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DSTATCOM Implemented On a 3 Phase 4 Wire Distribution System for Harmonic Elimination and System Balance

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ABSTRACT: This paper deals with the design and simulation of the performance of synchronous reference frame (SRF) and neural network controlled DSTATCOM along with a zig-zag transformer, implemented on a three phase four wire distribution system as a solution for power quality issues.

First part of the paper deals with the design and simulation of SRF controlled DSTATCOM based on three-leg and four-leg VSC topology and performance of both is evaluated and compared. Second part deals with the design and simulation of Neural-Network controlled DSTATCOM based on three leg VSC topology. Then the performance of DSTATCOM using both SRF and Neural Network will be compared. For the three-leg voltage-source- converter (VSC) based DSTATCOM configuration a zig-zag transformer is used for neutral current compensation at the PCC.

SRF strategy generates unit vectors from the grid voltage and operates a voltage source inverter. It uses co-ordinate transformations to generate the current reference. Whereas in ANN strategy the Adaline-based current decomposer estimates the reference currents through tracking of unit vectors together with tuning of the weights. The performance of the proposed DSTATCOM system is validated through simulations using MATLAB software with its Simulink and Power System Block set toolboxes.

KEYWORDS: Distribution Static Compensator (DSTATCOM), Synchronous Reference Frame (SRF), Artificial Neural Network (ANN), Power Quality Improvement, Voltage Source Converter (VSC), Zig-Zag transformer, Point of Common Coupling (PCC) etc.

I. INTRODUCTION

Ideally, the goal of power industry is to supply a purely sinusoidal voltage at fixed amplitude and fixed frequency. Whereas it is the duty of the supplier to provide an almost sinusoidal voltage with less variation in amplitude and frequency, the user also has a part to play in creating such a scenario.

Power quality problems in the ac distribution systems are mainly due to the proliferation of different types of nonlinear loads, unplanned expansion of the distribution system, etc. These power quality problems include high reactive power burden, harmonic currents, load unbalance, and excessive neutral current. The power quality at the point of common coupling (PCC) is regulated by the various standards such as IEEE-519 standard. A three-phase four-wire distribution static compensator (DSTATCOM) is used for neutral current compensation along with voltage regulation or power factor correction, harmonic elimination, and load balancing in a three-phase four-wire system with linear and nonlinear loads.

There are many strategies available for the generation of reference source currents for the control of VSC of DSTATCOM for a three-phase four-wire system. In this paper, a control approach based on Synchronous Reference Frame (SRF) strategy & Artificial Neural Network (ANN) is used under non-sinusoidal supply conditions for the three-



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leg & four-leg VSC based DSTATCOM implemented on a three-phase four-wire system. The estimated reference supply current is used for generating the gate pulses for the VSC of the DSTATCOM

II. METHODOLOGY

A. SRF control

The synchronous reference frame strategy uses co-ordinate transformations to generate the current reference. It employs the well-known *Clarke's Transformation* and *Park's Transformation* for this purpose.

1. Reference Signal Estimation.

The reference supply current is estimated using the sensed load current and voltage at PCC. The SRF method is also known as I_d - I_q method. Each current component has an average value or dc component and an oscillating value or ac component as

$$i_d = i_{d_{dc}} + i_{d_{ac}} \quad (1)$$

$$i_q = i_{q_{dc}} + i_{q_{ac}} \quad (2)$$

The reference source current is therefore as

$$i_d^* = i_{d_{dc}} + i_{loss} \quad (3)$$

$$i_q^* = i_{q_{dc}} + i_{qr} \quad (4)$$

where, i_{loss} is the loss current component and i_{qr} reactive power component.

The reference source current in the a-b-c frame is obtained by reverse transformation of the above current vector:

$$\begin{bmatrix} i_{s0}^* \\ i_{sa}^* \\ i_{sb}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} 0 \\ i_d^* \\ i_q^* \end{bmatrix} \quad (5)$$

2. Current-controlled PWM for generating gating pulses

In a current controller, the sensed and reference supply currents are compared with a triangular carrier signal to generate the gating signals for six switches.

B. ANN control

The basic theory of decomposer is based on the least mean square (LMS) algorithm, and its training is through ADALINE for generating the reference source currents.

For an ac system, the source voltages and load currents have harmonic components along with fundamental components

$$V_s = V_1 \sin \omega t + \sum_{n=2}^{\alpha} V_n \sin(n\omega t + \theta_n) \quad (6)$$

$$I_L = I_1 \sin \omega t + \sum_{n=2}^{\alpha} I_n \sin(n\omega t + \theta_n) \quad (7)$$

Where V_1 and V_n are the peaks of the fundamental and harmonic components of the voltage. Similarly, I_1 and I_n are the peaks of the fundamental and harmonic components of the current. The unit template for three phases can be represented as



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$$u_a = U \sin \omega t \quad u_b = U \sin(\omega t - 120) \quad u_c = U \sin(\omega t - 240) \quad (8)$$

$$x_a = U \cos \omega t \quad x_b = U \cos(\omega t - 120) \quad x_c = U \cos(\omega t - 240) \quad (9)$$

Where $U = 1$. The fundamental load current can be decomposed as

$$I_1 = I_p + I_q \quad (10)$$

Where I_p and I_q are the active and reactive power components of the load current, respectively.

