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Implementation of Fuzzy Logic Maximum Power Point Tracking Controller for Photovoltaic System

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ABSTRACT

In this study, simulation and hardware implementation of Fuzzy Logic (FL) Maximum Power Point Tracking (MPPT) used in photovoltaic system with a direct control method are presented. In this control system, no proportional or integral control loop exists and an adaptive FL controller generates the control signals. The designed and integrated system is a contribution of different aspects which includes simulation, design and programming and experimental setup. The resultant system is capable and satisfactory in terms of fastness and dynamic performance. The results also indicate that the control system works without steady-state error and has the ability of tracking MPPs rapid and accurate which is useful for the sudden changes in the atmospheric condition. MATLAB/Simulink software is utilized for simulation and also programming the TMS320F2812 Digital Signal Processor (DSP). The whole system designed and implemented to hardware was tested successfully on a laboratory PV array. The obtained experimental results show the functionality and feasibility of the proposed controller.

Keywords: Buck-Boost Converter, Fuzzy Logic Controller (FLC), Maximum Power Point Tracking (MPPT), Photovoltaic (PV)

1. INTRODUCTION

Nowadays, one of the major challenges for the engineers is to achieve power from clean and green energies. Among all the renewable and sustainable energy sources, solar energy provides the opportunity to generate various power scales without emitting any greenhouse gas (Lin, 2012; Dunn *et al*., 2012; Mekhilef *et al*., 2011; Safari and Mekhilef, 2011a). Being endless, clean and environment friendly make the solar energy become a possible solution for energy crisis. However, despite all the merits of solar systems, they suffer from having low efficiency in practice (Chouder *et al*., 2012).

The efficiency of a Photovoltaic (PV) array is quite dependent to the environmental and operational conditions. Among all the factors affecting the output power of a PV array, ambient temperature, insulation, dirt, shading and sunlight characteristics can be counted as more important ones. Decreasing the solar irradiation due to cloudy weather and ambient temperature increment are the common factors which decrease the output power of a PV panel (Rahmani *et al*., 2011). Maximum Power Point Tracking (MPPT) is the newest concept which helps to extract the maximum possible power from a PV array.

The MPPT methods are various in the complexity, convergence speed, popularity, cost, operating range, sensor dependence, capability of escaping from local optima and their applications (Jamri and Wei, 2010; Lopez-Lapena *et al*., 2012).

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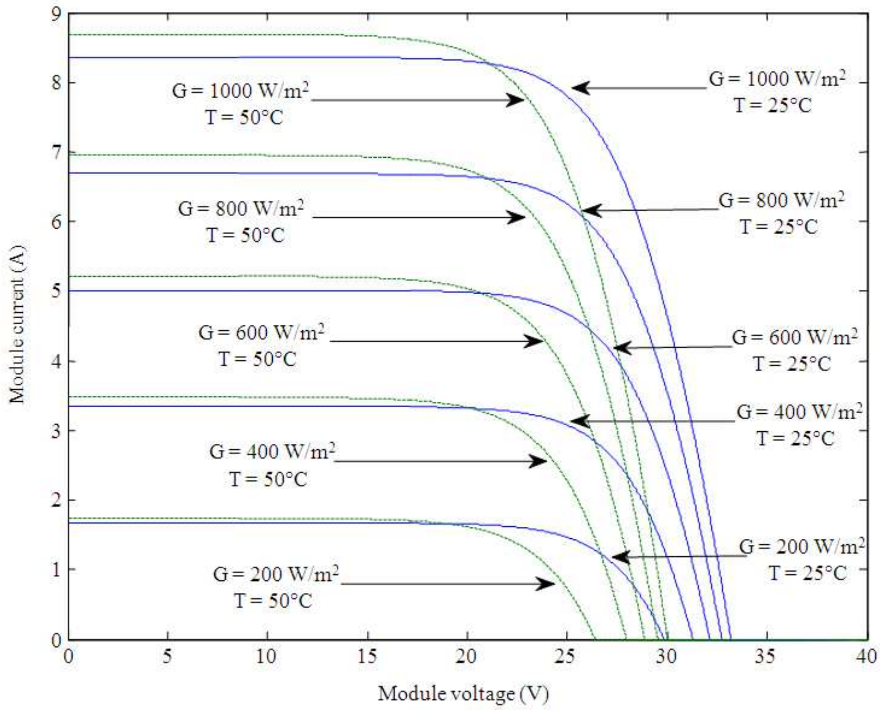

