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Fuzzy Based Current Harmonic Suppression and Reactive Power Compensation in a Grid Connected PV System Using Shunt Active Filter

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Abstract: ***The photovoltaic (PV) system exhibits a nonlinear current-voltage (I-V) characteristic that its maximum power point (MPP) varies with solar insolation and temperature. In this paper, a maximum power point tracking (MPPT) method using fuzzy logic control (FLC) is presented. This method is based on the concept of perturbation and observation (P & O) algorithm to track the MPP. The two stage grid interactive PV system described in this paper, which supplies active power as well as provides reactive power compensation and helpful for the reduction of harmonics by using APF. Active power filter has gained more attention because of its excellent performance of harmonic mitigation and reactive power compensation. This paper presents detailed analysis about mitigation of harmonics using APF in shunt active mode. The well known control method, instantaneous real active and reactive power method (p-q) method has been utilized in this paper. Extensive Simulations are carried out with fuzzy controller for p-q method under balanced voltage condition and adequate results were presented. Simulation results validate the harmonics suppression capability of shunt active power filter under active and reactive power control strategy (p-q) with fuzzy controller.***

Keywords: Photovoltaic system, Maximum power point tracking, Boost converter, Fuzzy logic controller, Harmonic elimination and reactive power compensation

1. Introduction

Due to energy crisis and environmental issues such as pollution and global warming effect, Photovoltaic (PV) systems are becoming a very attractive solution. An important characteristic of solar panels is that the available maximum power is provided only in a single operating point given by a localized known voltage and current is called Maximum Power Point (MPP). The tracking process of maximum power point is called maximum power point tracking (MPPT). Another problem is that the position of this point is not fixed but it moves according to the irradiance and temperature. To overcome this, MPPT controllers [1] are used. Such controllers are becoming an essential to PV systems. A significant number of MPPT control schemes have been elaborated since the seventies, one of the most popular algorithms of MPPT is P&O (Perturb and Observe) technique; however, the convergence problem and oscillation are occurred at certain points during the tracking. To enhance the performance of the P&O algorithm, this paper introduces a maximum power point tracking (MPPT) method, using fuzzy logic control (FLC) and hence increase the PV output power.

Power quality problem is the most sensitive problem in a power system. Most of the pollution issues created in power system is because of the nonlinear nature of loads. Due to large number of non-linear equipment and fluctuating loads (such as locomotive, arc furnace, heavy merchant mill, welding equipment etc.), problems of power quality is becoming more and more serious problem with time. To overcome this problem APF (Active power filter) has gained more attention because of its excellent performance of harmonic mitigation and reactive power compensation. At the point of common coupling (PCC), Shunt Active Power Filter produces current of equivalent and opposite in phase to the harmonic current drained by the non-linear load and it is being injected. Hence the currents were made to be pure sinusoidal in nature. To acquire preferred compensation currents the choice of control strategy designed for SAF shows a significant part. The instantaneous active and reactive power (*p-q*) method are control strategies which are extensively used in active filters. The p-q theory is based on the set of instantaneous power defined in time domain. No restrictions are imposed on the current or voltage waveform and it can be applied on the three phase system with or without neutral wire. The p-q theory first transformed three phase voltage and current waveforms from the a-b-c coordinates to α-β-0 coordinates and then defines instantaneous power on these coordinates. The p-q theory uses α-β-0 transformation or Clarke transformation which consists of a real matrix that transforms three phase components into α-β-0 stationary reference frames. In this method reference current is generated from the instantaneous active and reactive power of the non-linear load.

