International Journal of Electrical and Electronic Engineering & Telecommunications

ISSN 2319 – 2518 www.ijeetc.com
Vol. 3, No. 1, January 2014

Research Paper

ENHANCEMENT OF GRID INTERACTIVE PV SYSTEM USING A NOVEL FUZZY LOGIC BASED MPPT

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In this project, an MPPT based on simple fuzzy logic control strategy is proposed for two-stage grid interactive PV system. DC-DC boost converter as first stage and three-phase voltage source inverter as second stage. The boost converter stage provides not only the boosting of PV output voltage for grid connectivity but also used as MPP tracker. The second inverter stage is used for multiple functions: (i) active power injection, (ii) harmonic compensation of non linear load connected with the grid, and (iii) reactive power compensation of the load. The additional functionality of the PV inverter as a shunt active power filter increases the overall efficiency of the system. The proposed fuzzy logic MPPT controller accepts single input that is slope of P-V curve (dp/dv) and generates the duty cycle for the boost converter as an output to operate the PV array at MPP and gives the maximum PV power to be injected in the grid. The proposed technique gives faster convergence with less complexity. The PV system is extracting maximum power that varies with the change in solar insolation and temperature. To increase the efficiency of the PV system, it is required to operate at the Maximum Power Point (MPP). The simulation results validate the performance and stability of the grid interactive PV system using the proposed algorithm for active current injection as well as harmonics and reactive power compensation.

Keywords: Photovoltaic system, Maximum power point tracking, Fuzzy logic controller, Harmonic elimination, Reactive power compensation

INTRODUCTION

The worldwide increase in energy demand, rising rate of consumption of nuclear and fossil fuels, increasing awareness about global warming and environmental pollution, etc., have drawn attention towards an alternate non conventional source of energy. Photovoltaic (PV) amongst the renewable energy sources has gained popularity as it is clean and safe, zero fuel cost, negligible maintenance and running cost, zero noise and air pollution One of the challenges in using PV system is

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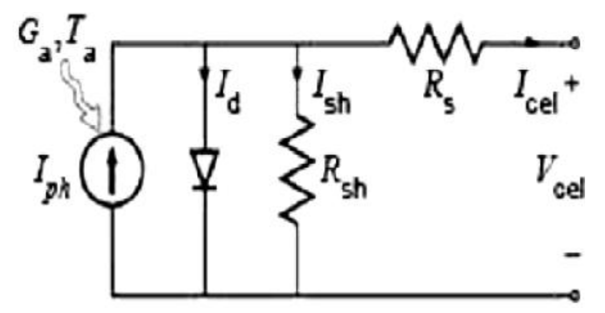
extracting maximum power that varies with the change in solar insolation and temperature. To increase the efficiency of the PV system, it is required to operate at the Maximum Power Point (MPP). Several methods are presented for Maximum Power Point Tracking (MPPT) from PV array (Esram and Chapman, 2007; and Jain and Agarwal, 2007) like Perturb and Observe1 (P&O), incremental conductance, open circuit voltage, short circuit current, ripple based, fuzzy based, - method, etc. Fuzzy logic is becoming popular for MPP tracking which overcomes the disadvantages of conventional methods. The MPPT control using fuzzy logic is simple to implement, gives better convergence speed, and improves the tracking performance with minimum oscillation.

In this paper, an MPPT based on simple fuzzy logic control strategy is proposed for two-stage grid interactive PV system. The proposed fuzzy logic MPPT controller accepts single input that is slope of P-V curve (dp/dv) and generates the duty cycle for the boost converter as an output to operate the PV array at MPP and gives the maximum PV power to be injected in the grid. The proposed technique gives faster convergence with less complexity. The validity and robustness of the proposed algorithm is demonstrated through simulation results.

PV ARRAY MODELLING AND CHARACTERISTICS

The characteristic equation of the PV cell model Icel = f(Vcel, Icel) is obtained by applying Kirchhoff's current law , where Icel [A] and Vcel [V] are the terminal current and voltage of the model respectively.

Figure 1: PV Cell Equivalent Circuit



$$I_{cel} = I_{ph} - I_d - I_{sh} \quad ...(1)$$

The photocurrent Iph [A] is directly dependent on the solar radiation Ga and on the ambient temperature Ta and is expressed by

$$I_{ph} = P1Ga[1 + P2(Ga - G0) + P3(T_j - T0)] \quad ...(2)$$

where $G0$ = 1000W/m² and $T0$ = 298 K correspond to a reference solar radiation and a reference ambient temperature, respectively; $P3$ is the temperature coefficient of the short circuit current Isc; $P1$ (= 1 Am²/W), and $P2$ (= 1 m²/W) are constant parameters which, in this work, were considered equal to one. The cell temperature depends on the junction temperature T J [K] e on the solar irradiation Ga. In this equation *Ta* [°C] is the ambient temperature, and the Normal Operating Cell Temperature (NOCT) parameter is provided by the data sheet of the PV manufacturer with values that usually range is 30 °C

The diode loss current I_d [A], is given by

$$I_d = I_{sat}\left[\exp\left(\frac{q}{A_f N_s k}\frac{V_{cel} I_{cel}}{T_j}\right) - 1\right] \quad ...(3)$$

I_{sat} is the cell reverse saturation current [A]; q is the charge of an electron [C]; A_f(= 1.525) is the ideality factor or emissivity factor of the PV module, which indicates how close the cells are from each other; N_s is the number of cells connected in series; k is the Boltzmann [J/K] constant; R_s is the series resistance.

Since I_{ph} and I_d are not easily obtained, a common practice is to describe the model by means of data 7 sheet parameters such as Voc (open circuit voltage), Isc (short circuit current) and maximum power (Pmax). Hence, by considering short7circuit condition, $Iph \approx Isc$, and by substituting $¢ = q/A_f N_s K$, one can write

$$I_{cel} = I_{sc}\left[1-\left(\frac{I_{sat}}{I_{sc}}\right)\exp ¢\left(V_{cel}+R_s I_{cel}\right)\right] \quad ...(4)$$

and by considering open circuit condition, $I_{cel} = 0$, $V_{cel} = Voc$, one can write

$$V_{oc} = V_{cel}\Big|_{I_{cel}=0} = \frac{1}{¢}\ln\left(\frac{I_{sc}}{I_{sat}}\right) \; or \; ¢ = \frac{1}{V_{oc}}\ln\left(\frac{I_{sc}}{I_{sat}}\right) \quad ...(5)$$

PV Characteristics

The PV model is simulated using Solarex MSX60, 60W PV module. The simulated I-V and P-V characteristics of the Solarex PV module at constant temperature and varying insolation are shown in Figures 2a and 2b respectively. It can be seen from Figure 2a that the decrease in insolation reduces the current largely but voltage fall is small. Figure 2b shows that the reduction in insolation reduces the power largely as both voltage and current are decreasing. The effect of temperature on I-V and P-V characteristics of Solarex PV module is shown in Figures 3a and 3b respectively. It can be seen from Figure 3a that the increase in temperature reduces the open circuit voltage largely but rise in current is very small. Figure 3b shows that the increase in temperature reduces the PV output power as the reduction in the voltage is larger than the increase in current due to temperature rise.

