Modeling and Control of DSTATCOM using adaptive hysteresis band current controller in Three-Phase Four-Wire Distribution systems

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***Abstract*— In this paper a three phase four wire Distribution Static Compensator (DSTATCOM) is proposed for power quality improvement. DSTATCOM is controlled to compensate reactive power, harmonic current, neutral current and unbalances in the load. The control algorithm extracts reference currents and generates gate pulses for IGBT switches by PWM technique. An adaptive hysteresis band current controller is proposed to control the hysteresis bandwidth according to the modulation frequency, supply voltage, DC capacitor voltage and slope of the reference compensator current wave. The performance of three phase four wire system with DSTATCOM is validated for harmonic elimination and balancing of loads by using simulation models in MATLAB /SIMULINK.**

***Keywords*—DSTATCOM; Hysteresis band current controller; Neutral current compensation; Power quality**

I. INTRODUCTION

Due to advances in solid state power conversion technology, there is a tremendous increase in linear and non-linear loads. The increasing consumption of the nonlinear loads e.g. rectifiers, power electronic converters cause various unexpected events in the power system. These loads draw currents with the lag power factor, and rise harmonics and reactive power in an electric power supply. This behavior leads to a voltage distortion and affects on other loads connected to the same point. Also, this situation becomes worse when excessive current passes through the neutral wire in three-phase four-wire distribution systems because of unbalanced loads. The above mentioned distortions are known as the most important power quality problems. These power quality problems may cause abnormal operations of facilities or even trip protection devices. Hence, the maintenance and improvement of electric power quality has become an important scenario today. In the past two decades, power electronic converters based devices e.g. active power filters and custom power devices have been extensively developed [1], [2].

A Distribution static compensator (DSTATCOM) is used for reactive power compensation, load balancing and harmonic elimination in the distribution system [3].

The performance of DSTATCOM depends on controlling algorithms used for the extraction of reference current components and generating gating pulses for switches. Control schemes such as instantaneous reactive power theory [4], [5], synchronous reference frame theory [6] and artificial neural network theory [7] for generating of reference currents are available in the literature. Modified modified power balanced theory is employed for control purpose in this paper[8]. Different topologies are presented for three-phase four-wire DSTATCOM such as four leg voltage source converter (VSC) topology [9], capacitor midpoint VSC topology [10] and H Bridge VSC topology [11]. Here, a four leg voltage source converter configuration is chosen as DSTATCOM because of less complex and more reliable control and efficient compensation of neutral wire current [12].

In this paper, the hysteresis current controller is used to achieve a significant compensation with fast control capabilities. Hysteresis band current controller PWM method has been widely used because of its simplicity comparing to the other PWM techniques. In addition to fast response and peak current limiting capabilities, this technique doesn't require precise knowledge of the system parameters. Despite of the above mentioned advantages, a disadvantage of a conventional hysteresis band current controller is that the switching frequency varies within a band and increases switching losses in the system. To avoid this limitation an adaptive band hysteresis current controller is proposed. This controller can be programmed to optimize the performance of the switching device as a function of the load and source parameters. This optimization will cause a considerable reduction in switching losses [13].

In this paper, a four leg three phase four wire DSTATCOM under non-sinusoidal supply condition is

978-1-4799-3479-9/14/$31.00 ©2014 IEEE

investigated. The performance of Dstatcom is controlled by modified power balanced theory and adaptive hysteresis band current controller. All simulations have been performed by Matlab software and the results show the effectiveness of the proposed control systems.

II. SYSTEM CONFIGURATION

Fig. 1 presents the power circuit of the four-leg DSTATCOM connected to the distribution system. The three phase four-wire supply system can be distinguished by the three single phase voltage sources which are connected in a star configuration. DSTATCOM is connected in parallel to the load in order to detect harmonic currents and inject compensating currents identical to the load harmonic currents. Therefore, the current drawn from the power system at the Point of Common Coupling (PCC) will be sinusoidal. A capacitor (C_F) and a resistor (R_F) indicate the ripple filter capacitor and resistor respectively are installed for filtering the high frequency signals of voltage at the PCC. Balanced and unbalanced three phase loads and DSTATCOM are connected at PCC. DSTATCOM consists of a four-leg voltage source converter and a DC capacitor. Midpoint of each leg is connected to the power system through an inductor. DSTATCOM is used for neutral current compensation, harmonic elimination and load balancing [14].