2. PV Array Modelling

PV array consists of several photovoltaic cells in series and parallel combinations. Series connections are responsible for increasing the voltage of the module, whereas the parallel connection is responsible for increasing the current in the array. Series resistance is due to hindrance in the path of flow of electrons from n to p junction and parallel resistance is due to leakage current. The electrical equivalent circuit model of PV cell consists of a current source in parallel with a diode [6] as shown Fig:1

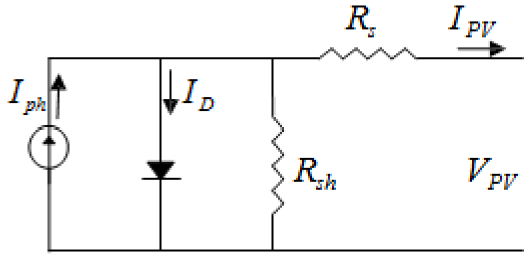

Figure 1: Electrical Equivalent Circuit Model of PV Cell

From the electrical equivalent circuit of the PV cell, PV output current (I_{PV}) is given by

$$I_{PV} = I_{ph} - I_D - I_{sh} \tag{1}$$

Where,

$$I_D = I_0\left(e^{\frac{q(V_{PV}+I_{PV}R_S)}{\eta kT}} - 1\right) \tag{2}$$

And

$$I_{sh} = \frac{V_{PV}+I_{PV}R_S}{R_{sh}} \tag{3}$$

The parameters q, η, k and T denote the electronic charge, ideality factor of the diode, the Boltzmann constant and temperature in Kelvin respectively. I_{ph} is photo current, I_0 is diode reverse saturation current, I_{pv} and V_{pv} are the PV output current and voltage respectively. Thus (1) can be simplified to

$$I_{PV} = I_{ph} - I_0\left(e^{\frac{q(V_{PV}+I_{PV}R_S)}{\eta kT}} - 1\right) \tag{4}$$

For PV array consisting of N_s series and N_p parallel connected PV modules, (4) become,

$$I_{PV} = N_p\left\{I_{ph} - I_0\left(e^{\frac{q(V_{PV}+I_{PV}R_S)}{\eta kTN_S}} - 1\right)\right\} \tag{5}$$

3. Proposed MPPT Controller

P&O algorithm [7] is widely used in MPPT because of their simple structure and high reliability. In this we use only one sensor, that is the voltage sensor, to sense the PV array voltage and so the cost of implementation is less and hence easy to implement. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn't stop at the MPP and keeps on perturbing on both the directions. When this happens the algorithm has reached very close to the MPP and we can set an appropriate error limit or can use a wait function which ends up increasing the time complexity of the algorithm. However the method does not take account of the rapid change of irradiation level (due to which MPPT changes) and considers it as a change in MPP due to perturbation and ends up calculating the wrong MPP. To avoid this problem we can implement this controller using FLC.

4. The Proposed Fuzzy Based MPPT Controller

A drawback of the P&O MPPT technique is that, at steady state, the operating point oscillates around the MPP giving rise to the waste of some amount of available energy and the system accuracy is low. Recently fuzzy logic controllers [8] have been introduced in the tracking of the MPP in PV systems. Fuzzy logic controllers (FLC) are suitable for systems that are structurally difficult to model due to naturally existing non linearity's and other model complexities FLC is relatively simple to design as they do not require the knowledge of the exact model. They do require in the other hand the complete knowledge of the operation of the PV system.

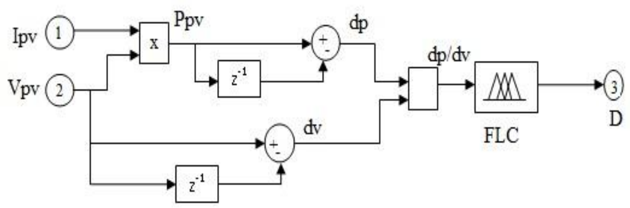

Figure 2: Block diagram of proposed fuzzy based MPPT controller

The proposed Fuzzy logic MPPT Controller, shown in Fig.2 After sampling the PV array voltage and current, ΔP(k) and ΔV(k) are determined as follows:

$$\Delta P(k) = P(k) - P(k-1) \tag{6}$$

$$\Delta V(k) = V(k) - V(k-1) \tag{7}$$

Where P(k) and V(k) are the power and voltage of PV array, respectively.

