Load Conductance Estimation Based Control Algorithm for Shunt Connected Custom Power Devices

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Abstract-In this paper, a control algorithm is developed for three phase DSTATCOM (Distribution Static Compensator). It is based on load conductance estimation through the fundamental load power calculation using second order generalized integrator (SOGI). Developed three phase system is simulated in power factor correction (PFC) and zero voltage regulation (ZVR) modes. In PFC mode, it provides compensation for reactive power, harmonics and load balancing whereas in ZVR mode it regulates the PCC voltage along with the harmonics elimination and load balancing. The simulation results are found satisfactory with the proposed control algorithm under dynamic loading conditions.

Keywords-Conductance, Susceptance, SOGI, Unit templates, ZVR.

I. Introduction

Power quality disturbances like harmonics, unbalanced load, voltage dips, flicker, etc are increasing every year [1]. It affects not only the performance of various power system components but also economy of electricity market [2]. Improved power quality is an important demand of distribution system [3-5]. Power quality issues are generated in distribution side by consumers, so it is desired to attenuate them at distribution side and this is achieved by custom power devices [6,7]. DSTATCOM is a shunt connected device which can be operated in PFC as well as ZVR mode [8]. It provides compensation for reactive power, harmonics as well as balances load and regulates voltage. Various topologies of DSTATCOM has been proposed in literature for three phase three wire and three phase four wire distribution system[9]. Effective use of DSTATCOM depends on its parameter design as per system requirement [10]. The dynamic and steady performance of DSTATCOM is decided by control algorithm used for generation of compensation currents.

Mindykowski *et al.* [11] have reported new concept based on instantaneous reactive power theory in ship electrical power system. It is based on mean value instead of traditional low pass filter under non-ideal ac mains. Singh *et al.* [12] have discussed basic control algorithm based on peak detection in four wire system. The implementation of SRF theory based in hybrid active filter is reported in the literature [13,14]. Massoud *et al.* [15] have reported a review on control algorithm used for shunt active compensation. In this paper control algorithms are divided in time domain and frequency domain. Again, in time domain control algorithm, various control algorithms are reported using different classical approaches. Detailed configuration, control and various topologies are reported in the literature [16, 19]. Kunjumuhammed and Mishra [20] have reported a new control algorithm in non stiff supply source with detailed synchronizing circuit of active filter during operation. It is based on power calculations in signal phase circuit. Shu *et al.* [21] have reported field-programmable gate array (FPGA) plated form for implementation of active filter. This platform has integrated whole procedure related to signal processing. Second order generalized integrator based extraction of fundamental line voltage under distorted condition algorithm for a single phase shunt active power filter has been proposed. Ciobotaru *et al.* [22] have proposed single phase SOGI-PLL with simple structure. It is able to provide information related to phase, amplitude and frequency of supply source for converter application. It can generate orthogonal system voltage without any delay. It is also adaptive with respect to frequency variations. Golestan *et al.* [23] have discussed structure, analysis and application of SOGI PLL in single phase active filter. Another application of SOGI [24] is reported in grid synchronization system where it is cable of providing desire response for the estimation of symmetrical components of PCC voltage under non ideal condition.

In this paper, Second order generalized integrator (SOGI) [22-24] is used in three phase three wire system for extraction of active and reactive component of load currents. Further, load physical parameters (conductance and susceptance) are estimated by calculating the fundamental power flowing from PCC to load. This algorithm presents a simpler way of calculating the load conductance and the generation of supply reference current. All parameters of control algorithm has physical meaning, it does not involve any assumption of parameters. Good detection accuracy, fast dynamic performance, simpler calculations are features of this control algorithm.

II. System Configuration

Fig.1 shows schematic of 3 leg VSC-based DSTATCOM connected to a three phase three wire distribution system, where an ac source with impedance (Zs) is feeding a non linear load. The L_f are an interfacing inductors connected on ac side of VSC, used for reducing the ripples in the current. A series combination of R_f-C_f are connected at point of common coupling (PCC) in parallel with the load circuit. It is a first order high pass passive filter used for filtering higher order switching harmonics produced by VSC. The C_{dc} is a DC link capacitor with voltage V_{dc} , which is regulated by PI regulator in DC link. The phase PCC voltages (v_{sa},v_{sb},v_{sc}), load currents (i_{La}.i_{Lb},i_{Lc}) and supply currents (i_{sa},i_{sb},i_{sc}) are sensed and fed to control algorithm.

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The DSTATCOM currents (i_{fa},i_{fb},i_{fc}) are injected to compensate the reactive and harmonic components present in the load current.

