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Design and control of a DSTATCOM for power quality improvement using cross correlation function approach

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Abstract

This paper presents the design of a three phase DSTATCOM (Distribution Static Compensator) and its control algorithm based on correlation and cross correlation function approach for power quality improvement under linear/ nonlinear loads in a distribution system. In this approach, an extraction of fundamental active and reactive power components of load currents is based on correlation and cross correlation functions in time domain. For estimation of fundamental active and reactive power components of load currents, a numerical integration is applied in correlation and cross correlation function. The DSTATCOM is modeled under linear and nonlinear loads and its performance is simulated in the MATLAB environment using SIMULINK and Sim Power System (SPS) toolboxes. The performance of DSTATCOM is found satisfactory under time varying and unbalanced loads.

Keywords: Correlation and cross-correlation coefficients, DSTATCOM, Power factor correction, Zero voltage regulation.

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1. Introduction

Power quality in distribution systems affects all the connected electrical and electronics equipments. It is a measure of deviations in voltage, current, frequency of a particular system and associated components (Devaraju *et al*, 2010; Fuchs and Mausoum, 2008). In recent years, use of power converters in adjustable speed drives, power supplies etc. is continuously increasing. These equipment draw harmonics currents from AC mains and increase the supply demands (Singh, 2009). These loads can be grouped as linear (lagging power factor loads), nonlinear (current or voltage source type of harmonic generating loads), unbalanced and mixed types of loads. Some of power quality problems associated with these loads include harmonics, high reactive power burden, load unbalancing, voltage variation etc. A survey on power quality problems is discussed for classification, suitable corrective and preventive actions to identify these problems (Saxena *et al*, 2010). A variety of custom power devices are developed and successfully implemented to compensate various power quality problems in a distribution system. These custom power devices are classified as the DSTATCOM (Distribution Static Compensator), DVR (Dynamic Voltage Restorer) and UPQC (Unified Power Quality Conditioner). The DSTATCOM is a shunt-connected device, which can mitigate the current related power quality problems. The power quality at the PCC is governed by standards such as IEEE-519-1992, IEEE-1531-2003 and IEC- 61000, IEC-SC77A etc (Ghosh and Ledwich, 2009; Munoz, 2007; Sankaran, 2001).

The effectiveness of DSTATCOM depends upon the used control algorithm for generating the switching signals for the voltage source converter and value of interfacing inductors. For the control of DSTATCOM, many control algorithms are reported in the literature based on the instantaneous reactive power theory, deadbeat or predictive control (Fuchs and Mausoum, 2008), instantaneous symmetrical component theory (Ghosh and Ledwich, 2009), nonlinear control technique (Rahmani *et al*, 2010), modified power balance theory(Singh and Kumar, 2010), enhanced phase locked loop technique (Sharma and Singh, 2011), addaline control technique, synchronous reference frame control technique (Singh and Solanki, 2009), ANN and fuzzy based controller, SVM based controller (Teke *et al*, 2011), correlation and cross-correlation coefficients based control algorithm (Tanaka

et al, 2007) etc. Other techniques applied in active filters are based on Hilbert transform (Wetula, 2008), soft phase locked loop (Wu *et al,* 2007) and novel hysteresis current controller (Zeng *et al,* 2010) etc. The control algorithm based on cross correlation function approach has been reported for single phase AC system (Tanaka *et al*, 2007). In this paper, this control algorithm based on the correlation and cross correlation function approach is used in a three phase distribution system for compensation of reactive current, harmonics current and load balancing in PFC and ZVR modes of operation of DSTATCOM.

2. Characteristics and Design of DSTATCOM

A DSTATCOM is a device which is used in an AC distribution system where, harmonic current mitigation, reactive current compensation and load balancing are necessary. The building block of a DSTATCOM is a voltage source converter (VSC) consisting of self commutating semiconductor valves and a capacitor on the DC bus (Singh *et al*, 2008). The device is shunt connected to the power distribution network through a coupling inductance that is usually realized by the transformer leakage reactance. In general, the DSTATCOM can provide power factor correction, harmonics compensation and load balancing. The major advantages of DSTATCOM compared with a conventional static VAR compensator (SVC) include the ability to generate the rated current at virtually any network voltage, better dynamic response and the use of a relatively small capacitor on the DC bus. The size of the capacitor does not play an important role in steady-state reactive power generation, which results in a significant reduction of the overall compensator size and cost (Ghosh *et al*, 2002; Padiyar, 2008).

Fig. 1 shows the schematic diagram of a DSTATCOM connected to a three phase AC mains feeding three phase loads. Three phase loads may be a lagging power factor load or an unbalanced load or non-linear loads or mixed of these loads. For reducing ripple in compensating currents, interfacing inductors (L_f) are used at AC side of the voltage source converter (VSC). A small series connected capacitor (C_f) and resistor (R_f) represent the ripple filter installed at PCC in parallel with the loads and the compensator to filter the high frequency switching noise of the voltage at PCC. The harmonics/reactive currents (i_{Cabc}) are injected by the DSTATCOM to cancel the harmonics /reactive power component of the load currents so that the source currents are harmonic free (reduction in harmonics) and load reactive power is also compensated. The rating of the switches is based on the voltage and current rating of the required compensation. For considered load of 35kVA, compensator data are given in Appendix, the rating of the VSC for reactive power compensation/harmonics elimination is found to be 25kVA (15% more reactive current from rated value). The selection of the DC bus voltage, DC bus capacitor, AC inductors and the ripple filter of DSTATCOM are given as,

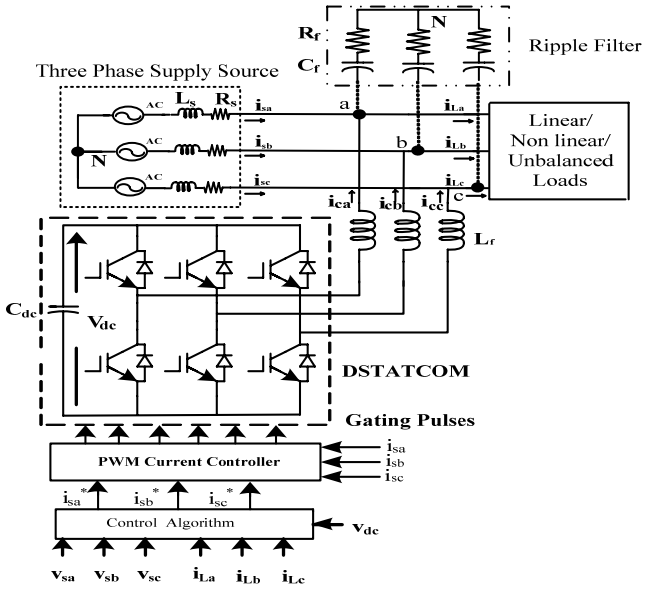


Figure 1. Schematic diagram of DSTATCOM

2.1 DC Bus Voltage

The value of DC bus voltage (V_{dc}) depends on the PCC voltage and its must be greater than amplitude of the AC mains voltage for successful PWM control of VSC of DSTATCOM. For a three-phase VSC, the DC bus voltage is defined as,

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

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 415V using Eq. (1) and it is selected as 700V.