The ΔP(k)/ΔV(k) obtained using (6) and (7) is given as an input to the FLC that generates the duty ratio (D) as an output for providing the switching pulses to the boost converter in order to operate the PV array at MPP. Depending upon the magnitude of the slope of P-V curve, the proposed FLC divides the input and output into seven linguistic fuzzy sets: negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive big (PB), positive medium (PM) and positive small (PS). The membership functions of the input and output variables are shown in Fig. 5 and Fig. 6 respectively. The membership functions for output duty ratio are so chosen that it maintains the dc link voltage higher than 650 V at the same time operate the PV array at MPP. Hence, proposed fuzzy controller eliminates the need for PI controller for dc-link voltage regulation.

Basically membership value should lies between 0 to 1.The operations performed are fuzzification, interference mechanism and defuzzification. The interference mechanism uses a collection of linguistic rules to convert the input conditions into a fuzzified output. The fuzzy inference is carried out by using mamadani's model. Finally defuzzification is used to convert the fuzzy outputs into required crisp signals and the defuzzification uses the centroid method.

$$z^* = \frac{\int \mu(z).z dz}{\int \mu(z) dz} \tag{8}$$

To compute the output of this FLC which is the duty cycle. The control rules are indicated in **Table 1** with $\frac{\Delta P}{\Delta V}$ as input and D as the output

Table 1: Fuzzy rule table

$\Delta P/\Delta V$	NB	NM	NS	ZO	PS	PM	PB
D	PB	PM	PS	ZO	NS	NM	NB

The membership functions of the input and output variables are illustrated in figures

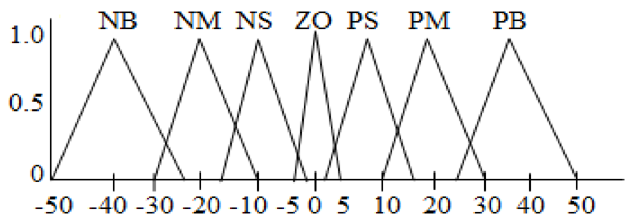

Figure 3: Membership function for input variable (ΔP/ΔV)

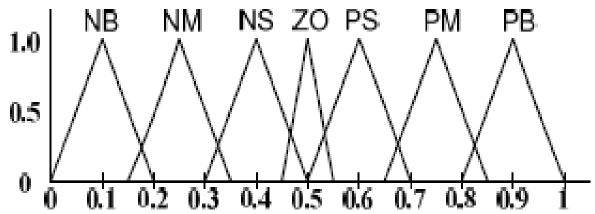

Figure 4: Membership function for output variable (D)

5. Control Strategies of Grid Connected PV System

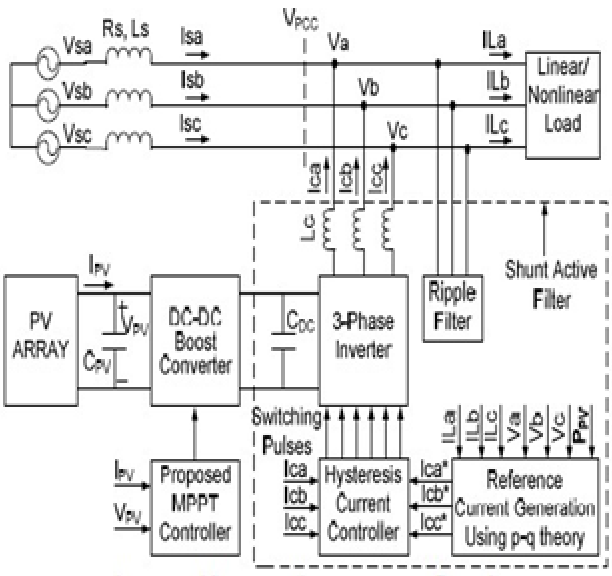

Figure 5: Grid connected PV system configuration

To reduce the harmonics and compensate the reactive power APF is the suitable solution. The harmonic distortions from the non – linear loads are being compensated by the use of the Active Power Filter which uses controlled power electronic switches. At the point of common coupling (PCC), Shunt Active Power Filter produces current of equivalent and opposite in phase to the harmonic current drained by the non-linear load and it is being injected. Hence the currents were made to be pure sinusoidal in nature. To acquire preferred compensation currents the choice of control strategy designed for SAF shows a significant part.