The estimates of the fundamental active power and fundamental reactive power components of the load current for a single phase are obtained by estimating the respective weights corresponding to the fundamental active components of the load current (w_{pa} , w_{pb} , w_{pc}) and the weights corresponding to the fundamental reactive components of the load current (w_{qa} , w_{qb} , w_{qc}). The weights are updated using the LMS algorithm.

$$\begin{aligned} W_{pa(k+1)} &= W_{pa(k)} + \eta \{i_{La(k)} - W_{pa(k)}u_a(k)\}u_a(k) \\ W_{pb(k+1)} &= W_{pb(k)} + \eta \{i_{Lb(k)} - W_{pb(k)}u_b(k)\}u_b(k) \\ W_{pc(k+1)} &= W_{pc(k)} + \eta \{i_{Lc(k)} - W_{pc(k)}u_c(k)\}u_c(k) \\ W_{qa(k+1)} &= W_{qa(k)} + \eta \{i_{La(k)} - W_{qa(k)}x_a(k)\}x_a(k) \\ W_{qb(k+1)} &= W_{qb(k)} + \eta \{i_{Lb(k)} - W_{qb(k)}x_b(k)\}x_b(k) \\ W_{qc(k+1)} &= W_{qc(k)} + \eta \{i_{Lc(k)} - W_{qc(k)}x_c(k)\}x_c(k) \end{aligned} \quad (11)$$

Where η is the coefficient of convergence and its value lies between 0 and 1. It is used as 0.2 in this LMS algorithm.

The average weight corresponding to the active and reactive components of the load is shown as

$$W_p = (W_{pa} + W_{pb} + W_{pc})/3 \quad (12)$$

$$W_q = (W_{qa} + W_{qb} + W_{qc})/3 \quad (13)$$

Two Proportional–Integral (PI) controllers are used for controlling the dc bus voltage and ac terminal voltage. This PI controller estimates the loss component of the source current (W_{loss}), and hence, this is added with the W_p . The second PI controller is used over the amplitude of PCC voltage and reference values, and it estimates the reactive component of the DSTATCOM current (W_{qr}), and hence, this is added with the W_q .

Now, the real and reactive components of the reference source currents are computed as

$$i_{pa} = W_p u_a \quad i_{pb} = W_p u_b \quad i_{pc} = W_p u_c \quad (14)$$

$$i_{qa} = W_q x_a \quad i_{qb} = W_q x_b \quad i_{qc} = W_q x_c \quad (15)$$

The reference source currents are obtained as the sum of active and reactive power currents as

$$i_{sa}^* = i_{pa} + i_{qa} \quad i_{sb}^* = i_{pb} + i_{qb} \quad i_{sc}^* = i_{pc} + i_{qc} \quad (16)$$

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The reference source currents in three phases are used for the control of the three-leg VSC. The sensed and reference source currents are compared, and the error is used to generate the gating signals for the IGBT switches

III. MODELLING

The four-leg VSC based DSTATCOM and three-leg VSC and the zig-zag transformer-based DSTATCOM for a three-phase four-wire system are modelled using SRF and ANN control strategies and simulated using MATLAB and its Simulink and Sim Power System (SPS) toolboxes. The multiwinding transformer model available in the SPS is used for modelling the zig-zag transformer. The ripple filter is connected to the VSC of the DSTATCOM for filtering the ripple in the PCC 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 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}). Following figures show the Simulink model of the DSTATCOM based on the different control strategies and the previous mentioned configurations. 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. The switching frequency is set as 10 kHz.

A. Three phase four wire system without DSTATCOM

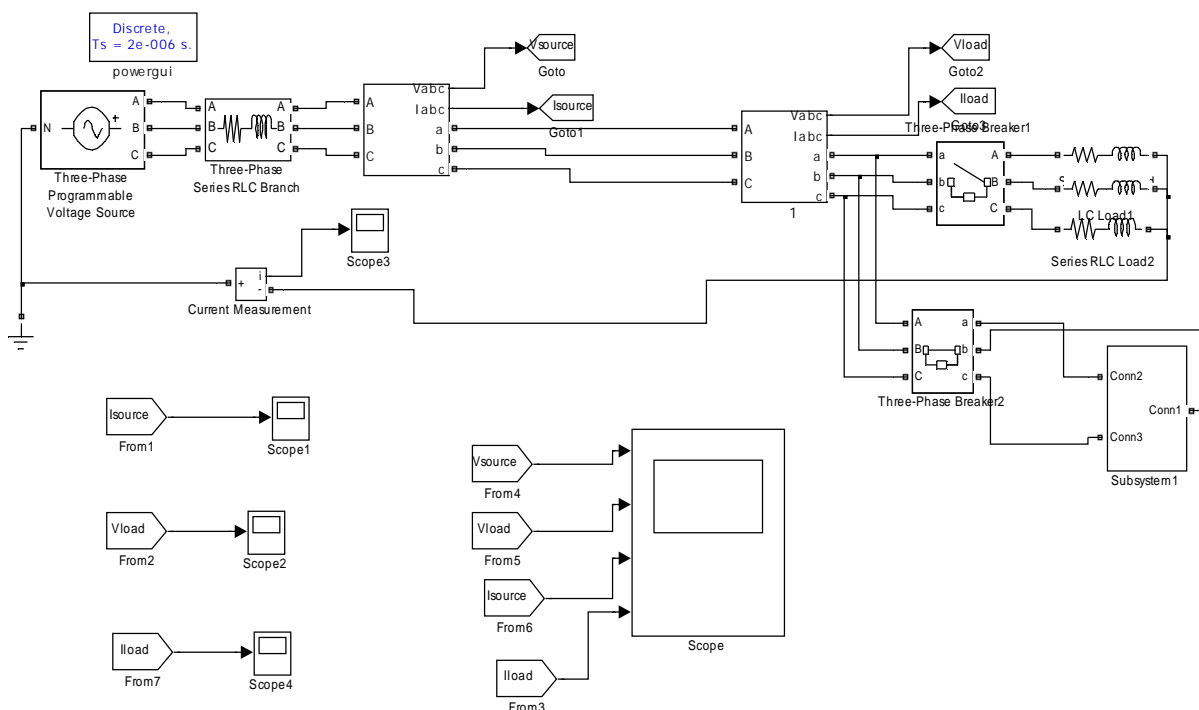


Fig.1 Three phase four-wire system without DSTATCOM

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B. Three phase four wire system with 4leg VSC based SRF controlled DSTATCOM