Figure 2: (a) I-V Characteristics, and (b) P-V Characteristics of the Solarex PV Module at Constant Temperature T = 30 °C and Varying Insolation

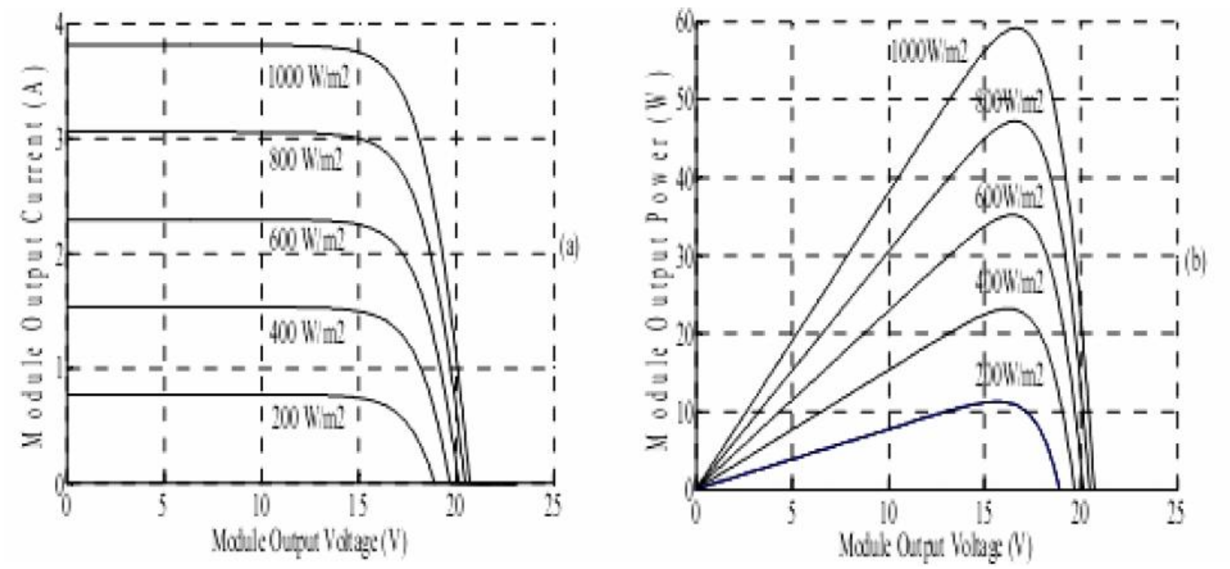
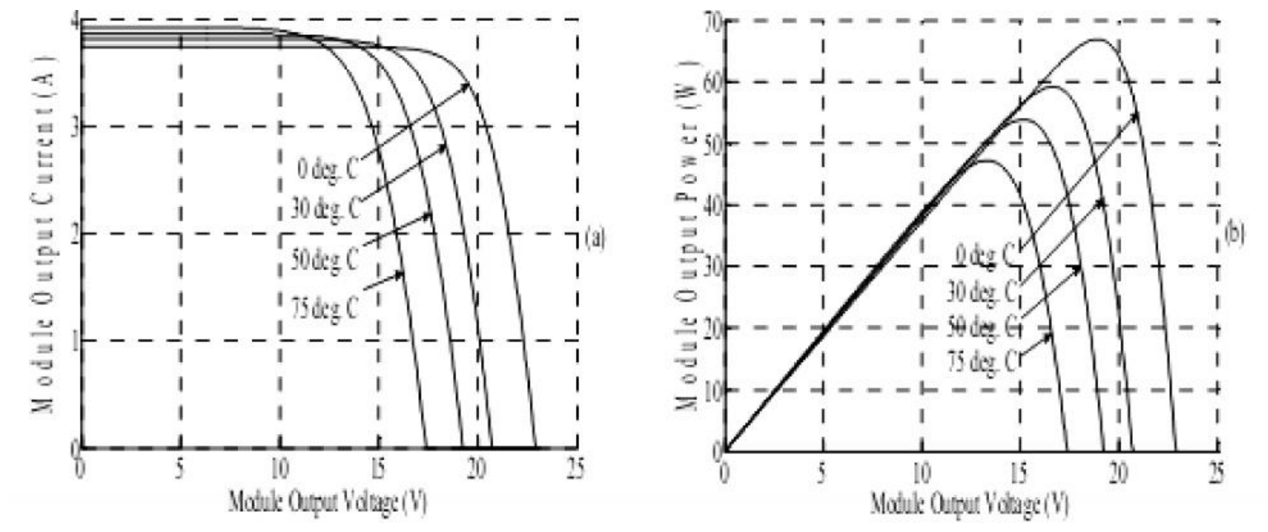


Figure 3: (a) I-V Characteristics, and (b) P-V Characteristics of the Solarex PV Module at Constant Insolation ^{a} =1000 W / m^2 and Different Temperature