2.2 DC Bus Capacitor

The design of the DC bus capacitor is governed by the depression in the DC bus voltage upon the application of the loads and rise in the DC bus voltage on removal of the loads. Using the principle of energy conservation, the equation governing C_{dc} is as,

$$0.5\, C_{dc} \{(V_{dc}^2)-(V_{dc1}^2)\}=k\{3V_{ph}(a\, I)t\} \quad (2)$$

where, V_{dc} is the nominal DC voltage and V_{dc1} is the minimum voltage level of DC bus, "a" is the over loading factor, V_{ph} is the phase voltage, I is the phase current of the VSC and t is time for which DC bus voltage is to be recovered.
Considering, V_{dc} = 700V, V_{dc1}= 677.69V, V_{ph}= 240V, I= 38.95 A, t= 0.04s, a= 1.2, and value of k factor is varying between 0.05 to 0.15. Using Eq. (2), the calculated value of C_{dc} is found to be 8822.33.69 μF and it is selected as 10000 μF.

2.3 AC Inductor

The selection of the AC inductance depends on the ripple current, i_{crpp} and switching frequency f_s. The AC inductance is given as[Singh *et al*, 2008],

$$L_f = \sqrt{3}mV_{dc}/\{12*a*f_s*i_{crpp)}\} \quad (3)$$

Considering, switching frequency (f_s) of 10kHz, modulation index (m) equal to 1, DC bus voltage (V_{dc}) of 700V, over load factor(a) equal to1.2, and using Eq. (3), the value of AC inductance (L_f) is found 2.15 mH and selected value of L_f is 2.25 mH.

2.4 Ripple Filter

A first order high pass filter shown in Figure 1 tuned at half of the switching frequency is used to filter the high frequency noise from the voltage at the point of common coupling. A capacitor with series resistance is selected as a ripple filter. The value of ripple filter capacitor and resistance are considered as 5μF and 5 Ω respectively. This filter offers high impedance(636.64Ω) at fundamental frequency and low impendence (8.09 Ω) at half of the switching frequency (here 5kHz) which prevents the flow of fundamental components at fundamental frequency in the ripple filter branch and allows the flow of high frequency noises through the ripple filter branch at higher than fundamental frequency.

3. Control Algorithm of DSTATCOM

Figure 2 shows the block diagram of control algorithm of a DSTATCOM based on the correlation and cross correlation function for extraction of reference source currents. Fundamental active and reactive power components of load currents for each phase are derived using correlation and cross correlation coefficients and the amplitude of fundamental active and reactive component of load currents are estimated using quadrature and in phase voltage unit templates, zero crossing detector (ZCD) and sample and hold circuit (SHC). The in phase and quadrature unit templates are estimated from phase value of PCC voltages. The zero crossing rising edge of quadrature and in phase voltage templates are the sensed position for extracting the per phase amplitude of fundamental active and reactive power components of load currents with sample and hold circuit. Similarly, amplitude of other phases active and reactive power components of the load currents are also extracted. For balancing the source currents, an average value is derived by the magnitude of active power current components of three phase load currents. The output of DC bus voltage proportional–integral (PI) regulator of VSC of DSTATCOM is added in the average amplitude of active power current component of the three phase load currents and this value (amplitude of active power components of load current) is multiplied with three phase in phase unit templates to compute the reference source active power components of currents. Similarly, reference source reactive power components of currents are estimated from the subtraction of an average value of fundamental reactive power components of load currents from the amplitude to output of voltage PI regulator and this value (amplitude of reactive current) which is multiplied with three phase quadrature components of unit templates. Total reference source currents are estimated by addition of reference active and reactive power components of source currents. Basic equation for estimation of different control signals of control algorithm are given below.

3.1 Estimation of in- Phase and Quadrature Unit Voltage Templates

The in phase unit templates are estimated using an amplitude of the PCC voltage (V_s) and phase voltage (v_{sa},v_{sb},v_{sc}) as

$$V_s = \sqrt{\frac{2(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}{3}} \tag{4}$$

$$u_{sap} = \frac{v_{sa}}{V_s}, u_{sbp} = \frac{v_{sb}}{V_s}, u_{scp} = \frac{v_{sc}}{V_s} \tag{5}$$

and the quadrature unit template are computed as[Singh and Kumar, 2010],

$$u_{saq} = \frac{(-u_{sbp} + u_{scp})}{\sqrt{3}}, u_{sbq} = \frac{(3u_{sap} + u_{sbp} - u_{scp})}{2\sqrt{3}}, u_{scq} = \frac{(-3u_{sap} + u_{sbp} - u_{scp})}{2\sqrt{3}} \tag{6}$$