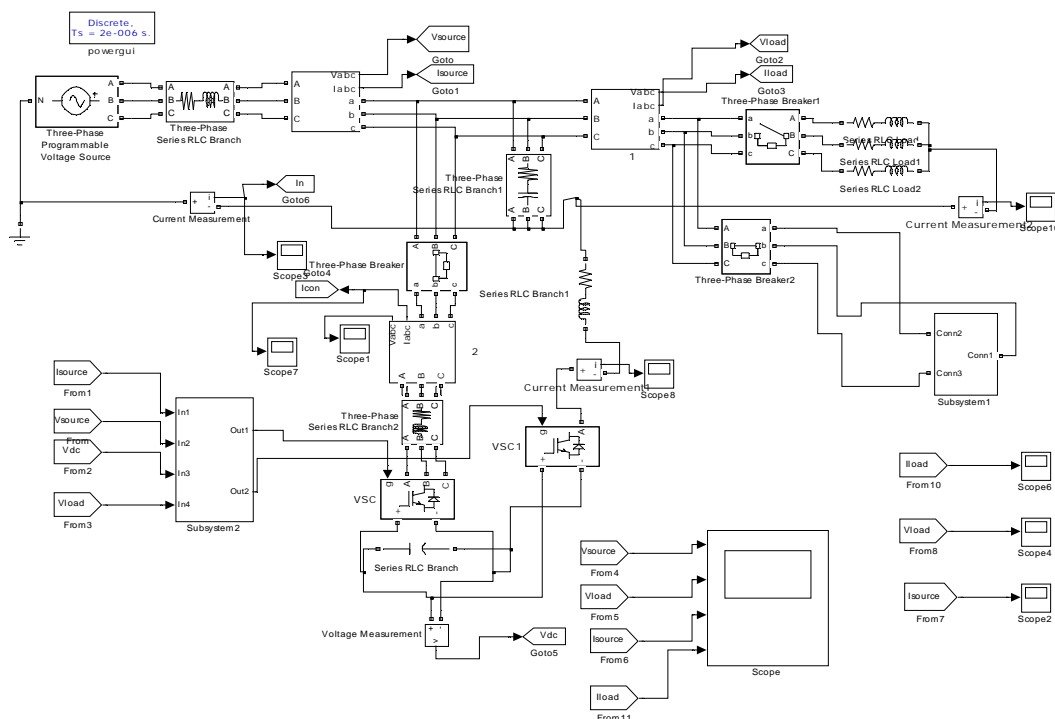


Fig.2 System with 4leg VSC based SRF controlled DSTATCOM

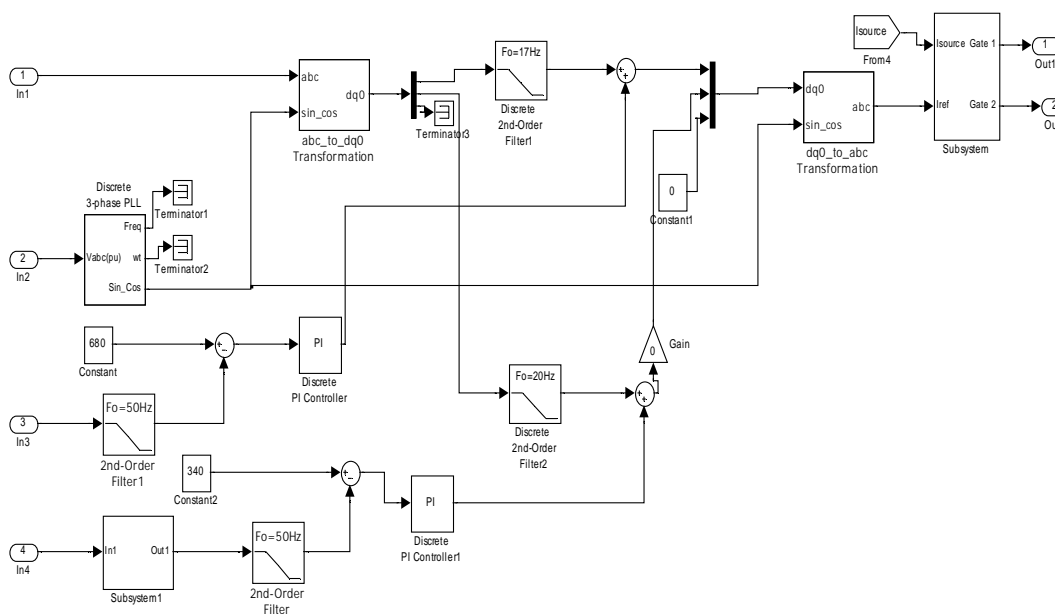


Fig. 3 Control circuit for 4leg VSC based SRF controlled DSTATCOM

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The three-phase four-wire DSTATCOM is used for reactive power and harmonic current compensation along with load balancing and neutral current compensation. There is 3 phase wire and one neutral wire. The first three legs will provide compensating currents for the three phases, while the fourth leg provides the compensating current for neutral.

