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Conductance Factor Based Control Method for DSTATCOM to Improve Power Quality

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***Abstract*—In this paper a conductance factor based reference current extraction method is presented to control Distribution STAtic COMpensator (DSTATCOM). The proposed control algorithm extract fundamental in phase and quadrature components of load currents using conductance factor and voltage unit vector at Point of Common Coupling (PCC). These fundamentals components are further used to generate reference source currents. The compensator with this control technique makes the system to operate in Unity Power Factor (UPF) mode or Zero Voltage Regulation (ZVR) mode during normal supply conditions, Perfect Harmonic Cancellation (PHC) mode during distorted supply conditions. The performance of the proposed control algorithm is validated with simulation studies using MATLAB/SIMULINK environment.**

***Index Terms*—Distribution STAtic COMpensator (DSTATCOM), Conductance factor, Unity Power Factor (UPF), Zero Voltage Regulation (ZVR).**

I. Introduction

In recent years distribution systems are majorly affected by power quality issues [1]. Power quality is the set of boundaries that allows a system to work in its intended manner without any significant loss in its performance. A DSTATCOM is a shunt active power filter used to compensate the power quality problems caused by unbalanced and non-linear loads. The effect of the compensation by DSATCOM depends on control algorithm [2]. There are several compensation techniques reported in literature [3]–[7]. Instantaneous power balance method assumes loss less active power systems which ignores the converter switching losses and it is not possible to maintain the capacitor voltage constant using this control technique [8]. Instantaneous reactive power (IRP) theory proposed in [9], [10] extracts active and reactive powers form voltages and currents which are converted from 3-φ to 2-φ. The performance of this control algorithm is not satisfactory under non-sinusoidal supply conditions. In Synchronous Reference Frame (SRF) theory dc equivalents of voltages and currents are extracted using parks transformation and low pass filtering. It will create time delay in filtering the dc quantities [11], [12]. In sine multiplication technique real fundamental components of load currents are extracted by integrating the product of a sine wave of supply frequency and the load currents. This method creates time delay due to sampling and integration [13]. 1-φ loads and 3-φ unbalanced loads on a distribution system will allow the flow of neutral current through the source, which cannot be eliminated by using a three leg DSTATCOM. Therefore, a four leg DSTATCOM is used to compensate the neutral current [14], [15].

In this paper, conductance factor based control algorithm for DSTATCOM is proposed, which is used to improve power factor, voltage regulation, load balancing and neutral current compensation. In this control technique, supply current is the sum of fundamental active component of load current and the current required to maintain the capacitor voltage as constant. Such that, there is no necessity to neglect the converter switching losses. Unlike IRP theory, this method will not be effected by the dc component in load current and it will directly work for $1-\varphi$ systems also. The other advantage of this control is, it will also work when there is distortion in supply voltage. Because a state observer is used here to estimate the distortion less unit vectors from PCC voltage [16]–[18].

This paper is organized as follows, configuration of DSTATCOM and its control algorithm is explained in section II using schematic diagram, followed by simulation studies using MATLAB/SIMULINK environment in section III.

II. Configuration of DSTATCOM and Proposed Control Algorithm

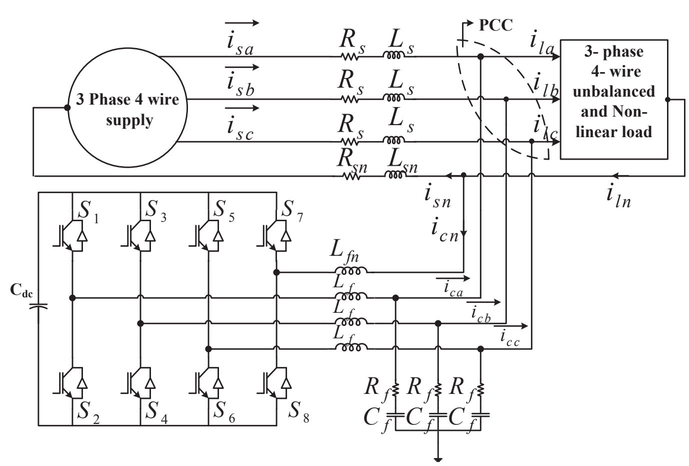

Fig. 1. Schematic diagram of VSC based three-phase DSTATCOM

In this paper a three phase four leg voltage source converter is considered as a DSTATCOM. The block diagram of the DSTATCOM connected distribution system is shown in Fig. 1. The VSC operate like an inverter and generates three