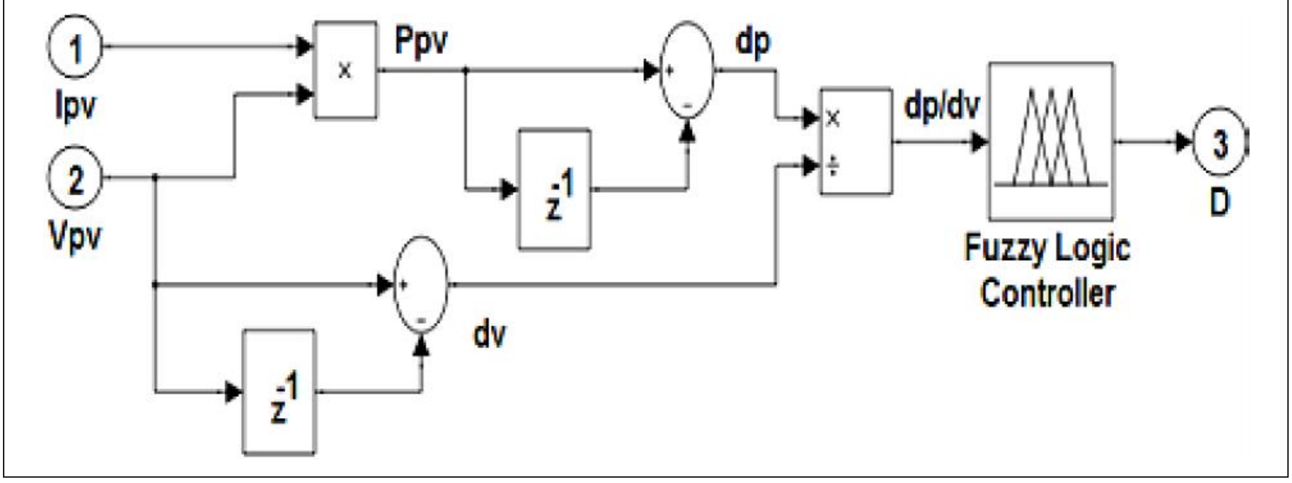


PROPOSED MPPT ALGORITHM

From the simulated I-V and P-V characteristics of the PV module, it can be seen that the characteristics are highly nonlinear. Also, there is single point on P-V curve where the PV can produce maximum power. The MPP changes with change in insolation and temperature. Therefore, an MPPT controller is required to extract maximum available power from the PV array under varying load and changing environmental conditions. This paper proposes a novel fuzzy logic based MPPT controller.

Fuzzy logic can model or control non-linear systems that are difficult to model mathematically. The block diagram of the proposed Fuzzy Logic Controller (FLC) is shown in Figure 4. The major functional blocks of the FLC are described as follows:

Figure 4: Block Diagram of Proposed Fuzzy Based MPPT Controller



Fuzzification

From the prior knowledge of input and output range, the fuzzification process divides the input and output into linguistic fuzzy sets. The proposed FLC takes single input that is the slope of the P-V curve and gives the duty ratio for switching the boost converter as an output. After sampling the *PV* array Voltage and Current, $\Delta P(k)$ and $\Delta V(k)$ are determined as follows:

$$\Delta P(k) = P(k) - P(k-1) \quad ...(6)$$

$$\Delta V(k) = V(k) - V(k-1) \quad ...(7)$$

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

The $\Delta P(k)/\Delta V(k)$ 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 Figures 5 and 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.

Figure 5: Membership Function for Input Variable (aP/aV)

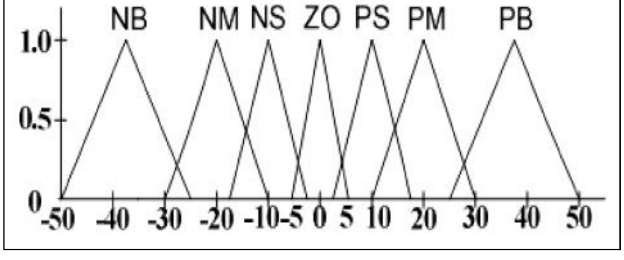
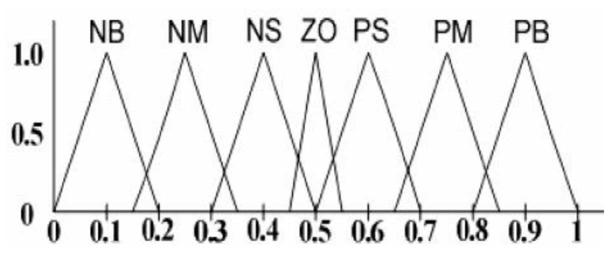


Figure 6: Membership Function for Output Variable (D)



Fuzzy Rule Base

The fuzzy rules should be precisely defined based on the knowledge in order to generate an output duty ratio as per the magnitude of the slope of P-V curve to operate the PV array at MPP. When the slope of P-V curve is positive then to reach towards MPP, the duty ratio of boost converter is decreased in order to increase the PV operating voltage. Similarly, if the slope of P-V curve is negative then to move the operating point at MPP, the duty ratio is increased. The seven rules used for tracking the MPP in the proposed technique are listed in Table 1.

Table 1: Fuzzy Rules

ΔP/ΔV	*NB*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
D	*PB*	*PM*	*PS*	*ZO*	*NS*	*NM*	*NB*

Defuzzification

The deffuzification process generates the single crisp value of output duty ratio (D) from the aggregated fuzzy set that includes a range of output values. The widely used centroid (centre of area) method is used to convert the fuzzy subset of duty ratio (D) to real number. It computes the centre of gravity from the final output fuzzy set, and gives a result which is highly related to all of the elements in the same fuzzy set. It is mathematically represented as

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

where, z^* = D which is the output of fuzzy logic controller, $\int$ denotes an algebraic integration and z is the aggregated fuzzy set of output.

GRID INTERACTIVE PV SYSTEM USING FUZZY LOGIC CONTROLLER

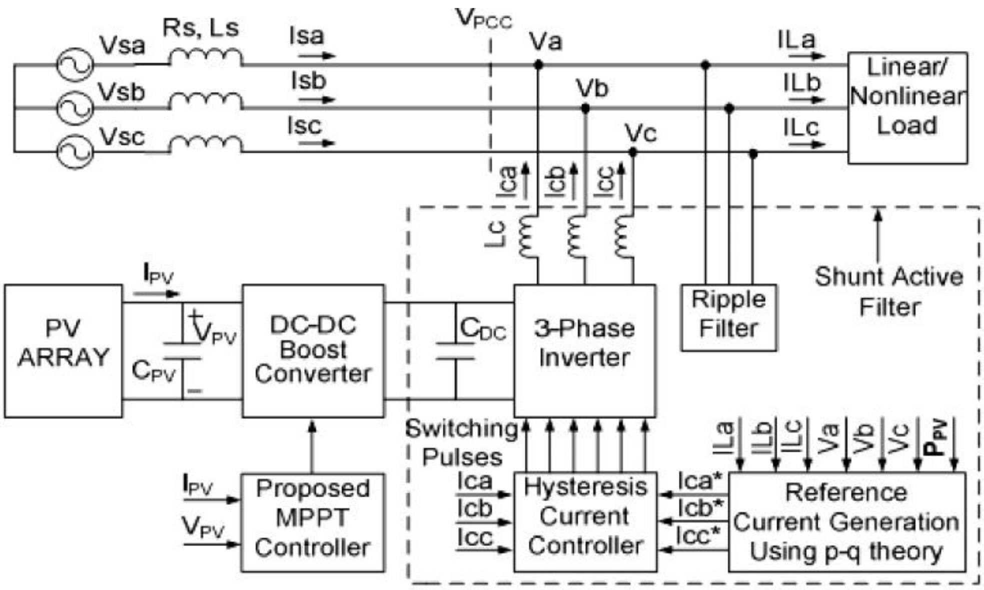
The grid interactive PV system configuration used for simulation study is shown in Figure 7. It consists of two power processing stages: DC-DC boost converter as first stage and three-phase voltage source inverter as second stage. The boost converter stage provides not only the boosting of PV output voltage for grid connectivity but also used as MPP tracker.