C. Three phase four wire system with 3leg VSC based SRF controlled DSTATCOM

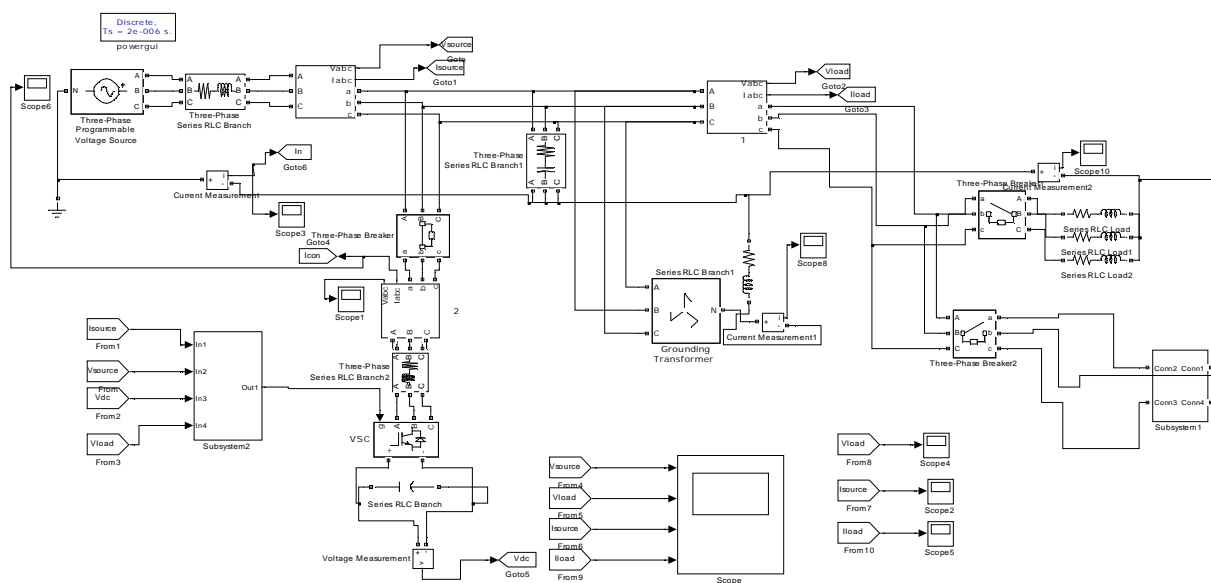


Fig 4. System with 3leg VSC based SRF controlled DSTATCOM

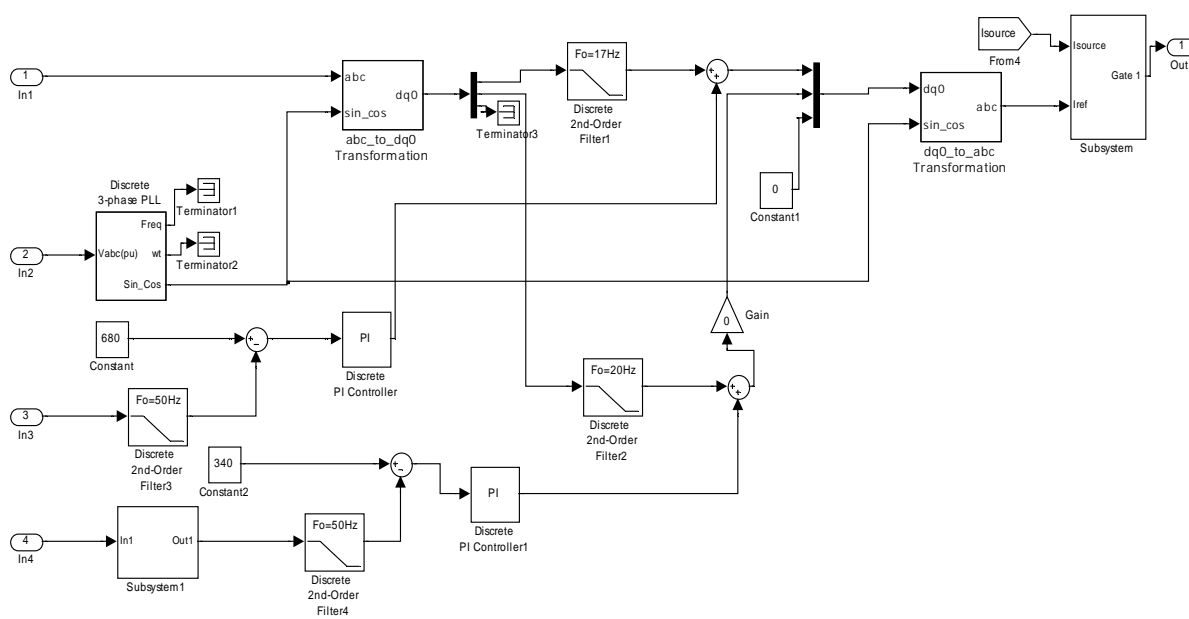


Fig 5 control circuit for 3leg VSC based SRF controlled DSTATCOM

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In three-leg VSC based DSTATCOM there is no fourth leg to provide compensation for neutral current. Hence a zig-zag transformer is incorporated to provide neutral current compensation.