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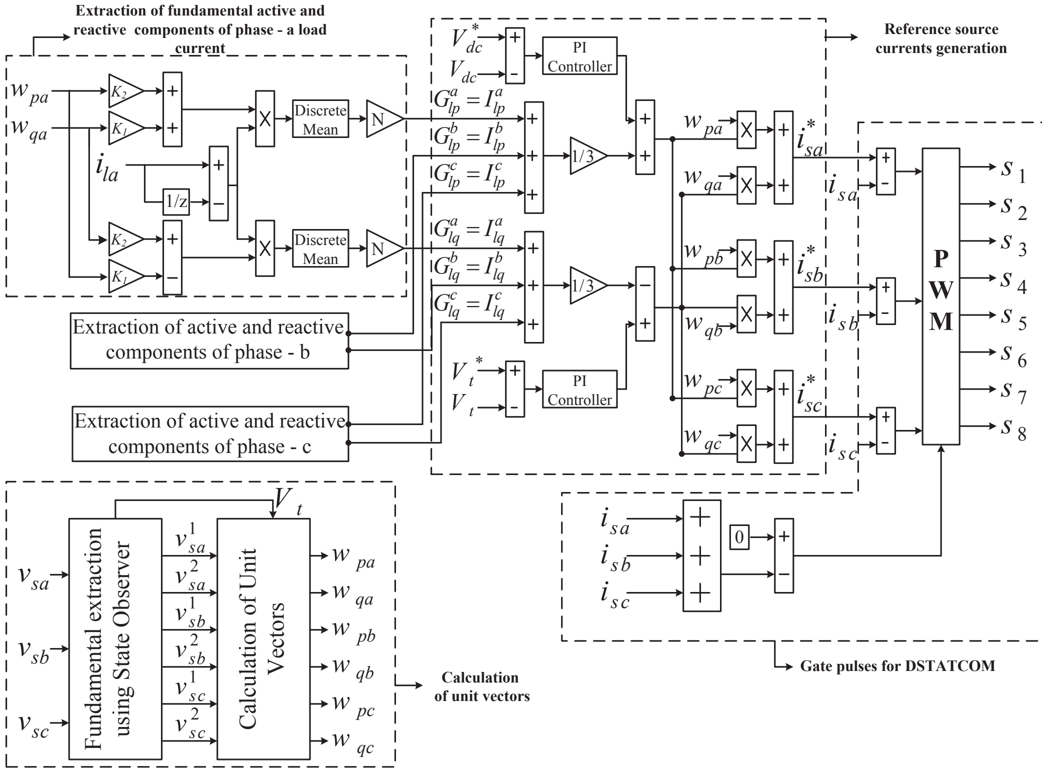

Fig. 2. Proposed Control algorithm for DSTATCOM using Conductance Factor

phase AC output PWM voltages for required compensation. The operation of DSTATCOM will depends upon its control algorithm and its functions will be different for different control algorithms. PCC voltages, load currents are sensed and they are used for the generation of switching pulses for DSTATCOM operation. The schematic diagram for complete control is shown in Fig. 2. Step by step procedure to generate switching pulses using this control algorithm is explained as follows.

