Application of Artificial Intelligence on Photovoltaic Solar Array System with Fuzzy Logic Controller for MPPT in Matlab Simulink

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ABSTRACT-
This paper's goal is to create a Maximum Power Point Tracker (MPPT). Due to population increase, new industrial development, and other factors, power demand has been steadily increasing. In PV systems, the maximum power point tracking system (MPPT) is critical for increasing solar cell efficiency. Many ways for generating MPPT from PV modules under various weather circumstances have been presented. This study used the Fuzzy Logic Control (FLC) algorithm to come up with a clever approach for maximum power point tracking. The error between the real power and the estimated maximum power is minimized using the fuzzy logic technique. The PV system is put to the test under varying levels of sun irradiance and temperature. The simulation findings reveal that the maximum power tracker could precisely and successfully track the maximum power in all scenarios evaluated, and the system performance was examined. With the help of Matlab/Simulink the FLC-based MPPT controller for the PV module is modeled.

Keywords: Solar Energy, Fuzzy logic controller, Maximum power point tracking MPPT, Photovoltaic system, Matlab Simulink.

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1. INTRODUCTION

Photovoltaic modules are defined by effects on external performance from ambient environmental variables such as irradiance, module temperature, and outside humidity. Direct MPPT techniques are used to measure PV voltage and PV current during online conditions, while indirect MPPT techniques are used for offline analysis of PV system performance. The direct technique [3] has been established in this study by employing a fuzzy logic controller to track the MPP of a PV system. The maximum power point (MPP) of a photovoltaic (PV) array is usually an important component of a PV system. The rapid increase in electricity demand, as well as recent changes in environmental conditions such as global warming, necessitated the development of a new source of energy that is less expensive, more sustainable, and emits less carbon emissions. In the search for a solution to the problem, solar energy has yielded promising results. To improve the efficiency of PV modules, a lot of research has been done. To overcome the efficiency problem, a number of ways for tracking the maximum power point of a PV module have been developed, and products based on these approaches have been manufactured and are now commercially available for customers [5-7]. The maximum power from the solar PV module is extracted and transferred to the load using an MPPT [2, 3]. This manuscript goes over a variety of methods in detail, with a brief description and classification of each. We've avoided talking about minor tweaks to existing methods as separate methods. As a result, MPPT procedures are required to keep the PV array running at MPP [9]. The Perturb and Observe (P & O) methods, Incremental Conductance (IC) approaches, Fuzzy Logic Method, and other MPPT techniques have all been proposed in the literature.

2. MODELING OF PHOTO VOLTAIC ARRAY

2.1. Photo voltaic cell

The analogous circuit of the perfect photovoltaic cell is shown in Figure 1. The I-V characteristic of the ideal photovoltaic cell is mathematically described by the following equation from the Theory of Semiconductors [9, 10]:

$$I = I_{pv,cell} - I_{0,cell}\left[\exp\left(\frac{qV}{aKT}\right) - 1\right] \qquad (1)$$

Ipv is the Shockley diode equation, $I_{0,cell}$ [A] is the reverse saturation or leakage current of the diode [A], *q* is the electron charge [1.60217646 • 1019C], *k* is the Boltzmann constant [1.3806503 • 1023J/K], *T* [K] is the temperature of the *p-n* junction, and an is the diode ideality constant.

2.2. Photovoltaic array model

The I-V characteristic of a practical solar array is not represented by the basic equation (1) of the simple photovoltaic cell. Practical arrays are made up of numerous connected photovoltaic cells, and observing the characteristics at the array's terminals necessitates the addition of several parameters to the basic equation [6]:

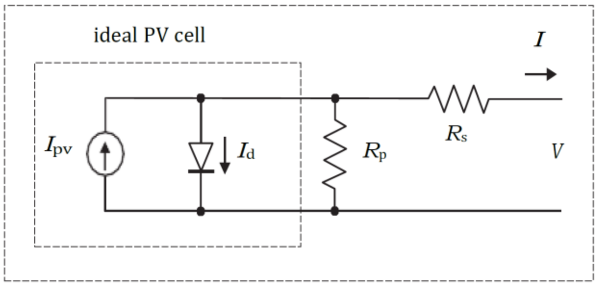

Figure 1. Single-diode model

Figure 1 shows a single-diode model of a theoretical photovoltaic cell and its equivalent circuit, which includes the series and parallel resistances.

