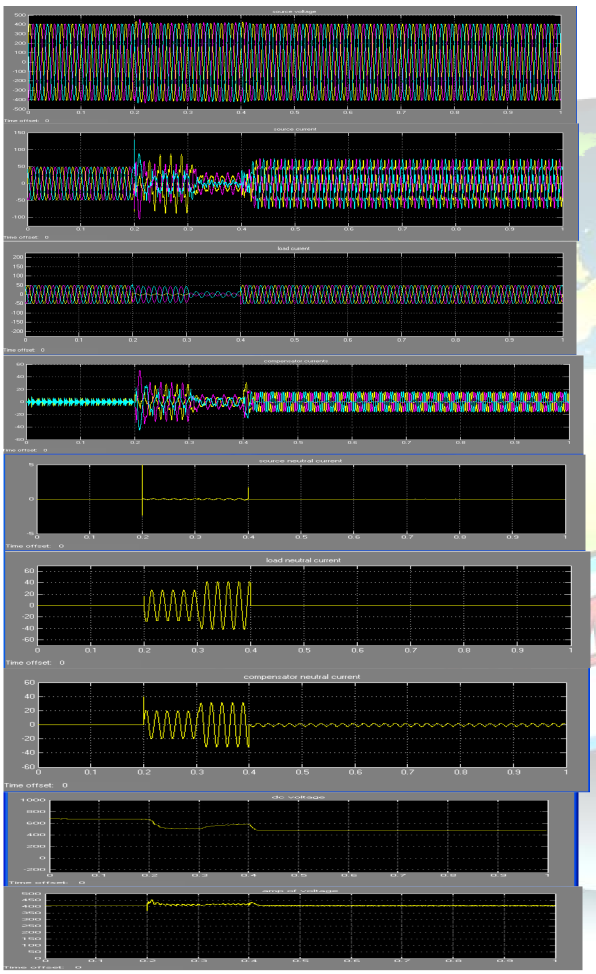
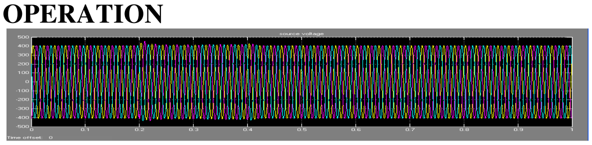
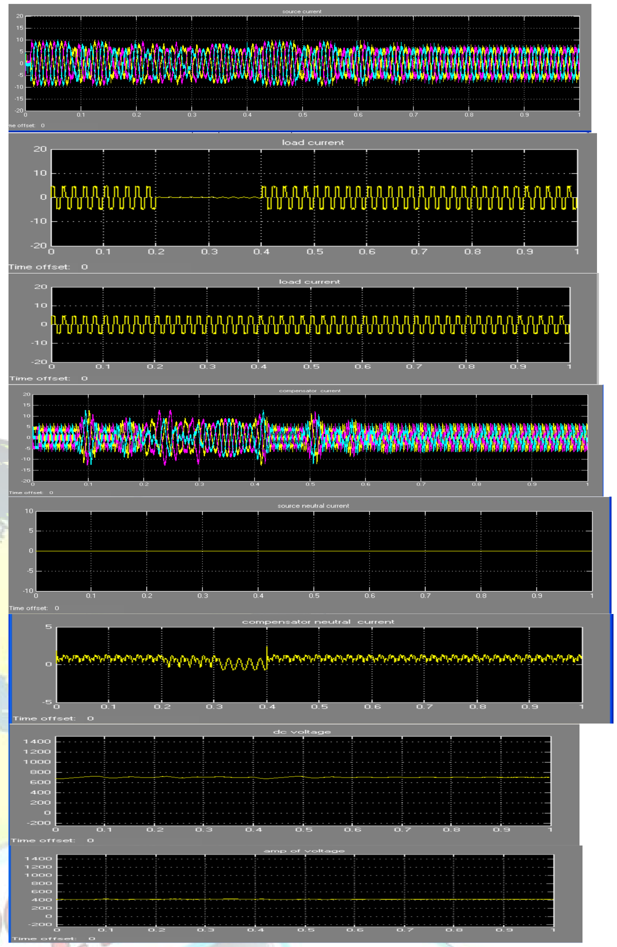
The performance of the three-phase four-wire DSTATCOM is demonstrated for power factor correction and voltage regulation along with harmonic reduction, load balancing and neutral current compensation. The developed model is analyzed under varying loads and the results are shown below.