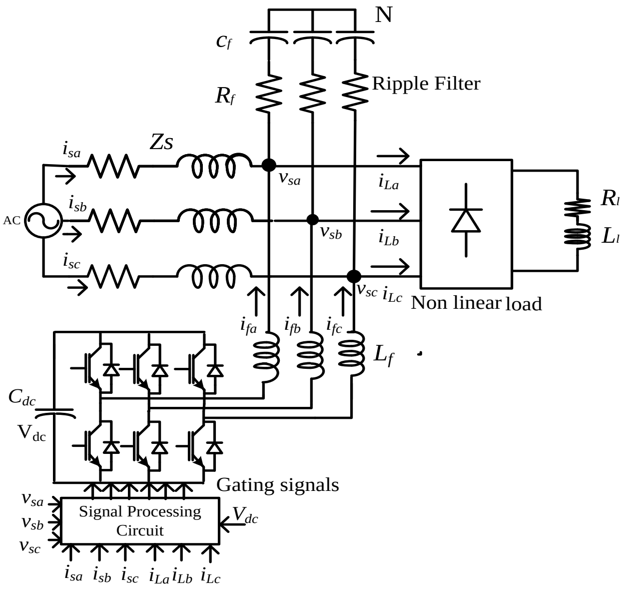


Fig.1. Schematic diagram of 3 Leg VSC-based DSTATCOM

III. CONTROL ALGORITHM

Fig. 2 shows the block diagram of estimation of reference supply currents based on conductance factor. In this algorithm PCC voltages (v_{sa},v_{sb},v_{sc}), load currents (i_{La}.i_{Lb},i_{Lc}) and supply currents (i_{sa},i_{sb},i_{sc}) are required for the extraction of reference supply currents (i_{sa}^*,i_{sb}^*,i_{sc}^*).Mathematical expressions used in control algorithm for the extraction of various control parameters are discussed as follows.

A. Extraction of Fundamental Active and Reactive Component from Distorted Load Current Using SOGI

Fig. 3 indicates block diagram of SOGI where load current is given as an input to SOGI. I_r and I_q are the fundamental in phase and quadrature components of currents. Transfer function of SOGI block is written as [22-24],

$$T.F. = \frac{i_1(s)}{i_L(s)} = \frac{k\omega s}{s^2+\omega^2+k\omega s} \tag{1}$$

where k is gain parameter, ω is the frequency of the desired frequency component to be extracted, in this case it is 314 rad/sec.

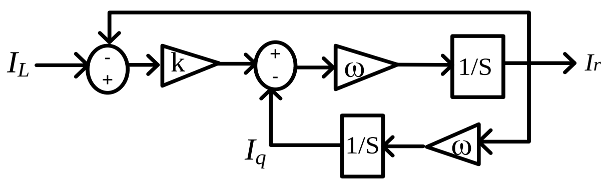


Fig.3 Second Order Generalized Integrator

Performance of SOGI totally depends on value of k. Changing load condition like increase or decrease in load current or harmonic contents causes some delay to stabilize output of SOGI. Dynamic response of SOGI is observed with a step input by putting various values of gain (k) in time domain.

Fig.4 shows the response of SOGI to unit step input. It is found that for higher values of 'k' dynamics of SOGI is faster. Similarly filtering performance of SOGI also depends on value of 'k'. It is found that more the lower values of 'k', bandwidth hence better filtering performance. Another side larger value of k is not able to give require bandwidth and the quality of extracted frequency component gets deteriorated. From the above analysis, it is found that there is a tradeoff between dynamic performance and filtering performance. Here the value of k is selected as 1, so that dynamic is quite fast and filtering performance is also satisfactory.

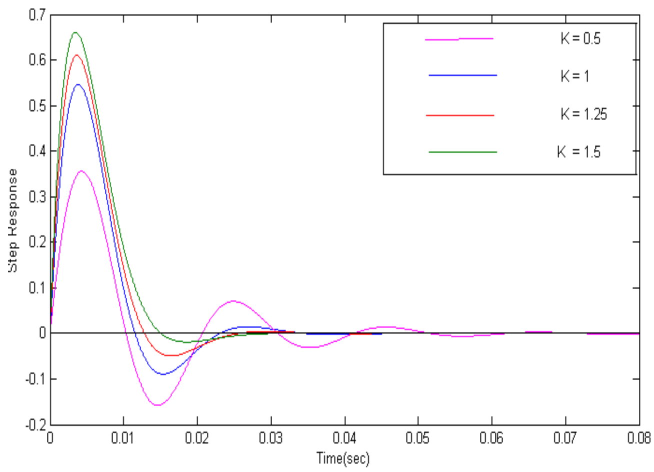


Fig.4 Step response of second order generalized integrator (SOGI)

After putting value of 'k' and w transfer function of SOGI becomes

$$T.F. = \frac{i_1(s)}{i_L(s)} = \frac{k\omega s}{s^2+\omega^2+k\omega s} \tag{2}$$

It is second order system, its characteristic equation can be written as,

$$s^2+314s+314^2=0 \tag{3}$$

Poles of transfer function come out to be (-157+j271.93) and (-157-j271.93), which are located on left half of 's' plane hence for the selected value of k and w response of SOGI is stable.