A PV grid connected system incorporating shunt active power filter (APF) feeding the nonlinear load. Two voltage source inverters (VSI) namely; PV inverter and APF inverter are connected to each other in the system. The PV inverter used to convert dc power to ac power while the APF inverter used as the harmonics compensation hence reduce low-frequency ripple problem in the system. The control algorithm for harmonics detection is based on the two theories. Such as p-q theory and d-q theory.

6. Instantaneous Active and Reactive Power (p-q) Method

Instantaneous Active and Reactive Power (p-q) theory proposed by Akagi[9].To determine the compensation current to be injected by the APF system for harmonic elimination and reactive power. p-q theory uses Park's transformation from three-phases (a, b, c) to two phases (a and b). The three phase supply voltages and load currents could be transformed into the a-b. orthogonal coordinates as follows:

$$\begin{bmatrix} v_{s\alpha}(t) \\ v_{s\beta}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{sa}(t) \\ v_{sb}(t) \\ v_{sc}(t) \end{bmatrix} \quad \textbf{(9)}$$

$$\begin{bmatrix} i_{l\alpha}(t) \\ i_{l\beta}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{la}(t) \\ i_{lb}(t) \\ i_{lc}(t) \end{bmatrix} \quad \textbf{(10)}$$

According to p-q theory, determination instantaneous real power $p_1(t)$ and imaginary power $q_1(t)$ is given by the expression:

$$\begin{bmatrix} p_1(t) \\ q_1(t) \end{bmatrix} = \begin{bmatrix} v_{s\alpha}(t) & v_{s\beta}(t) \\ -v_{s\beta}(t) & v_{s\alpha}(t) \end{bmatrix} \begin{bmatrix} i_{l\alpha}(t) \\ i_{l\beta}(t) \end{bmatrix} \quad (11)$$

Where, $p_1(t)$ and $q_1(t)$ contain dc and ac terms. While the dc components $\overline{p}$ and $\overline{q}$, arise due to the fundamental, the ac components p and q are a result of harmonic components. and can be written as:

$$p_1(t) = \overline{p} + \tilde{p} \quad (12)$$

$$q_1(t) = \overline{q} + \tilde{q} \quad (13)$$

To achieve unity power factor and harmonic elimination, the ac term $\tilde{p}$ and the imaginary power $q_1(t)$ have to be eliminated. The compensation power $p_c{*}(t)$ could be obtained by filtering out the ac components from $p_1(t)$ Thus:

$$p_c^*(t) = \tilde{p} \quad (14)$$

And

$$q_c^*(t) = \tilde{q} \quad (15)$$

The reference compensation current in the $\alpha - \beta$ plane is given by the expression:

$$\begin{bmatrix} i^*_{c\alpha}(t) \\ i^*_{c\beta}(t) \end{bmatrix} = \begin{bmatrix} v_{s\alpha}(t) & v_{s\beta}(t) \\ -v_{s\beta}(t) & v_{s\alpha}(t) \end{bmatrix}^{-1} \begin{bmatrix} p_c^*(t) \\ q_c^*(t) \end{bmatrix} \quad (16)$$

and the reference compensation currents for phase a, phase b and phase c could be evaluated using Park's backward transformation and given in matrix form as follows:

$$\begin{bmatrix} i_{ca}^*(t) \\ i_{cb}^*(t) \\ i_{cc}^*(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha}^*(t) \\ i_{c\beta}^*(t) \end{bmatrix} \quad (17)$$

7. Simulation Results

Here simulation results are carried out under different load conditions as well as various controlling techniques.

1. Simulation model of grid connected non-linear load without compensator.
2. Simulation model of grid connected pv system with APF using P-Q theory.

