International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume35 العدد
Part 1 المجلد
October 2024 اكتوبر

تم استلام الورقة بتاريخ: 7/ 10/2024م وتم نشرها على الموقع بتاريخ: 31/ 10/2024م

Design Fuzzy Logic Controller of MPPT for Photovoltaic System

www.doi.org/10.62341/maad1254

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[2]DOI: www.doi.org/10.62341/ISTJ, ORCID:0009-0009-0615-3837,
ISSN: 2519-9854
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Abstract

This research paper presents the method of fuzzy logic system to optimize the energy extraction in a photovoltaic (PV) power system. The maximum power of a (PV) module varies due to changing temperature, solar radiation, and load. To maximize efficiency, PV systems use a maximum power point tracker (MPPT) to constantly extract the highest power that can be produced by a solar panel and then deliver it to the load. The general structure of an (MPPT) system contains a (DC-DC) converter (an electronic device that converts a source of direct current DC from one voltage level to another) and a controller. The (MPPT) finds and maintains operations at the maximum power point using a tracking algorithm during variations in weather conditions. Because of the nonlinear behavior of (PV) module current-voltage characteristics and the nonlinearity of (DC-DC) converters due to switching, conventional controllers are unable to provide the best response, especially when dealing with wide parameter variations and line transients. The goal of this work is to design andimplement a maximum power point tracker that uses a fuzzy logic control algorithm. Fuzzy logic naturally provides a superior controller for this type of nonlinear application. This method also benefits from the artificial intelligence approach for overcoming the complexity in modeling nonlinear systems. In order to succeed in this work, an (MPPT) system consisting of a

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(PV) module, a (DC-DC) converter, and a fuzzy logic controller is designed and simulated in Simulink. Analyses of buck- boost converter characteristics are carried out to find the most suitable topology for the PV system used. An integrated model of the PV module with the identified converter is simulated in MATLAB to derive the expert knowledge needed to formulate and tune the fuzzy logic controller. The simulation results show that, the fuzzy logic controller is able to obtain the desired outcomes which are actual power generation of solar panels at different irradiance and temperature.

Keywords: Fuzzy logic, PV, MPPT, DC-DC converter, MATLAB programming.

تصميم متحكم المنطق الضبابي لتتبع أقصى نقطة قدرة لنظام الطاقة الكهروضوئية

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الملخص:

تقدم هذه الورقة البحثية طريقة نظام المنطق الضبابي لتحسين استخلاص الطاقة في نظام طاقة كهروضوئي (PV) .تختلف الطاقة القصوى لوحدة (PV) بسبب تغير درجة الحرارة والإشعاع الشمسي والحمل. لتحقيق أقصى كفاءة، تستخدم أنظمة (PV) جهاز تتبع نقطة الطاقة القصوى (MPPT) لاستخلاص أعلى طاقة يمكن أن تنتجها اللوحة الشمسية باستمرار ثم توصيلها إلى الحمل. يتكون الهيكل العام لنظام (MPPT) من محول (DC–DC) وهو جهاز إلكتروني يحول مصدر التيار المستمر من مستوى جهد إلى آخر ووحدة تحكم. يقوم (MPPT) بالعثور على نقطة الطاقة القصوى والمحافظة على العمليات عند هذه النقطة باستخدام خوارزمية تتبع أثناء التغيرات في الظروف