OUTPUT WAVEFORMS OF DSTATCOM WITH LINEAR LOAD UNDER ZVR OPERATION



5.5. OUTPUT WAVEFORMS OF DSTATCOM WITH NON-LINEAR LOAD UNDER ZVR OPERATION

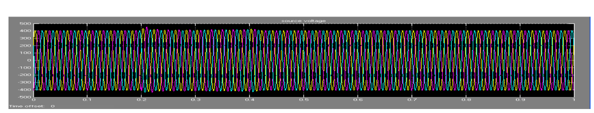




INFERENCES

The source neutral current is observed as nearly zero, and this verifies the proper compensation. It is also observed that the dc bus voltage of DSTATCOM is able to maintain close to the reference value under all disturbances. The amplitude of PCC voltage is maintained at the reference value under various load disturbances, which shows the ZVR mode of operation of DSTATCOM. The dc bus voltage of DSTATCOM is maintained at nearly its reference value under all load disturbances

5.7 OUTPUT WAVEFORMS OF DSTATCOM WITH LINEAR LOAD UNDER UPF OPERATION



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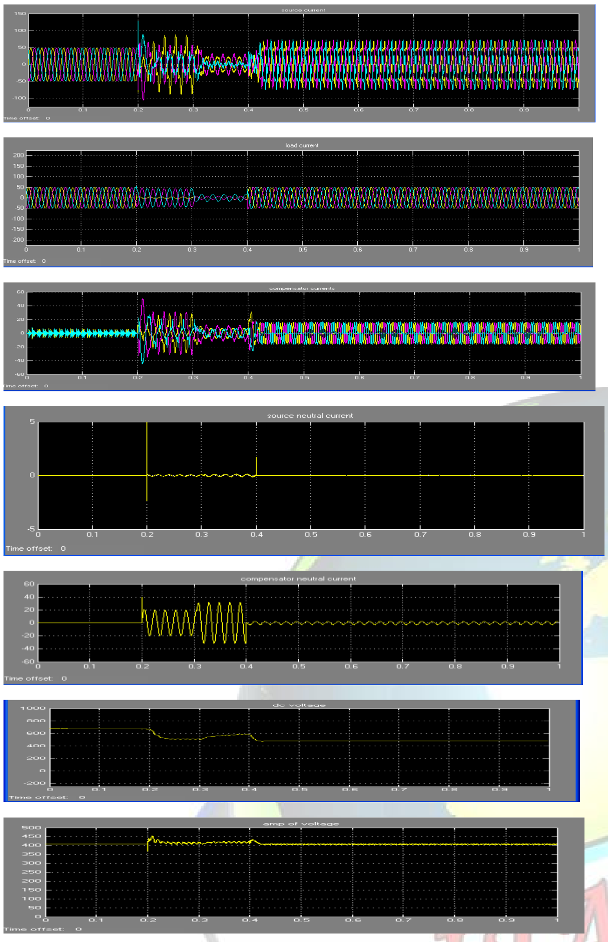
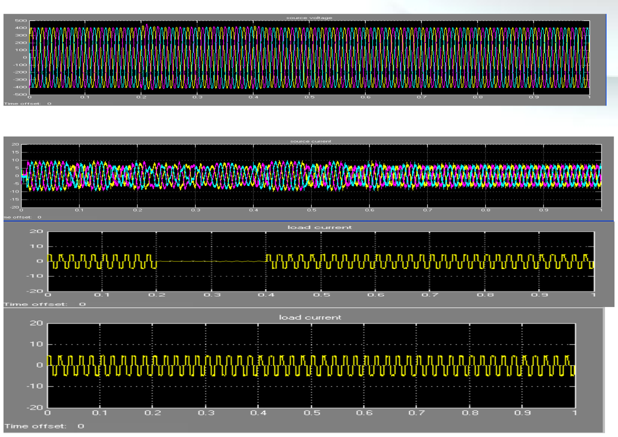
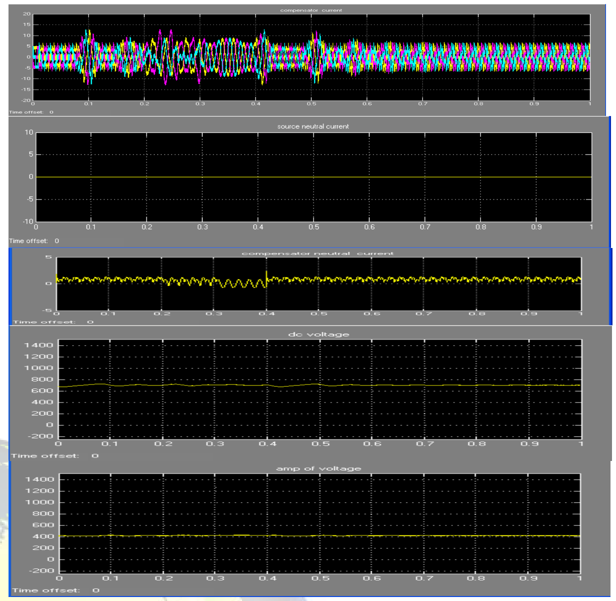


5.9. OUTPUT WAVEFORMS OF DSTATCOM WITH NON-LINEAR LOAD UNDER UPF OPERATION





CONCLUSION

The performance of a new topology of three-phase four-wire DSTATCOM consisting of three-leg VSC with a T-connected transformer has been demonstrated for neutral current compensation harmonic elimination, and load balancing. The T-connected transformer has mitigated the source-neutral current. The voltage regulation and power factor correction modes of operation of the DSTATCOM have been observed and are as expected. The dc bus voltage of the DSTATCOM has been regulated to the reference dc bus voltage under all varying loads. The performance of DSTATCOM is verified under linear and non-linear load conditions. The Simulink result shows that the DSTATCOM compensates the harmonic current and balances the load.