The various calculations of SOGI based control algorithm is given below.

The PCC voltages (v_{sa},v_{sb},v_{sc}) are sensed to calculate in phase and quadrature unit templates as follows [12].

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

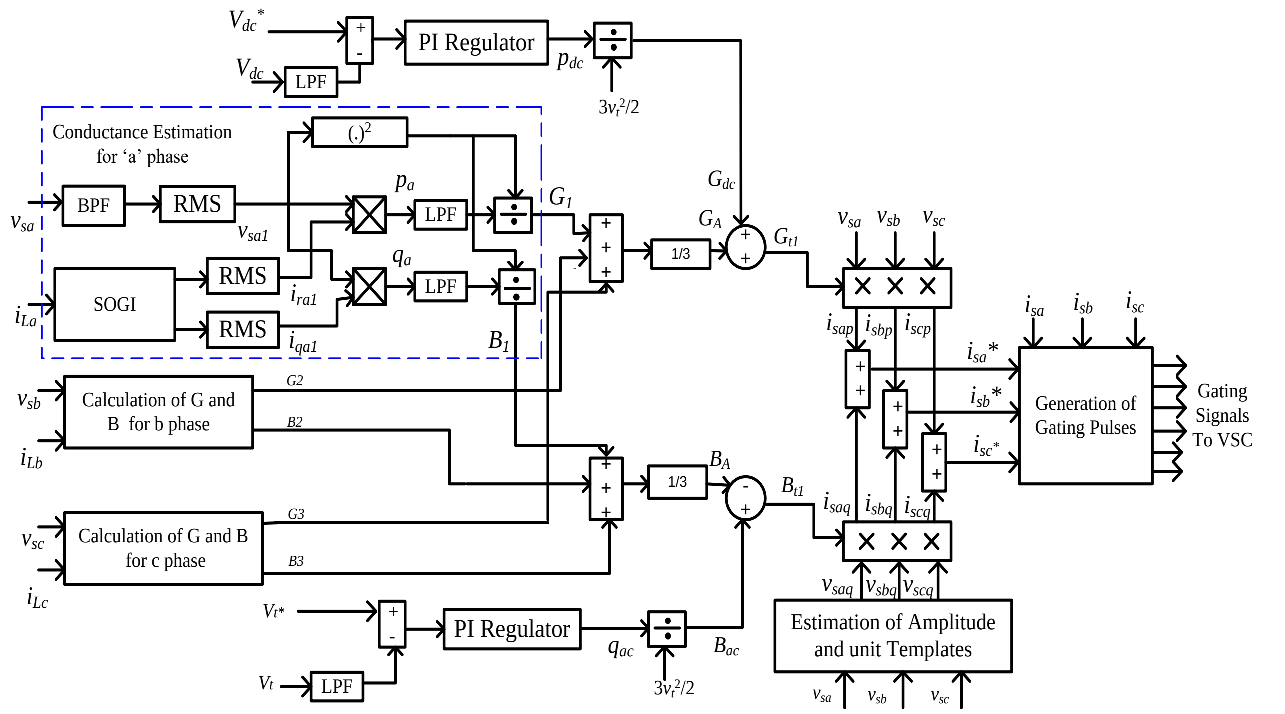


Fig. 2 SOGI based control algorithm for DSTATCOM

In phase Unit templates with phase voltages (w_{pa},w_{pb},w_{pc}) are calculated as,

$$w_{pa} = \frac{v_{sa}}{v_t}, w_{pb} = \frac{v_{sb}}{v_t}, w_{pc} = \frac{v_{sc}}{v_t} \tag{5}$$

Similarly, the quadrature unit templates (w_{qa},w_{qb},w_{qc}) are calculated as,

$$w_{qa} = \frac{(-w_{pb} - w_{pc})}{\sqrt{3}}, w_{qb} = \frac{(3w_{pa} + w_{pb} - w_{pc})}{2\sqrt{3}}, \quad w_{qc} = \frac{(-3w_{pa} + w_{pb} - w_{pc})}{v_t} \tag{6}$$