A. Calculation of Unit Vectors

Unit vectors are computed using fundamental components of PCC voltage. Fundamental component and its quadrature components are extracted using a state observer. A linear second order observer at frequency ω_1 is shown in Fig. 3. Fundamental component v_1 and its quadrature component v_2 can be represented by

$$\left.\begin{aligned} \dot{v} &= Av + Re(t) \\ y(t) &= C^T v. \end{aligned}\right\} \tag{1}$$

where $A = \begin{bmatrix} 0 & \omega_1 \\ -\omega_1 & 0 \end{bmatrix}, \quad v = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}, \quad C^T = \begin{bmatrix} 1 & 0 \end{bmatrix}.$

$$R = \begin{bmatrix} r_{11} & r_{12} \end{bmatrix}^T. \tag{2}$$

composite constant gain vector R is determined using the specified pole location. After extracting the fundamental components, in-phase unit vectors can be expressed as

$$w_{pa} = \frac{v_{sa1}}{V_t}, w_{pb} = \frac{v_{sb1}}{V_t}, w_{pc} = \frac{v_{sc1}}{V_t}. \tag{3}$$

Similarly, the quadrature unit vectors can be expressed as

$$w_{qa} = \frac{v_{sa2}}{V_t}, w_{qb} = \frac{v_{sb2}}{V_t}, w_{qc} = \frac{v_{sc2}}{V_t}. \tag{4}$$

Here, $v_{sa1}, v_{sb1}, v_{sc1}$ are the fundamental in-phase voltages, $v_{sa2}, v_{sb2}, v_{sc2}$ are the orthogonal components. V_t is amplitude of the individual phase voltage and it is given in (5)

$$V_t = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \tag{5}$$

where v_{sa}, v_{sb}, v_{sc} are the three individual phase voltages at PCC.

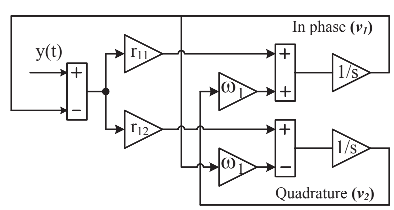

Fig. 3. Fundamental extraction using state observer

B. Extraction of Fundamental Active and Reactive Components of Load Currents using Conductance Factor

Generally non linear load current is the sum of active(i_p), reactive(i_q), harmonic (i^h), and DC components, it is given as

$$i(t) = i_p(t) + i_q(t) + i^h(t) + I_{dc}. \quad (6)$$

Individual load currents in (6) is expressed as

$$\begin{aligned} i_p(t) &= I_{mp} \sin \omega t \\ i_q(t) &= I_{mq} \sin(\omega t - \frac{\pi}{2}) \\ i^h(t) &= \sum_{h=2}^{\infty} I_m^h \sin(h\omega t + \varphi_h) \end{aligned} \quad (7)$$

expressing (6) using PCC voltage

$$i(t) = \frac{v_s(t)}{R} + \frac{1}{L}\int v_s(t)dt + i^h(t) + I_{dc} \quad (8)$$

From (8) we can define

$$\frac{1}{R} = G \qquad \frac{1}{L} = P \quad (9)$$

To find conductance factor (G) take the derivative of (8) using trapezoidal rule over N consecutive intervals.

$$i_j - i_{j-1} = G(v_j - v_{j-1}) + \frac{T_s}{2}(v_j + v_{j-1})P + (i_j^h - i_{j-1}^h) \quad (10)$$

where $j = 1, 2, 3, ..., N-1, N$. T_s represents the step size, $i_j = i(t_j)$, $i_j^h = i^h(t_j)$,$v_j = v_s(t_j)$. Expressing (10) in matrix form

$$\begin{bmatrix} v_1 - v_0 & \frac{T_s}{2}(v_1 + v_0) & i_1^h - i_0^h \\ \vdots & \vdots & \vdots \\ v_N - v_{N-1} & \frac{T_s}{2}(v_N + v_{N-1}) & i_N^h - i_{N-1}^h \end{bmatrix} \begin{bmatrix} G \\ P \\ 1 \end{bmatrix} = \begin{bmatrix} i_1 - i_0 \\ \vdots \\ i_N - i_{N-1} \end{bmatrix} \quad (11)$$

