PHOTOVOLTAIC BASED SHUNT ACTIVE POWER FILTER USING P-Q THEORY FOR ENHANCING THE POWER QUALITY

R. BALAMURUGAN[1], R. NITHYA[2]

[1,2] Electrical and Electronics Dept, K.S.Rangasamy College Technology, Tiruchengode, Tamil Nadu, India
drnrbals@gmail.com, nithibals@gmail.com

Abstract: *This paper proposes a three phase shunt active power filter with photovoltaic array and battery, incorporated with DC-DC boost converter. The filter consists of a three phase voltage source PWM converter with a DC capacitor at the input side. It provides source harmonic reduction with reactive power compensation for loads. The PV array is connected to VSC (Voltage Source Converter) with the help of boost converter in order to maintain the load. The instantaneous p-q theory based control algorithm is proposed for the shunt active power filter. In this algorithm, the PI controller is used to regulate the DC link capacitor voltage of the converter with respect to the reference value and the reference current calculation is done according to it. The hysteresis PWM current controller gives the switching to the converter. The effectiveness of the proposed system is verified by using the MATLAB/Simulink software.*
Keywords: *Photovoltaic,Shunt Active power filter, Voltage source converter, p-q theory, Total Harmonic Reduction.*

1. Introduction

Due to the increasing power demand, technology advancement and environmental issues, systems based on renewable energies are rapidly developing nowadays. Recently many of the researches are aimed at using this renewable system to provide power quality at the utility side of the distributed systems [1]. Photovoltaic (PV) cell or solar cell, fuel cell (FC), wind power are major types of renewable energy sources. From the above sources the PV cell and fuel cell are the low DC voltage generating systems. For getting the required voltage PV is the right choice and can be connected in series to get the necessary DC voltage. This generated DC voltage from the PV array is again increased by using the DC/DC converter from low voltage to high voltage, according to the need of application.

The distribution systems are always facing the power quality problem with the intrusion of nonlinear loads. Some of the industrial and commercial loads with non linearity are personal computers, electronic lighting ballasts, variable and adjustable speed drives, electronic house hold appliances, etc. These loads create the power quality problems like harmonics in source current, high neural currents, unbalanced loads and high reactive power compensation, etc. The solution for the above power quality issues are provided by many compensators like shunt active power filter (SAPF), dynamic voltage restorer (DVR) and unified power quality conditioner (UPQC), etc. [2]. Even though all these compensators are well known for its merits, but all suffers by its own drawbacks like usage of high passive elements, increase in size, more losses, slow response, etc. But compared to all the above devices, the SAPF has faster response with full current and voltage compensation. There are different topologies and control techniques of SAPF are available in the literature [3], for mitigating the current harmonics, reactive power compensation and load balancing [4]. Among such, the single phase VSC with instantaneous *p-q* theory [5] is most suitable for compensation of current and voltage under harmonics condition.

The objective of this paper is to maintain the DC link voltage of the VSC to provide continuous compensation current and voltage. The main purpose of the PV array is to drive the single switch IGBT (Insulated Gate Bipolar Transistor) boost converter for high voltage to maintain the voltage at DC link side. For continuous compensation, the PV is used as the source for boost converter in day time and battery/ FC in night time. If the compensation is not required or during the excess power of PV, battery is charged. The maximum power point algorithm is not discussed in this paper and the boost converter uses PWM (Pulse Width Modulation) technique for utilizing constant input from source.

2. Design of SAPF

The The boost converter fed single phase VSC connected with nonlinear loads at the Point of Common Coupling (PCC) is shown in Figure 1. The single phase

Received on: 12.06.2014
Accepted on: 09.07.2015

VSC [6] consists of single switch IGBT, inductors, DC link capacitor. The voltage across the DC link capacitor [4], [7] can be calculated by using the formula,

$$V_{dc} = \frac{2\sqrt{2}V_L}{\sqrt{3}}\left(\frac{1}{M_a}\right) \quad (1)$$

Where Ma is the modulation index and its value is 1, VL is the line voltage. The Vdc obtained is 653.197 V for VL= 400 V and it is chosen as 670 V.