Fig. 1. The I-V characteristics for 25 and 50°C

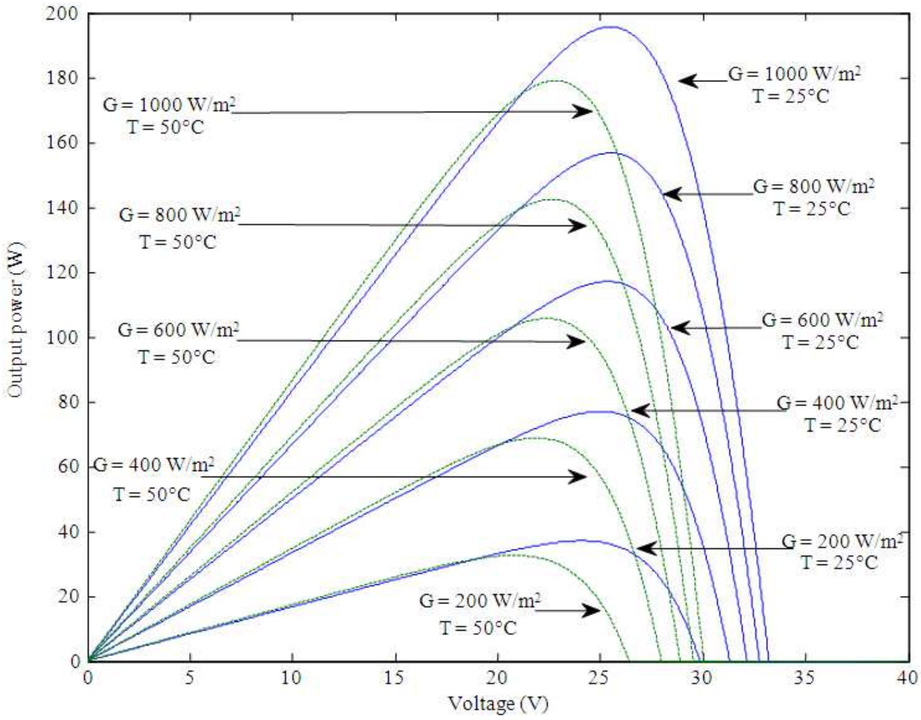

Fig. 2. The P-V characteristics for 25C and 50°C

Table 1. Electrical specifications of the 200 W multi-crystalline photovoltaic module KD205GX-LPU

Parameter (at STC)	Abbreviation	Value
Maximum power	P_{max}	200 W
Rated voltage	V_{MPP}	26.6 V
Rated current	I_{MPP}	7.52 A
Open circuit voltage	V_{OC}	33.2 V
Short circuit current	I_{SC}	8.36 A
Temperature coefficient of I_{SC}	k_i	5.02×10^{-3} A/°C
Temperature coefficient of V_{OC}	k_v	-1.20×10^{-1} V/°C
Normal operating cell temperature	NOCT	47.9°C
Cell serial modules	n_s	54

Ease of implementation and simplicity are the parameters that can make some methods, such as hill climbing and P and O, popular (Ishaque *et al*., 2011; Safari and Mekhilef, 2011b; 2011c). On the other hand, accuracy and speed are the parameters considered by some methods such as fuzzy logic (Nabulsi and Dhaouadi, 2012) and neural network (Lin *et al*., 2011). From swarm intelligence techniques, Particle Swarm Optimization (PSO) is also used to track the MPP of PV array (Miyatake *et al*., 2011; Ishaque *et al*., 2012). PSO method has the ability of finding the maximum point if several local maximum points exist. However, it does not provide a direct control method for online controlling. In contrast, fuzzy logic technique is rapid and provides direct control system (Jamri and Wei, 2010).

