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# Design and Control of 3-phase, 4-wire, 4-Leg VSC Based DSTATCOM using Synchronous Reference Frame Theory

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**ABSTRACT**

This paper presents three-phase, four-leg, VSI based AC shunt D-STATCOM feeding AC voltage controller having resistive-inductive (RL) load for reducing the harmonic current and to maintain UPF using Synchronous Reference Frame (SRF) based control algorithm. This theory is employed to calculate compensating current while the three phase source is feeding a non-linear load. Simulation is performed for an unbalanced load in PFC mode in MATLAB environment using sim-power system (SPS) toolbox.
**Keywords :** DSTATCOM, power quality, non-linear load, load balancing, harmonic compensation, voltage regulation, Neutral current compensation

## I. INTRODUCTION

In recent era of development the distribution system (especially three-phase, four-wire) is facing the problem of excessive neutral current besides the reactive power burden, unbalanced loading of phases and harmonic current injection. In three-phase, four-wire system unbalanced loading of phase causes the flow of neutral current and cause the unbalanced load on load point. This leads to the poor power quality problem on load side [1-4]. These power quality problems can be eliminated with the help of DSTATCOM connected at point of common coupling (PCC). For this purpose there are a no. of topologies of DSTATCOM such as a four-leg VSC [3], three single phase VSC [4], H-bridge VSC with star-delta transformer [5].

Now for controlling the switches a no. of control algorithm such as Instantaneous Reactive Power theory (IRP), Instantaneous Symmetrical Component (ISC), Synchronous Reference Theory (SRF) [1-4]. This is a classical time-domain control theory and has been reviewed by Bhattacharya et al [7]. In the following paper three-phase, four-leg, four-wire VSI based DSTATCOM is used for compensating the neutral current and load balancing. In the design topology the mid-point of $4^{th}$ leg of DSTATCOM is connected to the neutral terminal and its switching is controlled in such a way so as to make the neutral current zero.

The application of STATCOM includes aerospace power supply [8], voltage and frequency controller for isolated wind energy system [9], grid connected electrical vehicle charging station [10]. The development of active power filter is to solve power quality problem [11-12] and the main part of this APF is voltage source inverter (VSI) which is operated in current controlled mode [13]. The instantaneous active and reactive power can be computed in terms of transformed voltage and current signals [14]. This algorithm works very well if we can find positive sequence voltages for unbalance supply voltages and substitute these voltages in control algorithm based on the instantaneous symmetrical components theory both under stiff and non stiff sources [15-16]. Many control techniques have been incorporated such as instantaneous reactive power theory power balance theory, indirect current control technique [18-19] etc.

In this paper, a 4-leg VSC based DSTATCOM is implemented with synchronous reference frame theory (SRF) based control algorithm [19-20] for the voltage regulation and used with an indirect current control technique. Four-leg single-capacitor VSC topology has compact power circuit, magnetic circuit-free neutral current compensation and easy to maintain DC bus voltage compared to other four-wire DSTATCOM topology [21–25].

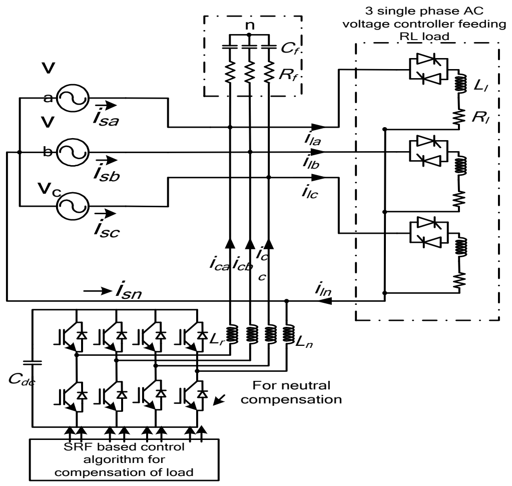
## II. Circuit Configuration

The basic circuit diagram of 3-phase, 4-wire, 4-leg VSC based AC shunt DSTATCOM is shown in Fig.1 (a). The DSTATCOM is connected to the 3-phase, 4-wire system in parallel of 3 single-phase AC voltage controller with resistive-inductive (RL) load. The switching signals for the six IGBTs of three legs of DSTATCOM is generated by Synchronous Reference Frame (SRF) theory and the IGBTs of the 4th leg is connected so as to make the neutral current zero. Hence by using this method load compensation as well as neutral current elimination is achieved.