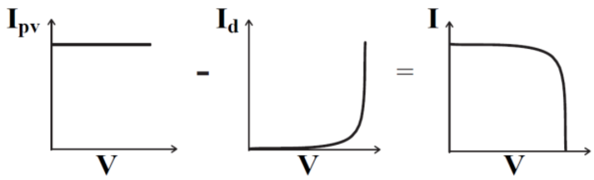

Figure 2. Characteristic the solar cell's I-V curve. The light-generated current I_{PV} and the diode current I_d make up the net cell current *I*.

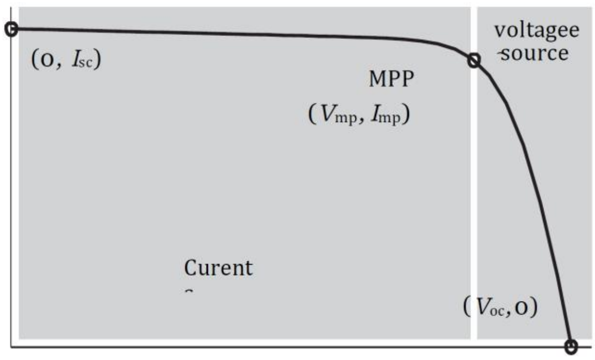

Figure 3. Short circuit $(0, I_{sc})$, maximum power point (V_{mp}, I_{mp}), and open-circuit are three notable places on the I-V curve of a realistic photovoltaic device $(V_{oc}, 0)$.

$$I = I_{pv} - I_0\left[\exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] - \frac{V + R_s I}{R_p}, \qquad (2)$$

The photovoltaic cell's light-generated current is proportional to sun irradiation and is also impacted by temperature, as shown by the equations [3], [8, 9]:

$$I_{pv} = \left(I_{pv,n} + K_1 \Delta T\right)\frac{G}{G_n}, \tag{3}$$

where $I_{pv,n}$ [A] is the light-generated current at the nominal condition (typically 25°C and 1000 W/m^2), and $T = TT_n$ is the temperature. G [W/m^2] is the irradiation on the device surface, and G_n is the nominal irradiation (where T and T_n are the actual and nominal temperatures [K]). (4) [9], [4], [3-5] can be used to express the diode saturation current I_0 and its temperature dependence:

$$I_0 = I_{0,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{aK}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right], \tag{4}$$

where E_g represents the semiconductor's band gap energy ($E_g = 1.12\,\text{eV}$ for polycrystalline Si at 25°C [1], [3] and $I_{0,n}$ represents the nominal saturation current:

$$I_{0,n} = \frac{I_{oc,n}}{\exp\left(\dfrac{V_{oc,n}}{aV_{t,n}}\right) - 1}. \tag{5}$$

Nominal saturation current $I_{0,n}$ is determined indirectly from experimental data in this study through (5), which is obtained by analyzing (2) at the notional open-circuit condition, with $V = V_{oc,n}$, $I = 0$. If necessary, the value of a can be changed later to improve the model fitting. This constant impacts the curvature of the I-V characteristic thus altering a can somewhat enhance the model accuracy.

2.3. Improving the model

If equation (4) is changed by the photovoltaic model provided in the preceding section, then it can be improved [9]:

$$E_g = \ln\left[\frac{\left(\dfrac{I_{sc}, T_{\max}}{I_{0,n}}\right)\left(\dfrac{T_n}{T_{\max}}\right)^3}{\exp\left(\dfrac{qV_{oc}, T_{\max}}{aN_s K T_{\max}}\right) - 1}\right] \cdot \frac{aKT_n T_{\max}}{q\left(T_n - T_{\max}\right)}. \tag{6}$$

The goal of this change is to match the model's open-circuit voltage to experimental data over a wide temperature range. When we add (4) and (6) together and solve for E_g at $T = T_{\max}$.

where: $I_{sc}, T_{\max} = I_{sc,n} + KI\Delta T$

and $V_{oc}, T_{\max} = V_{oc,n} + KV\Delta T$,

with $\Delta T = T_{\max} - T_n$.