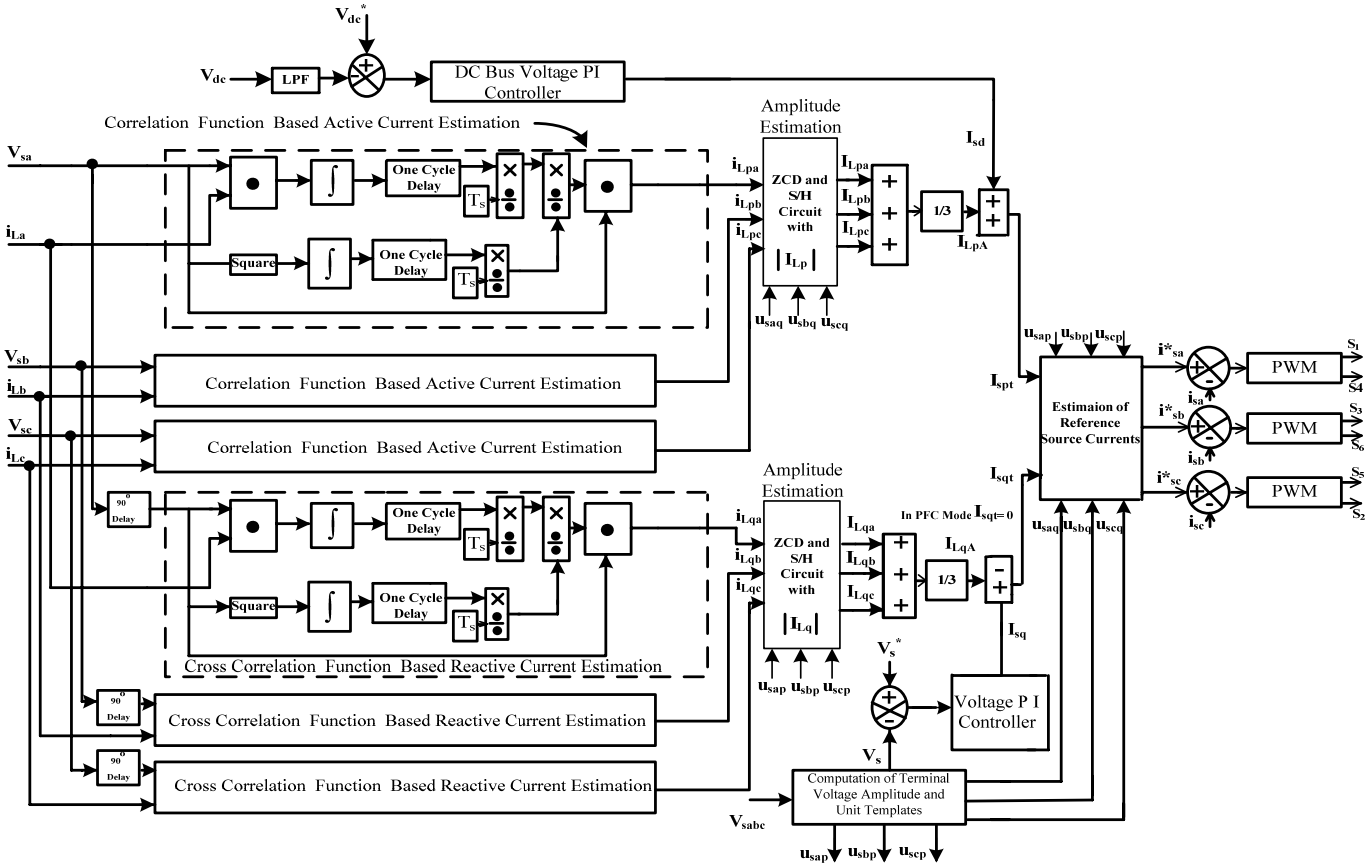


Figure 2. Generation of reference currents using correlation and cross correlation function based control algorithm

3.2 Estimation of Fundamental Active and Reactive Power Components of Load Currents

Fundamental active and reactive power components of load currents are estimated by using the correlation and cross-correlation function coefficients respectively. Considering that balanced phase 'A' supply voltage $v_{sa}(t)$ and distorted load current $i_{La}(t)$ and their time varying (instantaneous) expressions are as,

$$v_{sa}(t) = V_{ma} \sin \omega t$$

$$i_{La}(t) = I_{La1} \sin(\omega t - \phi_1) + I_{La3} \sin(3\omega t - \phi_3) + I_{La5} \sin(5\omega t - \phi_5) \ \ldots \tag{7}$$

The norms of $v_{sa}(t)$ and $i_{La}(t)$ are given as

$$\left\| v_{sa}(t) \right\|^2 = \frac{1}{T_s} \int_{t-Ts}^{t} v_{sa}^2(t) dt \tag{8}$$

$$\left\| i_{La}(t) \right\|^2 = \frac{1}{T_s} \int_{t-Ts}^{t} i_{La}(t)^2 dt \tag{9}$$

where T_s is equal to time period of one cycle. The product of $v_{sa}(t)$, $i_{La}(t)$ can be expressed as,

$$\left[v_{sa}(t), i_{La}(t)\right] = \frac{1}{T_s}\int_{t-Ts}^{t} v_{sa}(t).i_{La}(t)dt \tag{10}$$

From equations (6), (7) and (8) the correlation coefficient is defined as,

$$r = \left[v_{sa}(t), i_{La}(t)\right] / \left[\left\|v_{sa}(t)\right\|.\left\|i_{La}(t)\right\|\right] \tag{11}$$

From equations (6), (7), (8) and (9) the fundamental active power component of load current of phase 'A' (i_{Lpa}) is defined as,

$$i_{Lpa}(t) = \frac{\left[v_{sa}(t), i_{La}(t)\right]}{\left\|v_{sa}(t)\right\|^2}.v_{sa}(t) \tag{12}$$

Similarly, other phase fundamental active power component of load currents (i_{Lpb} and i_{Lpc}) are also extracted.

The cross correlation is used to estimate the fundamental reactive power component of load current. It is derived after 90^o delay of PCC phase voltage (v_{sqa},v_{sqb},v_{sqc}). Phase 'A' fundamental reactive power component of load current can be defined as,

$$i_{Lqa}(t) = \frac{\left[v_{sqa}(t), i_{La}(t)\right]}{\left\|v_{sqa}(t)\right\|^2}.v_{sqa}(t) \tag{13}$$

where $v_{sqa}(t) = \frac{(-v_{sbp} + v_{scp})}{\sqrt{3}}$

Similarly, other phase fundamental reactive power component of load currents (i_{Lqb} and i_{Lqc}) are also estimated.

3.3 Estimation of Amplitude of Active Power and Reactive Power of Current Components of Load Currents

The amplitude of active and reactive power component of load currents are estimated using quadrature and in phase voltage unit templates, zero crossing detector (ZCD) and sample and hold circuit(SHC). The in phase (u_{spa}, u_{spb}, u_{spc}) and quadrature (u_{sqa}, u_{sqb}, u_{sqc}) unit templates are estimated from phase value of PCC voltages. To extract the amplitude of the fundamental active power component of load current in phase of phase voltage, a zero crossing detector is used with quadrature unit template in respective phase. A sample and hold circuit is used with load fundamental active power component as the input signal and zero crossing detector output (O_{ZCD1}) as rising edge trigger pulse. The magnitude of the output of sample and hold circuit (O_{SHC1}) is considered as the amplitude of phase A fundamental active power component of load current (I_{Lpa}). Similarly, other phase B and phase C active power current components of load currents (I_{Lpb} and I_{Lpc}) are also estimated. To extract the magnitude of fundamental reactive power component of the load current, another zero crossing detector is used with in phase voltage unit template and sample and hold circuit. Sample and hold circuit is used with fundamental reactive power component of load current as a input and output of zero crossing detector (O_{ZCD2}) as a trigger pulse. The magnitude of the output of sample and hold circuit (O_{SHC2}) is considered as the amplitude of phase 'A' reactive power component of load current (I_{Lqa}). Similarly, other phase 'B' and phase 'C' reactive power current components (I_{Lqb}, I_{Lqc}) are also estimated.