By controlling the duty ratio of boost converter using the proposed fuzzy based MPPT controller described in section-III, the current corresponding to maximum power is injected into the grid. The second inverter stage is used for multiple functions: (i) active power injection, (ii) harmonic compensation of non linear load connected with the grid, and (iii) reactive power compensation of the load. The additional functionality of the PV inverter as a shunt active power filter increases the overall efficiency of the system. The inverter switching signals are generated using the current control technique based on hysteresis current controller.

Reference Current Generation

The reference current generator block generates the reference current to be injected into the grid upon sensing the voltage at the Point of Common Coupling (VPCC) and load currents using instantaneous active and reactive power (p–q) theory. For the

Figure 7: Grid Connected PV System Configuration



computation of *p* and *q*, the three phase voltages at the Point of Common Coupling (PCC) and load currents must first be transformed to the stationary two axis (~–) co-ordinates. The instantaneous real and reactive power *p* and *q* are determined using Equations (9)-(13).

$$V_{\sim} \quad = C \times V_{abc} \quad ...(9)$$

$$I_{\sim} \quad = C \times I_{L\,abc} \quad ...(10)$$

where

$$C = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad ...(11)$$

$$p = V_{\sim} \times I_{\sim} + V \quad \times I \quad ...(12)$$

$$q = V_{\sim} \times I \quad - V \quad \times I_{\sim} \quad ...(13)$$

Both instantaneous power quantities *p* and *q* consists of dc and ac components. While the *dc* components $\bar{p}$ and $\bar{q}$, arise due to the fundamental, the ac components $\tilde{p}$ and $\tilde{q}$ are a result of harmonic components. In order to inject active power generated by PV obtained using the proposed MPPT controller and also to provide harmonic as well as reactive power compensation as per the load demand, the reference for active and reactive power are generated according to (14) and (15).

$$p^* = P_{PV} + \tilde{p} \quad ...(14)$$

$$q^* = q = \bar{q} + \tilde{q} \quad ...(15)$$

The ac component $\tilde{p}$ is determined by first extracting $\tilde{q}$, using a very low cut off low pass filter and then subtracting it from *p* obtained using (12). Finally, the reference currents are generated as per (16) and (17).

$$\begin{bmatrix} i_{\sim} * \\ i \quad * \end{bmatrix} = \begin{bmatrix} v_{s\sim} & v_{s} \\ -v_{s} & v_{s\sim} \end{bmatrix}^{-1} \begin{bmatrix} p* \\ q* \end{bmatrix} \quad ...(16)$$

$$\begin{bmatrix} i_{ca} * \\ i_{cb} * \\ i_{cc} * \end{bmatrix} = [C]^{T} \begin{bmatrix} i_{\sim} * \\ i \quad * \end{bmatrix} \quad ...(17)$$

Hysteresis Current Controller

The hysteresis current controller compares the three phase reference currents (i_{ca}*, i_{cb}*, i_{cc}*) generated using (17) with the actual inverter currents (i_{ca}, i_{cb}, i_{cc}) and generates the switching pulses as per the logic given below:

if ($i_{ca} > i_{ca}^* + hb$) leg-a upper switch is OFF and lower switch is ON

if ($i_{ca} < i_{ca}^* - hb$) leg-a upper switch is ON and lower switch is OFF

where, *hb* is the hysteresis band around the reference current which is usually 5% of the maximum current to be injected by the inverter. Similarly, control signals for leg-b and leg-c of the inverter switches are generated.