III. CONTROL STRATEGY

Fig. 2 shows the control algorithm based on modified power balance theory. For extracting reference source currents, PCC voltages (V_a, V_b, and V_c), source currents (i_{sa}, i_{sb} and i_{sc}), load currents (i_{La}, i_{Lb} and i_{Lc}) and DC bus voltage (V_{dc}) of the DSTATCOM are sensed in this algorithm. The amplitude of the PCC voltage is calculated as (1),

$$V_t = \sqrt{2\left(v_{sa}^2 + v_{sb}^2 + v_{sc}^2\right)/3} \tag{1}$$

Unit templates in phase with PCC voltages are estimated as (2),

$$u_{sap} = v_a / V_t;\; u_{sbp} = v_b / V_t;\; u_{scp} = v_c / V_t \tag{2}$$

Unit templates in quadrature with the PCC voltage are,

$$\begin{aligned} u_{saq} &= \left(-u_{sbp} + u_{scp}\right)/\sqrt{3} \\ u_{sbq} &= \left(u_{sap}\sqrt{3} + u_{sbp} - u_{scp}\right)/2\sqrt{3} \\ u_{scq} &= \left(u_{sap}\sqrt{3} + u_{sbp} - u_{scp}\right)/2\sqrt{3} \end{aligned} \tag{3}$$

Instantaneous active and reactive powers of the load are as (4),

$$\begin{aligned} p_L &= V_t\left(u_{sap} i_{La} + u_{sbp} i_{Lb} + u_{scp} i_{Lc}\right) \\ q_L &= V_t\left(u_{saq} i_{La} + u_{sbq} i_{Lb} + u_{scq} i_{Lc}\right) \end{aligned} \tag{4}$$

The active power component of the source currents (I_{sm}^*) has two parts. First one is I^*_{smp}, which is required DC component of the load active power and second one is I^*_{smd} which is required for the self supporting DC bus of DSTATCOM. The active component of the load current I^*_{smp} and I^*_{smd} can be expressed as (5) and (6):

$$I_{smp}^* = \left(\frac{2}{3}\right) \overline{p}_{lav} / V_t \tag{5}$$

$$I_{smd}^* = K_{pd} V_{dce} + K_{id} \int V_{dce}\, dt \tag{6}$$

Where $V^*_{dce} = V^*_{dc} - V_{dc}$ = error in DC bus voltage. V^*_{dc} and V_{dc} are the reference voltage and sensed filtered voltage of DC bus of DSTATCOM respectively. K_{pd} and K_{id} are the proportional and integral gains of the PI controller over the DC bus voltage of DSTATCOM given in (6).