Based on the aforementioned advantages of fuzzy logic controller, it is implemented in the current study to perform MPPT for a PV panel. The simulation and hardware implementation are done utilizing MATLAB/Simulink software and TMS320F2812 DSP hardware. The waveform results of both simulation and experimental setup are shown as well. The demonstrated results indicate that proposed and designed FL MPPT controller is capable of tracking the MPP while it is fast and accurate.

1.1. Modeling of PV Panel

PV cells are basic units in the structure of a PV module. Based on the photoelectric phenomenon, they can transfer the energy of sunlight photons to the electrical energy. Since the amount of produced power generated by a solar cell is very small, almost 45 milliwatts, they have to be organized and installed in series or parallel to produce a useful range of electrical power whether for industry or domestic. The nonlinear and exponential relation between current and voltage of a PV module is extensively described in (Etier *et al*., 2011; Rahmani *et al*., 2011; Mahmodian *et al*., 2012). The generated current by a solar cell is obtained based on the equation in below (Rahmani *et al*., 2011) Equation 1 and 2:

$$I_{ph} = \left(I_{ph,n} + k_i \Delta T\right)\frac{G}{G_n} \quad (1)$$

where, I_{ph} is called photocurrent generated by the influence of solar irradiation and cell's temperature. ΔT is the difference of temperature from the reference STC (T_0 = 25°C). G is the insulation and G_n is its normal rated value which is equal to 100 mW m^{-2}. While k_i is the temperature coefficient of short circuit current. The main famous equation of a PV cell is as follow (Rahmani *et al*., 2011):

$$I_C = I_{ph} - I_0\left[\exp\left(\frac{V_C + R_S I_C}{m.V_T}\right) - 1\right] \quad (2)$$

where, I_C and V_C are the output current and voltage of the cell respectively. I_0 is the diode reverse saturation current and R_S is the series resistor modeled for the cell. V_T is called temperature voltage and it is applied 25mV and m is the diode factor which is equal to 1.5 in practice.

The parameters of the PV module used in our experiment are tabulated in **Table 1** and its I-V and P-V characteristics are depicted in **Fig. 1-2** respectively. The resultant waveforms show the effects of weather condition in the generated current and output power (Etier *et al*., 2011).

2. MATERIALS AND METHODS

The block diagram of the MPPT system configuration is n shown i **Fig. 3**. The system consists of PV modules and a resistive load while the terminal voltage of the PV panel is controlled by an IGBT buck-boost converter which is cheap and proper for low power laboratory prototypes. The steady state transfer function of a buck boost converter is obtained from Equation (3):

$$\frac{V_o}{V_i} = \frac{D}{D-1} \quad (3)$$

where, V_o and V_i are the output and input voltages of the converter respectively. D is the duty cycle and can vary from 0 to1, although there is no practical value of D equal to 1 due to voltage limitation issues.