The following equivalent I-V equation is applicable for any array formed by $N_{ser} \times N_{par}$ identic modules [9]:

$$I = I_{pv}N_{par} - I_0 N_{par}\left[\exp\left(\frac{V + R_s\left(\frac{N_{ser}}{N_{par}}\right)I}{aV_t N_{ser}}\right) - 1\right] - \frac{V + R_s\left(\frac{N_{ser}}{N_{par}}\right)I}{R_p\left(\frac{N_{ser}}{N_{par}}\right)}. \tag{7}$$

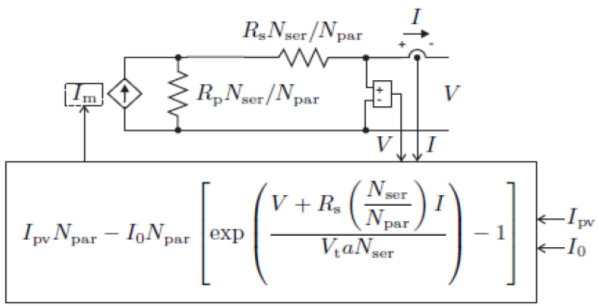

Figure 4. Array model circuit made out of $N_{ser} \times N_{par}$ modules.

3. MAXIMUM POWER POINT TRACKING CONTROL PRINCIPLE

The maximum power point tracking (MPPT) approach is straightforward and relies on the link between load voltage and PV panel open-circuit voltage. As a result, when a direct connection is made between the source and the load, the PV module's output is rarely maximum, and the operating point is rarely ideal [1]. Between the source and the load, an adaptation device, such as an MPPT controller with a DC-DC converter, is required to solve this problem (Figure 4).

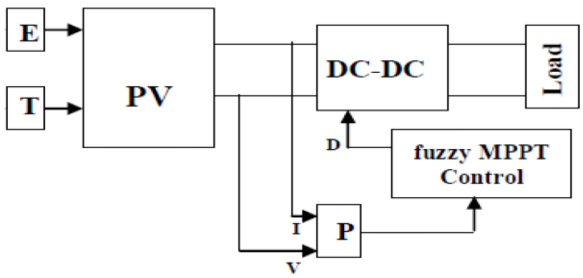

Figure 5. Mathematical model of a solar array In this paper, we used Matlab Simulink to choose the Fuzzy Logic control method for MPPT of our PV array mode.

4. SYSTEM SIMULATION AND FUZZY LOGIC CONTROLLER DESIGN

This section investigates the use of fuzzy logic control as an algorithm for solar system maximum power point tracking. The fuzzy system's architecture and performance were further tested in Simulink/MATLAB with a PV module and a buck-boost converter, and fuzzy logic rules were written and validated. Finally, the conclusions presented in this section were applicable to a real-world fuzzy control system.

4.1. Parameter design for fuzzy logic controllers

4.1.1. PV module with fuzzy logic controller based on MPPT

The fundamental diagram of a fuzzy logic-based maximum power point tracker is shown in Figure 5. The fuzzy logic controller generates a signal proportionate to the converter duty cycle (D) based on measurements, which is delivered to the converter through a pulse width modulator. This modulator drives the value of D to generate the control signals for the converter switch using Pulse Width Modulation (PWM) (s). A closed loop system is defined as a fuzzy logic controller scheme [6].

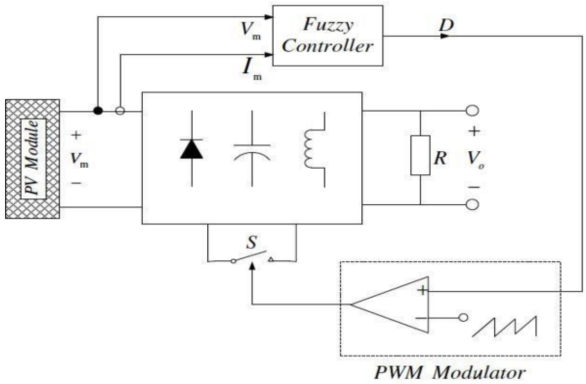

Figure 6. A maximum power point tracker with a fuzzy control method [8].