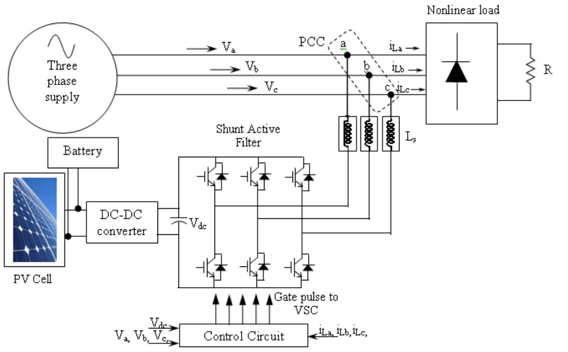

Figure1. Proposed three phase three wire VSC based on PV

$$C = \frac{6V_{ph}(\alpha I_{ph})T}{(V_{ref}^2 - V_{o1}^2)} \quad (2)$$

where: Vref is the reference DC voltage and Vo1 the minimum voltage level of DC bus, α the overloading factor, Vph the phase voltage, Iph the phase current, and T the time by which the DC bus voltage is to be recovered. The value of capacitor is calculated as 2324 µF by considering the values for Vref = 670 V, Vo1 = 660 V, Vph = 400/√3 =230.94 V, T = 300 µs and the value of Iph, α is 57.2 A and 1.3 respectively. So the capacitor value is chosen as 2500 µF. The VSC is connected to the three phase lines at the PCC through the star/delta transformer. The primary winding voltage of the transformer is selected as 230 V for the line to line voltage of 400 V. The voltage ratio of the transformer is 1:1. The secondary voltage is also chosen like the same primary voltage.

3. Modeling of PV

A PV cell is a semiconductor material and it works on the photo voltaic effect. A group of PV cells are connected in series to meet out the required voltage and current [8]. The equivalent circuit of the PV cell is shown in the Figure 3. The voltage produced by PV cell depends on factors like solar irradiation level and temperature with respect to the time to time weather conditions, as it is shown in Figure 2. The Table 1 shown below shows the solar radiation in Tamil Nadu (TN) in the year 2012-2013 and the annual radiation is 5.44 kWh/m2.

The first page of the manuscript must contain the title of the paper, author(s) name(s) and affiliation(s) all centered on the top of the page and spanning both columns. The title must be written using 14-point Times, boldface type with single spacing. Initially capitalize the title except for articles, coordinate conjunctions, or prepositions. Full names of authors should be given. There must be one-line separation between the title and author name(s), and two-line separation between the authors and their affiliation(s). A one-line separation is needed between the author affiliation(s) and the abstract.

Table 1. Temperature observed in TN during the year 2012-2013

Month	Temperature in ° C		kWh/m²
	Max	**Min**	
Aug-12	34.2	21.3	5.21
Sep-12	34	20.6	4.78
Oct-12	35.2	19.9	4.4
Nov-12	34.3	18.5	4.32
Dec-12	32.4	18.8	4.78
Jan-13	31.3	17.6	5.5
Feb-13	32.5	21.7	6.4
Mar-13	38	23.1	6.76
Apr-13	36.4	19.8	6.83
May-13	35.2	20.15	6.8
Jun-13	35.7	19.83	5.9
Jul-13	36.5	20.75	4.67
Aug-13	34.8	20.3	4.43
Average	34.65	20.17	5.44

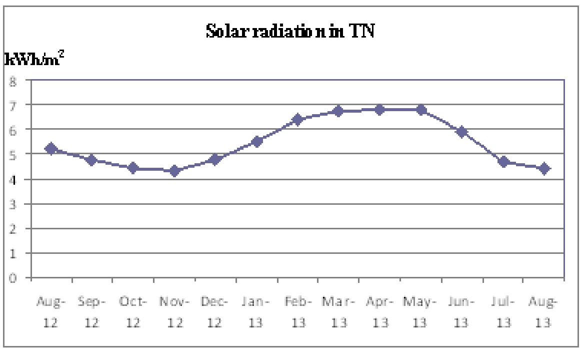

Figure 2. Solar radiation in Tamil Nadu during the year 2012-2013

Table 2. Electrical Characteristics of SHARP ND-Q250F7 solar panel

Maximum power (Pmax)*	250W
Tolerance of P_{max}	+5%/-0%
Type of the cell	Polycrystalline Silicon
Cell Configuration	60 in Series
Open circuit Voltage(V_{oc})	38.3V
Maximum Power Voltage(V_{pm})	29.8V
Short Circuit Current(I_{sc})	8.90A
Maximum Power Current (I_{pm})	8.4A
Module Efficiency(%)	15.3%
Temperature Coefficient(P_{max})	-0.485%/◦C
Temperature Coefficient (V_{oc})	-0.36%/◦C
Temperature Coefficient (I_{sc})	0.053%/◦C

The PV parameters are taken from the SHARP ND-Q250F7 datasheet which is having the illumination of 1 kW/m2 solar irradiance at a cell temperature of 25°C. The electrical characteristic of the PV model is given in the Table 2.