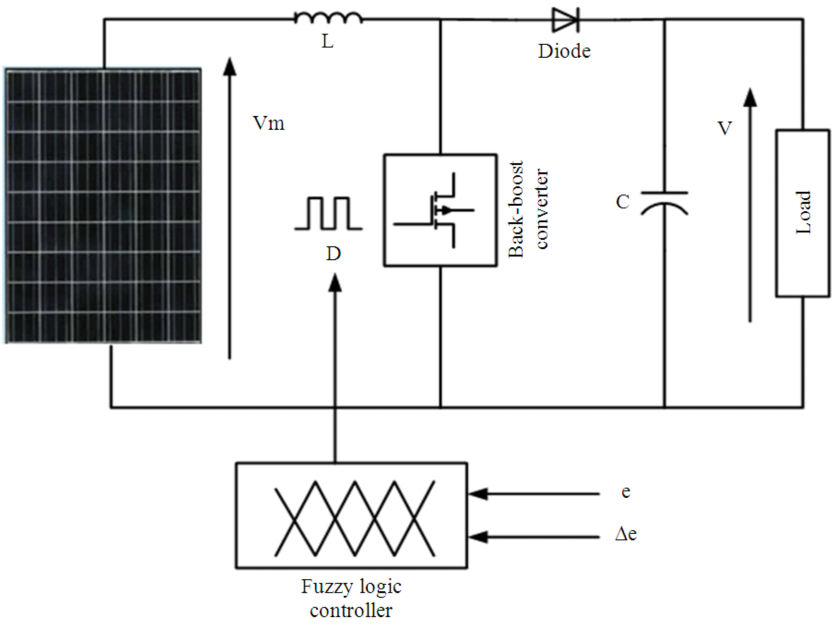

Fig. 3. The block diagram of the designed and implemented MPPT system

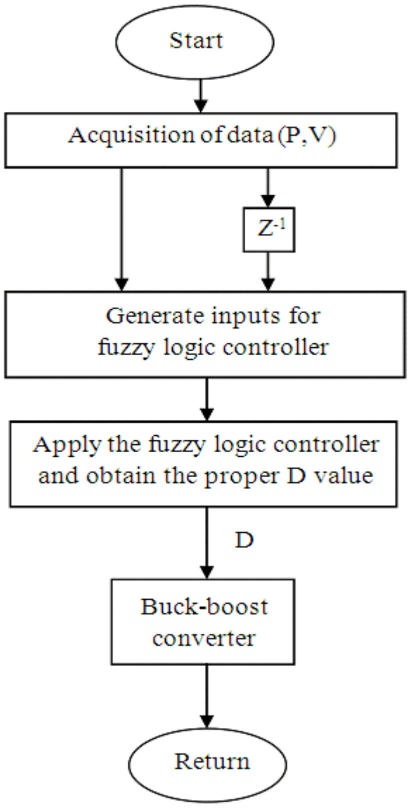

Fig. 4. Flowchart of the algorithm steps

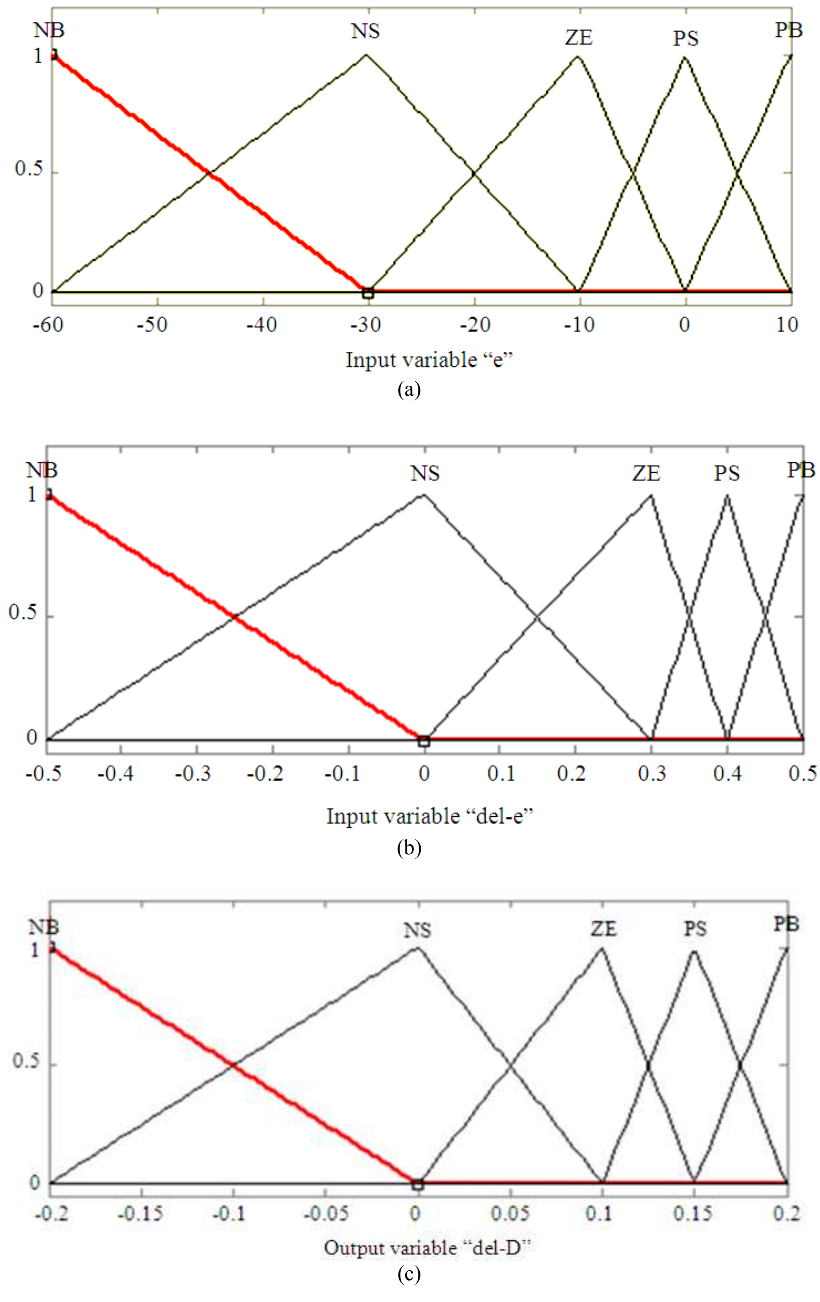

Fig. 5. Membership function of (a) input e, (b) input Δe and (c) output ΔD

The input voltage of the buck-boost converter is supplied by a 15 V DC source.

The voltage and current of the PV panel are measured instantly and connected to the MATLAB software by a DAQ card. Then, the power is calculated and saved in a vector. The input variables of the Fuzzy logic controller are created based on the Equations (4) and (5). The algorithm steps are shown in the flowchart shown in **Fig. 4**:

$$e(t) = \frac{\Delta P(t)}{\Delta V(t)} = \frac{P(t) - P(t-1)}{V(t) - V(t-1)} \quad (4)$$