4.1.2. Structure of a fuzzy controller

The construction of a fuzzy logic controller is based on fuzzy sets, in which a variable belongs to one or more sets with a specified degree of membership. The use of fuzzy logic has several advantages, including the ability to simulate human reasoning in computers, quantify imprecise data, and make decisions based on ambiguous data, such as when a resistive load is connected to a PV module via a buck boost dc-dc converter [8]. Figure 6 [7] shows a block schematic of MPPT-based fuzzy logic control.

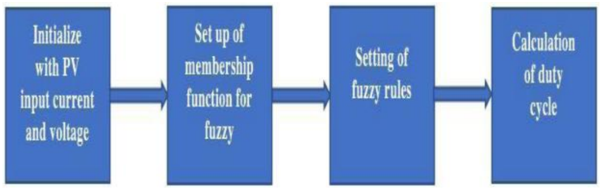

Figure 7. The fuzzy logic control is depicted as a block diagram.

The process of converting a fuzzy quantity into a crisp quantity is known as defuzzification. Defuzzification can be accomplished in a variety of ways. The centroid approach is the most frequent, as shown by the following formula:

$$\int \frac{\mu(x)\,x\,dx}{\mu(x)\,dx}, \qquad (8)$$

where μ is the membership degree of output x.

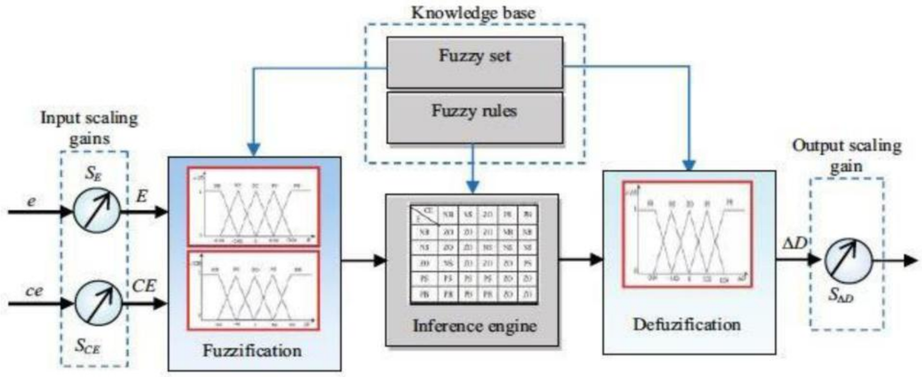

Figure 8. Structure of fuzzy logic controller [9].

4.1.3. Control rules adjustment

The fuzzy rules of the proposed system have been derived from the system behavior and tested in Simulink/MATLAB. Table III indicates the rules based on the membership functions that shown in Figure 9.

Table 1. Fuzzy controller rules

Current / Voltage	Small	Medium	High
Small	H	H	M
Medium	H	H	M
High	M	M	M

The following are the rules in the table:

1. If (current) AND (voltage) are both modest, then (MD is high)
2. If the (current) is low and the (voltage) is medium (MD is high)
3. If the (current) is low and the (voltage) is high (MD is medium)
4. If (current is moderate) and (voltage is low) (MD is high)
5. If (current) AND (voltage) are both medium, then (MD is high)
6. If the (current) is medium and the (voltage) is high (MD is medium)
7. If both (current) and (voltage) are high, then (MD is medium)
8. If both (current) and (voltage) are high, then (MD is medium)
9. If (current) AND (voltage) are both high, then (MD is medium)

where MD is the duty cycle of the fuzzy controller's output.

The fuzzy logic algorithm was simulated using the fuzzy logic toolbox in Simulink/MATLAB, and the rules were fine-tuned. Figure 9 shows the basic window of fuzzy designer, which shows the controller based on Mamdani's fuzzy inference method and the centroid method as a defuzzification process.

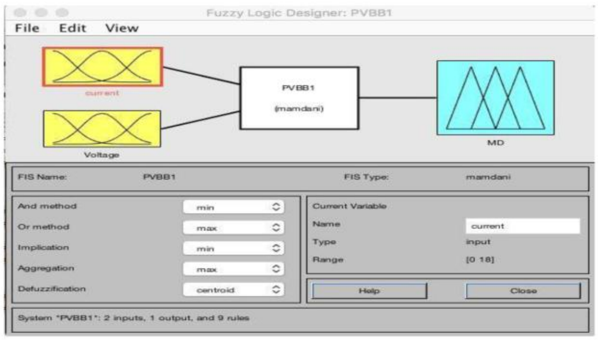

Figure 9. Fuzzy logic designer in MATLAB tool box.