The above equation is similar to $AX = B$, then compute G using

$$X = (A^T A)^{-1} A^T B \quad (12)$$

Matrix $(A^T A)$ and $A^T B$ are expressed in (13), (14). From (13) $A^T A$ is a symmetrical matrix. Simplify the individual elements by assuming sinusoidal PCC voltage. It is sufficient to consider sampling window is equal to half of the fundamental cycle because most of the loads consist of only odd harmonics. In other cases like load currents consist of both even and odd harmonics sampling window of one full cycle of supply system will be considered for accurate calculations.

$$A^T B = \begin{bmatrix} \sum_{j=1}^{N} (i_j - i_{j-1})(v_j - v_{j-1}) \\ \left(\frac{T_s}{2}\right) \sum_{j=1}^{N} (i_j^h - i_{j-1}^h)(v_j + v_{j-1}) \\ \sum_{j=1}^{N} (i_j - i_{j-1})(v_j + v_{j-1}) \end{bmatrix} \quad (14)$$

Non diagonal elements of Matrix in (13) will be zero after simplification. Inverse of $A^T A$ is required to calculate the conductance factor, and it is given in (15). Substituting (14), (15) in (12) to find conductance factor.

$$G(t_n) = \frac{\sum_{j=1}^{N} (i_j - i_{j-1})(v_j - v_{j-1})}{\sum_{j=1}^{N} (v_j - v_{j-1})^2} \quad (16)$$

Active and reactive components of load current can be calculated by multiplying conductance factor with instantaneous voltages.

$$i_l^a(t_n) = G(t_n)V(t_n) \quad (17)$$

From (17), if the voltage signal has harmonics, the active current will also have harmonics. Therefore replace voltages in (16), (17) with in-phase voltage unit vectors (w_{pa}) to get the active component of load current without any harmonics. Similarly to get the reactive component of load current replace voltages with orthogonal unit vectors (w_{qa}). Conductance factors for 'a' phase will be given as

$$G_{lp}^a(t_N) = \frac{\sum_{j=1}^{N} (i_j - i_{j-1})(w_{pa(j)} - w_{pa(j-1)})}{\left(w_{pa(j)} - w_{pa(j-1)}\right)^2} \quad (18)$$

$$G_{lq}^a(t_N) = \frac{\sum_{j=1}^{N} (i_j - i_{j-1})(w_{qa(j)} - w_{qa(j-1)})}{\left(w_{qa(j)} - w_{qa(j-1)}\right)^2} \quad (19)$$

Similarly substitute respective unit vectors to find conductance factors for 'b' and 'c' phases. Simplify (18) and (19) using Riemann integral, the simplified equations are given in (20) and (21).

$$G_{lp}^a(t_N) = \sum_{j=1}^{N} (i_j - i_{j-1})(w_{qa(j)} * K_1 + w_{pa(j)} * K_2) \quad (20)$$

$$G_{lq}^a(t_N) = \sum_{j=1}^{N} (i_j - i_{j-1})(w_{pa(j)} * K_1 - w_{qa(j)} * K_2) \quad (21)$$

where $K_1 = \frac{\cos(\omega T_s/2)}{N \sin(\omega T_s/2)}$, $K_2 = \frac{1}{N}$

$$A^T A = \begin{bmatrix} \sum_{j=1}^{N} (v_j - v_{j-1})^2 & \left(\frac{T_s}{2}\right) \sum_{j=1}^{N} (v_j^2 - v_{j-1}^2) & \sum_{j=1}^{N} (v_j - v_{j-1})(i_j^h - i_{j-1}^h) \\ \left(\frac{T_s}{2}\right) \sum_{j=1}^{N} (v_j^2 - v_{j-1}^2) & \left(\frac{T_s}{2}\right) \sum_{j=1}^{N} (v_j + v_{j+1})^2 & \left(\frac{T_s}{2}\right) \sum_{j=1}^{N} (v_j + v_{j+1})(i_j^h - i_{j-1}^h) \\ \sum_{j=1}^{N} (v_j - v_{j-1})(i_j^h - i_{j-1}^h) & \left(\frac{T_s}{2}\right) \sum_{j=1}^{N} (v_j + v_{j+1})(i_j^h - i_{j-1}^h) & \sum_{j=1}^{N} (i_j^h - i_{j-1}^h)^2 \end{bmatrix} \quad (13)$$