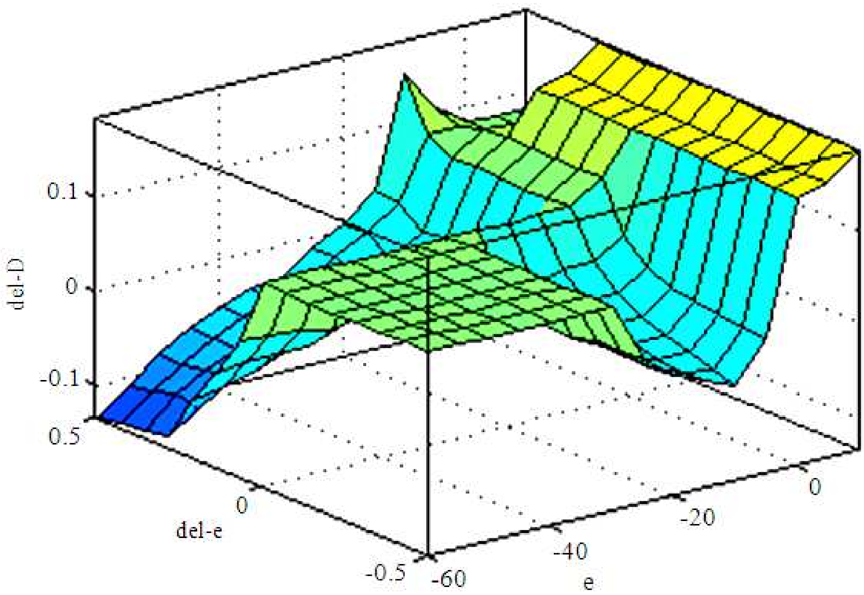

Fig. 6. The input-output surface waveform of the FLC

Table 2. The control rules of FL

Δe e	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

$$\Delta e(t) = e(t) - e(t-1) \quad (5)$$

2.1. Fuzzy logic MPPT controller

Fuzzy Logic (FL) is one of the most popular control methods which is known by its multi-rule-based variable's consideration (Salah and Ouali, 2011). This method provides faster results compared to other Artificial Intelligent control methods such as Genetic Algorithm and Neural Networks. Being fast and robust are the main reasons of choosing FL for MPPT in the current study (Salah and Ouali, 2011; Messai *et al.*, 2011). To implement the FL in a problem, different steps of this algorithm must be taken which are as follows.

2.2. Fuzzification

The input defined in Equations (4) and (5) need to be fuzzified by some membership functions. For each input value, the respective membership function returns a value of μ. The max-min method was applied to extract the μ from the triangle type membership function. **Figure 5** depicts the membership functions for inputs *e* and Δe and output ΔD which is the variation needs to be applied to the current D value.

2.3. Inference Diagram

A rule base must be applied to the obtained membership function according to Mamdani. The rule table is designed and shown in **Table 2**. The 3D input-output surface is also obtained by using MATLAB FL Inference (**Fig. 6**).

2.4. Defuzzification

For the Defuzzification, the centroid method (Nabulsi and Dhaouadi, 2012) is applied to return a proper value for the duty cycle variation (ΔD). The difuzzified output value of the FLC must be added to a reference value of duty cycle which is considered equal to 0.5 for the current study. The result is the optimum value of D that has to be sent to the buck-boost converter as a control signal.

3. RESULTS AND DISCUSSION

The block diagram of the simulation in MATLAB/Simulink environment is shown in **Fig. 7** which includes models for PV panel, buck-boost converter and the FL MPPT controller. The PV panel is modeled based on the electrical characteristics shown in **Table 1**. To test the operation of the designed system, the irradiation was changed while the temperature maintained its value at 25°C.

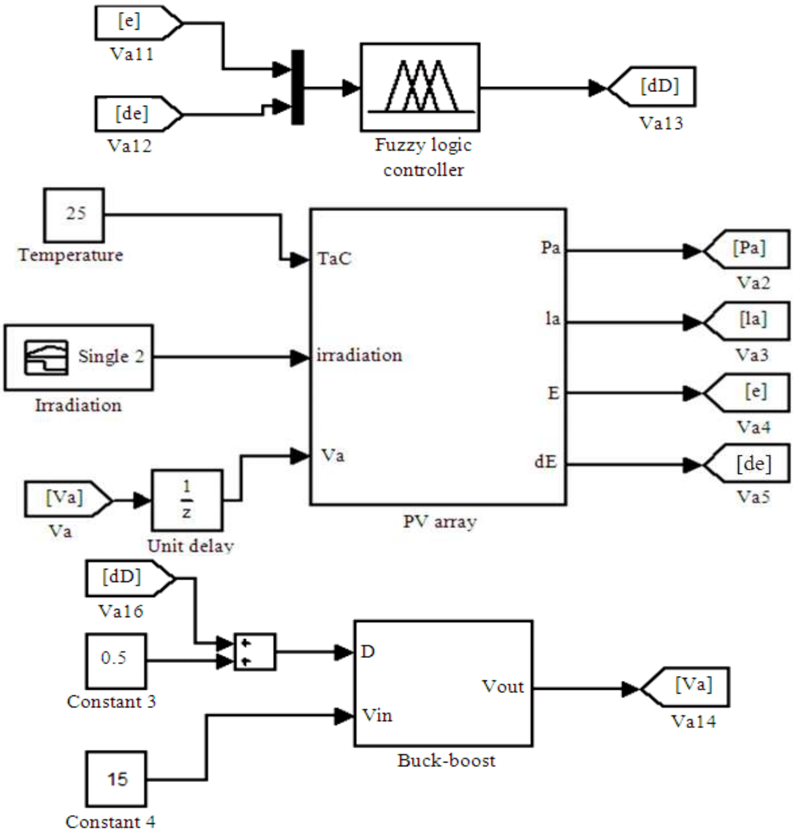

Fig. 7. The FL-MPPT controller and PV system designed in MATLAB/Simulink environment