D. Three phase four wire system with 3leg VSC based ANN controlled DSTATCOM

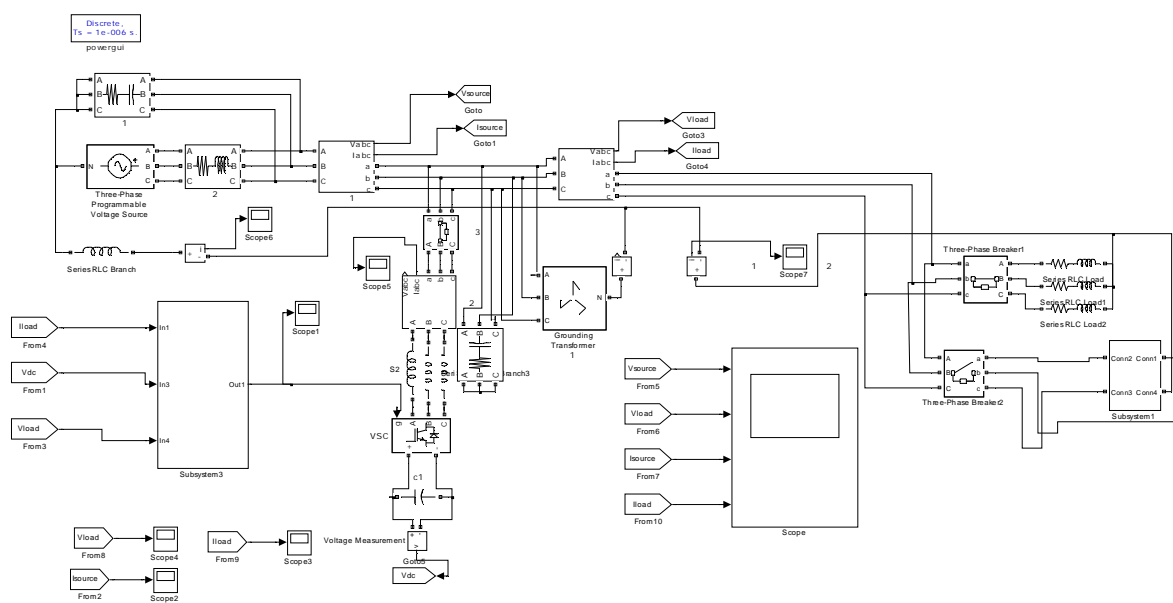


Fig 6. System with ANN controlled DSTATCOM

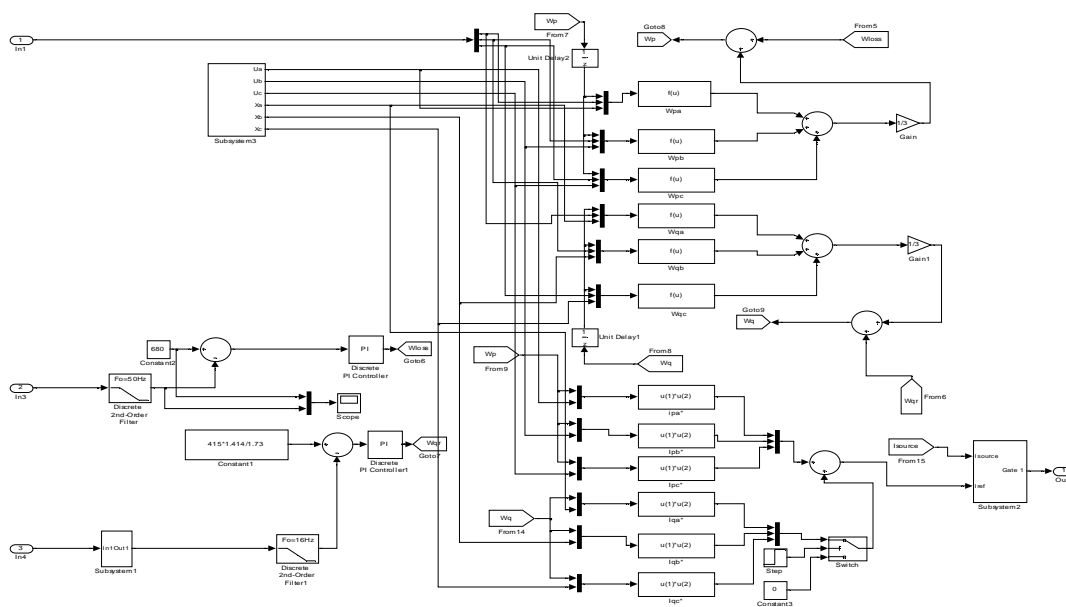


Fig 7. ANN control system

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IV. SIMULATION RESULTS

The performance of DSTATCOM for PCC voltage regulation, harmonic elimination, neutral current compensation and load balancing, is shown in following graphs. The performance of the three-phase VSC-based DSTATCOM for PCC voltage regulation, along with neutral current compensation and load balancing of a three-phase four-wire linear load, is shown in above Figures. It is observed that the amplitude of PCC voltage (V_S) is regulated to the reference amplitude by the required reactive power compensation and that the source neutral current (i_{sn}) is maintained at nearly zero because of the zig-zag transformer. The dc bus voltage of the capacitor (V_{dc}) of the VSC of DSTATCOM is regulated by the controller, and the dc voltage is maintained near the reference dc voltage under varying load disturbances. The total harmonic distortion (THD) of source current is observed to be less than 5%, which meets the requirement of IEEE-519 standard.