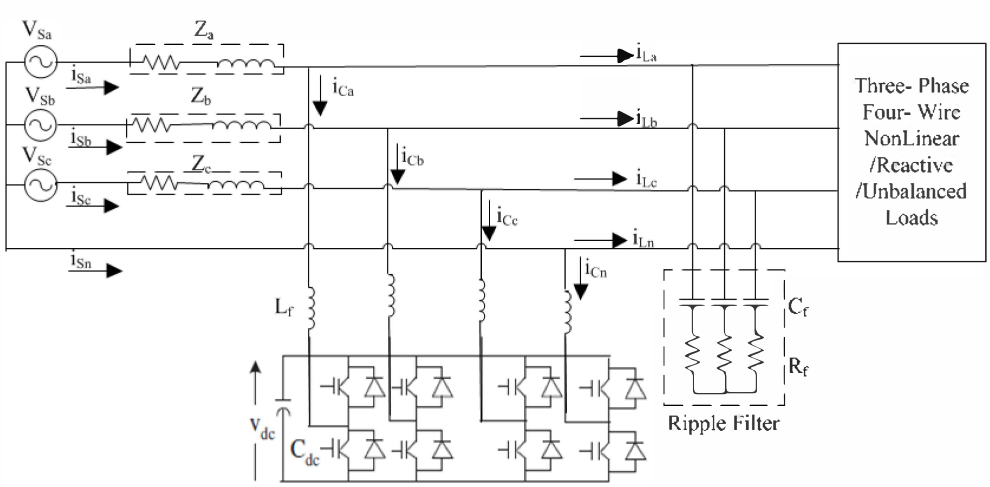

Fig. 1. Schematic diagram of four-wire DSTATCOM connected distribution system

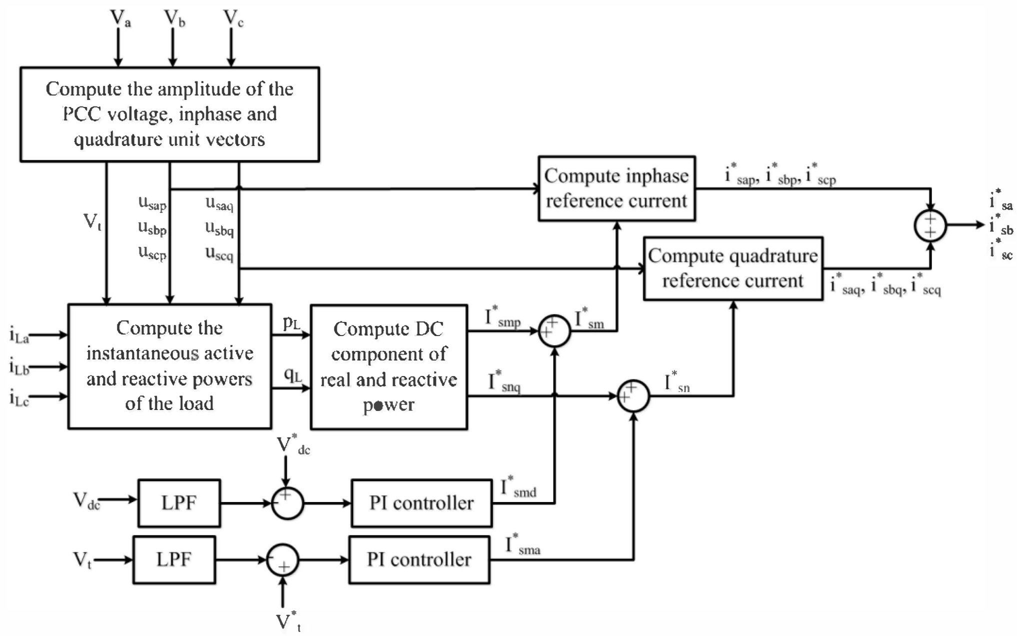

Fig. 2. Block diagram of extracting reference source currents using Power Balance Theory based controller

The amplitude of the active component of reference source currents I^*_{sm} is,

$$I^*_{sm} = I^*_{smd} + I^*_{smp} \tag{7}$$

Three phase active power component of the reference source currents are as (8),

$$i^*_{sap} = I^*_{sm}u_{sap};\ i^*_{sbp} = I^*_{sm}u_{sbp};\ i^*_{scp} = I^*_{sm}u_{scp} \tag{8}$$

Moreover, the reactive component of the source current has also two parts. First one is I^*_{snq}, which is required DC component of the load reactive power and second one is I^*_{sna} which is required for maintaining the amplitude of the PCC voltage. The amplitude of the reactive component of the load current I^*_{snq} can be given as (9),

$$I^*_{snq} = \left(\frac{2}{3}\right)\bar{q}_{lav} / V_t \tag{9}$$

The amplitude of reactive component I^*_{sna} required for regulating the amplitude of the PCC voltage can be given as (10),

$$I^*_{sna} = K_{pa}V_e + K_{ia}\int V_e dt \tag{10}$$

Where $V_e = V^*_t - V_t$ = error in amplitude of the PCC voltage. V^*_t and V_t are reference voltage and the amplitude of PCC voltage respectively. K_{pa} and K_{ia} are proportional and integral gains of the PI controller over the PCC voltage given in (10). The amplitude of the reactive power component of the reference source currents I^*_{sn} is as (11),

$$I^*_{sn} = I^*_{sna} + I^*_{snq} \tag{11}$$

Where I^*_{sna} is the output of the AC voltage PI controller and it is required to regulate the PCC voltage at load terminals. Three phase reactive power component of the reference source currents are as (12),

$$I^*_{saq} = I^*_{sn}u_{saq};\ I^*_{sbq} = I^*_{sn}u_{sbq};\ I^*_{scq} = I^*_{sn}u_{scq} \tag{12}$$