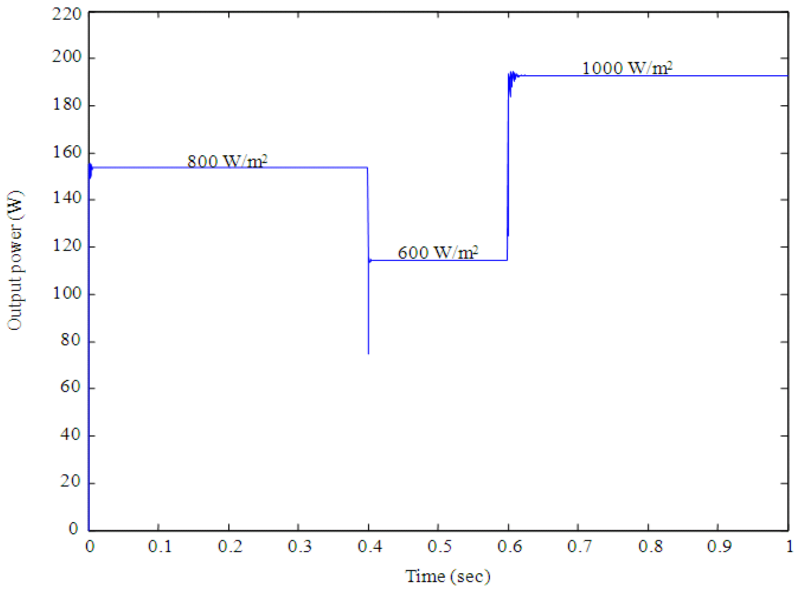

Fig. 8. Change in the output power of the PV system due to change in the irradiation

Fig. 9. Hardware circuit prototype

Table 3. Performance indicators for the simulation results

Metrics	Value
Rise time (t_r)	0.001s
Settling time (t_s)	0.02s
Over Shoot (OV)	1.1%
Ripple factor (ΔP/P)	0%

The illumination varies between three different levels. The first level is 800 W/m^2 which starts at 0.0 s and finishes at 0.4 s. Another level, which is 600 W/m^2, starts at 0.4 s and lasts for 0.2 s and finally, we have a 1000 W/m^2 irradiation level starts right after previous level and ends at 1.0 s. In these three levels chosen, we have sudden rise and fall in the illumination values, hence, we can get a fair evaluation of the FL MPPT controller.

Figure 8 shows the output waveform of the generated power for the PV panel. Its voltage is controlled by the buck-boost converter while FLC builds the control signal of duty cycle of the converter. The graph shows that the obtain power for different illumination levels of 800, 600 and 1000 W/m^2 are 154, 115 and 193 W respectively. The obtained power values are definitely equal to the expected maximum power in **Fig. 2**. To prove and evaluate the quality of waveform, **Table 3** is tabulated based on some general metrics.

3.1. Experimental Setup

A prototype of the control system and the buck boost converter was implemented to validate the functionality of the proposed method. The control signal for the buck-boost converter was built by using TMS320F2812 DSP. The interface for the FL algorithm and PWM pulses are built, debugged and run in the MATLAB/Simulink software as a DSP development tool.

The terminals of the buck boost converter terminal are joint the terminals of the PV panel. The voltage and current of the terminals are measured using Hall-effect sensors and the output power is calculated by MATLAB software. However, due to the limitation of DSP in tolerating more than 3.3 V, the voltages are scaled down to be compatible with the voltage rating of DSP.