Quadrature components of PCC voltages are calculated as,

$$v_{saq} = v_t w_{qa}, v_{sbq} = v_t w_{qb}, v_{scq} = v_t w_{qc} \tag{7}$$

C. Estimation of Average Conductance (G_A), Susceptance (B_A) and *Reference Supply Currents*

The sensed PCC phase voltages (v_{sa},v_{sb},v_{sc}) are passed through band pass filter and these values are calculated as (v_{sa1},v_{sb1},v_{sc1}). The load current contains undesirable components like fundamental reactive component, harmonics and DC component along with the fundamental active component because of nonlinear loading. It is desired that source should supply only fundamental component of active current and rest of the components should be compensated by DSTATCOM. A second order generalized integrator is used for the extraction of active and reactive components of the three phase load current. The fundamental active and reactive components of load currents are represented as i_r and i_q respectively. The Fundamental active and reactive power are calculated as,

$$p_a = v_{sa1} i_{ra1}, q_a = v_{sa1} i_{qa1} \tag{8}$$

Similarly it can be calculated for phase B and C as,

$$p_b = v_{sb1} i_{rb1}, q_b = v_{sb1} i_{qb1} \tag{9}$$

$$p_c = v_{sc1} i_{rc1}, q_c = v_{sc1} i_{qc1} \tag{10}$$

The value of the conductances and susceptances observed from PCC are calculated as,

$$G_1 = \frac{p_a}{v_{sa}^{\ 2}}, B_1 = \frac{q_a}{v_{sa}^{\ 2}} \tag{11}$$

$$G_2 = \frac{p_b}{v_{sb}^{\ 2}}, B_2 = \frac{q_b}{v_{sb}^{\ 2}} \tag{12}$$

$$G_3 = \frac{p_c}{v_{sc}^{\ 2}}, B_3 = \frac{q_c}{v_{sc}^{\ 2}} \tag{13}$$

The average amplitude of conductances (G_A) and susceptances (B_A) are calculated as [19],

$$G_A = \frac{G_1 + G_2 + G_3}{3} \text{ and } B_A = \frac{B_1 + B_2 + B_3}{3} \tag{14}$$

Averaging is done for load balancing operation under unbalanced loading. The reference DC voltage (V_{dc}^*) is compared with the measured DC bus voltage (V_{dc}) and the error voltage at r^{th} sampling instant is calculated as,

$$v_{de}(r) = v_{dc}^*(r) - v_{dc}(r) \tag{15}$$

The DC link voltage is regulated by using PI controller. The output of PI controller (P_{cd}) at r^{th} sampling instant is expressed as

$$p_{cp}(r) = p_{cp}(r-1) + k_{dp}[v_{de}(r) - v_{de}(r-1)] + k_{di} v_{de}(r) \tag{16}$$

Where $p_{cp}(r)$ is considered as the per phase active current component drawn from ac mains. k_{dp} and k_{di} are the proportional and integral gain constants of DC link PI voltage controller. The conductance corresponding to DC link (G_{dc}) is calculated as,

$$G_{dc} = \frac{2p_{cp}}{3v_t^{\ 2}} \tag{17}$$

Total conductance (G_{t1}) corresponding to the fundamental active power of source is calculated as,

$$G_{t1} = G_A + G_{dc} \quad (18)$$

Similarly in ZVR mode, PCC voltage is regulated by AC bus PI controller. Output of this PI controller (q_{ac}) at r^{th} sampling instant is expressed as,

$$q_{ac}(r) = q_{ac}(r-1) + k_{tp}[v_{te}(r) - v_{te}(r-1)] + k_{ti} v_{te}(r) \quad (19)$$

Where considered as per phase active current component drawn from ac mains. k_{tp} and k_{ti} are the proportional and integral gain constants of AC bus PI controller. Corresponding value of susceptance (B_{ac}) is calculated as,

$$B_{ac} = \frac{2q_{ac}}{3v_t^2} \quad (20)$$

Total susceptance corresponding to the fundamental reactive power of source is calculated as,

$$B_{t1} = B_A + B_{ac} \quad (21)$$

In phase and quadrature components of reference supply current are calculated as,

$$i_{sap} = G_{t1} v_{sa}, i_{sbp} = G_{t1} v_{sb}, i_{scp} = G_{t1} v_{sc}, \quad (22)$$

$$i_{saq} = B_{t1} v_{sa}, i_{sbq} = B_{t1} v_{sb}, i_{scq} = B_{t1} v_{sc}, \quad (23)$$

Total supply reference currents are calculated as,

$$i_{sa}^* = i_{sap} + i_{saq}, i_{sb}^* = i_{sbp} + i_{sbq}, i_{sc}^* = i_{scp} + i_{scq} \quad (24)$$

Sensed supply currents (i_{sa}, i_{sb}, i_{sc}) are compared with reference supply currents (i_{sa}^*, i_{sb}^*, i_{sc}^*) of respective phases and gating signals for six IGBTs are generated

IV. SIMULATION RESULTS AND DISCUSSION

MATLAB environment with simulink and sim power system tool boxes are used for developing model of DSTATCOM connected to three phase with conductance factor based estimation of reference supply currents. The performance of given control algorithm is observed by simulating it in time domain. The given model is simulated in PFC and ZVR mode with non linear load. Three phase diode based rectifier with R-L load is considered as nonlinear load. Data related to simulation is given in the APPENDIX.