The fuzzy controller rule surface, which is a graphical representation of the rule base, is shown in Figure 10. Figure 11 illustrates the rule viewer, which shows how the fuzzy controller operates when the inputs change.

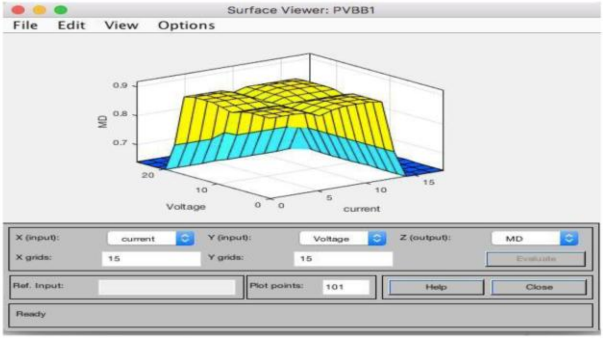

Figure 10. Graphical representation of fuzzy controller rules.

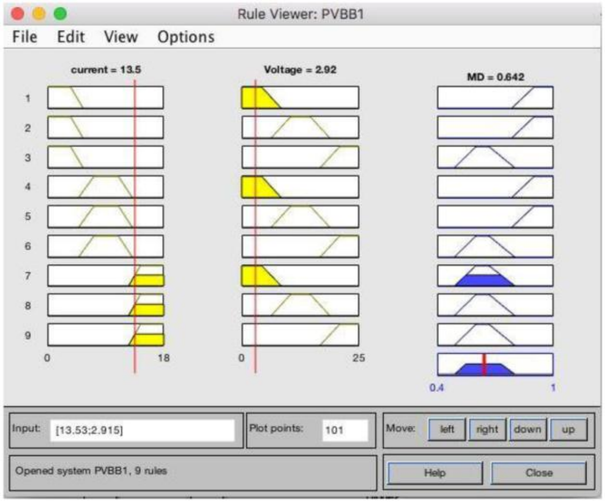

Figure 11. Fuzzy controller rule viewer.

The FIS file was created after the fuzzy controller was changed in MATLAB so that it could be invoked in the Simulink system. We can see the performance of the fuzzy controller in Figure 12 by reading the output of the fuzzy controller at various input values. Input and output readings were taken in large quantities, and the results are given in Table 4. The FIS file was created after the fuzzy controller was changed in MATLAB so that it could be invoked in the Simulink system. We can see the performance of the fuzzy controller in Figure 12 by reading the output of the fuzzy controller at various input values. Input and output readings were taken in large quantities, and the results are given in Table 2.

Table 2. Optimal duty cycle for various input current and voltage values

Current	Voltage	Duty cycle
0.5	12	0.919
3	15	0.9169
5	18	0.7293
10	17	0.8454
10	25	0.6402
15	17.33	0.6429

As illustrated in Figure 12, the entire system was assembled and evaluated in Simulink/MATLAB for various quantities of solar irradiation.

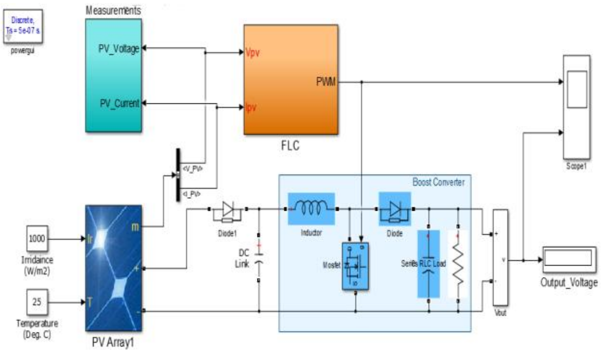

Figure 12. Maximum power point tracking of photovoltaics using fuzzy system simulation.