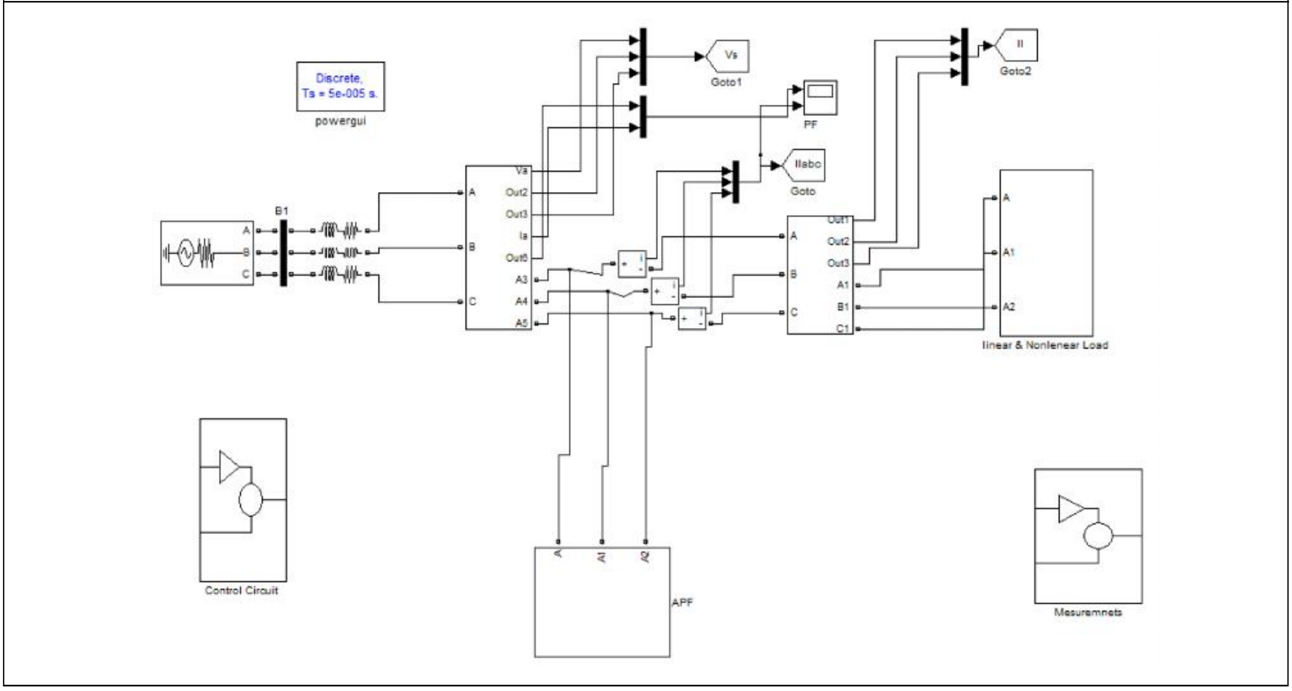
Ripple Filter

The ripple filter as shown in Figure 7 is used to absorb the switching frequency ripples. The ripple filter is a series R-C filter whose component values are so chosen as to absorb the high frequency components in multiple of switching frequency with the constraint that the fundamental current drawn by ripple filter should not exceed 5% of the maximum load current.

SIMULATION MODEL FOR GRID CONNECTED PV SYSTEM USING FLC

The above figure shows the simulation model for grid connected PV system in which their

Figure 8a: Simulation Model for Grid Connected PV System



will be an internal FLC. The below figure shows the in detailed view of the FLC.

Along with fuzzy logic controllers came another technique of implementing M PPT-neural networks, which are also well adapted for microcontrollers. Neural networks commonly have three layers: input, hidden, and output layers. The number of nodes in each layer varies and is user- dependent. The input variables can be PV array parameters like VOC and ISC, atmospheric data like irradiance and temperature, or any combination of these. The output is usually one or several reference signal(s) like a duty cycle signal used to drive the power converter to operate at or close to the MPP. Since most PV arrays have different characteristics, a neural network has to be specifically trained for the PV array with which

Figure 8b: Simulink Diagram of Fuzzy Logic Controller

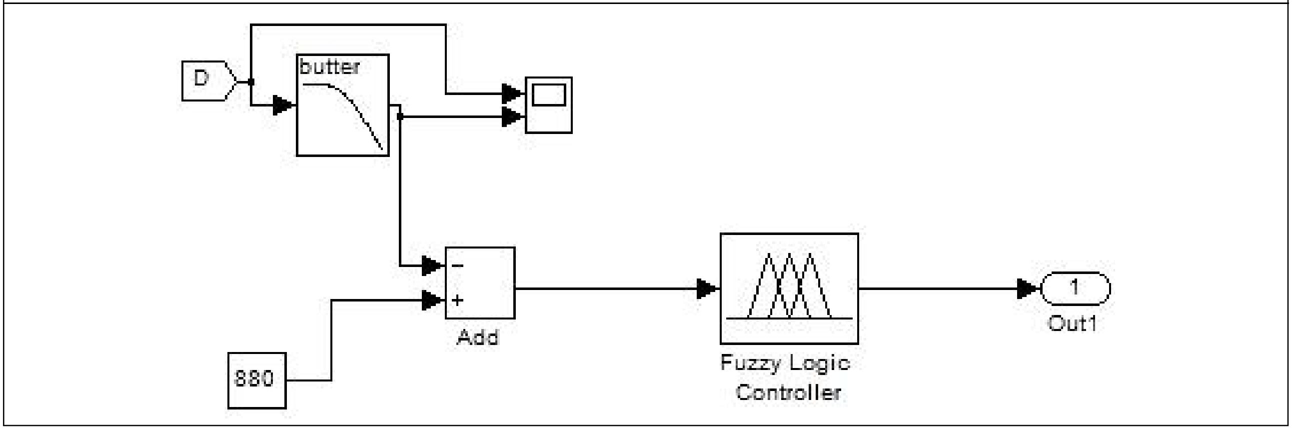
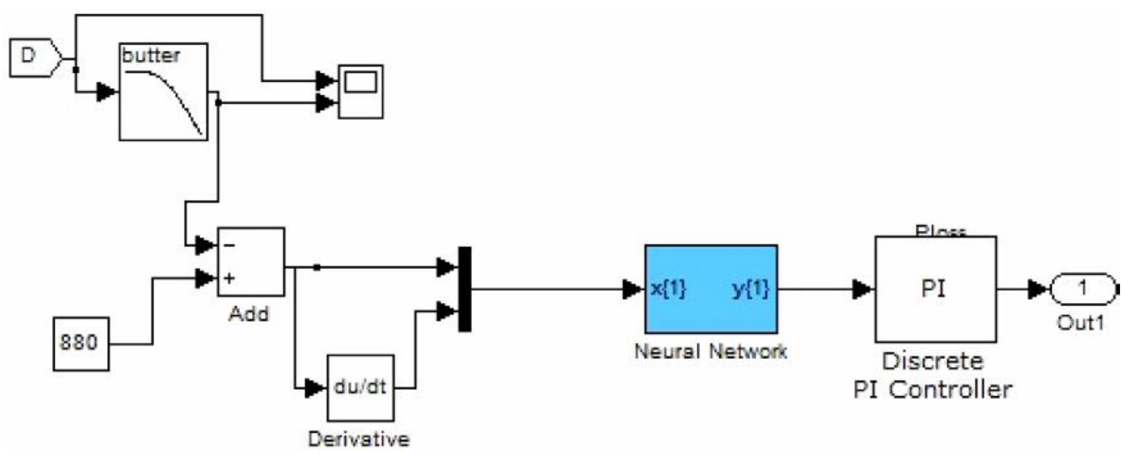


Figure 8c: Simulink Diagram of Neural Network



it will be used. The characteristics of a PV array also change with time, implying that the neural network has to be periodically trained to guarantee accurate MPPT.

SIMULATION RESULTS

The simulation of grid interactive PV system shown in Figure 7 is performed using Matlab/ Simulink. The Solarex MSX60, 60 W PV module is used for simulation that has 36 series connected polycrystalline cells. The PV system of 7.2 kW is developed using 10 parallel connected strings with each string having 12 series connected PV modules. The parameters of the PV system and electrical power system that are used in simulation are given in Tables 2 and 3 respectively. The circuit parameters shown in Table 3 are designed based on the design equations in Zue and Chandra, 2006).