3.4 Estimation of Average Amplitude of Active and Reactive Power Current Components of Load Currents

The average fundamental amplitude of active and reactive power components of the three phase load currents are estimated using amplitude of load active and reactive power currents. Average value is given for extraction of three phase reference source current as,

$$I_{LpA} = \frac{I_{Lpa} + I_{Lpb} + I_{Lpc}}{3} \tag{14}$$

$$I_{LqA} = \frac{I_{Lqa} + I_{Lqb} + I_{Lqc}}{3} \tag{15}$$

3.5. Amplitude of Active Power Component of Reference Source Currents

To compute amplitude of active power components of source current, a reference DC bus voltage is compared with sensed DC voltage. The difference between this error in DC bus voltage of the DSTATCOM at the n^{th} sampling instant is

$$V_{dcer}(n)=V_{dcref}(n)-V_{dc}(n) \quad (16)$$

where, $V_{dcref}(n)$ is the reference DC bus voltage and $V_{dc(n)}$ is the sensed DC bus voltage of DSTATCOM.

The output of DC bus PI controller for maintaining DC bus voltage of the DSTATCOM of the n^{th} sampling instant is expressed as,

$$I_{sd}(n)= I_{sd}(n-1) +K_{pd}\{V_{dcer(n)}- V_{dcer(n-1)}\}+K_{id}V_{dce} \quad (17)$$

where $I_{sd}(n)$ considered as the active power component of source current requirement for the self supporting DC bus of the DSTATCOM and K_{pd} and K_{id} are the proportional and integral gain constants of the DC bus PI voltage controller.

The amplitude of active power component of the reference source current is computed as the addition of active power requirement for the self supporting DC bus of the DSTATCOM reference currents and average magnitude of active power component of the load currents as,

$$I_{spt}=I_{sd}+I_{LpA} \quad (18)$$

3.6 Amplitude of Reactive Power Component of Reference Source Currents

The amplitude of reactive power component of the reference source current is calculating using a voltage PI controller over the amplitude of the PCC voltage (V_s) and its reference value (V_s^*). The output of the voltage PI controller for regulated load terminal voltage at the n^{th} sampling instant is expressed as,

$$I_{sq}(n)= I_{sq}(n-1) +K_{pq}\{V_{e(n)}- V_e(n-1)\}+K_{iq}V_e(n) \quad (19)$$

where V_e is equal to(V_s*-V_s)and it is the error in amplitude of the PCC voltage and reference terminal voltage. K_{pq} and K_{iq} are the proportional and integral gains of the PI controller over the PCC voltage.

The amplitude of reactive power component of the reference source current is computed as the difference of output of the voltage PI controller and average reactive power component of load currents as,

$$I_{sqt}=I_{sq}-I_{dqA} \quad (20)$$

3.7 Estimation of Source Reference Currents and Generation of Gating Pulses

Three phase source reference currents are computed using amplitude of active and reactive power component of source current and in phase and quadrature unit voltage templates. Three phase source reference active and reactive power current components are estimated as

$$i_{sap} =I_{spt}*u_{sap},\ i_{sbp}= I_{spt}*u_{sbp},\ \ i_{scp} =I_{spt}*u_{scp} \quad (21)$$

$$i_{saq} =I_{sqt}*u_{saq},\ i_{sbq}= I_{sqt}*u_{sbq},\ \ i_{scq} =I_{sqt}*u_{scq} \quad (22)$$

Total reference source currents are calculated after addition of reference active and reactive power current components as

$$i^*_{sa}= i_{sap}+ i_{saq,}\ \ i^*_{sb}= i_{sbp}+ i_{sbq,}\ i^*_{sc}= i_{scp}+ i_{scq} \quad (23)$$

For gating signal generation, extracted three phase reference source currents (i^*_{sa}, i^*_{sb}, i^*_{sc}) are compared with source currents (i_{sa},i_{sb},i_{sc}). These current errors are amplified using a proportional controller and outputs of current controller are compared with carrier wave signal to generate PWM pulses for the VSC switches S_1,S_4,S_3,S_6,S_5,S_2 of DSTATCOM.

4. Development of MATLAB Based Model

A model of the three leg VSC based DSTATCOM connected to a three-phase system is developed and its performance is simulated in MATLAB environment using SIMULINK and Sim Power System(SPS) toolboxes. The developed MATLAB model is shown in Figure 3. The ripple filter is connected to a DSTATCOM for filtering the ripple in the voltage at the PCC. The system data are given in the Appendix. 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.

5. Results and Discussion

The performance of the correlation and cross-correlation based control algorithm for the three-phase DSTATCOM is simulated for PFC (Power Factor Correction) and ZVR (Zero Voltage Regulation) modes of operation with unbalance in the loads currents. The performance of DSTATCOM is analyzed under time varying loads and the results are discussed below.

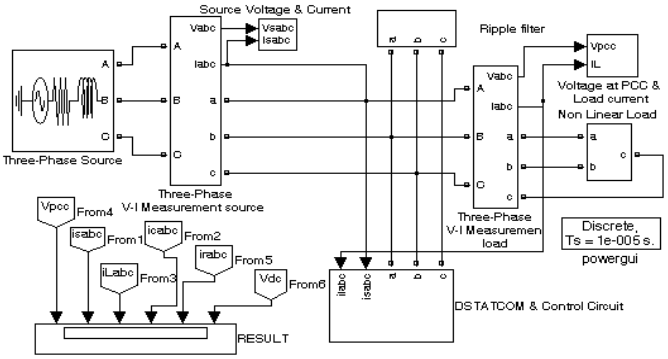


Figure 3. MATLAB based simulation model of DSTATCOM

5.1 Performance of Control Algorithm

Figure 4 shows the various intermediate signals of the control algorithm which include fundamental active power components of load current (i_{Lp}), reactive power components of load current (i_{Lq}), average amplitude value of active power component of load currents (I_{LpA})and reactive currents (I_{LqA}), output of DC bus PI controller (I_{sd}) and voltage PI controller (I_{sq}), amplitude of active (I_{spt}) and reactive (I_{sqt}) power component of reference source current, three phase source reference active power (i_{sp})and reactive power (i_{sq})components of current and three phase reference current (i_s*) respectively. These signals are shown with respect to AC supply mains voltage (v_s) and load currents (i_L). It clearly demonstrates the accurate extraction of control signals even under distorted load currents.