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الجوية. بسبب السلوك غير الخطي لخصائص التيار والجهد لوحدات (PV) وعدم خطية محولات (DC–DC) نتيجة التبديل، فإن وحدات التحكم التقليدية غير قادرة على تقديم أفضل استجابة، خاصة عند التعامل مع التغيرات الواسعة في المعلمات والتحولات السريعة في الخطوط. الهدف من هذا العمل هو تصميم وتنفيذ جهاز تتبع نقطة الطاقة القصوى باستخدام خوارزمية تحكم تعتمد على المنطق الضبابي. يوفر المنطق الضبابي بشكل طبيعي وحدة تحكم متفوقة لهذا النوع من التطبيقات غير الخطية. كما تستفيد هذه الطريقة من نهج الذكاء الاصطناعي للتغلب على التعقيد في نمذجة الأنظمة غير الخطية. من أجل تحقيق النجاح في هذا العمل، تم تصميم نظام (MPPT) يتكون من وحدة (PV) ومحول (DC–DC) ووحدة تحكم بالمنطق الضبابي، وتمت محاكاته في (Simulink)ثم إجراء تحليلات لخصائص محول (buck–boost) لاختيار أفضل طوبولوجيا للنظام الشمسي المستخدم. تم محاكاة نموذج متكامل لوحدة PV مع المحول المحدد في برنامج الماتلاب لاشتقاق المعلومات الدقيقة اللازمة لصياغة وضبط وحدة التحكم بالمنطق الضبابي. تظهر نتائج المحاكاة أن وحدة التحكم بالمنطق الضبابي قادرة على تحقيق النتائج المرجوة وهي توليد الطاقة الفعلية للألواح الشمسية عند ظروف إشعاع ودرجة حرارة مختلفة.

الكلمات المفتاحية: المنطق الضبابي، الطاقة الكهروضوئية (PV) ، تتبع نقطة الطاقة القصوى (MPPT) ، محول DC–DC ، برنامج ماتلاب.

1. Introduction

There is a noticeable increase in energy consumption due to increases in industrial development and human consumption. This issue has driven interest in research and technological investments related to the optimization of energy efficiency and the use of sustainable and renewable energy sources. At the same time, the use of fossil fuels for the generation of power is decreasing and also becoming more expensive. The most important consideration in replacing conventional energy sources with more environmentally friendly renewable sources (such as solar and

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wind energy) is finding out how to extract the maximum energy and deliver the maximum power at a minimum cost for the desired load. Integration of two or more types of energy sources may offer the best way of improving power generation by varying the contribution from each energy source, depending on the load demand. The main purpose of this work is to develop and optimize maximum power point tracking and control of a multi-source alternative energy generation system consisting of photovoltaic (PV) modules, wind generators and other sources. PV power is are new able energy source that has recently sparked significant interest and may in the near future replace nonrenewable sources such as fossil fuels. However, to achieve this change-over, PV power cost per kilowatt-hour has to be competitive in comparison to fossil fuel energy sources. The material used in the structure of solar cells and the technology used in arranging the solar cells to form a module are considered key factors that affect the efficiency of PV modules. At the present time, PV modules have only about 12-26% efficiency in converting solar irradiance to electricity, which is quite low [1]. Gallium Arsenide solar cells have a high rate of efficiency of 29%, whereas Silicon solar cells have about 12-14% efficiency [2]. Moreover, efficiency can drop due to load conditions, PV module temperature, or decreases in solar insulation. In order to capture the maximum-rated power from a PV module, it is necessary to operate the module at its optimal power point. To do this, a controller called a maximum power point tracker (MPPT) is required. PVmodules are non-linear power sources and their output power depends on the terminal operating voltage. Therefore, the function of the MPPT is to compensate for the varying current-voltage characteristics of the solar cell. The MPPT modifies the output voltage and current of the PV module and determines the operating point that will give the maximum power. The MPPT must be able to accurately track the constantly varying operating point where the maximum power is delivered to increase the efficiency of the PV module. The main purpose of this research is to design and implement a fuzzy logic-based maximum power point tracker for a photovoltaic power supply. In order to accomplish this work, an MPPT model consisting of a dc-dc converter and a fuzzy logic controller is developed. The most suitable topology of buck-boost converter has been chosen to fit all components of the entire PV system. A combined model of the PV module and the selected buck-boost converter is simulated, and the results used to obtain the best design needed to formulate and tune the fuzzy logic control algorithm for tracking the maximum power.

2. Equivalent Circuit of Solar Cell

The equivalent circuit of a solar cell consists of an ideal current generator in parallel with a diode in reverse bias, both of which are connected to a load. The generated current is directly proportional to light intensity. Although the amount of current produced varies with light intensity, there are other limitations in solar cells which cap their efficiency. These limitations are represented by the other components in the circuit as shown in figure 1 below.