Case-1: Simulation model of grid connected non-linear load without compensator

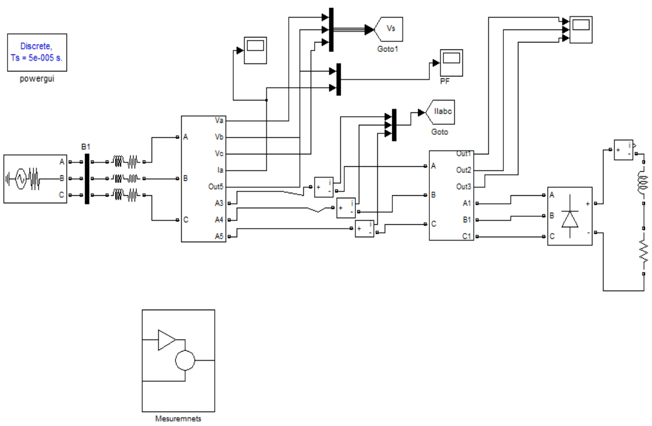

Figure 6: Simulink model of grid connected non-linear load without compensator

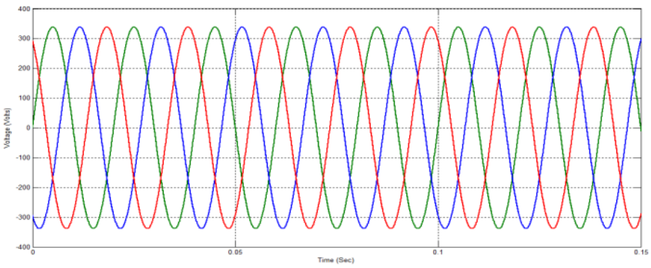

Figure 7: Source voltage of grid connected non linear load without compensator

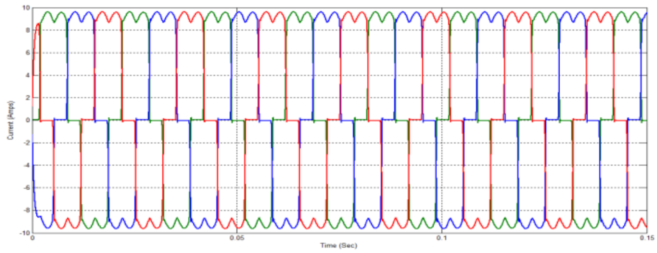

Figure 8: Source currents of grid connected non linear load without compensator

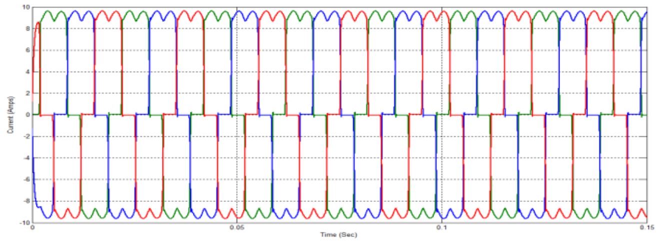

Figure 9: Load currents of grid connected non linear load without compensator

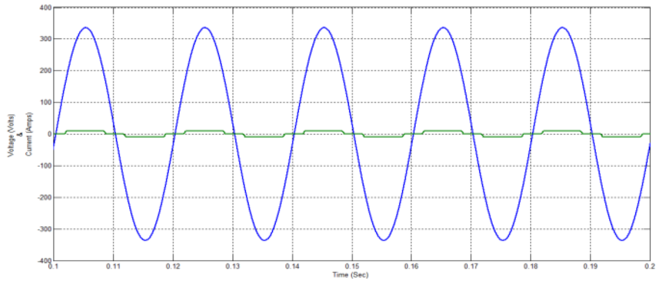

Figure 10: Power factor of grid connected non linear load without compensator

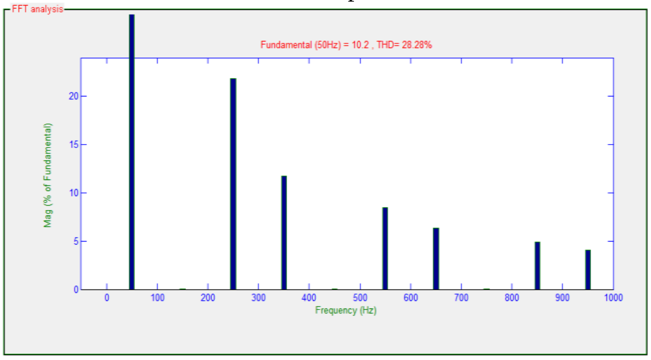

Figure 11: FFT Analysis of source current without compensator, we get THD is 28.28%