A. Performance of the Control Algorithm

Fig. (5) shows the various parameters including PCC phase voltages (v_{pcc}), load currents (i_L), supply currents (i_s), output of DC link voltage controller (G_{dc}), total conductance (G_{t1}), output of ac bus voltage controller (B_{ac}), total susceptance (B_{t1}) and extracted three phase reference supply currents (i_{abc}^*). These waveforms demonstrate the extraction of control variables under varying non linear load in the ZVR mode of operation. At time (t) = 2.6s, phase 'a' load is injected and it results a small dip into DC link voltage. The 'G_{dc}' represents the active power as a loss component VSC as demands from supply to recover the DC link voltage. It is adjustable during load dynamics as shown in Fig. (5).

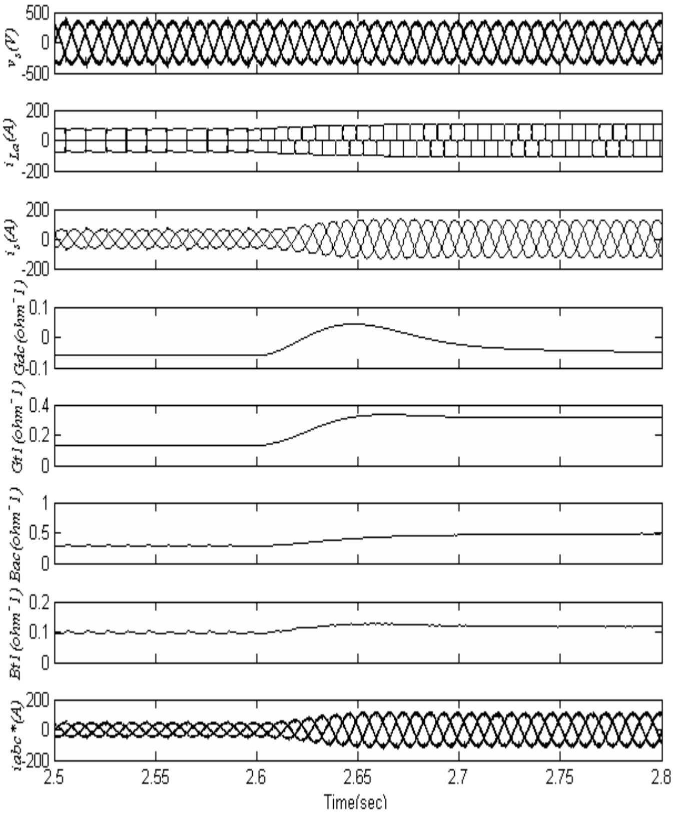


Fig. 5 Variation of internal control parameters under varying nonlinear loads in ZVR mode

B. Performance of DSTATCOM in PFC Mode

The performance of DSTATCOM in PFC mode under varying loading condition is shown in Fig. 6. The performance variables are PCC phase voltages (v_s), supply currents (i_s), load currents (i_{La},i_{Lb},i_{Lc}), shunt currents (i_{fa},i_{fb},i_{fc}) and DC link voltage (V_{dc}) which are shown under load variations (t =2.6s). Before period (t =2.6 s) load is unbalanced but the l supply current remains balanced. At this time, load is connected in phase 'a' which causes momentary dip in DC link voltage. Moreover, it is recovered within some cycles. It is also observed that THD in phase voltages (v_s) and the supply currents are found to be 4.63% and 1.62% respectively where load current THD is 28.31%.

C. *Performance of DSTATCOM in ZVR Mode*

In ZVR mode, DSTATCOM regulates the PCC voltage by injecting extra leading reactive power through the local loop. It is desired to regulating PCC voltage under dynamic loading conditions. Fig. 8, shows dynamic performance of DSTATCOM which is regulating the PCC voltage. After inserting the load at t = 2.6s, DC link voltage is recovered within some cycles. Another side, The PCC voltage is regulated between 325V to 335.5V. In ZVR mode, apart from voltage regulation DSTATCOM also eliminates the harmonics and balances load which can be observed from Fig. 8. In both mode of operation, the voltage and current THD are within 5% as per the guidelines of IEEE standard 519.