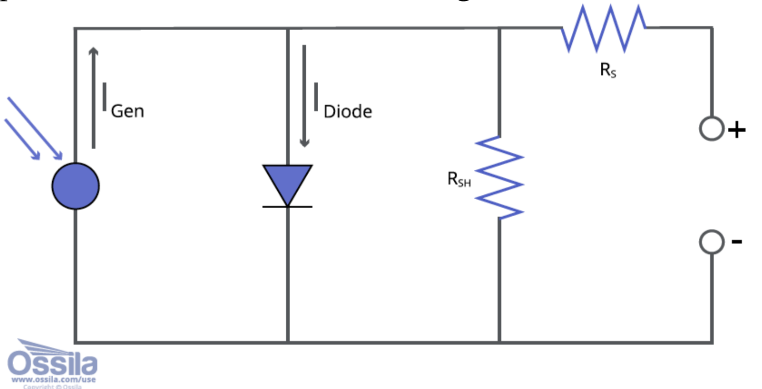

Figure1. Equivalent circuit of solar cell [3]

Parallel to this ideal current generator is a diode. The power that can be extracted from a device (P) is equal to current (I) times by voltage (V):

$$P = V \times I \tag{1}$$

To describe and model solar cells there are some equations that can be extracted from the equivalent circuit of solar cell. In its

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simplest form, the current through the load can be described as the amount of current generated minus the current that flows through the diodes and the current lost to shunt resistance.

$$I = I_{Gen} - I_{Diode} - I_{Sh} \qquad (2)$$

where I is current extracted, $I_{Gen}$is the generated current, $I_{Diode}$is diode current, and $I_{Sh}$is current lost to shunt resistance.
The ideal diode equation I_{Diode} is:

$$I_D = I_0 \{\exp\left[\frac{qV}{nkT}\right] - 1\} \qquad (3)$$

Where $I_0$is the reverse saturation current, n is the diode ideality factor, q is the charge constant, k is the Boltzmann constant, and T is absolute temperature. Therefore, the overall current equation can be written as:

$$I = I_{Gen} - I_0 \{\exp\left[\frac{qV}{nkT}\right] - 1\} - I_{Sh} \qquad (4)$$

Equation (4) gives us the relationship between a current and a voltage produced by solar cell [3].

3. Reference Model

Table (1) below shows the electrical characteristics of the proposed 130 W solar panel, which here is used as the simulation reference module and the modified model for this work is two modules of 130Wconnected in parallel.

Table (1). Electrical Characteristics Data of the proposed 130W solar panel.

Rated Power	130 Watts
Voltage at maximum power (Vmp)	17.33 V
Current at maximum power (Imp)	7.1 A
Open circuit voltage (Voc)	25 V
Short circuit current (Iscr)	8.5 A

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Total number of cells in series (Ns)	36
Total number of cells in parallel (Np)	2

The test condition electrical specifications are: cell temperature at 25°C; spectrum at 1.5 air mass; and irradiance at 1 kW/m2.

4. DC-DC Buck-Boost Converter

The averaged output and input voltage and current values for an optimized buck-boost converter are as follows [4]:

$$V_0 = V_g\left(\frac{D}{1-D}\right) \tag{5}$$

$$I_0 = I_g\left(\frac{1-D}{D}\right) \tag{6}$$

The input side's load resistance R' is equated as:

$$R' = R\left(\frac{1-D}{D}\right)^2 \tag{7}$$

As such, the load seen by the source can be decreased or increased by varying D as ($0 < D < 1$). Therefore, the buck-boost converter can operate successfully in Zones either I or II as shown in Figure (2). The next section sees the development of a state space converter model [4].