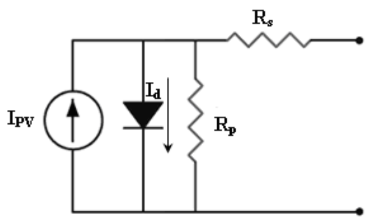

Figure 3. Equivalent model of PV cell

By applying Kirchoff's current law to this circuit

$$I = I_{sc} - I_d \quad (3)$$

where:

Isc is the short circuit current i.e., equal to the photon generated current

Id is the current shunted through intrinsic diode.

The diode current I_d is given by the Schottky's diode equation

$$I_d = I_o(e^{qv/KT} - 1) \quad (4)$$

where:

Io is the diode saturation current (A)

q is the electron charge [1.602 $\times 10^{-19}$ C]

k is the Boltzmann constant [1.3806 $\times 10^{-23}$ J/K]

V is the voltage across the PV cell

T is the junction temperature in kelvin (K)

Combining the equations (3) and (4),

$$I = I_{sc} - I_o(e^{qv/KT} - 1) \quad (5)$$

The reverse saturation current Io is constant under constant temperature. Now I= 0 substitute in equation (3) and consider the series resistance Rs and shunt resistance Rp, the equation becomes

$$I = I_{sc} - I_o(e^{qv/KT} - 1) - (V + IR_s)/R_P \quad (6)$$

Practical arrays are composed of several connected photovoltaic cells and the observation of the characteristics at the terminals of the photovoltaic array requires the inclusion of additional parameters to the basic equation (3).

$$I = I_{PV} - I_o(\exp\left(\frac{V + IR_S}{V_t a}\right) - 1) - ((V + IR_S)/R_P) \quad (7)$$

where:

a is the diode ideality constant

$V_t = \dfrac{N_s KT}{q}$, is the thermal voltage of array with Ns cells connected in series.

The equations from (3) to (7) are used to simulate PV model in MATLAB/Simulink.

The proposed PV based VSC operates in three modes viz,

Mode1: Compensation by PV in day time, in this mode the voltage from PV arrays operates the single switch boost DC-DC converter fed VSC which compensates the source current as well as charges the battery (48 V).

Mode2: Continuous Compensation by PV, in this mode continuous source current compensation is provided by PV based single switch boost DC-DC converter without charging the battery.

Mode3: Compensation in night time, in this mode battery / FC supplies the boost converter to provide compensation.

4. Control of Single switch boost converter

The single switch boost converter is used to increase the input voltage to get the required output voltage [9]. The PV/ battery based boost converter is shown in the Figure 4. The circuit operation can be explained in two modes [10-11]. In mode 1, the input current is charges the inductor L when the switch S is in ON condition upto a period of T_{ON} and in mode 2, when S is OFF, the inductor discharges. In this mode 2, the inductor voltage adds with the supply voltage and the current is made to flow through the load via Diode (D) for a period of T_{OFF}.

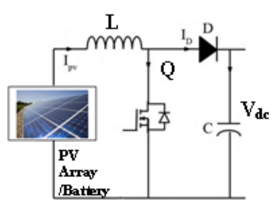

Figure 4. Boost converter

The input voltage to boost converter is 48 V and the output voltage obtained is 670 V in order to maintain the DC link voltage of the Shunt active filter. The switching frequency used is 20 kHz and the value of the inductor is chosen as 0.0151 mH. The value of capacitor C is 2500 μF and it is chosen as per the equation (2). The output voltage Vo equation for the single switch boost converter is given in the equation as follows and it is higher than the input voltage Vs and it is shown in the equation as,

$$V_o = V_s \left(\frac{T}{T - T_{ON}} \right) \tag{8}$$

$$V_o = V_s \left(\frac{1}{1 - D} \right) \tag{9}$$

Dutycycle, $D = \frac{T_{ON}}{T_{ON} + T_{OFF}}$,

$V_o = V_{dc}$, $V_s = V_{in}$ = PV or battery voltage,

Here

T_{ON} - ON period of boost converter switch,

T_{OFF} - OFF period of boost converter switch.