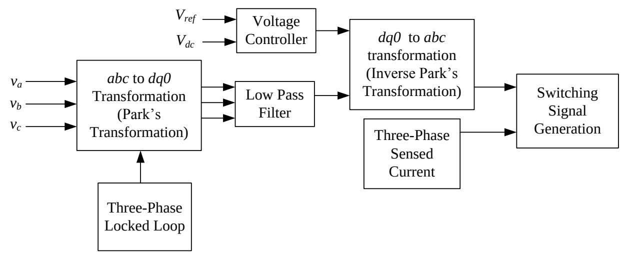
AC inductors are used to interface Voltage source Converter (VSI) to the system and to reduce the ripple in the injected current. RC filters are used in parallel with the load to reduce the switching ripple in PCC voltage injected at the time of switching of DSTATCOM.

## III. Control Algorithm

The block diagram of control algorithm is given in Fig.1 (b). The system voltage $V_a$, $V_b$, $V_c$ and load currents $I_{La}$, $I_{Lb}$, $I_{Lc}$ are sensed and used for reference current generation which is further used to generate the switching signals for the three legs of DSTATCOM. Through Park Transformation three phase load current is converted to two phase revolving vector current direct axis $I_d$, quadratic axis $I_q$, and zero sequence $I_0$ according to the following transformation:




(a)




(b)

**Figure 1.** (a) Line Diagram of 3-phase 4-wire 4-leg compensated system (b) Block diagram for controlling the DSTATCOM switches

### A. Phase Transformation Equations

The various transformation equations are given in this section.

$$V_d = 2/3*[V_a*sin(\omega t) + V_b*sin(\omega t - 2\pi/3) + V_c*sin(\omega t + 2\pi/3)] \quad (1)$$

$$V_q = 2/3*[V_a*cos(\omega t) + V_b*cos(\omega t - 2\pi/3) + V_c*cos(\omega t + 2\pi/3)] \quad (2)$$

$$V_0 = 1/3*[V_a + V_b + V_c] \quad (3)$$

where ω= rotation speed of rotating frame

A three-phase phase locked loop (PLL) is used to provide the phase difference required for the reference current generation. These are then compared with the sensed phase current $I_a$, $I_b$, $I_c$ and error signals are used to control the switches of the all three phases of the DSTATCOM.

The equations used for the transformation of dq0 to abc frame is given below and better known as Clarks transformation: These equations are used to generate reference phase currents.

$$I_a = [I_d * sin\,(\omega t) + I_q * cos\,(\omega t) + I_o] \quad (4)$$

$$I_b = [I_d * sin\,(\omega t - 2\pi/3) + I_q * cos\,(\omega t - 2\pi/3)\omega t + I_o] \quad (5)$$

$$I_c = [I_d * sin(\omega t + 2\pi/3) + I_q * cos\,(\omega t + 2\pi/3) + I_o] \quad (6)$$

where ω= rotation speed (rad/s) of the rotating frame.

### Gating scheme for the 4th Leg (neutral leg)

The neutral current is considered to be the opposite of sum of 3-phase supply currents $I_{sa}$, $I_{sb}$, $I_{sc}$

$$I_{sn} = -(I_{sa} + I_{sb} + I_{sc}) \quad (7)$$

This neutral current is compared with the zero, and the current error is used to generate the gating signal for neutral leg of 4-leg VSC to force the neutral current zero [6].

## IV. MODELING OF PROPOSED TOPOLOGY

Mathematical Model of AC Voltage Controller

$$V_0 = V_s\left[\frac{1}{\pi}\left(\beta - \alpha + \frac{1}{2}\sin 2\alpha - \frac{1}{2}\sin 2\beta\right)\right]$$

and

$$I_r = \frac{Vs}{Z}\left[\frac{1}{\pi}\int_\alpha^\beta\left(\sin(\omega t - \theta) - \sin(\alpha - \theta)e^{(\frac{R}{L})*(\frac{\alpha}{\omega} - t)}\right)^2 d(\omega t)\right]^{\frac{1}{2}}$$

(8,9)

$$I_{r0} = \sqrt{2} \times I_r$$

(10)

Mathematical Modeling of DSTATCOM

The mathematical expressions for the modeling of DSTATCOM is given as,

$$V_{dc} = \frac{2\sqrt{2}V_{L-L}}{\sqrt{3}m}, \quad C_{dc} = \frac{(I_0)}{2\omega V_{dc\,p-p}} \quad \text{and} \quad L_r = \frac{\sqrt{3}mV_{dc}}{12af_s i_{cr(p-p)}}$$

(11)

where output voltage ($V_0$)= 200 volts , Source rms voltage ($V_s$)=230 volts, DC link voltage ($V_{dc}$) =750 volts, DC link capacitance ($C_{dc}$)= 1500μF, AC inductance ($L_r$)= 10mH, Over-loading factor (a)= 1.2, Modulation index ($m$)= 0.8, Ripple filter parameters ($R_f$ and $C_f$)= 5Ω and 5μF.