At various irradiance variations, the simulation model presented in Figure 11 was implemented in Simulink/MATLAB. The readings of input power and output power of the MPPT, as well as duty cycle, were observed at the same radiation values in order to assess the fuzzy controller's performance and the converter's efficiency. More information about the simulation results may be found in Table 3.

Table 3. Simulation results of fuzzy MPPT

Irradiance (W/m^2)	Input Power (w)	Output Power (w)	Duty cycle	Efficiency %
1000	257.7	252	0.65	0.97788126
800	209.7	200.9	0.65	0.95803529
600	150.9	142.7	0.59	0.94565938
400	98.98	92.5	0.49	0.93453223
200	48.86	44.4	0.35	0.90871879

5. SIMULATION RESULTS AND DISCUSSIONS

The introduced method, i.e., Design and operation of the fuzzy logic-based MPPT Controller, is compared with buck-boost converter vs pulse at each input and output power under unknown situations in this Simulation Model. The signal builder block in MATLAB/SIMULINK is used to provide the device's uncertain situation. The evaluation is carried out by comparing the results in order to determine the most efficient and accurate approach for determining maximum power under unknown situations. The model is created with the MATLAB/SIMULINK software (Figure 11).

The PV module, 1Soltech 1STH- FRL-4H-250-M60-BLK, is included in the model. The PV Module's output is coupled to the DC-DC Buck-Boost converter, which houses the electric drive, which is a MOSFET that receives the gate signal pulse from the Fuzzy Logic Controller. Changes in temperature, irradiance, and power are all examples of unpredictable situations. The PV Module receives the uncertainty through a signal block that contains the various input signals. For a better comparison, the uncertainty for both methods is similar.

The converter's average efficiency was around 94.49 percent, implying that the fuzzy controller receives the maximum power that can be collected from the PV module at the suggested system's specification. Figures 12 and 13 in the table show the curves of the MPPT based fuzzy logic controller's input and output power at each input and output power.

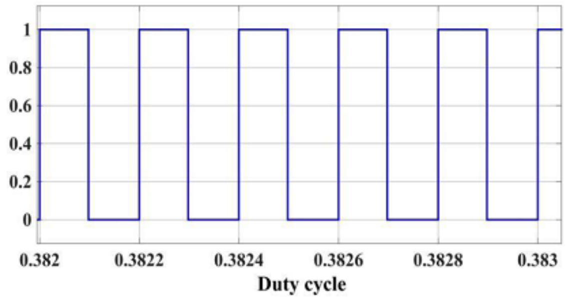

Figure 13. Without a Fuzzy Logic controller, input power against output power.

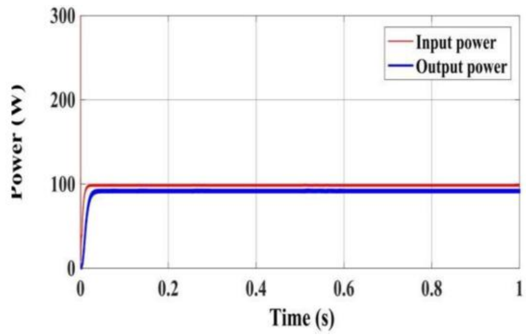

Figure 14. With a Fuzzy Logic controller, you can compare input power to output power.

Table 4 shows sample input power readings for each MPPT at various periods. These figures were plotted in Excel to compare the performance of these MPPTs based on the curves in Figure 15.

Table 4. The original MPPT's input power vs. the fuzzy MPPT's input power

Original MPPT			Fuzzy MPPT				
PV Voltage	PV current	PV power	PV voltage	PV current	PV power	Time	Date
15.38	0	0	22.24	0	0	0:00	28/2/2022
15.36	10.01	153.7536	14.48	10.84	156.9632	0:01	28/2/2022
15.41	9.912	152.74392	14.89	10.986	163.58154	10:49	28/2/2022
15.45	10.059	155.41155	14.99	10.498	157.36502	10:50	28/2/2022
15.58	9.668	150.62744	15.06	10.498	158.09988	10:53	28/2/2022
15.58	9.668	150.62744	14.99	10.303	154.44197	10:54	28/2/2022
15.36	9.033	138.74688	15.04	10.4	156.416	10:56	28/2/2022