Table 2: Parameters of PV System

Parameter	Value
Open circuit voltage (V_{OC}) of a PV module	21.0 V
Short circuit current (I_{SC}) of a PV module	3.74 A
Module voltage at maximum power point (V_m)	17.1 V
Module current at maximum power point (I_m)	3.5
Maximum Power (P_m) of a PV module	60 W
Reference temperature	25° C
Reference solar radiation (1 sun)	1000W/m^2
No. of series PV modules in a string	12
No. of parallel connected PV strings	10

Table 3: Parameters of Electrical System

Circuit Parameter	Value
L_s, R_s	0.15 mH, 1 mΩ
L_c, L_{boost}	1.2 mH, 0.1 mH
C_{pv}, C_{DC}	1000 μF , 4000 μF
V_p (peak grid voltage)	360V
Ripple filter (R,C)	10 Ω, 20 μF
Linear Load (R-L)	24 Ω, 45 mH
Non-linear Load	3-phase diode bridge rectifier with resistor of 25 Ω Connected across DC side.

In simulation, the performance of proposed algorithm for extracting maximum power from the PV array is analyzed under varying insolation and load conditions. The additional feature of harmonic and reactive power compensation for different load and insolation is also studied.

Performance of MPP Tracking with Step Change in Insolation

The tracking of MPP using the proposed fuzzy logic based MPPT algorithm is shown in

Figure 9. At t = 0, with full insolation the algorithm tracks the MPP point A. When the insolation is reduced to half at t = 0.35 sec, the algorithm moves the operating point from point A to a new MPP point B and when the insolation is reduced to zero at t = 0.5 sec, the algorithm moves the operating point from B to C. It can be seen that the algorithm applies variable step change in duty ratio as per the current operating point that increases the tracking speed.

Figure 9: Tracking of MPP Using Proposed Algorithm for Different Insolation

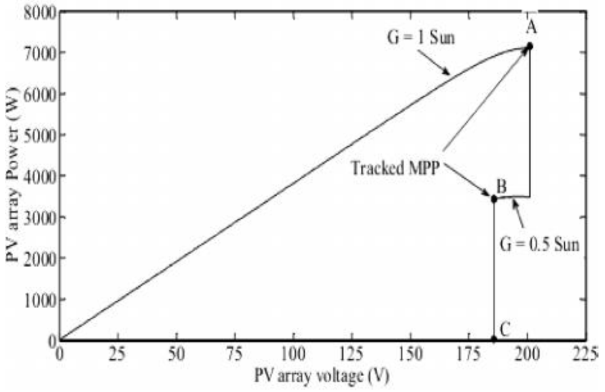
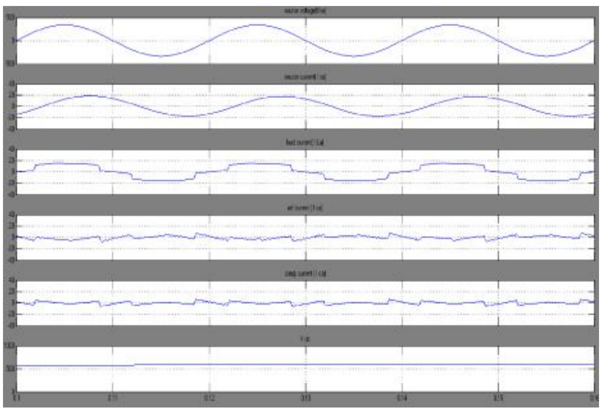


Figure 10: Performance with Constant Insolation and Combination of Linear and Nolinear Load (i) Voltage at the PCC, (ii) Source Current After Compensation, (iii) Load Current, (iv) Reference Current, (v) Compensator Current, (vi) DC Bus Voltage

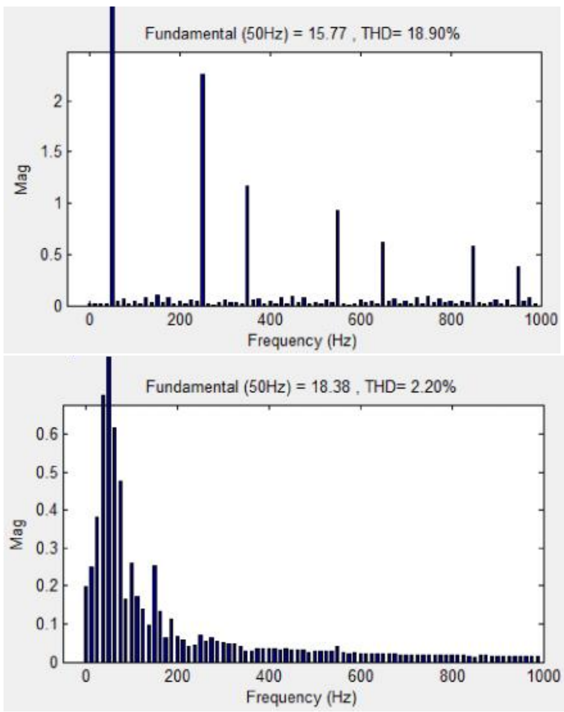


Performance of the System with Constant Insolation and Combination of Linear and Nonlinear Load

Figure 10 shows the performance of the PV system for active power injection as well as harmonic and reactive power compensation for combination of linear and nonlinear load specified in Table 3 with constant insolation of 1000 W/m^2. It can be seen from Figure 10b that the current drawn from the grid is sinusoidal and in phase with the grid voltage as shown in Figure 10a. This verifies the harmonic and reactive power compensation with active current injection.

The Total Harmonic Distortion (THD) of load current is 18.90% as seen in Figure 11a and after compensation the source current THD is reduced to 2.84% seen from Figure 11b which

Figure 11: Magnitude Spectrum of Source Current (a) Before Compensation, and (b) After Compensation



is well below the limit specified in IEEE-519 standard.