### Simulation Diagram of Proposed Model

The simulation diagram of proposed model is given in Fig. 3. This model is developed in MATLAB environment with simulink and sim-power system tool-box. The source consists of 3-phase AC with neutral with non-linear load. DSTATCOM consists of 8 IGBTs anti-parallel with diodes. The simulation diagram for SRF control approach is given in Fig.4.

## V. RESULTS AND DISCUSSION

Figs.5 (a-c) show the harmonic spectra of the supply current, Load current and supply voltage and it is observed that the THD level of supply current and voltage is well within 5% as per given IEC norms and regulation. Fig. 8 shows the behavior of the proposed model for the given steady state conditions and the performance of the DSTATCOM for load balancing and neutral current compensation. It is observed that the load balancing and harmonics are eliminated soon after the starting of the simulation within 0.06s. The plot shows the supply voltage, Input current, DSTATCOM current DC bus voltage, supply and load neutral current, output voltage and output current with respect to time. It is observed from the plot that the DC bus voltage of the filter reaches its calculated value of 750 volts within 0.1s of the starting of the simulation and the source currents follow the voltage as per computed result with the power factor of 0.2295.

## VI. CALCULATION OF PERFORMANCE PARAMETERS

The following Table I show the performance parameters viz. Total Harmonic Distortion (THD), Crest Factor (CF) and rms value of AC mains current and load current respectively. With the help of these parameters Displacement Power Factor (DPF), Distortion Factor (DF) and Power Factor (PF) has been calculated.

The various operating formulae used to calculate these parameters are described below:

$$Distortion\,Factor(DF) = \frac{1}{\sqrt{1+THD_i^2}}$$ and

$$Displacement\,Power\,Factor(DPF) = \frac{Power.Factor}{DF} \quad (14)$$

The active and reactive power has been calculated and the results have been obtained as follows:
Input active power ($P_i$): 2001W, Input reactive power ($Q_i$): 43.32 VAR, Output active power ($P_0$): -622.5W and Output reactive power ($Q_0$): 2863 VAR, Voltage rating of DSTATCOM ($V_c$): 600 volts, Current rating of DSTATCOM: 10.63A, VA rating of DSTATCOM: 6378 VA.

## VII. CONCLUSION

The simulation of 3-phase, 4-wire, 4-leg VSI based AC shunt DSTATCOM for reducing harmonic current of a three single phase AC voltage controllers having RL load has been carried out here. The DSTATCOM has been controlled by using Synchronous reference frame (SRF) theory. The harmonic current has been successfully mitigated and voltage has been fairly regulated. The DC bus voltage has been regulated to its reference value. The proposed topology and control theory has been found effective for the load compensation and neutral current elimination.