5. Control algorithm of SAPF

Many control algorithm available in the literature viz, instantaneous reactive power theory (p – q theory) [5], synchronous reference frame theory, power balance theory etc., for controlling the shunt active filter by generating a reference current. The instantaneous reactive power theory (p – q theory) is found suitable for the control of three phase VSC [12-13] and the control block is shown in the Figure 5.

The system voltages (vSa, vSb, vSc) and the load currents (iLa, iLb, iLc) are sensed and converted to α-β-0 reference frame by applying the Clarke matrices, shown on equations (10) and (11).

$$\begin{bmatrix} v_{s0} \\ v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_{L0} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{11}$$

After the transformation to α-β-0 reference frame, the p-q theory components are calculated using the equations (12-13),

$$p = v_{s\alpha} i_{L\alpha} + v_{S\beta} i_{L\beta} = \bar{p} + \tilde{p} \tag{12}$$

$$q = v_{s\alpha} i_{L\alpha} - v_{s\alpha} i_{L\beta} = \bar{p} + \tilde{p} \tag{13}$$

Here p is the instantaneous real power, and

q is the instantaneous imaginary power.

$\bar{p}$ - mean value of the instantaneous real power. It corresponds to the energy per unit time that is transferred from the power source to the load. It is the only desired power component that is to be supplied by the power source.

$\tilde{p}$ -alternating value of the instantaneous real power. It is the energy per unit time that is exchanged between the power source and the load.

$\bar{q}$ - mean value of instantaneous imaginary power,

$\tilde{q}$ - alternating value of instantaneous imaginary power. The instantaneous imaginary power (q) corresponds to the power exchanged between the system phases and there is no transference or exchange of energy between the power source and the load [14]. It is the undesirable power component and should be compensated.

In addition to the power components, the capacitor voltage is regulated by using the pr component in the DC side of the shunt active power filter. This regulation is done with a proportional controller [15] and the error between the reference voltage Vref and the voltage measured at the dc side of the inverter Vdc.

$$p_r = k_p (v_{ref} - v_{dc}) \tag{14}$$

For eliminating the harmonics components of active $\tilde{p}$ and reactive power $\tilde{q}$, the reference compensation current is calculated by

$$\begin{bmatrix} i_{ref,C\_\alpha} \\ i_{ref,C\_\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\alpha \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -(\bar{q} + \tilde{q}) \end{bmatrix} \tag{15}$$

$$i_{ref,C\_0} = i_{L0} \frac{1}{\sqrt{3}} (i_{La} + i_{Lb} + i_{Lc}) \tag{16}$$

By taking the inverse Clarke transformation to the currents in the α-β-0 coordinates, the reference compensation currents in the a-b-c coordinates iref_a, iref_b, iref_c are determined and expressed as given below equation 17.

$$\begin{bmatrix} i_{ref,C\_a} \\ i_{ref,C\_b} \\ i_{ref,C\_c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{ref,C\_0} \\ i_{ref,C\_\alpha} \\ i_{ref,C\_\beta} \end{bmatrix}$$

(17)

The hysteresis current controller is employed for each phase to generate the switching patterns for the PV based VSC. It forces a bang – bang instantaneous control to draw the sinusoidal current. This current follows the reference signal within a certain band limits.

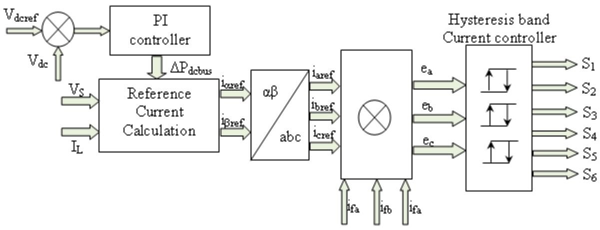

Figure 5. Control Structure for VSC

The actual current ifa, ifb, ifc is compared with reference current iaref, ibref, icref and the resulting error ea, eb, ec is subjected to a hysteresis controller to determine the gating signals of the VSC as shown in Figure 5.