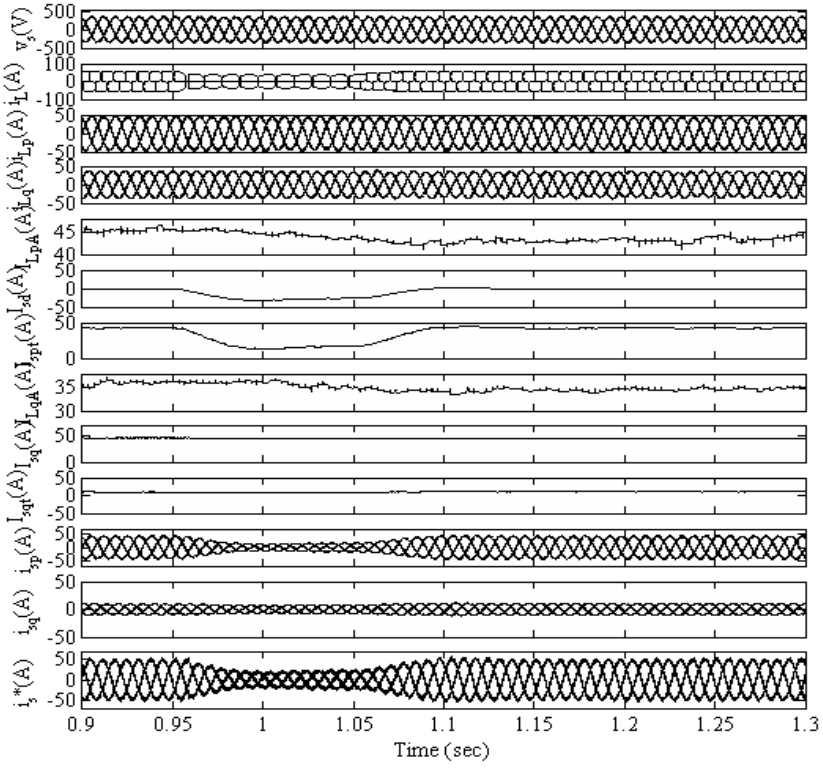


Figure 4. Various intermediate signals of control algorithm with respect to AC supply mains (v_s) and load currents (i_L)

5.2 Performance of DSTATCOM in PFC Mode

The dynamic performance of a three-leg VSC based DSTATCOM for PFC mode of operation under a linear load is shown in Figure 5. Performance indices are as phase voltage at PCC (v_s), source currents (i_s), load currents (i_L), compensator currents ($i_{Ca,}$ $i_{Cb,}$ i_{Cc}), and DC bus voltage (V_{dc}) which are shown under varying loads (at t = 0.95 s to 1.05 s) conditions. It clearly shows the satisfactory operation of DSTATCOM.

Similarly, current and voltage source type of harmonics generating nonlinear loads are also connected to the supply system. The dynamic performance of DSTATCOM and waveforms of phase 'A' voltage at PCC (v_{sa}), source current (i_{sa}) and load current (i_{La}) are shown in Figure 6 and Figures 7(a-c) respectively in case of current source type of harmonic generating load. In Figure 7(a-c), THD % of the phase 'A' at PCC voltage, source current, load current are 2.02%, 3.55% and 24.31% respectively. Dynamic performance of voltage source type of harmonics generating nonlinear load and waveform of phase 'A' voltage at PCC (v_{sa}), source current (i_{sa}) and load current (i_{La}) are shown in Figure 8 and Figures 9 (a-c) respectively. In Figure 9(a-c), THD% of the phase 'A' at PCC voltage, source current, load current are 3.43%, 3.45% and 44.87% respectively. It is observed that the DSTATCOM is able to perform the functions of load balancing, harmonic elimination and power factor correction from above discussion.