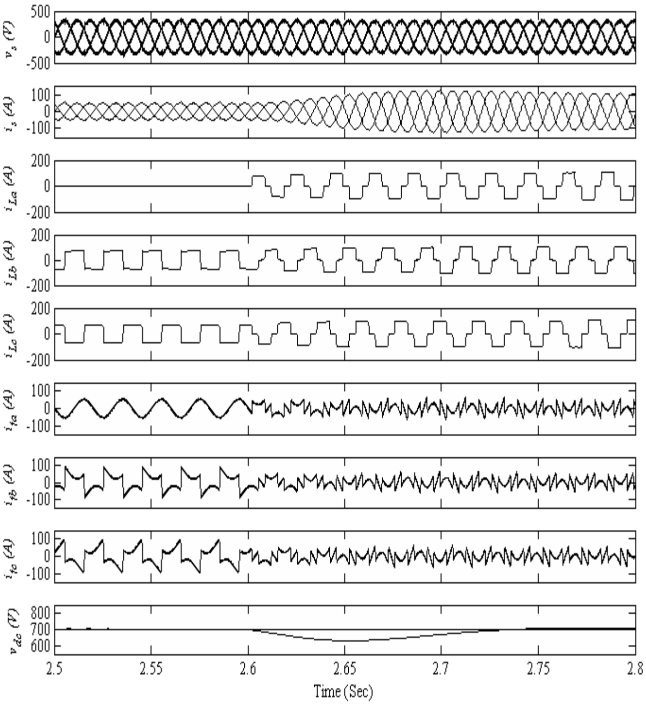
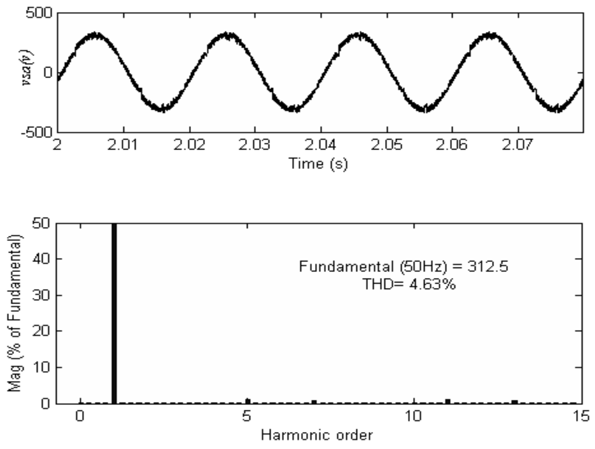
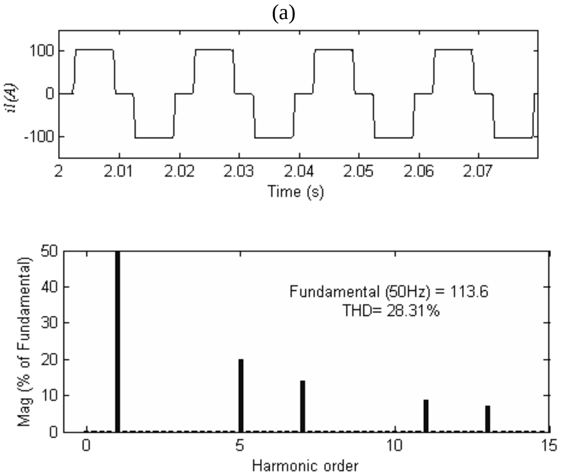


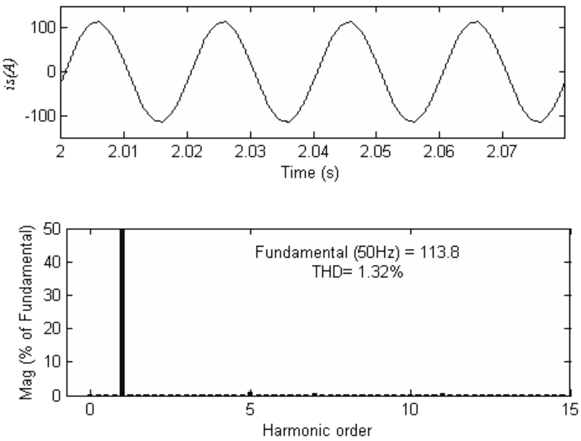
Fig.6 Performance of DSTATCOM in PFC mode



(a)



(b)



(c)

Fig. 7 Waveform Distortion (THDs) (a) PCC phase voltage (b) Load current (c) Supply current.