Total three phase reference source currents are obtained as,

$$i^*_{sa} = i^*_{sap} + i^*_{saq};\ i^*_{sb} = i^*_{sbp} + i^*_{sbq};\ i^*_{sc} = i^*_{scp} + i^*_{scq} \tag{13}$$

These extracted reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) and the respective sensed source currents (i_{sa}, i_{sb}, and i_{sc}) are compared respectively and the current error is amplified and used in the current controller to generate the switching signals for the DSTATCOM. The supply neutral current is computed as (14):

$$i_{sn} = i_{sa} + i_{sb} + i_{sc} \tag{14}$$

The reference current of the supply neutral current is taken as (15):

$$i^*_{sn} = 0 \tag{15}$$

IV. ADAPTIVE HYSTERESIS BAND CURRENT CONTROLLER

The hysteresis band current controller technique is suitable for all applications of the voltage source converter in permanent magnet machines, grid connected systems and active power filters. The hysteresis band current controller responses are fast and accurate[15].

On the other hand, the hysteresis technique has several undesirable features, such as the asymmetrical switching frequency which causes acoustic noise and difficulty in designing input filters. The conventional hysteresis band current controller scheme used for the control of DSTATCOM line current is shown in Fig. 3 and the adaptive hysteresis bandwidth calculation diagram is shown in 4. DSTATCOM reference line current is referred to i^*_{ca} and the actual line current is referred to i_{ca}. The hysteresis band current controller determines the switching pattern of DSTATCOM. However, this method results in switching losses. To overcome these deficiencies, an adaptive band is incorporated in the system. This adaptive band programs the hysteresis band as a function of system parameters and maintains the modulation frequency to nearly constant. Equation (16) expresses the adaptive hysteresis logic:

$$HB = \left\{ \frac{0.125 * V_{dc}}{f_c L} \left[1 - \frac{4L^2}{V_{dc}^2} \left(\frac{v_s}{L} + \frac{di^*_{ca}}{dt} \right)^2 \right] \right\} \qquad (16)$$

Where f_C is the modulation frequency, L is the interfacing inductance and ($\frac{di^*_{ca}}{dt}$) is the slope of the reference current. The adaptive hysteresis band current controller changes the hysteresis bandwidth according to the DC capacitor voltage and the slope of the reference compensator current to minimize the effect of distortion in the current wave [16].

V. SIMULATIONS AND RESULTS

DSTATCOM performance for reactive power compensation, harmonic elimination, load balancing and neutral current compensation is investigated. The modified power balanced theory is studied for generating reference current. Moreover, an adaptive hysteresis band current controller is also investigated in order to generate the gate signals of DSTATCOM switches. The presented simulation results were obtained by using Matlab-Simulink for a three-phase four-wire power distribution system with a four-leg DSTATCOM. The required data for simulation purposes are given in the appendix.