$$(A^TA)^{-1} = \begin{bmatrix} \frac{1}{\sum_{j=1}^{N}(v_j - v_{j-1})^2} & 0 & 0 \\ 0 & \frac{4}{T_s^2\sum_{j=1}^{N}(v_j + v_{j-1})^2} & 0 \\ 0 & 0 & \frac{1}{\sum_{j=1}^{N}(i_j^h - i_{j-1}^h)^2} \end{bmatrix} \quad (15)$$

Multiply w_{pa} with (20) to get fundamental active component of load current, w_{qa} with (21) to get fundamental reactive component of load current.

$$i_{lp}^a(t_N) = G_{lp}^a(t_N) * w_{pa}$$
$$i_{lq}^a(t_N) = G_{lq}^a(t_N) * w_{qa}. \quad (22)$$

In general, fundamental component of load current can be represented as

$$i_{lp}^a(t_N) = I_{lp}^a * w_{pa}$$
$$i_{lq}^a(t_N) = I_{lq}^a * w_{qa}. \quad (23)$$

Where I_{lp}^a, I_{lq}^a are amplitudes of fundamental active and reactive components of load currents. By comparing (22) and (23) conductance factor is same as fundamental component of load current, i.e,

$$I_{lp}^a = G_{lp}^a(t_N) \qquad I_{lq}^a = G_{lq}^a(t_N)$$
$$I_{lp}^b = G_{lp}^b(t_N) \qquad I_{lq}^b = G_{lq}^b(t_N)$$
$$I_{lp}^c = G_{lp}^c(t_N) \qquad I_{lq}^c = G_{lq}^c(t_N). \quad (24)$$

To make source currents balanced and sinusoidal, Fundamental component of load current will be considered as average of three phase load currents.

$$I_{lp} = \frac{I_{lp}^a + I_{lp}^b + I_{lp}^c}{3}$$
$$I_{lq} = \frac{I_{lq}^a + I_{lq}^b + I_{lq}^c}{3}. \quad (25)$$

C. Reference Source Current Generation

Case i : **UPF mode of operation**

DSTATCOM operates in UPF mode to make the source current sinusoidal and unity power at PCC. In this mode, source will supply only active component of load currents. The active component source current is the sum of fundamental active component of load current, current required to maintain capacitor voltage as constant. Voltage across capacitor is measured and compared with the reference value and the error is given to a PI controller. Output of PI controller is added with fundamental active component of load current to get reference source current.

$$I_s^p = I_{lp} + I_c. \quad (26)$$

Where I_c is output of capacitor voltage PI controller. During UPF operation source has to send only active component of load current. Hence, reference source currents will be given as

$$i_{sa}^* = I_s^p \times w_p^a \qquad i_{sb}^* = I_s^p \times w_p^b \qquad i_{sc}^* = I_s^p \times w_p^c \quad (27)$$

Case ii : **ZVR mode of operation**

PCC voltage is not at its rated value because of feeder impedance. DSTATCOM should be operate in ZVR mode to make the value as rated. To achieve this the reactive component of source current will be the difference between current required to maintain rated voltage, fundamental reactive component of load current. The difference between the measured voltage and reference voltage is given to a PI controller and it is used to estimate the current required to maintain rated PCC voltage. The reactive power component of source current will be given as

$$I_s^q = I_{PCC} - I_{lq} \quad (28)$$

Where I_{PCC} is output of the PCC voltage PI controller. In ZVR mode the reference source currents can be expressed as

$$i_{sa}^* = (I_s^p \times w_p^a) + (I_s^q \times w_q^a)$$
$$i_{sb}^* = (I_s^p \times w_p^b) + (I_s^q \times w_q^b)$$
$$i_{sc}^* = (I_s^p \times w_p^c) + (I_s^q \times w_q^c) \quad (29)$$