Normally the output power of a single solar panel is not adequate for industrial or domestic purposes. Hence, they are used in serial or parallel connections to produce higher value of the power. Each type of configuration provides a special feature that might be useful depending on the application. In the current experiment, we used 5 PV modules connected in series to achieve higher voltage. The hardware circuit prototype is shown in **Fig. 9**.

Since the buck-boost converter used is an IGBT type converter and requires 0.2 s to be stabled, a sampling time of 0.2 s is chosen for the converter to track the MPP smoothly. To demonstrate the ability of our direct method in tracking the MPP, we changed the number of modules from 4 to 3 and then from 3 to 5. This variation in the number of modules is performed as fast as possible to show the fastness of the implemented FLC. In fact, changing the number of modules can model the variation in the irradiation under constant temperature. The experiment was performed under irradiation almost equal to 1000 W/m^2. The variation in the output power waveform is shown in **Fig. 10**. Some performance indicators are tabulated in **Table 4** to show the quality of experimental result.

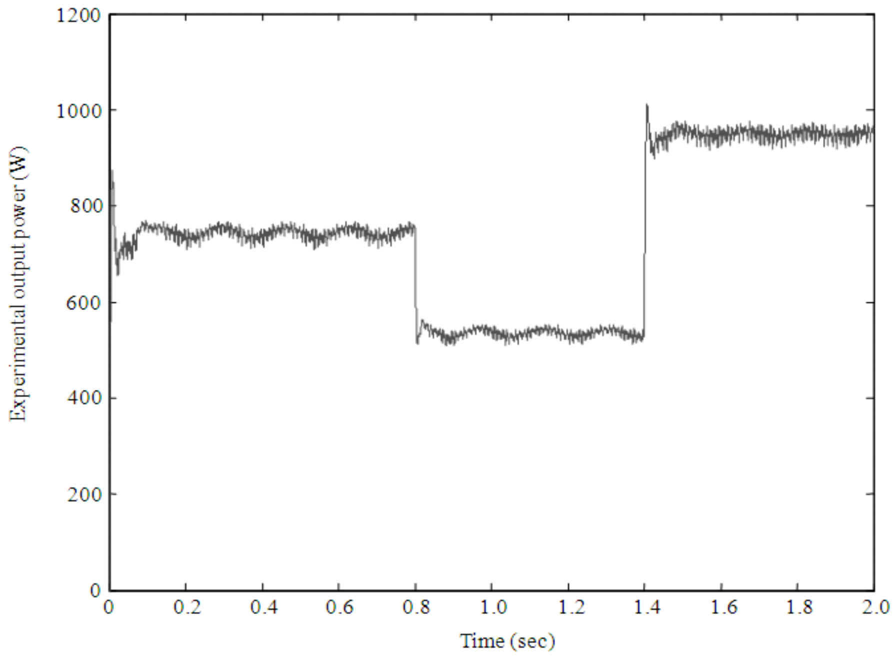

Fig. 10. Change in power waveform due to changing the number of modules

Table 4. Performance indicators for the experimental results

Metrics	Value
Rise time (t_r)	0.01 s
Settling time (t_s)	0.05 s
Over Shoot (OV)	5%
Ripple factor (ΔP/P)	5.3%

The figure proves the ability of designed MPPT system to track the proper voltage, besides; it shows the fastness of the algorithm as well.

4. CONCLUSION

In this study, a fuzzy logic MPPT controller is proposed to extract maximum possible power from a photovoltaic array. The algorithm works as a direct method of MPPT through a buck-boost converter placed in parallel with the PV array. The proposed system is simulated and constructed in both simulation and hardware and its functionality was proven. The obtained results from simulation and experimental setup confirm that the designed system is fast, robust and efficient. The results also show the capability of the proposed FL MPPT system to track the voltage which is respective to the maximum output power. It results in increasing the efficiency of the PV panel and reducing the bad effects of weather changing as much as possible.

5. ACKNOWLEDGMENT

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