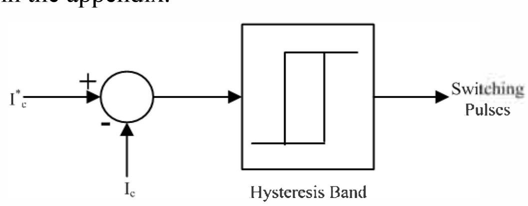

Fig. 3. Conventional hysteresis band current controller

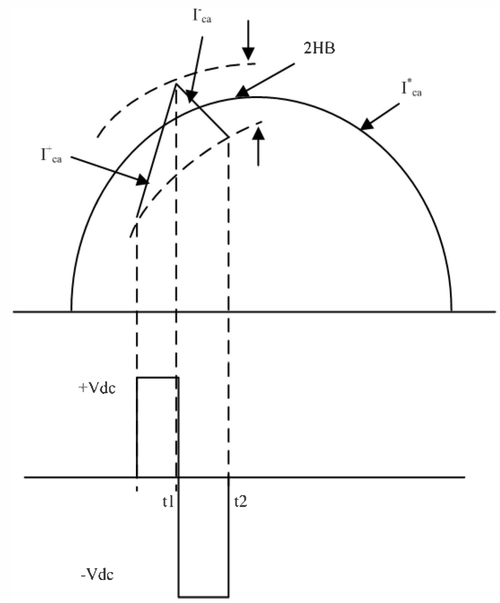

Fig. 4. Current and voltage waves with hysteresis band current controller

The three-phase thyristor rectifier and single-phase diode rectifier nonlinear loads are connected to the power system, in order to produce an unbalance, harmonic and reactive current in the phase currents and zero-sequence harmonics in the neutral current. The 4-leg DSTATCOM is switched on 0.15 s later. After 0.2 s, a single-phase diode bridge rectifier load is connected to phase "c" to evaluate the dynamic performance of the 4-leg DSTATCOM. Firing angle of 3-phase thyristor rectifier is $\alpha=30°$ and RL load is connected on the DC side. DC side of single-phase diode rectifiers is connected to RC load. The comprehensive simulation results are discussed below.

Fig. 5 shows the dynamic performance of the DSTATCOM using modified power balanced control strategy and adaptive hysteresis band current controller for harmonic current filtering and load current balancing. The PCC voltages, load currents (I_L), DSTATCOM injected currents (I_C), source currents (I_S) and DC bus voltage (V_{dc}) is shown in Fig. 5. Three-phase source currents are balanced and sinusoidal after compensation. It is also found that the DC bus voltage of DSTATCOM is able to maintain close to the reference value under all disturbances.

The load neutral current (I_{Ln}), DSTATCOM neutral current (I_{Cn}), source neutral current (I_{Sn}) are shown in Fig. 6. The neutral current is successfully compensated and the supply neutral current is observed at nearly zero which verifies the proper compensation of DSTATCOM.

The reactive power compensation simulation results with the proposed control method are shown in Fig. 7. Since reactive power compensation performance of the four-leg DSTATCOM is shown clearly, load and source current are enlarged to two times in phase "c". Compensated source currents are in phase with three-phase PCC voltages.