6. Results and discussion

The three phase VSC based shunt active filter is modeled and simulated with the help of MATLAB SIMULINK software and its tool boxes. The source voltage and source current under nonlinear condition and without compensation is shown in Figure 6. The source current without compensation for Phase A and its FFT analysis with harmonic spectrum is shown in Figure 7. The load is changed to two phase load at 0.1 s and for the same, the load currents are made zero between 0.2 to 0.3 s. At 0.3 s, these loads are applied again and the source current is still sinusoidal even if the load current is zero, as shown in Figure 8. From the waveform, it is observed that source current THD is reduced and current is made sinusoidal. The source current for phase A after compensation with its harmonic spectrum is shown in Figure 9. The parameters used for the simulation is given in Appendix A. The solar PV panel data are given in Table 2. The source current THD (Total Harmonic Distortion) for the proposed PV based three Phase VSC shunt active filter is given in Table 3.

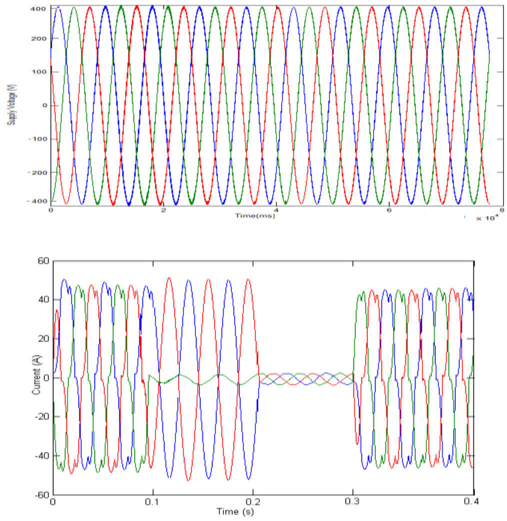

Figure 6. Source current and source voltage before compensation by PV based SAF

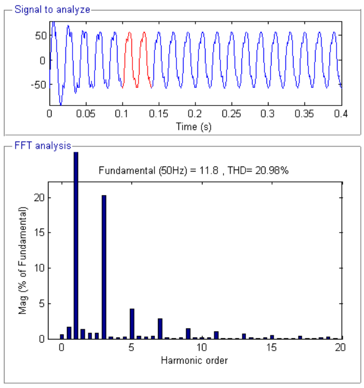

Figure 7. Phase A current waveform taken before compensation

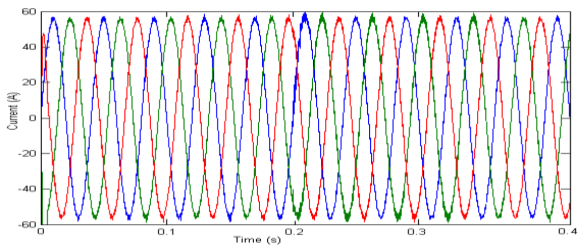

Figure 8. Source current waveform obtained after compensation

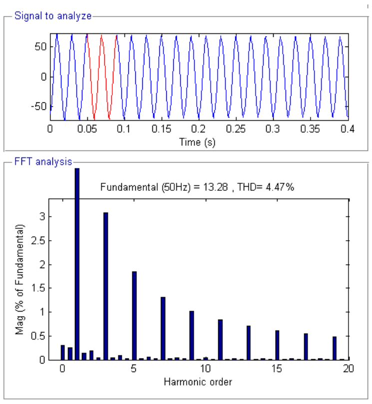

Figure 9. THD measurement of phase A after compensation

Table 3. Source current THD for single switch boost converter fed three phase shunt active filter

Source current THD	**PV fed VSC based shunt active filter**	
	Without compensation	With compensation
Phase A	20.98	4.47
Phase B	19.84	4.78
Phase C	19.82	4.89

7. Conclusions

The working of the photovoltaic/battery based three phase shunt active power filter is simulated in MATLAB SIMULINK software. An instantaneous p-q theory for source harmonic reduction and reactive power compensation has been presented in this paper. The DC link voltage of the shunt active filter is maintained by using the single switch boost converter. The source current THD of the phase A is reduced from 20.98 % to 4.47 %.

Appendix:Simulation Parameters

3-phase AC line voltage	400V,50Hz
Non-linear load	Three phase diode bridge rectifier with R load
AC inductor	3.5mH
DC bus capacitor	2500μF
DC bus voltage	670V
PI controller for DC voltage	K_p =0.01, K_i=1

8. References

[1] Pinto JP, Pregitzer R, Monteiro LFC, Afonso JL., 3-Phase 4-wire shunt active filter with renewable energy interface. *Proc. of IEEE Conference, Renewable Energy & Power Quality*, Seville, Spain (2007).