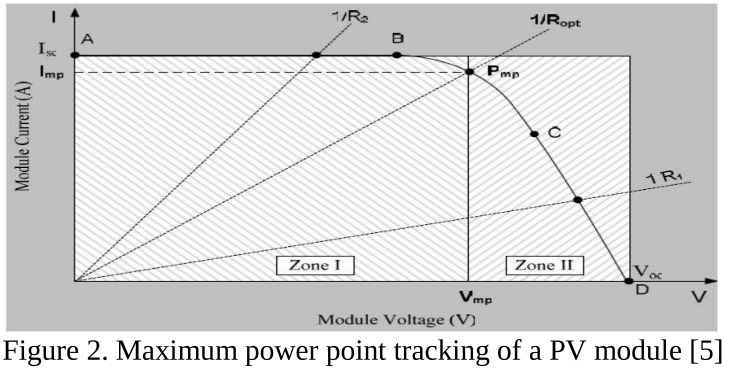

Figure 2. Maximum power point tracking of a PV module [5]

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Figure (3) below, shows the selected components parameters of buck-boost converter with the proposed solar panel.

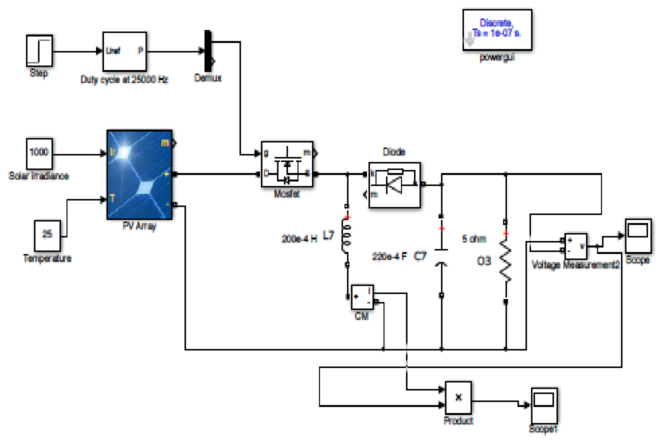


Figure 3. Simulink/ MATLAB model of buck-boost converter with the proposed solar panel

5. Fuzzy Logic Controller Design & System Simulation

Fuzzy logic controller plays the main role in this research, which controls PWM of dc-dc converter based on output of fuzzy controller. In other words, designing fuzzy controller in this work depends on studying behavior of solar panel at different irradiance, temperature, and dc-dc converter characteristics. The inputs of proposed fuzzy controller are current and voltage and the output of fuzzy controller is duty cycle. Firstly, the proposed fuzzy controller was tested in MATLAB by changing the inputs manually and the output was observed at different changes of inputs to validate the performance of the designed fuzzy controller. Figure 4 illustrates the followed mechanism of the full system in this research. In addition, specific details of designing fuzzy controller are mentioned in next paragraphs of section 5.

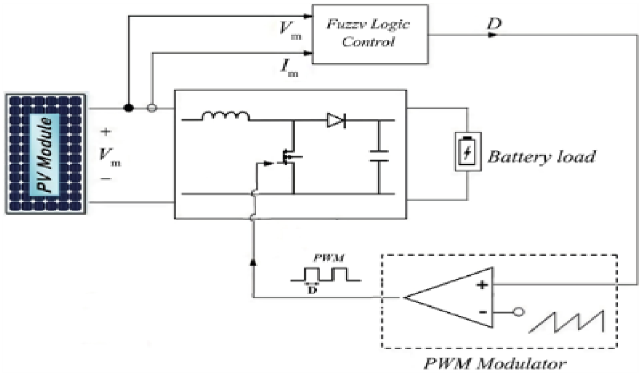


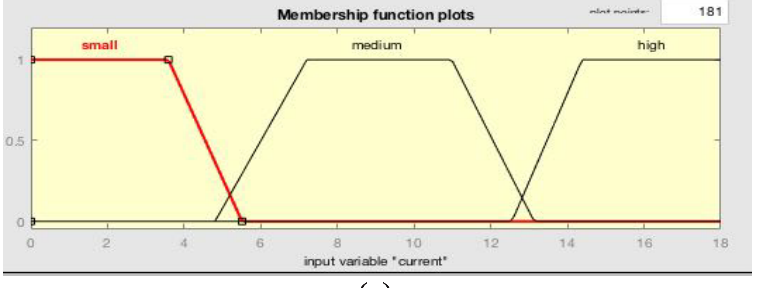
Figure 4. Fuzzy control scheme for a maximum power point tracker [6]