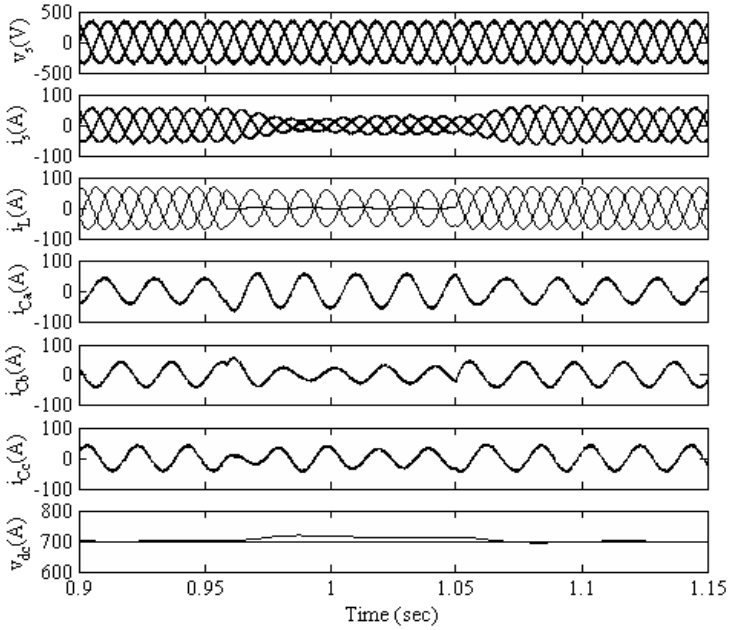


Figure 5. Dynamic performance of DSTATCOM under varying linear load in PFC mode

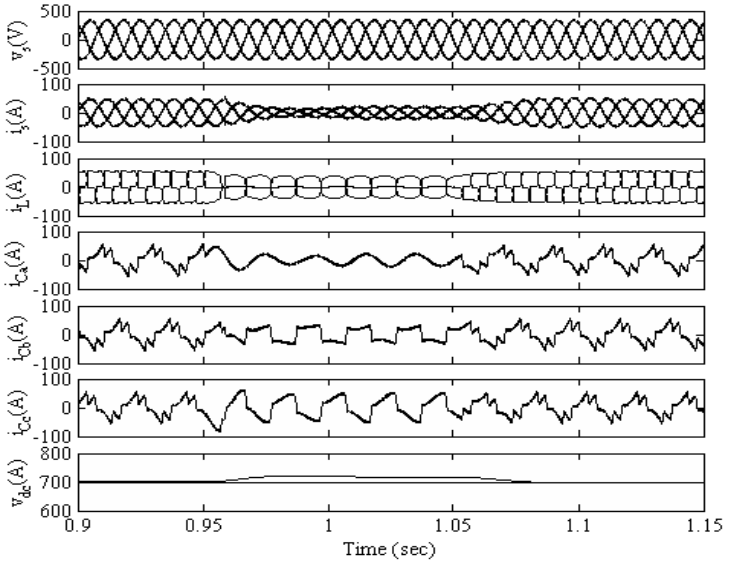
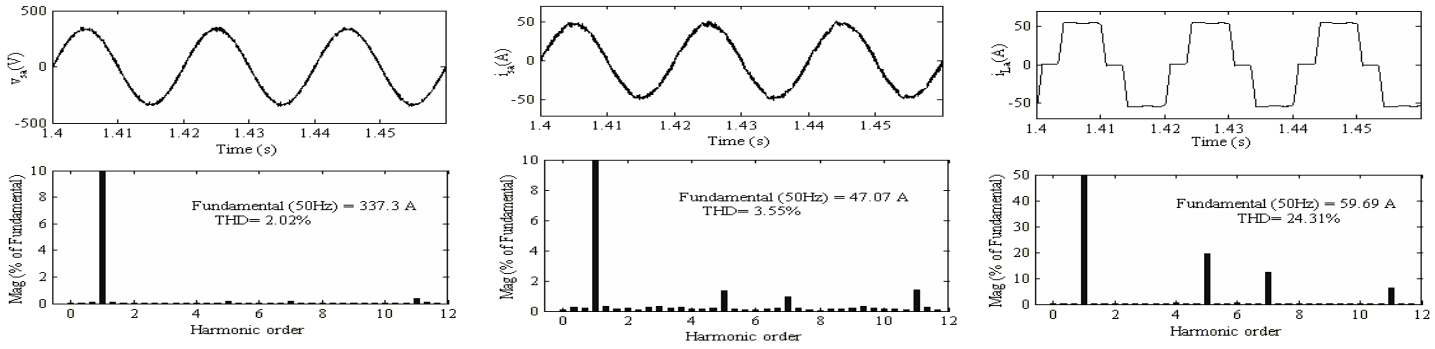


Figure 6. Dynamics performance of DSTATCOM under varying nonlinear load (current source type) in PFC mode



(a) (b) (c)

Figure 7. Waveforms, THD and harmonic spectra of (a) PCC voltage of phase 'A' (b) source current of phase 'A' (c) load current of phase 'A' in PFC mode

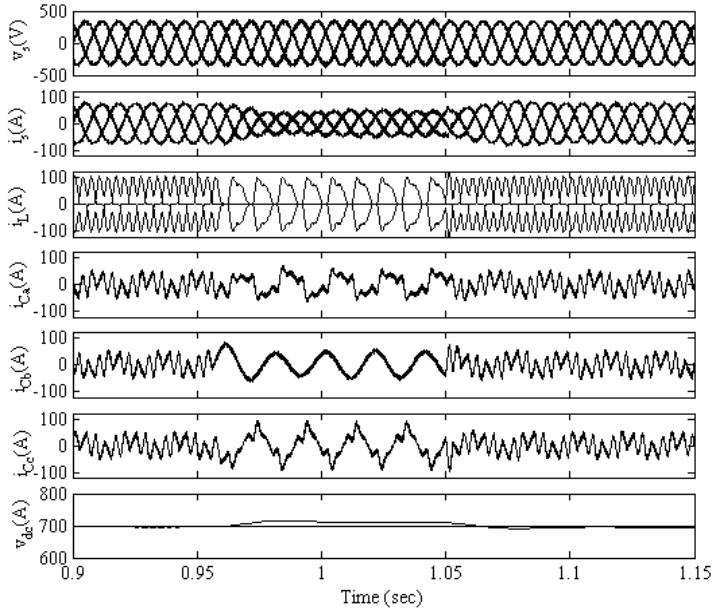
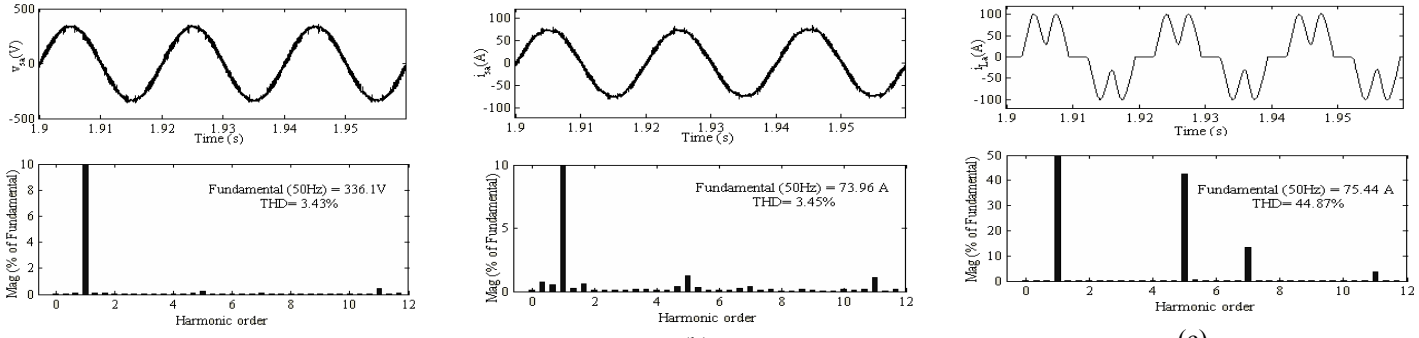


Figure 8 . Dynamics performance of DSTATCOM under varying nonlinear load (voltage source type) in PFC mode



(a) (b) (c)

Figure 9. Waveforms, THD and harmonic spectra of (a) PCC voltage of phase 'A' (b) source current of phase 'A' (c) load current of phase 'A' in PFC mode

5.3 Performance of DSTATCOM at ZVR Mode

In ZVR mode, the amplitude of PCC voltage is regulated to the reference amplitude by injecting the required reactive power compensation. Figure 10 shows the dynamic performance of the DSTATCOM used in three phase system for reactive power

compensation with voltage regulation and load balancing of linear loads (at t = 0.95 s to 1.05 s). The performance indices are as PCC phase voltages (v_s), balanced source currents (i_s), load currents (i_L), compensator currents (i_{Ca}, i_{Cb}, i_{Cc}), amplitude of voltages at PCC (V_s) and DC bus voltage (v_{dc}) under time varying linear loads.