In, in-direct control error between Reference source currents and actual source currents has given to a PWM generator to generate gate pulses for 3 legs. Fourth leg of DSTATCOM is used to compensate source neutral current. To achieve this source neutral current is compared with zero and the error is used to switch the fourth leg of DSTATCOM.

III. Simulation Studies

Various parameters of distribution system and DSTATCOM are mentioned in Table 1. Simulation studies are carried out for UPF, ZVR and Perfect harmonic elimination (PHC) modes under balanced and unbalanced load conditions. During 0 to 0.3 s balanced load is connected to the distribution system then it is switched to unbalanced load at 0.3 s. The peak values of balanced load currents are 32.58 A with 15.05 % THD. During unbalanced load the load currents are changed to 50.26 A, 46.06 A, 58.6 A respectively. THD spectra of all the load currents during balanced and unbalanced load conditions are shown in Fig. 4.

Case i : **UPF mode**

In this mode of operation, compensator will make source current sinusoidal and in-phase with the voltages at PCC which is shown in Fig. 5. During balanced load condition, the source

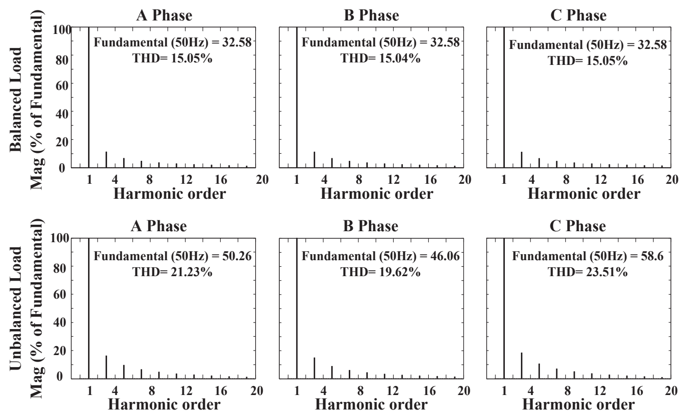

Fig. 4. THD spectra of source currents for balanced and unbalanced load without DSTATCOM

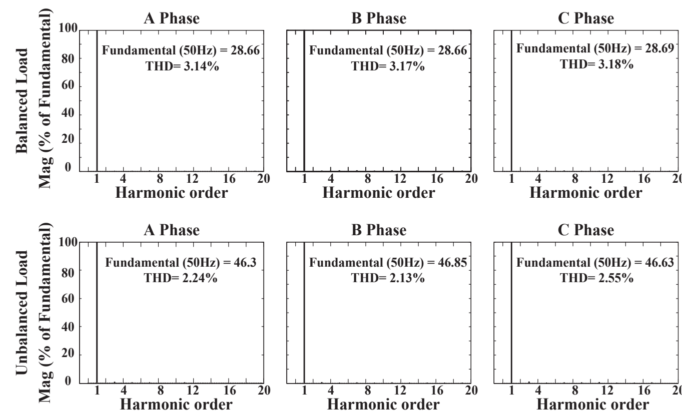

Fig. 6. THD spectra of source currents for balanced and unbalanced load during UPF mode