5.1 Membership Functions of the Proposed Fuzzy System

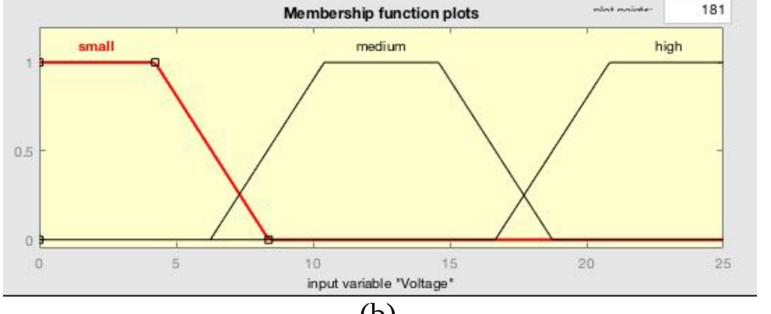
Fuzzy sets for each input and output variable are defined as shown in Figure (5). Three fuzzy subsets; small, medium, and high were chosen for the inputs and output variables of fuzzy controller. Moreover, in Figure (5), trapezoidal shapes have been adopted for the member ship functions. The range of the inputs memberships which are PV voltage and PV current were modified according to the characteristics of proposed solar panel mentioned in table 1 ($V_{oc} = 25V$, $I_{scr} = 8.5A$). Also, the duty cycle which represents the output of fuzzy controller was ranged between zero and one to give more flexibility for switching the buck-boost converter.

5.2 Derivation of Control Rules

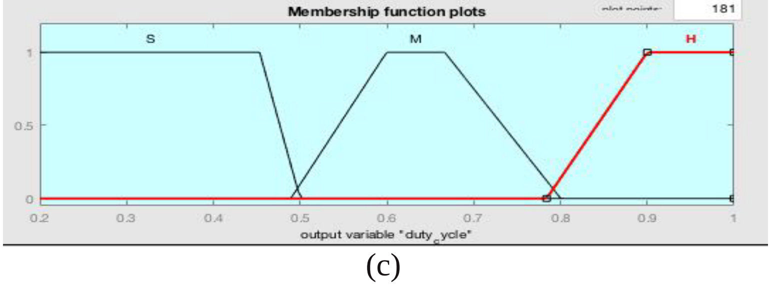
Fuzzy control rules are extracted by analyzing the system behavior. The different operating conditions are considered in order to improve tracking performance in terms of dynamic response and robustness. The algorithm can be explained as follows: The tracking process is started with an initial duty cycle, $D = 0$. The converter input current I_m, and voltage V_m, are then measured and sense the duty cycle that can give maximum power outputof the converter at that time based on predicted values that have already been entered into fuzzy system. This operation repeats itself continuously until the power reaches the maximum value and the system becomes stable.



(a)



(b)



(c)

Figure.5 Membership functions for (a) Input current of converter (b) Input voltage of converter (c) Output duty cycle of fuzzy controller

5.3 Tunning of Control Rules

The fuzzy rules of the proposed system have been derived from the system behavior and tested in Simulink/MATLAB. Table (2) below indicates the rules based on the membership functions that shown in Figure (5) above.

Table (2): Fuzzy controller rules.

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

The fuzzy logic algorithm was simulated in Simulink/MATLAB using the fuzzy logic toolbox and the rules were tuned precisely. The basic window of fuzzy designer is illustrated in Figure (6), where the controller based on Mamdani's fuzzy inference method and centroid method as a defuzzification process is used.