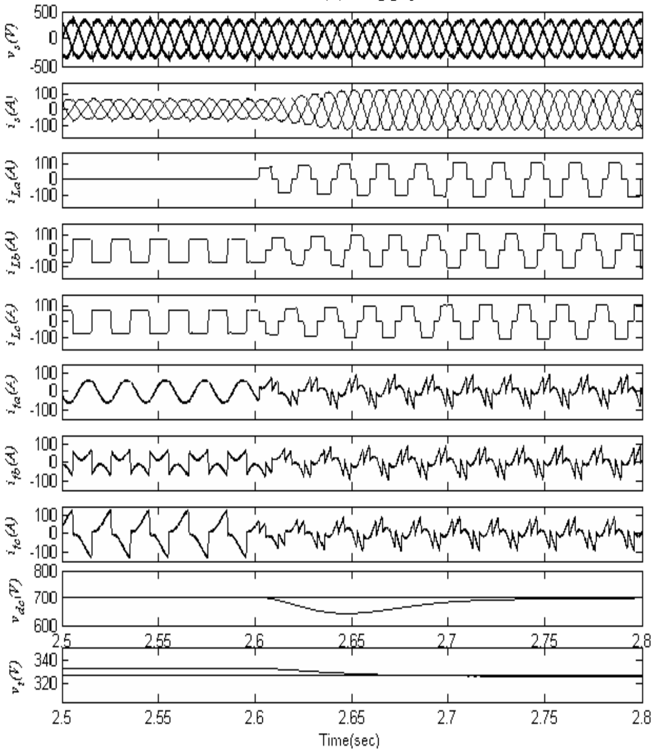
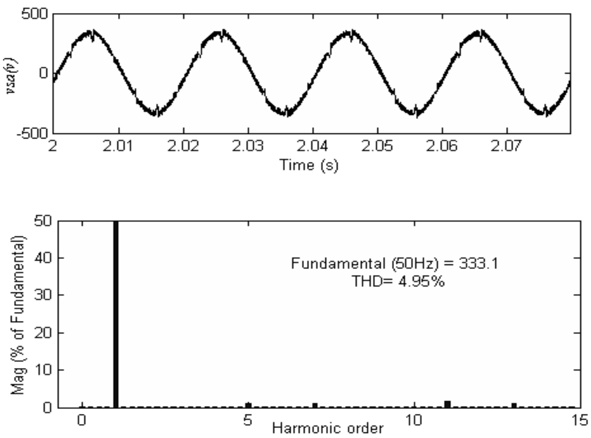
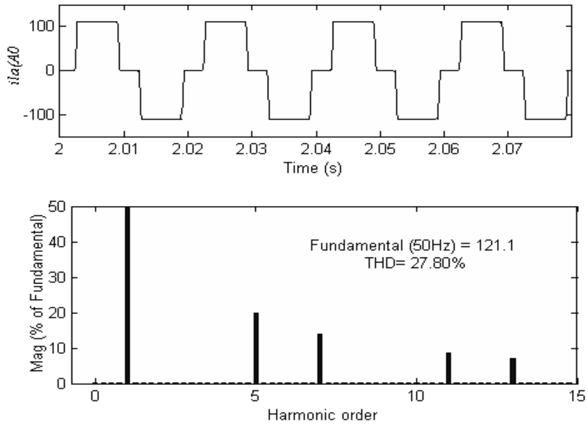


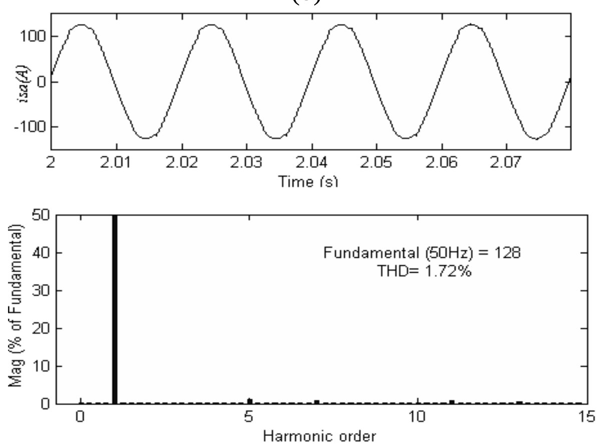
Fig 8 Performance of DSTATCOM in ZVR mode.



(a)



(b)



(c)

Fig 9. Waveform Distortion (THDs) (a) PCC phase voltage (b) Load current (c) Supply current.

V. CONCLUSION

Three phase DSTATCOM has been simulated after the estimation of load physical parameters through SOGI under nonlinear loads. The performances are obtained by the conductance and susceptance estimation of the load circuit. After application of band pass filter, this algorithm can also able to extract desired supply reference currents under distorted voltage conditions. Some functions of DSTATCOM such as harmonic elimination and load balancing are verified in PFC and ZVR mode under time varying nonlinear load. Source voltage and current are satisfying guidelines of IEEE Std.519-1992 with regulated DC and AC bus voltage. The structure of this algorithm is simple and does not involve any complex calculations or stability issues.

APPENDIX

AC supply: Three phase, 400 V(L-L), 50 Hz; source impedance: R_s=0.08Ω, L_s=1.8 mH; Load-three phase diode rectifier with RL load (current fed type): 5Ω, L=200mH; Ripple filter: R_f=6 Ω,C_f=10μf; DC bus capacitance (C_{dc}) =8000 μf; Reference DC bus voltage (V_{dc}) =700V; Interfacing inductors (L_f) =2mH; DC bus PI controller k_{dp} = 0.4 ,k_{di} = 0.35 ; PCC voltage PI controller k_{pt} =7.2, k_{it} =5.5, Frequency band for band pass filter = 30-70Hz, Cut off frequency of low pass filter = 10 Hz.

REFERENCES

[1] C. Sankaran, Power Quality, CRC Press, New York, 2001.

[2] J. Arrillaga and N. R. Watson, Power System Harmonics: John Wiley and Sons, 2004.