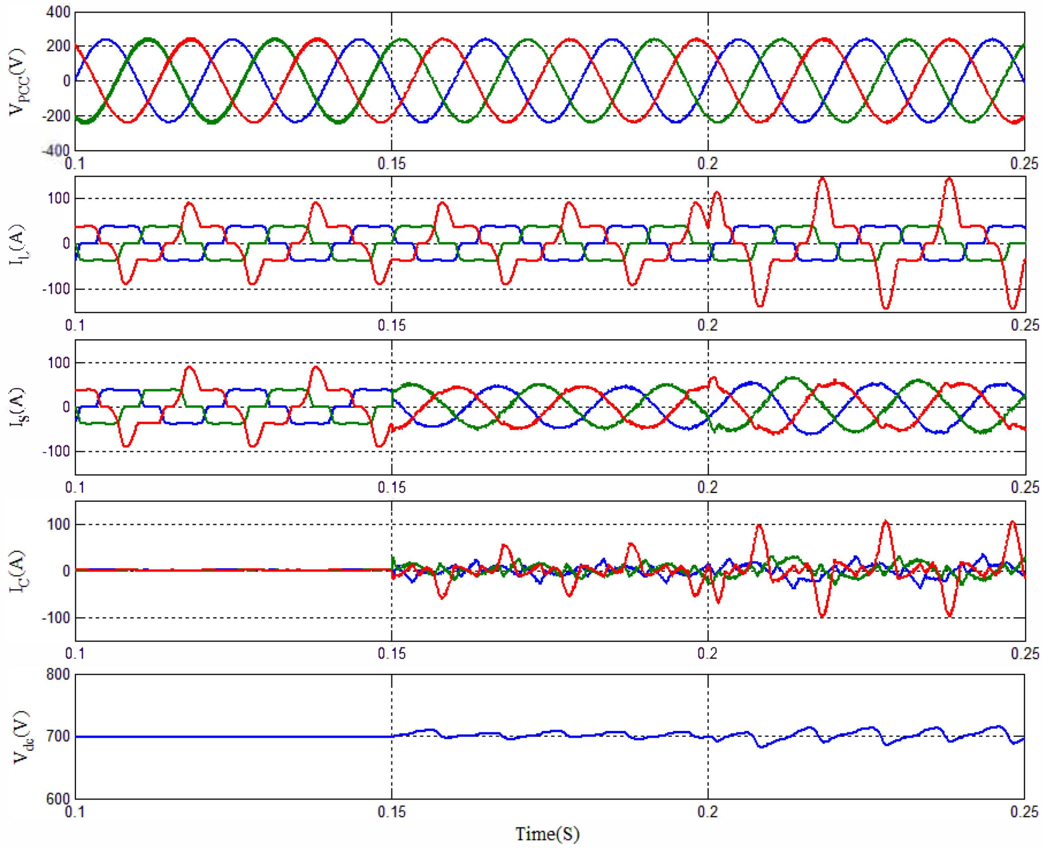

Fig. 5. Harmonic current filtering and load current balancing simulation results using DSTATCOM

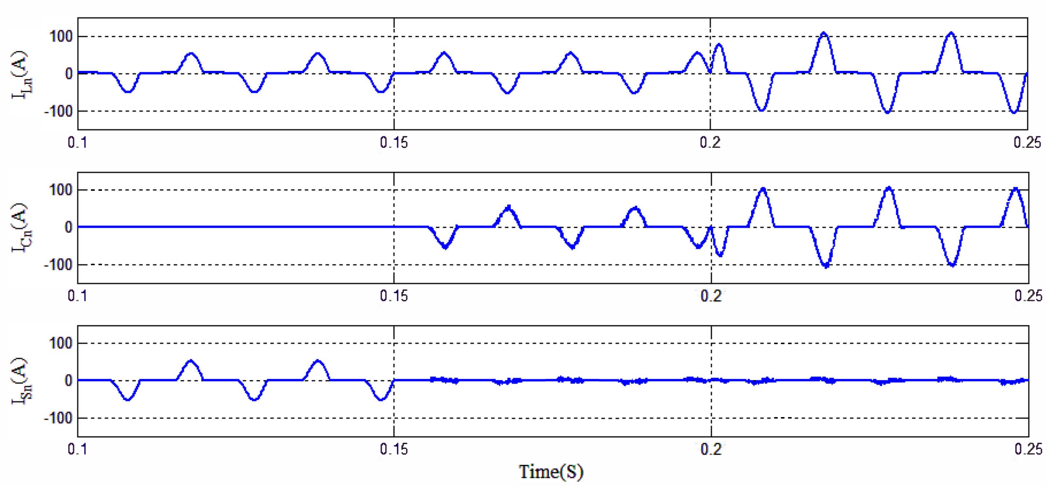

Fig. 6. Neutral current elimination simulation results using DSTATCOM

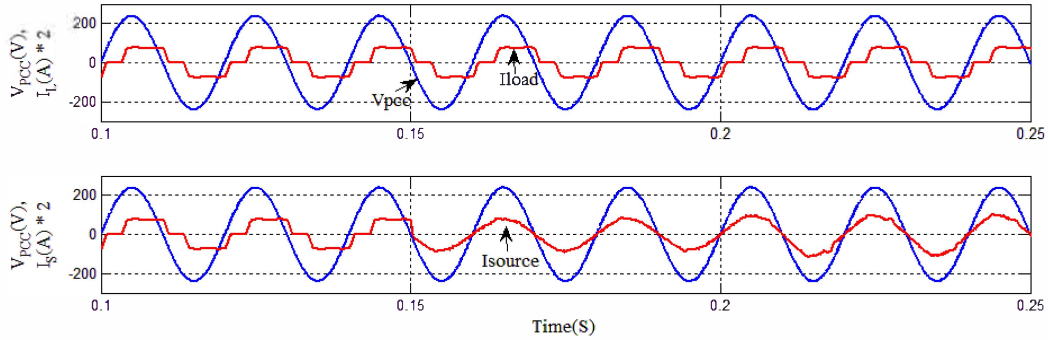

Fig. 7. Reactive power compensation simulation results using DSTATCOM

Harmonic spectra of i_{Lc} load and i_{Sc} source current is shown in Fig. 8. It can be seen that the THD value at phase C load current is 39.98%, while the THD value of phase C source current with proposed control theory decreases to 3.53%.