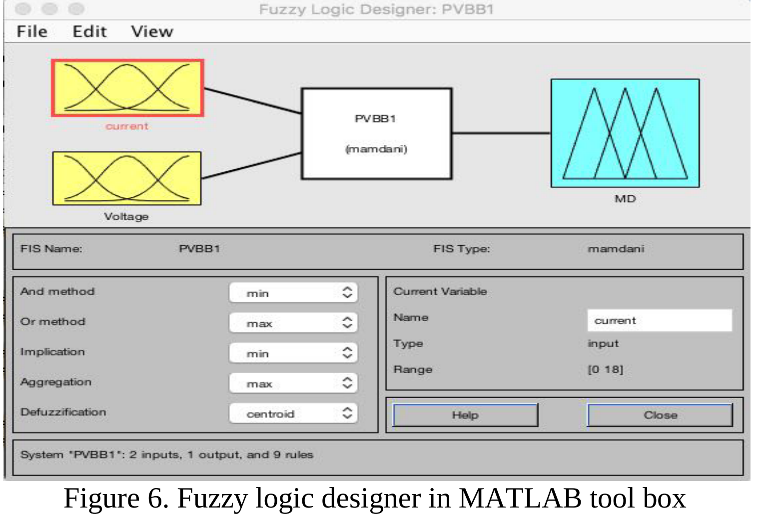


Figure 6. Fuzzy logic designer in MATLAB tool box

Figure (7) demonstrates the fuzzy controller rule surface which is a graphical representation of the rule base. And Figure (8) shows the

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rule viewer which indicates the operation of the fuzzy controller during the change of inputs.