[3] Hirofumi Akagi, Edson Hirokazu Watanabe and Mauricio Aredes, Instantaneous Power Theory and Applications to Power Conditioning, Willey Interscience, New Jersey, 2007.

[4] IEEE Recommended Practices and Requirement for Harmonic Control on Electric Power System, IEEE Std.519, 1992.

[5] IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Std.1159, 1995.

[6] B. Singh, G. Bhuvaneswari and S.R. Arya,"Review on power quality solution technology," Journal of Asian Power Electronics, vol. 6, no. 2, pp. 19-27, Dec 2012.

[7] Arindam Ghosh and Gerard Ledwich, Power Quality Enhancement Using Custom Power Devices, Springer International Edition, Delhi, 2009.

[8] Bhim Singh and Sabha Raj Arya, "Design and control of a DSTATCOM for power quality improvement using cross correlation function approach,"International Journal of Engineering, Science and Technology, vol. 4, no. 1, pp. 74-86, 2012.

[9] B. Singh, P. Jayaprakash, D. P.Kothari, A. Chandra and K. Al-Haddad, "Comprehensive Study of Three Phase DSTATCOM Configurations,"Accepted for publication in IEEE Transactions on Industrial Informatics.

[10] S. K. Khadem, M. Basu, and M. F. Conlon, "Harmonic power compensation capacity of shunt active power filter and its relationship with design parameters," IET Power Electronics, vol. 7, pp. 418-430.

[11] Janusz Mindykowski, Xiaoyan Xu and Tomasz Tarasiuk,"A new concept of harmonic current detection for shunt active power filters control,"Journal of Measurement, vol. 46, pp. 4334–4341, 2013.

[12] B. Singh, S.R. Arya and C. Jain," Simple peak detection control algorithm of distribution static compensator for power quality improvement,"IET Power Electronics, vol.7, no.7, pp.1736-1746, July 2014.

[13] S. Bhattacharya and D. Divan,"Synchronous frame based controller implementation for a hybrid series active filter system,"in Proc. of Thirtieth IAS Annual Meeting, 1995, pp. 2531-2540.

[14] N. Mendalek and K. Al-Haddad,"Modelling and nonlinear control of shunt active power filter in the synchronous reference frame,"in Proc. of Ninth International Conference on Harmonics and Quality of Power, 2000, pp. 30-35.

[15] A. M. Massoud, S. J. Finney, and B. W. Williams,"Review of harmonic current extraction techniques for an active power filter,"in Proc. of 11th International Conference on Harmonics and Quality of Power, 2004, pp. 154-159.

[16] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement,"IEEE Transactions on Industrial Electronics, vol. 46, No. 5, pp. 960-971, 1999.

[17] M. I. M. Montero, E. R. Cadaval and F. N. B. Gonzailez,"Comparison of control strategies for shunt active power filters in three-phase four-wire systems,"IEEE Transactions on Power Electronics, vol. 22, No. 1, pp. 229-236, 2007.

[18] Naimish Zaveri and Ajitsinh Chudasama,"Control strategies for harmonic mitigation and power factor correction using shunt active filter under various source voltage conditions," Journal of Electrical Power and Energy Systems, vol. 42, pp. 661–671, 2012.

[19] S.R. Arya and Bhim Singh,"Power quality improvement under nonideal AC mains in distribution system, Journal of Electric Power Systems Research, vol. 106, pp. 86– 94, 2014.

[20] L.P. Kunjumuhammed and M.K. Mishra,"A control algorithm for single-phase active power filter under non-stiff voltage source," IEEE Transactions on Power Electronics, vol.21, no.3, pp.822-825, May 2006.

[21] Zeliang Shu, Yuhua Guo and Jisan Lian,“Steady-state and dynamic study of active power filter with efficient FPGA-based control algorithm,”IEEE Transactions on Industrial Electronics, vol.55, no.4, pp.1527-1536, April 2008.

[22] M. Ciobotaru, R. Teodorescu, and F. Blaabjerg,“A new single-phase PLL structure based on second order generalized integrator,”in Proc. of Power Electronics Specialists Conference, 18-22 June 2006, pp.1-6.

[23] S. Golestan, M. Monfared, and J. M. Guerrero,“Second order generalized integrator based reference current generation method for single-phase shunt active power filters under adverse grid conditions,” in Proc. of Power Electronics, Drive Systems and Technologies Conference (PEDSTC), 13-14 Feb. 2013, pp. 510-517.

[24] P. Rodriguez, A. Luna, R. l. S. Munoz-Aguilar, I. Etxeberria Otadui, R. Teodorescu, and F. Blaabjerg,“A stationary reference frame grid synchronization system for three-phase grid-connected power converters under adverse grid conditions,”IEEE Transactions on Power Electronics, vol. 27, No. 1, pp. 99-112, January 2012.

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