Case-2: Simulation model of grid connected pv system with APF using P-Q theory.

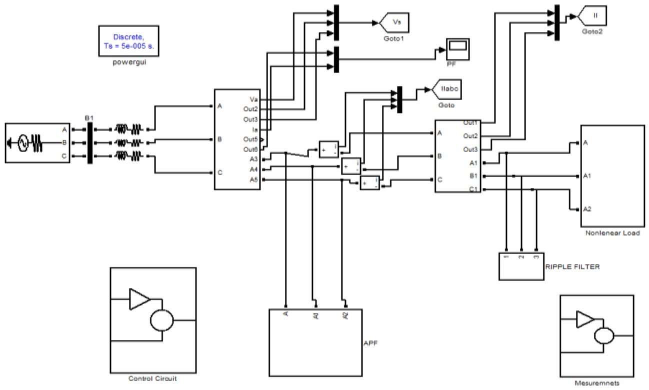

Figure 12: Simulink model of Grid connected PV system with shunt Active Power Filter

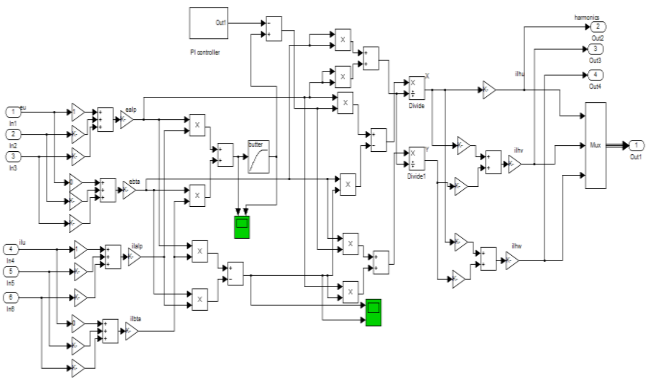

Figure 13: Control circuit by using Ip-q theory

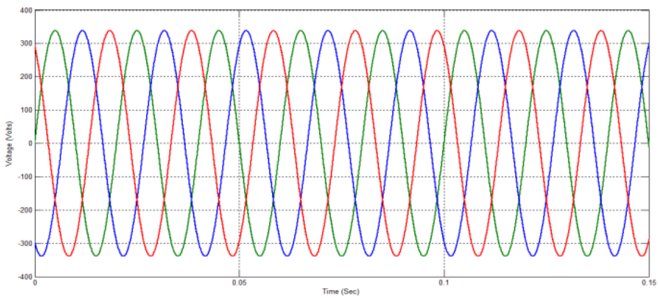

Figure 14: Shows the source voltage of PV based APF under Ip-q control technique

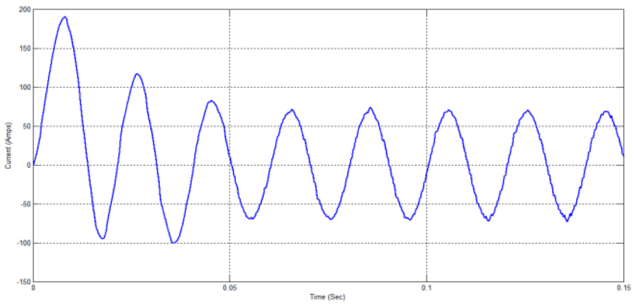

Figure 15: shows the source current of PV based APF under Ip-q control technique

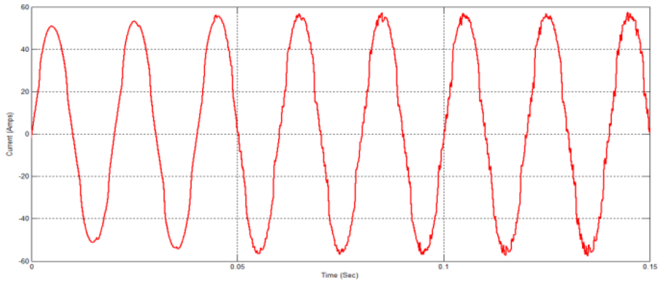

Figure 16: shows the load current of PV based APF under Ip-q control technique

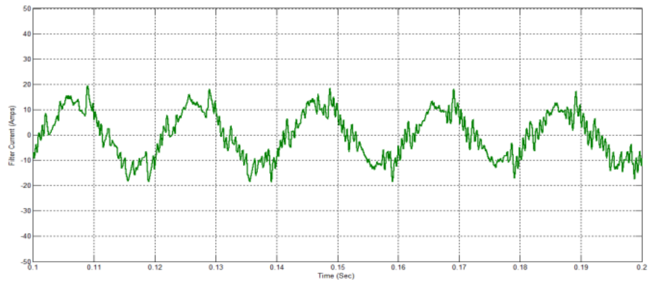

Figure 17: Compensating current supplied by the APF using Ip-q control technique

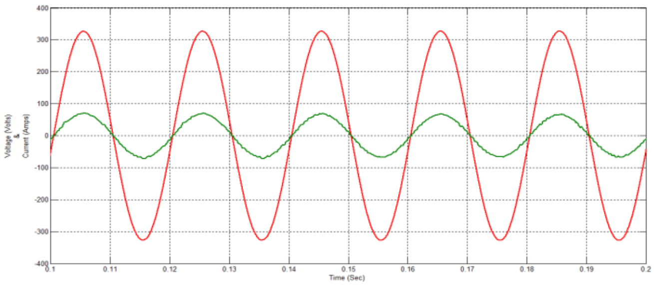

Figure 18: Shows the source side power factor is unity condition due to compensator is active

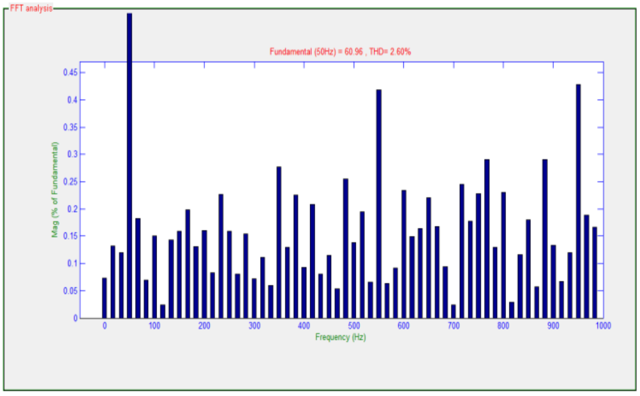

Figure 19: Shows the FFT Analysis of source current with APF using Ip-q control technique, we get THD is 2.60%

8. Conclusion

A photovoltaic (PV) system connected to a three phase grid incorporating with shunt active power filter is successfully done in Matlab/simulink environment. In this work, multi functional grid interactive PV system is demonstrated utilizing a fuzzy logic based MPPT. The PV system is operating at the maximum power point which uses to supply maximum voltage to the grid. . In order to inject the power into the grid the proposed fuzzy controller maintains the DC link voltage within the limit. In addition, the effectiveness of PI controller in maintaining DC bus voltage is discussed. This work stresses worth of suitable control strategy for shunt active filter in a 3-phase, 3-wire distribution system with non-linear load to improve power quality under sinusoidal source voltage conditions. The THD of the source current is being reduced to the considerable quantity as per the IEEE norms. . This is evident by the reduction of source current THD from 28.28% to nearly 2.60%. Controlling the THD of the source current is accomplished through p-q theory.

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