Performance with Constant Insolation and Nonlinear Load

Figure 11 shows the harmonic compensation of nonlinear load specified in Table 3 with constant insolation of 1000 W/m^2. It can be seen from Figures 12a and 12b that the grid current is in phase with the grid voltage. The THD of load current is 28.53% as shown in

Figure 12: Performance with Constant Insolation and Nonlinear Load (i) Voltage at the PCC, (ii) Source Current After Compensation, (iii) Load Current, (iv) Reference Current, (v) Compensator Current, (vi) DC Bus Voltage

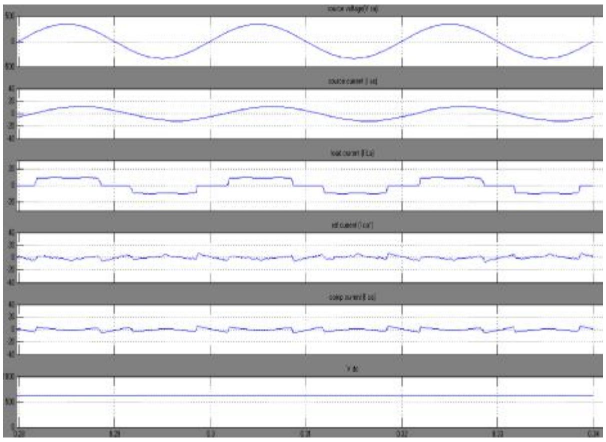


Figure 13: Magnitude Spectrum of Source Current (a) Before Compensation, and (b) After Compensation

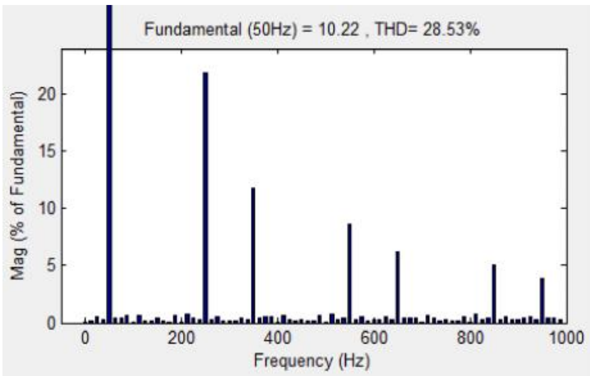


Figure 13 (Cont.)

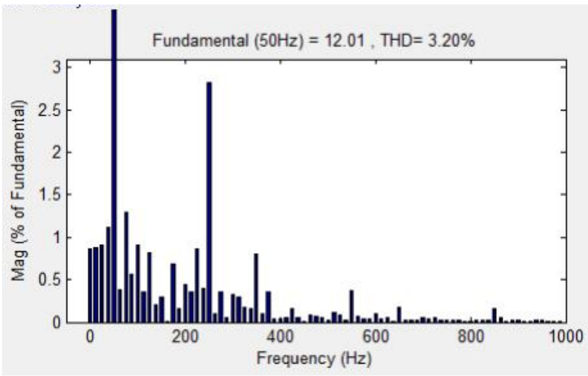


Figure 13a that is reduced to 3.20% in the source current after compensation as seen from Figure 13b.

Performance with Step Change in Insolation and with Non-linear Load

In this part, the performance of the system is analyzed for the shunt active power filter in the absence of sun. At, $t = 0.5$ sec, with non-linear load connected with the system, the insolation is reduced from 500 W/m^2 to zero. It can be seen from Figure 14b that the current drawn from the grid is increased as PV current becomes zero. After $t = 0.5$ sec, the PV system still supplies the harmonic and reactive components of the non-linear load. The THD of source current is 28.75% as shown in Figure 15a before compensation that is reduced to 1.03% after compensation as shown in Figure 15b satisfying the permissible limit of 5%.

Thus, from the simulation results, it is verified that the proposed grid interactive PV system provides the control of active and reactive power as well as harmonic compensation using novel MPPT algorithm under most of the situations of insolation and load variation. It can be remarkably noticed from Figure 10f, Figure 12f and Figure 14f that

Figure 14: Performance Under Varying Insolation and Nonlinear Load (i) Voltage at the PCC, (ii) Source Current After Compensation, (iii) Load Current, (iv) Reference Currentm (v) Compensator Current, (vi) DC Bus Voltage

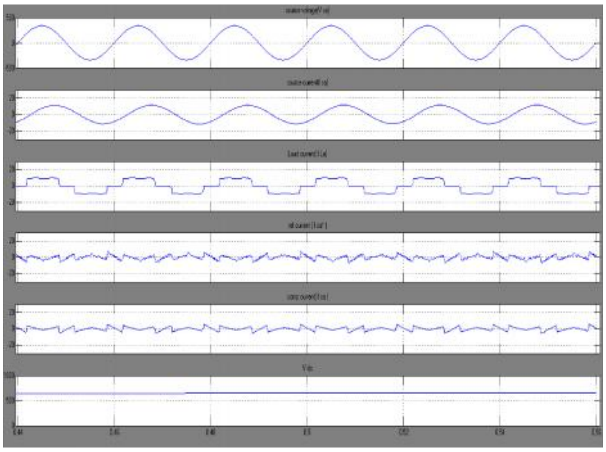
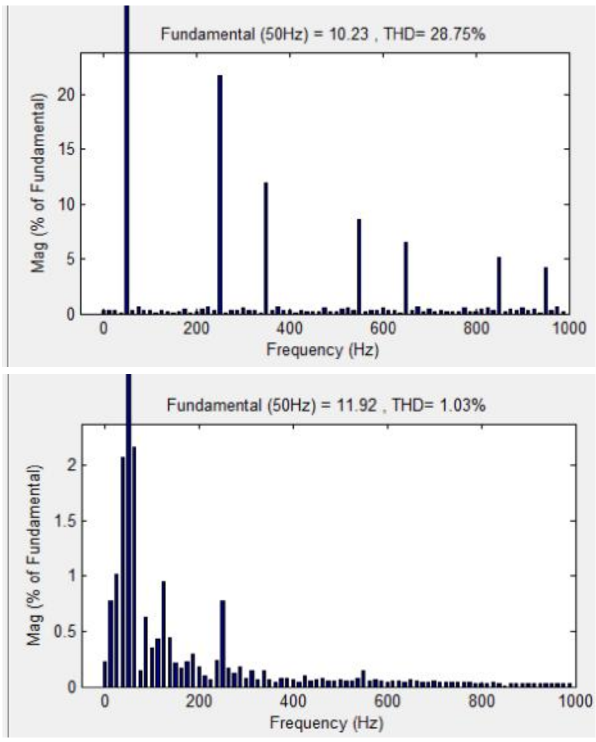


Figure 15: Magnitude Spectrum of Source Current, (a) Before Compensation, and (b) After Compensation



the proposed fuzzy logic based MPPT controller maintains the dc bus voltage well regulated under varying insolation and load conditions while tracking the MPP.