[2] Joorabian, M., Jassas, N., and Barati, H., Active power filter simulation for nonlinear Load Harmonics Effects Reduction. *Proc. of the 6th International Conference on Industrial Electronics and Applications (ICIEA)*:1376-1380 (2011).

[3] Thirumoorthi Ponnusamy and Yadaiah Narri., Control of shunt active power filter using soft computing techniques. *Journal of Vibration and Control 20(5)*: 713–723 (2012).

[4] Singh BN, Rastgoufard P, Singh B, Chandra A, Haddad K. Al., Design, simulation and implementation of three pole/four pole topologies for active filters. *IEE Electric Power Appl.* 151(4) : 467–76 (2004).

[5] Joao Afonso, Carlos Couto, and Julio Martins., Active Filters with Control Based on the p-q Theory. *IEEE Industrial Electronics Society Newsletter* 47(3): 5-10 (2000).

[6] Premalatha K, Vasantharathna S and Dhivyaah T., Self-excitation system for control of wind turbine driven induction generator using direct torque control, *Journal of Vibration and Control*: 1–20 (2014).

[7] Hongbo Li, Kai Zhang, and Hui Zhao., Active DC-link power filter for single phase PWM rectifiers. *Proc. of the 8th IEEE International Conference on Power Electronics and ECCE Asia (ICPE & ECCE)*, Wuhan, China: 2920 – 2926 (2011).

[8] Jan T, Bialasiewicz., Renewable energy systems with photovoltaic power generators: operation and modeling. *IEEE Transtractions on Industrial Electronics* 55(7): 2752–2758 (2008).

[9] Balamurugan, R. Kamsala K., Nithya R. “Current Fed Full-Bridge Converter with Voltage Doubler For Photovoltaic System Applications” *Journal of Electrical and Electronics Engineering, IU-JEEE,* Vol. 14, No. 2, pp. 1779-1784, 2014.

[10] Wei Jiang, Yu-fei Zhou, Jun-ning Chen ., Modeling and simulation of boost converter in CCM and DCM. *In: Proc. of the IEEE conference*, pp. 288–291(2009).

[11] Abdullah Abusorrah , Mohammed M. Al-Hindawi , Yusuf Al-Turki , Kuntal Mandal Damian Giaouris, Soumitro Banerjee, Spyros Voutetakis, Simira Papadopoulou., Stability of a boost converter fed from photovoltaic source, *Solar Energy 98* : 458-471 (2013).

[12] Juraj Altus, Jan Michalik, Brainislav Dobrucky, and Viet, L.H., Single phase power active filter using instantaneous reactive theory - theoretical and practical approach. *Electrical Power Quality and Utilization Journal XI* (5): 33-38 (2005).

[13] Leszek, S. and Czarnecki., Limitations of the IRP p-q Theory as Control Algorithm of Switching Compensators. In: *Proceedings of the 9th International conference on Electrical Power Quality and Utilisation,* Barcelona (2007).

[14] Leszek, S. and Czarnecki ., On Some Misinterpretations of the Instantaneous Reactive Power p-q Theory. *IEEE Transactions on Power Electronics* 19(3): 828-836 (2004).

[15] Karuppanan P, Kamala Kanta Mahapatra., PI and fuzzy logic controllers for shunt active power filter — A report. *ISA Transactions* 51:163–169 (2012).

R. Balamurugan received his B.E degree in Electrical and Electronics Engineering from Anna University Chennai, in 2005 and he completed his post graduation in Power Electronics and Drives from Anna University Chennai in 2007. He completed his PhD in the area of power electronics from Anna University Chennai, in 2012. Presently, he is working as Associate professor in the Department of Electrical and Electronics Engineering, K.S.Rangasamy College of Technology, Tiruchengode. He has published 30 papers in the International Journals/ Conferences. He is a life member of Indian Society for Technical Education (ISTE), New Delhi. His current interests include Power Electronics, Renewable Energy Systems, DC-DC Converters, Soft Switching, Power Quality, Intelligent Control and PFC Converters.

R. Nithya received her B.E degree in Electrical and Electronics Engineering from Anna University Chennai in 2009 and she completed her post graduation in Power Electronics and Drives from Anna University Chennai in 2013. She is presently working as Assistant professor in the Department of Electrical and Electronics Engineering, K. S. Rangasamy College of Technology, Tiruchengode. She has published 7 papers in the International Journals/ Conferences. Her research interests include Power Converters, Soft Switching Converters, Power Factor Correction and Intelligent Control.