15.36	9.033	138.74688	15.04	10.4	156.416	10:57	28/2/2022
15.36	9.033	138.74688	15.04	10.4	156.416	10:58	28/2/2022
15.36	9.033	138.74688	15.11	10.449	157.88439	10:59	28/2/2022
15.63	10.01	156.4563	15.16	10.498	159.14968	11:00	28/2/2022
15.63	10.01	156.4563	15.16	10.498	159.14968	11:01	28/2/2022
15.55	9.863	153.36965	15.16	10.449	158.40684	11:03	28/2/2022
15.55	9.766	151.8613	15.19	10.547	160.20893	11:06	28/2/2022
15.7	10.01	157.157	15.21	10.498	159.67458	11:07	28/2/2022

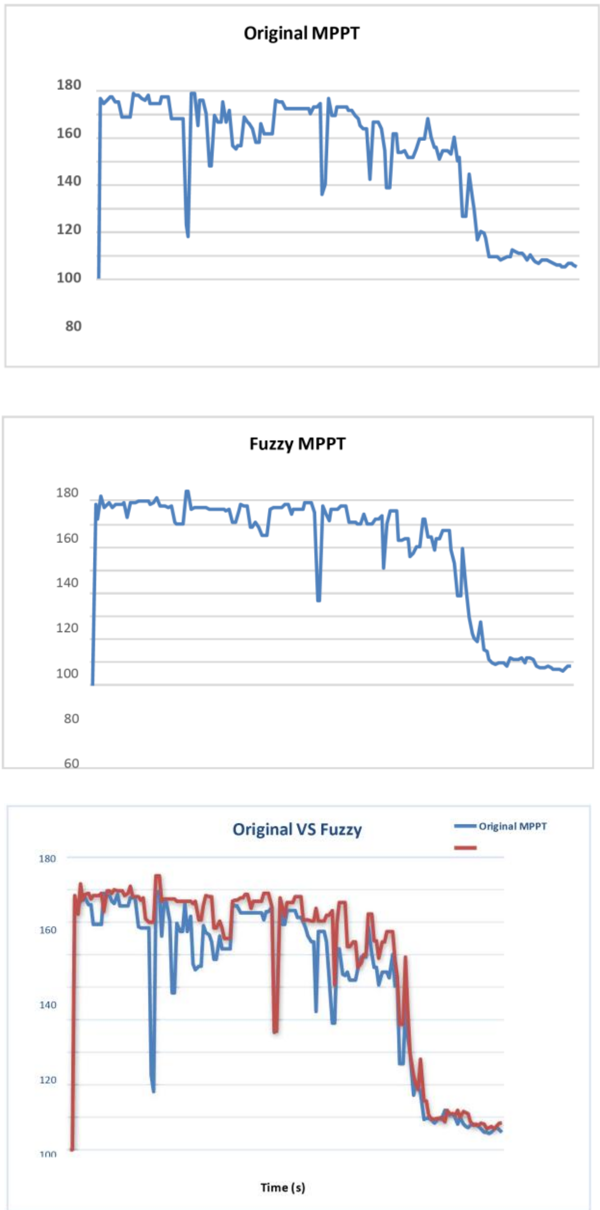

Figure 15. In terms of input power, original MPPT and fuzzy MPPT are compared.

6. CONCLUSION

The goal of this research was to come up with a method for getting the most energy out of a photovoltaic (PV) power system. To that purpose, we offered maximum power point tracking for PV modules, as well as different techniques for dealing with current unsolved issues. We suggested a fuzzy logic control method for tracking optimal power in particular. This chapter presented and simulated a fuzzy controller for tracking the maximum power point of a solar source in MATLAB/SIMULINK. The fuzzy system's basic components were used to build the controller (Fuzzification, Inference, and Defuzzification). These blocks read fuzzy inputs and program the plant's process, then translate the program into output activity. In this controller, trapezoidal input and output membership functions were proposed, and Mamdani's fuzzy inference approach and the centroid method as a Defuzzification procedure were also adopted. PV, buck-boost converter, fuzzy controller, and load were all modeled and simulated under varied irradiance variations. The findings show that the proposed fuzzy controller performed well and is suitable for use in a real-time system.

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