Figure 16a: Load Current with Constant Insolation

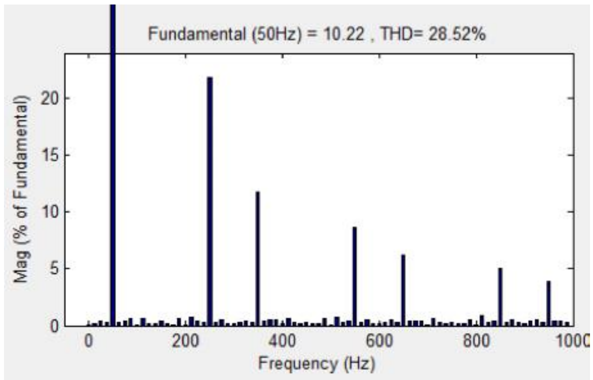


Figure 16b: Source Current with Constant Insolation

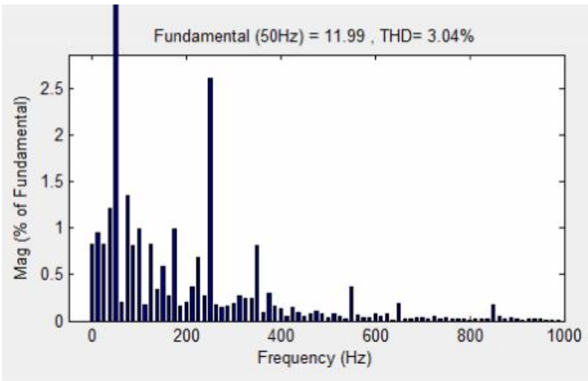


Figure 16c: Load Current with Varying Insolation for Nolinear Load

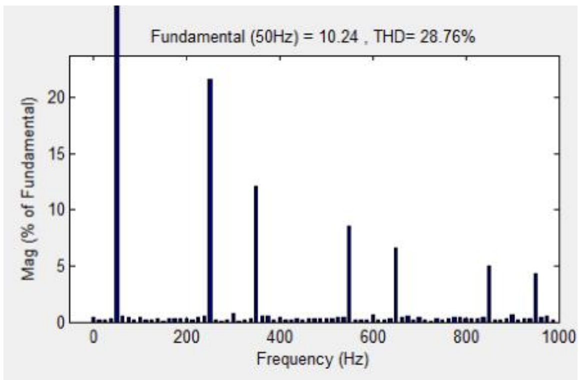


Figure 16d: Load Current with Varying Insolation for Nonlinear Load

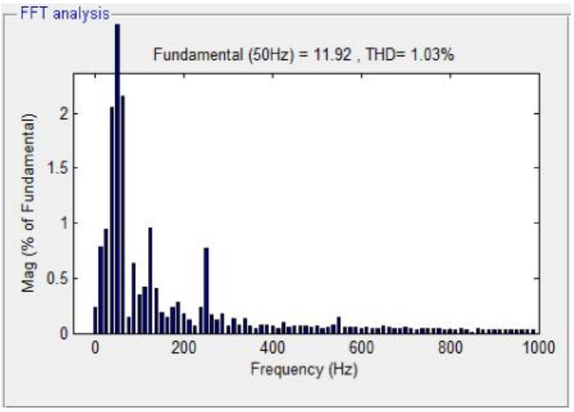


Figure 16e: Load Current with Constant Insolation for Both Linear and Nonlinear Load

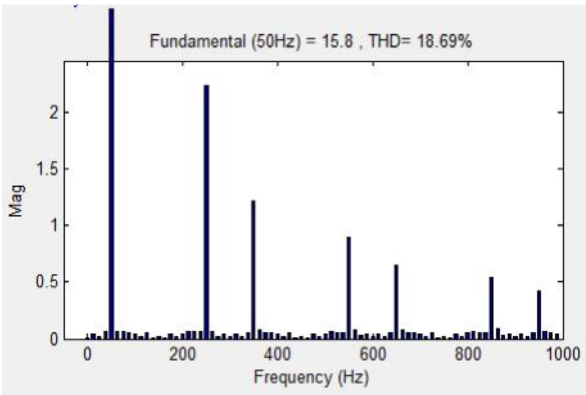
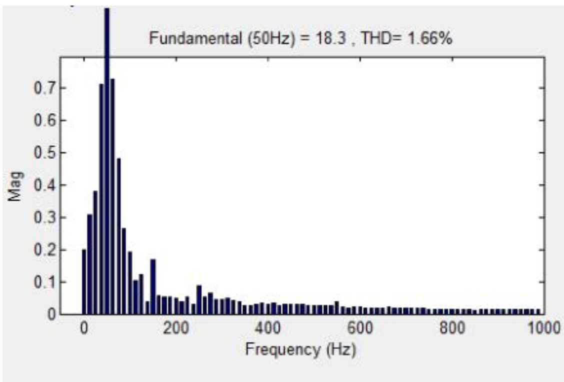


Figure 16f: Source Current with Constant Insolation for Both Linear and Nonlinear Load



Graphs Showing Different Results for Load Current and Source Current by Using Neural Network

The following results (Figures 16a to 16f) will give the better performance when we reduce the THD of load current and source current by using neural network instead of FLC under varying load conditions.

Table 4: Comparison of THD for Both FLC and Neural Network

Load Conditions	Fuzzy Logic Controller		Neural Network	
	THD of Load Current	THD of Source Current	THD of Source Current	THD of Load Current
Constant insolation and combination of linear and nolinear load	18.90%	2.20%	18.69%	1.66%
Constant insolation and nonlinear load	28.53%	3.20%	28.52%	3.04%
Varying insolation and nonlinear load	28.75%	1.03%	28.76%	1.03%

CONCLUSION

In this paper, multi functional grid interactive PV system is presented using a novel fuzzy logic based MPPT. The proposed MPPT controller is able to track the MPP accurately under uniformly varying as well as rapidly changing insolation and gives faster convergence as a variable step size in duty ratio is applied inherently by the algorithm. The proposed fuzzy controller maintains the dc link voltage within the limit for injecting the power into the grid. Apart from injecting active power during day time, the PV inverter also compensates the harmonics and reactive power during day time as well as at night. The current drawn from the grid is sinusoidal and the total harmonic distortion is well below the specified limit by using neural network as compared to FLC. The simulation results validate the performance of grid interactive PV system for both active power injection as well as shunt active power filter functionality to mitigate the power quality issues thus increases the utilization factor of the system.

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