TABLE I
SYSTEM PARAMETERS

Parameter	Value
System voltage	415 (L-L) V
feeder impedance	$(0.07 + j0.6283)\ \Omega$
Interfacing Inductor	3.5 mH
Ripple Filter	$5\ \Omega$, 10μF
DC link voltage	700 V
DC capacitor	7000 μF
Composite constant gain vector	$r_{11} = 62.8$ $r_{12} = 3.14$
Linear load	10 kVA , 0.8 PF
Non linear load (Three phase diode bridge rectifier)	$(15 + j31.4)\Omega$
Non linear load (Three single phase diode bridge rectifiers)	$(15 + j31.4)\Omega$ $(20 + j31.4)\Omega$ $(10 + j31.4)\Omega$

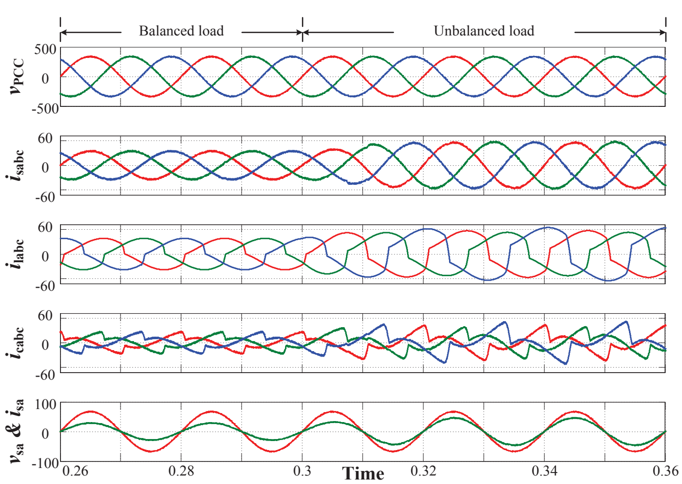

Fig. 5. Dynamic operation during UPF mode

current THDs are 3.14%, 3.17% and 3.18% respectively. During unbalanced load conditions source will send equal amount of load currents with THDs 2.24%, 2.13% and 2.55% respectively. THD spectra of source current under balanced and unbalanced load conditions are shown in Fig. 6.

Case ii : **ZVR mode**

In this operating mode DSTATCOM will pump extra leading reactive components in addition to load reactive power demand. Fig. 7 shows PCC voltages (v_{PCC}), source currents (i_{sabc}), Load currents (i_{labc}), Compensatror currents (i_{cabc}) respectively. The source currents THDs are 2.97%, 2.98% and

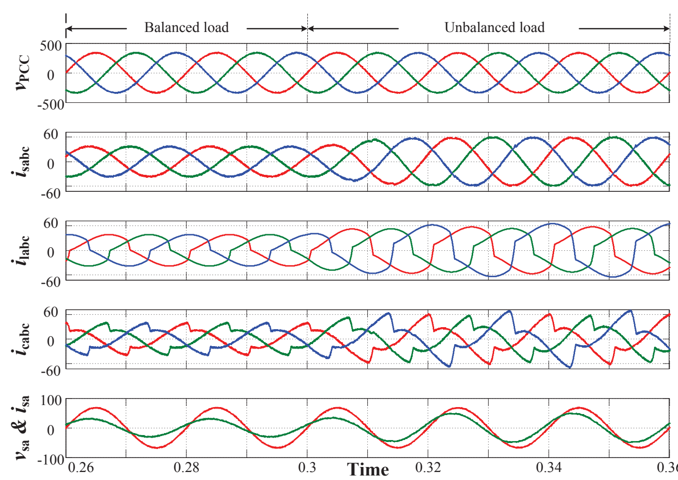

Fig. 7. Dynamic operation during ZVR mode

3.02% respectively during balanced load. During unbalanced load condition the THDs of source currents are 2.21%, 2.12% and 2.42%. THD spectra of source currents under different load conditions are shown in Fig. 8.

Case iii : **PHC mode**

Using this control method DSTATCOM can maintain sinusoidal source currents during distortions in the supply system also. Because unit vectors are generated here using fundamental components of PCC voltage, so that there is no transfer of distortions from voltage signal to current signal. To evaluate this we are injecting 10% fifth harmonic into the supply system. The THD values of source currents are 2.97%, 2.98%, 3.02% during balanced load condition and 2.21%, 2.12%, 2.42% at the time of unbalanced load condition.