Detailed summary of load currents, source currents and their total harmonic distortion (THD) levels are shown in Table 1.

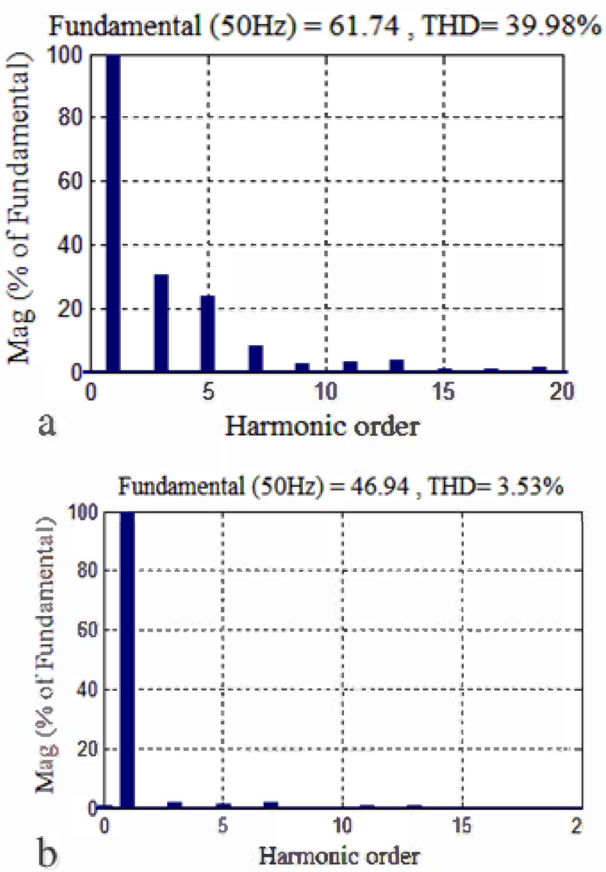

Fig. 8. Harmonic spectra of (a) i_{Lc} load current and (b) i_{Sc} source current

TABLE I. THD% OF THE LOAD AND SUPPLY CURRENT

Three phases	THD% of Load currents		THD% of the Source currents	
	t < 0.2s	**t > 0.2s**	**0.15 < t < 0.2s**	**t > 0.2s**
THD%				
Phase A	23.9	24.37	3.4	3.64
Phase B	23.97	24.17	3.42	3.78
Phase C	39.98	51.89	3.53	4.29

VI. CONCLUSION

In this paper, a three-phase four-wire and four-leg DSTATCOM control algorithm has been proposed to improve the performance of the four-leg DSTATCOM. The control theory has been presented, which is suitable for four-wire DSTATCOM design under unbalanced and distorted mains voltage. The computer simulation has verified the effectiveness of the proposed control scheme. The simulation results prove that the following objectives have been successfully achieved:

1) Current harmonics filtering

2) Reactive power compensation

3) Balancing load currents

4) Compensation of excessive neutral current

The four-leg inverter based DSTATCOM is found effective to meet IEEE 519-1992 standard recommendations on harmonics. The studied control approach compensates neutral current, reactive power and harmonics as well as unbalanced and reactive current components, and this will be really appreciated by the distribution system.

APPENDIX

Line impedance: R_S=0.01Ω, L_S=50µH

1) Three-phase thyristor rectifier load:

R_{DC}=12 Ω, L_{DC}=20mH

Firing angle=30°

2) Single-phase diode rectifier load:
R_{DC}=15 Ω, L_{DC}=1mH, C_{DC}=470μF
Ripple filter: R_f=5, C_f=5μF
DC bus capacitance: 3000μ F
DC bus voltage: 700 V
AC line voltage: 415 V, 50 Hz.

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