A. System without DSTATCOM

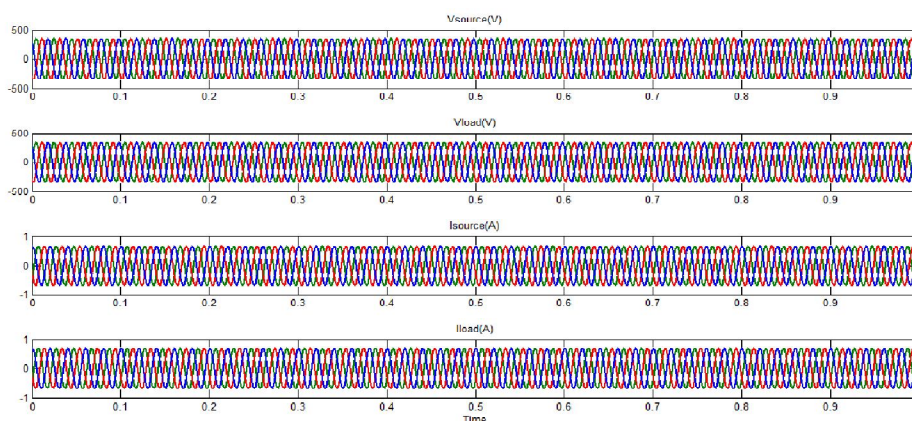


Fig 8. Simulation output of Three-Phase four wire system with linear load and without DSTATCOM

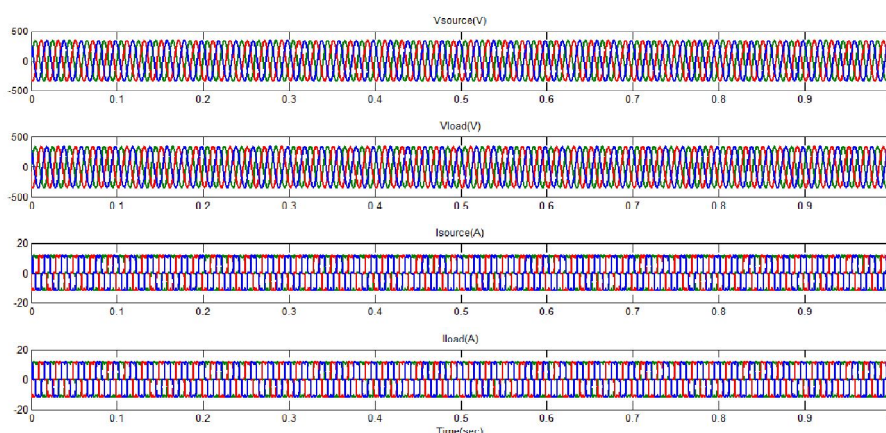


Fig 9. Simulation result of three phase four-wire system with non-linear load and without DSTATCOM

The result shows that for linear load the source current and load (pcc) voltage is purely sinusoidal and for non-linear load the source current and load (pcc) voltage is very much distorted. FFT analysis shows that the THD content in pcc voltage, source current and load current is very high about 5.05% , 27.39% and 27.39%.

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B. SRF control strategy

1. FOUR-LEG VSC based DSTATCOM

It has better performance than conventional filters. But the higher power rating of inverters increase the cost of system. Also it can be applied only for 3 phase 4 wire systems. The terminal voltage is maintained to the reference voltage by adjusting the reactive power injection.. FFT analysis shows that the THD content in pcc voltage and load current is very high about 4.37% and 25.53%, but source current is reduced to 3.12%.

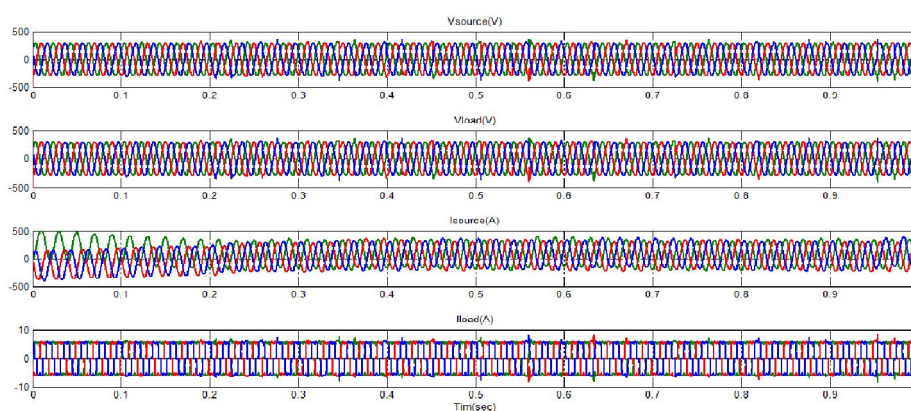


Fig 10. Simulation output of Three-Phase four wire system with DSTATCOM (4leg VSC) and Non-Linear load

2. THREELEG VSC based DSTATCOM

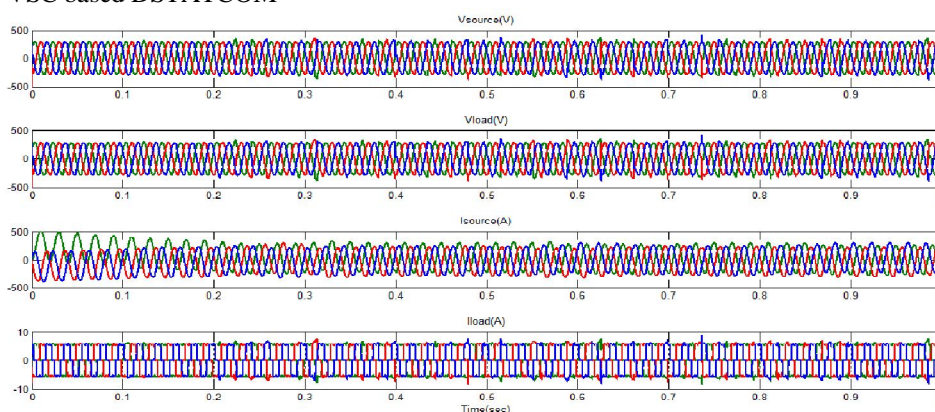


Fig 11. Simulation output of Three-Phase four wire system with DSTATCOM (3leg VSC and zig-zag transformer) and Non-Linear load

It has better performance than 4 leg VSC based DSTATCOM. It can be designed for both 3 phase 3 wire and 4 wire systems. It is cost effective too. The supply neutral current is nearly zero and it verifies the proper compensation by the zig-zag transformer. Power rating of converter can be reduced. The terminal voltage is maintained to the reference voltage by adjusting the reactive power injection.. FFT analysis shows that the THD content in pcc voltage and load current is very high about 4.8% and 26.81%, but source current is reduced to 1.42%.