Similarly, performance of DSTATCOM is found satisfactory under current and voltage source types of harmonics generating nonlinear loads. The dynamic performance of DSTATCOM and waveforms of phase 'A' voltage at PCC (v_{sa}), source current (i_{sa}) and load current (i_{La}) are shown in Figure 11 and Figures 12(a-c) respectively in case of three phase controlled rectifier with series 'R' and 'L' load used as current source type of harmonic generating nonlinear load. In Figure 12(a-c), THD % of the phase 'A' at PCC voltage, source current, load current are 2.06%, 3.76% and 24.53% respectively. Three phase un-controlled rectifier with parallel 'R' and 'C' is modeled as a voltage source type of harmonics generating nonlinear load. Dynamic performance of a DSTACOM under a voltage source type of harmonics generating nonlinear load and waveform of phase 'A' voltage at PCC (v_{sa}), source current (i_{sa}) and load current (i_{La}) are shown in Figure 13 and Figures 14 (a-c) respectively. In Figure 14(a-c), THD % of the phase 'A' at PCC voltage, source current, load current are 3.59%, 3.39% and 44.45% respectively. It may be observed that the THD of the source current and PCC voltage are within IEEE-519-1992 standard limit of 5%. Table 1 shows the summarized results demonstrating the performance of DSTATCOM. These results show satisfactory performance of DSTATCOM for harmonic elimination, reactive power compensation and load balancing for variety of loads.

Table 1. Performance of DSTATCOM in different operating modes

Operating mode	Performance parameters	Linear load (Lagging power factor load)	Nonlinear load	
			Current source type (3-phase controlled rectifier, $\alpha=30^o$)	Voltage source type (3-phase un-controlled rectifier with 'R' and 'C' load)
PFC mode	PCC voltage (V) , %THD	238.1 (1.61%)	238.86 (2.02%)	237.65 (3.43%)
	Supply current (A), %THD	38.76 (2.67%)	33.28 (3.55%)	52.29 (3.55%)
	Load current (A) , %THD	48.38 (0.1%)	42.20 (24.31%)	53.34 (44.87%)
ZVR mode	PCC voltage (V), %THD	239.7 (1.67%)	239.63 (2.06%)	239.49 (3.59%)
	Source current (A),%THD	40.32 (2.05%)	34.31 (3.76%)	53.85 (3.76%)
	Load current (A), %THD	48.69 (0.08%)	42.23 (24.53%)	53.73 (44.45%)
	DC bus voltage (V)	700	700	700

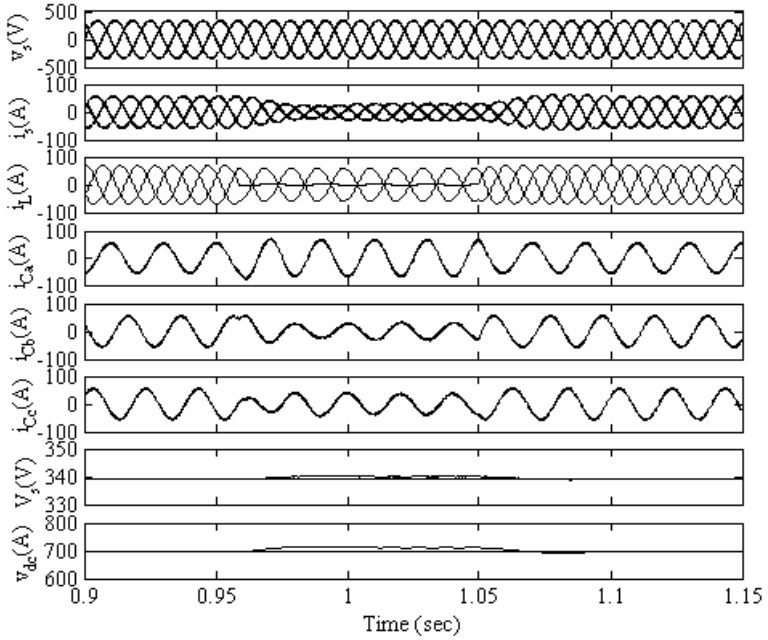


Figure 10. Dynamics performance of DSTATCOM under varying linear load in ZVR mode

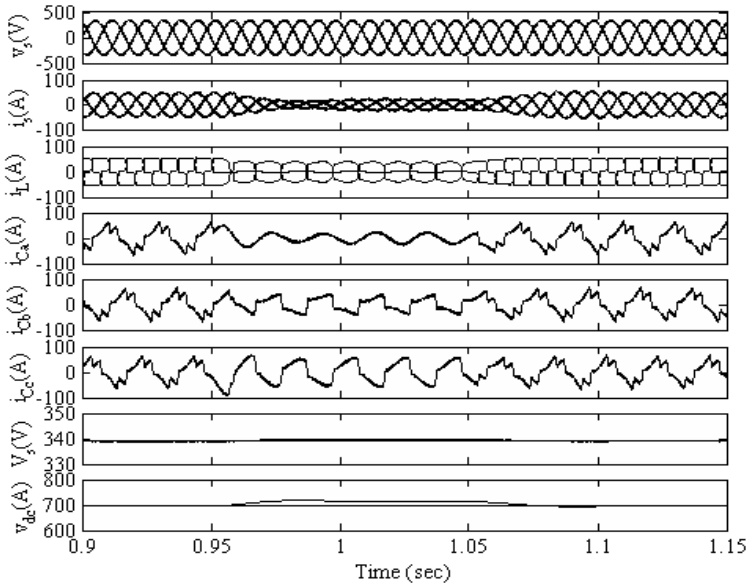
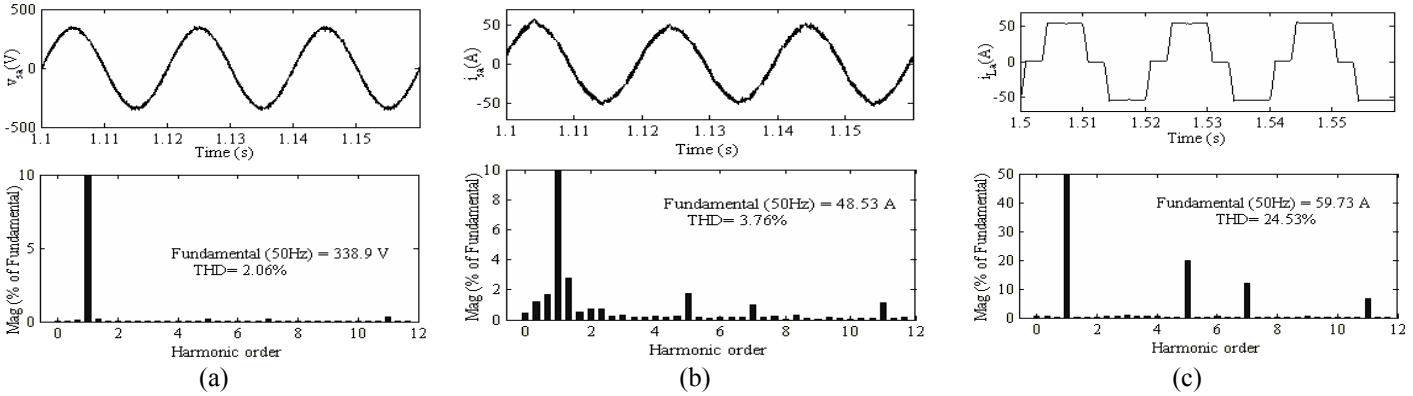