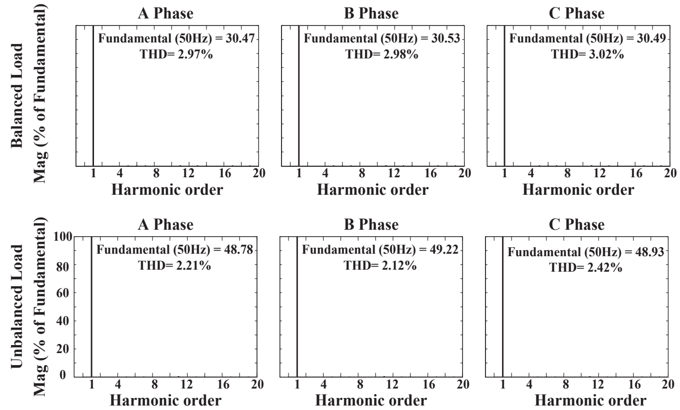

Fig. 8. THD spectra of source current for balanced and unbalanced load during ZVR mode

Using this control technique DSTATCOM drastically reduces the source neutral current which is shown in Fig. 9. THD spectra of source currents is shown in Fig. 10.

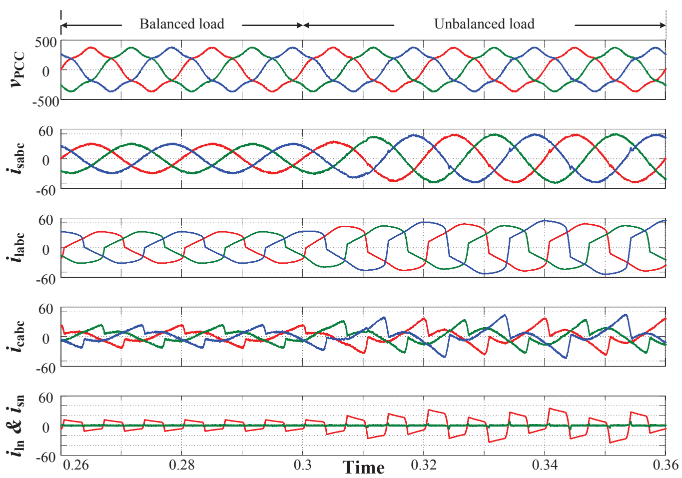

Fig. 9. Dynamic operation during PHC mode

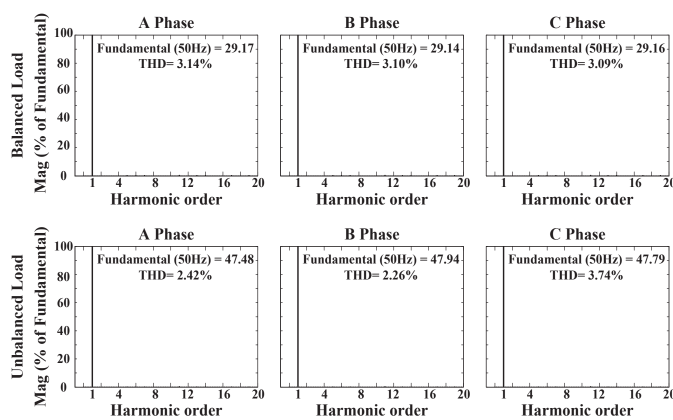

Fig. 10. THD spectra of source current for balanced and unbalanced load during PHC mode

IV. Conclusion

In this paper, a control algorithm for DSATCOM is presented, which is based on conductance factor in generation of reference current. The advantage of this method is, DSTATCOM improves the power quality in the weak system without affecting its performance. Also, the THD's of source currents are within the IEEE 519 standards (*i.e.*, less than 5%) under UPF and ZVR operating modes for balanced and unbalanced load conditions.

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