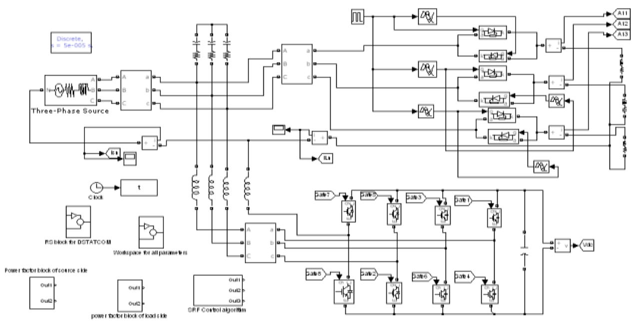


**Figure 2.** MATLAB modeling of DSTATCOM system

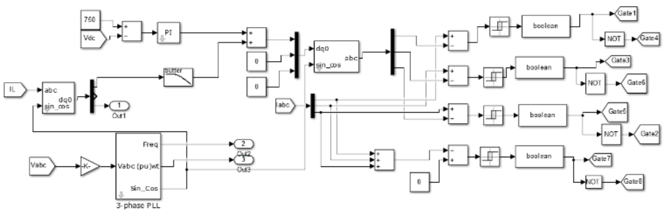
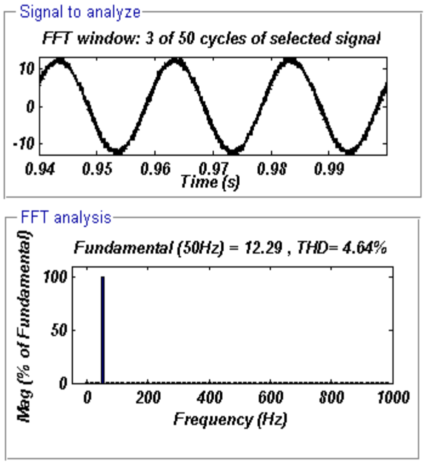
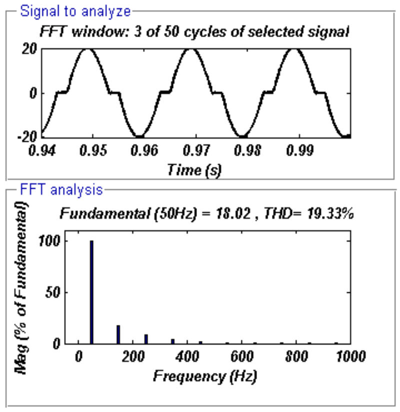


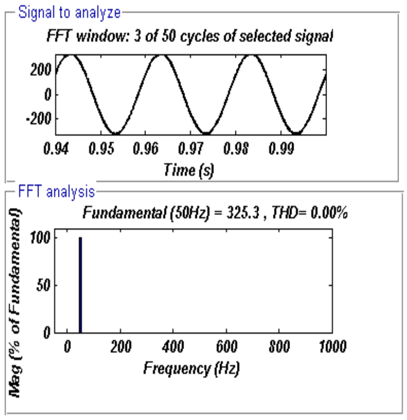
**Figure 3.** SRF theory implementation for switching control




(a)




(b)




(c)

**Figure 3.** THD of (a) Input AC current (b) load current (c) AC mains voltage

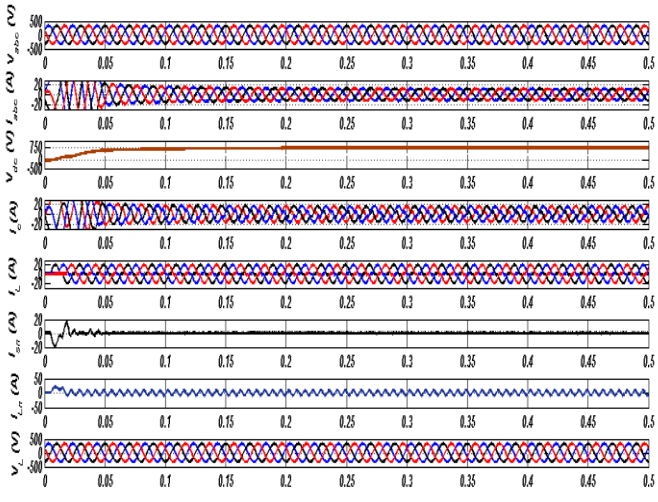


**Figure 4.** Performance of DSTATCOM in proposed model for load balancing and neutral current elimination

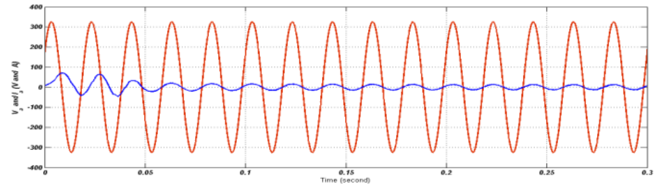


**Figure 5.** Fundamental component of input voltage and Input current

TABLE I. PERFORMANCE PARAMETERS OF CIRCUIT

| | AC main current ($I_s$) | AC load current ($I_L$) |
|---|---|---|
| **$THD_i$ (%)** | 4.64 | 19.33 |
| **CF** | 1.41 | 1.40 |
| **rms value** | 8.715 | 12.85 |
| **DF** | 0.9989 | 0.9818 |
| **PF** | 0.9015 | 0.2991 |
| **DPF** | 0.9024 | 0.3046 |

## VIII. APPENDIX

Three-phase, 4-wire AC voltage source with $V_{rms}$=230 volts, 50 Hz; Load: 3 single-phase AC voltage controller with RL load having R=3Ω, L=20mH, DSTATCOM parameters: Interfacing Inductance ($L_r$)= 15mH, Ripple filter resistance ($R_f$)=5Ω, Ripple filter capacitance ($C_f$)=5μF, Gains for PI controller for DC bus voltage regulation: $K_i$=0.5, $K_p$=0.1, pass-band frequency of LPF (DC bus)= 10 Hz.

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