Figure 11. Dynamic performance of DSTATCOM under varying nonlinear load (current source type) in ZVR mode



(a) (b) (c)

Figure 12. Waveforms, THD and harmonic spectra of (a) PCC voltage of phase 'A' (b) source current of phase 'A' (c) load current of phase 'A' in ZVR mode

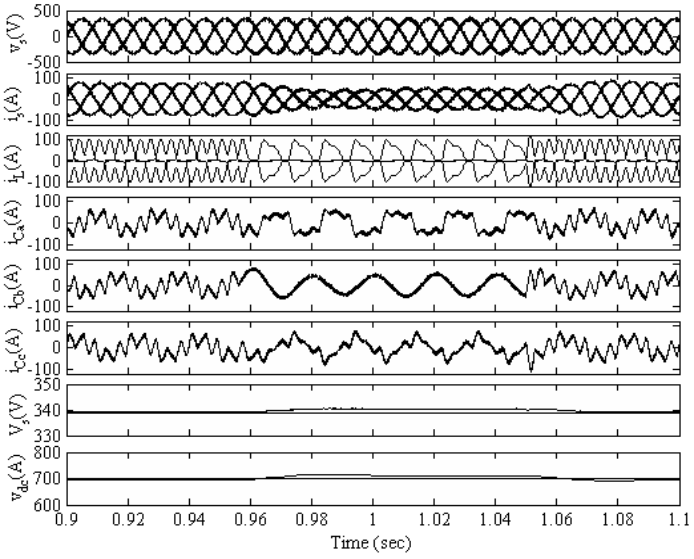


Figure 13. Dynamic performance of DSTATCOM under varying nonlinear load (voltage source type) in ZVR mode

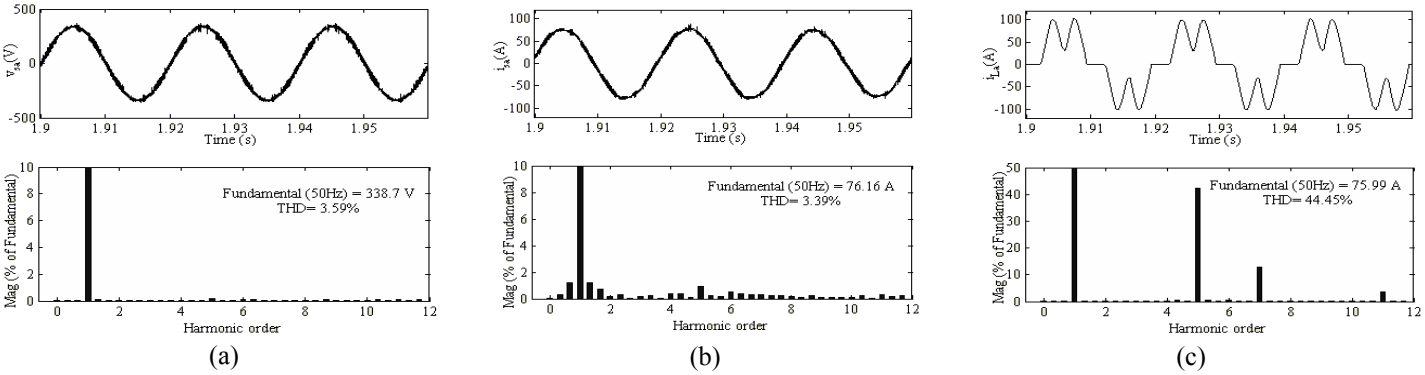


Figure 14. Waveforms, THD and harmonic spectra of (a) PCC voltage of phase A (b) source current of phase A (c) load current of phase A in ZVR mode

5. Conclusions

The design and control of a DSTATCOM have been carried out for a three phase distribution system. A control algorithm based on correlation and cross correlation function has been found suitable for generating the switching signals of DSTATCOM in a three phase system. The performance of DSTATCOM has been demonstrated for harmonic elimination, reactive power compensation and load balancing for variety of loads in PFC and ZVR modes of operation. The performance of DSTATCOM has been found satisfactory under varying load conditions. For estimation of active and reactive power components of load currents only numerical integration is used so it has been found simple and accurate compared to others control algorithms. The DC bus voltage of the DSTATCOM has also been regulated without much overshoot to desired value under varying load conditions.

Nomenclature

AC	Alternating current
DC	Direct current
Eq.	Equation
PCC	Point of common coupling
R	Resistance
L	Inductance
C	Capacitance
m	Mille
s	Time in second
THD	Total Harmonic Distortion
‖ ‖	Norm
α	Firing angle of control rectifier
∫	Integration
ϕ	Phase angle
%	Percentage

Appendix

AC supply source: 3-phase, 415 V (L-L), 50Hz; Source Impedance: R_s=0.04 Ω, L_s=0.5 mH; Load: (1) Linear: 35kVA, 0.8 p.f. lagg. (2) Non-linear: (a)Three phase full bridge controlled rectifier, α=30^o with R= 8Ω and L= 100mH, (b) Three phase full bridge uncontrolled rectifier with R= 8Ω and C= 180μf; Ripple filter: R_f = 5 Ω, C_f = 5μF; DC bus capacitance: 10000μF; Reference DC bus voltage: 700 V; Gains of PI controller for DC bus voltage: K_{pd}=0.92, K_{id}=0.108; Gains of voltage PI controller: K_{pq}=2.56, K_{iq} =4.22; Switching frequency (f_s) = 10 kHz

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