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C. ANN control strategy

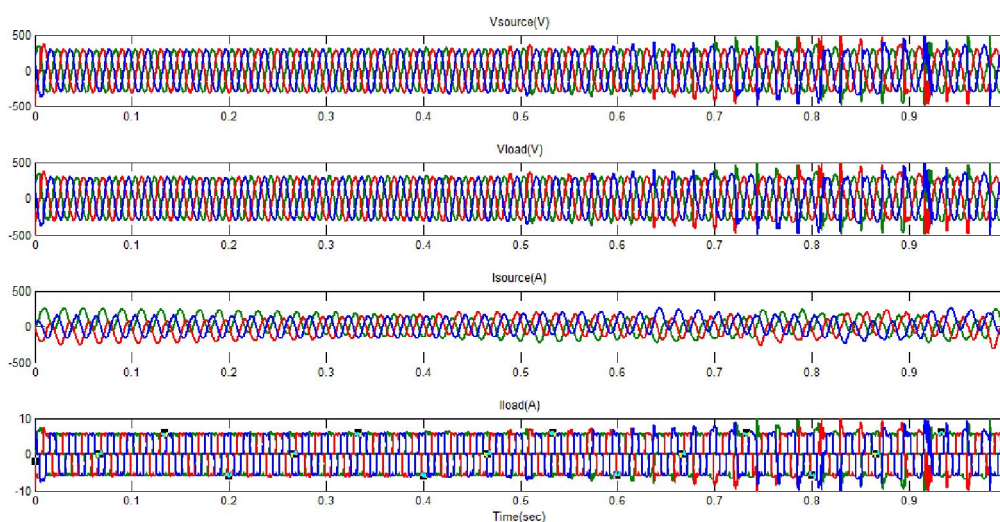


Fig 12. Simulation output of Three-Phase four wire system with ANN Controlled DSTATCOM (3leg VSC and zig-zag transformer) and Non-Linear load

Neural Network strategy has better performance than SRF control strategy and it is cost effective too. The supply neutral current is nearly zero and it verifies the proper compensation by the zig-zag transformer. The terminal voltage is maintained to the reference voltage by adjusting the reactive power injection. It is also observed that the dc bus voltage of DSTATCOM is maintained at the reference value under all disturbances. FFT analysis shows that the THD content in pcc voltage and source current is very high about 6.37% and 22.1%, but source current is reduced to 0.62%.

D. THD Analysis of system with non-linear load

TABLE-I

	PCC VOLTAGE	SOURCE CURRENT	LOAD CURRENT
Without DSTATCOM	5.05%	27.39%	27.39%
With SRF controlled 4leg VSC DSTATCOM	4.37%	3.12%	25.53%
With SRF controlled 3leg VSC DSTATCOM & Zig-Zag transformer	4.8%	1.42%	26.81%
With ANN controlled 3leg VSC DSTATCOM	6.37%	0.62%	22.81%

It is observed that by the use of SRF and ANN control techniques though the load current and PCC voltage harmonics remain uncompensated, the harmonic content in the source current is reduced and attained IEEE standard. By comparing the THD content, it is obvious that 3leg VSC based ANN controlled DSTATCOM gives better harmonics mitigation than 3-leg and 4-leg VSC based SRF controlled DSTATCOM.

E. System with linear unbalanced load

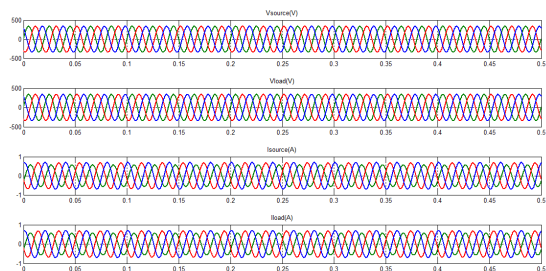


Fig 13. Uncompensated system

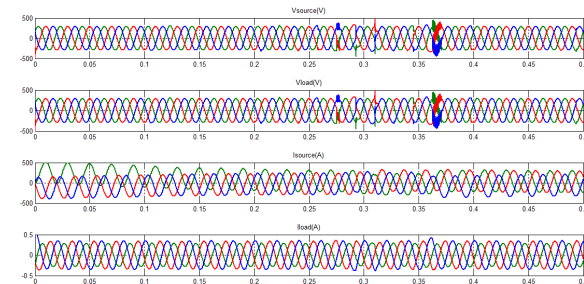


Fig 17. 3leg VSC based DSTATCOM with SRF control

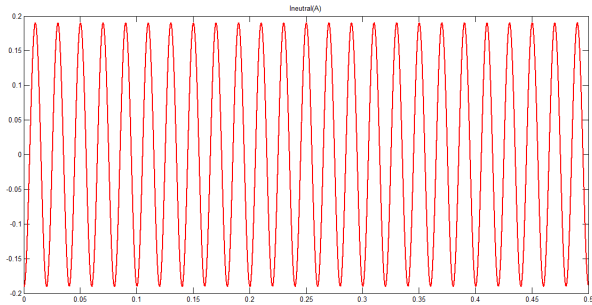


Fig 14. Neutral current of uncompensated system

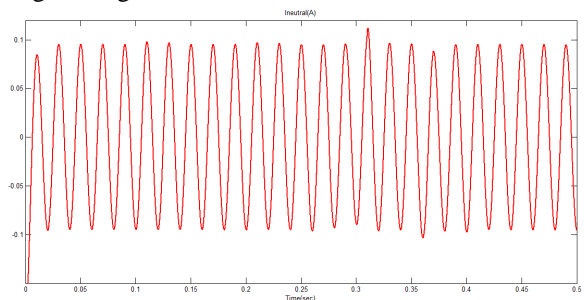


Fig 18. Neutral current of SRF controlled 3leg VSC based DSTATCOM system

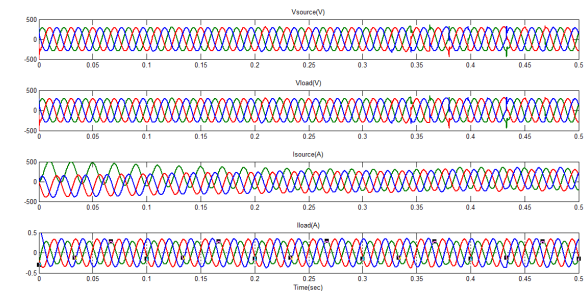


Fig 15. 4leg VSC based DSTATCOM with SRF control

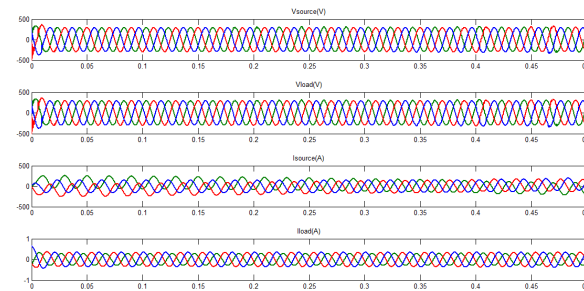


Fig 19. ANN controlled DSTATCOM

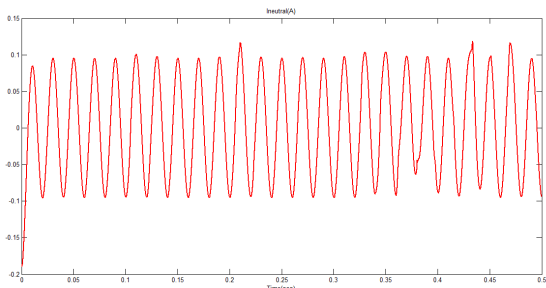


Fig 16. Neutral current of SRF controlled 4leg VSC based DSTATCOM system

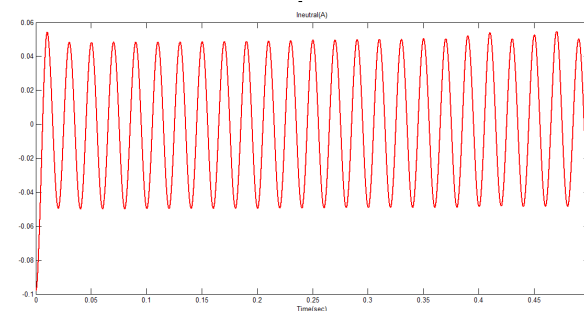


Fig 20. Neutral current of ANN controlled DSTATCOM

The 3-leg VSC based DSTATCOM system with zig-zag transformer has been found to be effective for compensating the zero-sequence fundamental and harmonic neutral currents than a 4-leg VSC based DSTATCOM system. By comparing



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the neutral current, it is obvious that 3leg VSC based ANN controlled DSTATCOM gives better load balancing and neutral current compensation than 3-leg and 4-leg VSC based SRF controlled DSTATCOM. The uncompensated neutral current is of about 0.2A and its limited to a value less than 0.1A for SRF controlled DSTATCOM and it is further reduced to a value less than 0.05A for ANN controlled DSTATCOM.

V. CONCLUSION

The analysis & simulation of a three-phase four-wire DSTATCOM controlled with SRF and ANN its performance has been demonstrated for neutral current elimination along with reactive power compensation, harmonic elimination, and load balancing. It is observed that the amplitude of PCC voltage is regulated to the reference amplitude by the required reactive power compensation and that the source neutral current is maintained at nearly zero because of the zig-zag transformer. The dc bus voltage of the capacitor of the VSC of DSTATCOM is regulated by the controller, and the dc voltage is maintained near the reference dc voltage. The total harmonic distortion (THD) of source current is observed to be less than 5%, which meets the requirement of IEEE-519 standard.

But on comparing between SRF and ANN it has been found that the ANN control technique is simple to implement & fast in response. Also, ANN reduces waveform distortion and THD of the PCC voltage and source current much better than SRF. It also reduces the initial phase shifting and waveform settling time.

APPENDIX

Line impedance: $R_s = 0.01 \text{ X}$, $L_s = 2\text{mH}$

Load,

Linear: 2000 kVA, 0.707 pf lag

Non-linear: Three-phase bridge rectifier

and series R–L load with

$R = 50 \text{ X}$ and $L = 1 \text{ mH}$

Ripple filter : $R_f = 5 \text{ X}$, $C_f = 5 \text{ I F}$

DC bus capacitance : 3000IF

DC bus voltage: 680 V

AC line voltage: 415 V, 50 Hz

PWM switching frequency : 10 kHz

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BIOGRAPHY



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