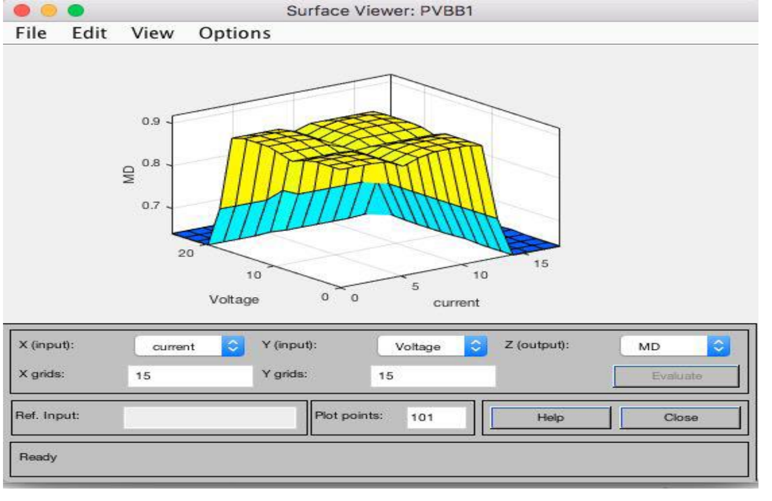

Figure.7 Graphical representation of fuzzy controller rules

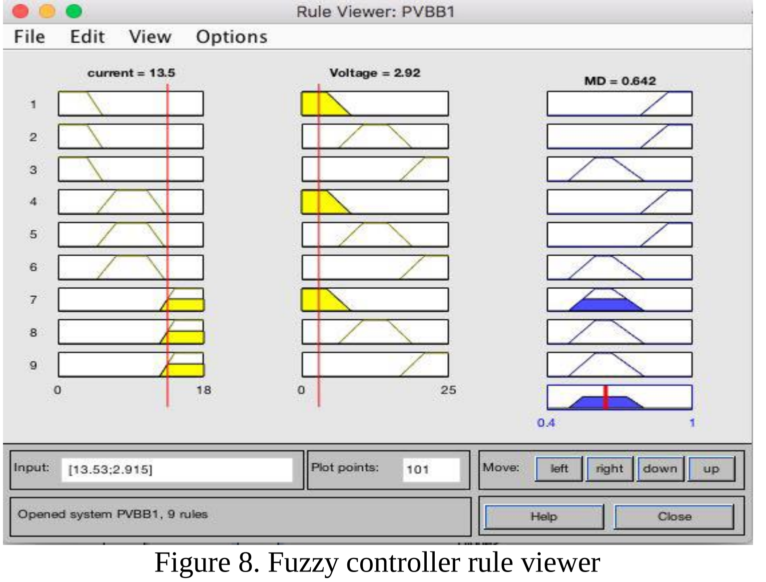

Figure 8. Fuzzy controller rule viewer

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After the fuzzy controller was modified in MATLAB the FIS file was created in order to be called in the Simulink system. In Figure (9) we can observe the performance of the fuzzy controller by reading the output of fuzzy controller at different values of inputs. Many readings of inputs, which represent current and voltage of PV, and outputs which represent duty cycle were taken and listed in Table (3) in results and discussion section.

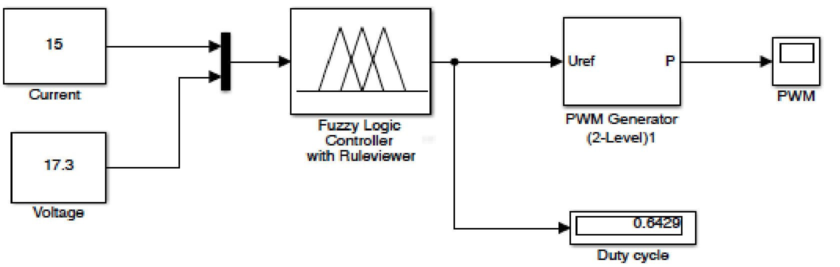

Figure 9. The optimum duty cycle from fuzzy controller

The simulation model shown in Figure (10) below was implemented in Simulink/MATLAB at different changes of irradiance.

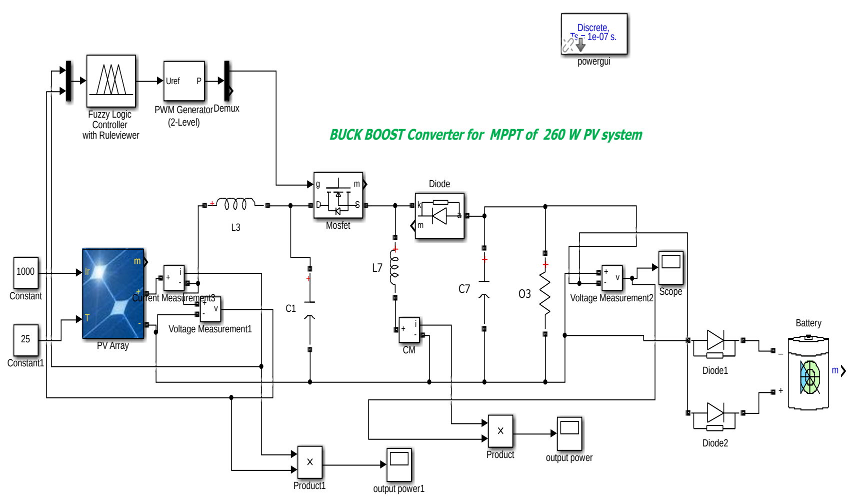

Figure 10. The complete simulated design of proposed photovoltaic system with fuzzy logic controller

In order to check the fuzzy controller performance and the efficiency of the converter the readings of input power and output power of the MPPT were taken at solar irradiance **(1000w/m^2, 800w/m^2, 600w/m^2, 400w/m^2, 200w/m^2),** and also duty cycle was observed at the same values of radiation. Table (4) illustrates more details about simulation results.

6. Simulation Results & Discussion

Table 3 below shows the test results of simulated fuzzy controller that is shown in figure (9) above. Many readings were taken of duty cycle based on manually changes of current and voltage to emulate current and voltage of solar panel. The readings show that the proposed fuzzy controller responds to the change of inputs as illustrated in table 3. Therefore, to validated that the fuzzy controller works well, it was implemented in Simulink with entire system of PV based MPPT. The table 4 illustrates the efficiency of MPPT controller based fuzzy logic design, which indicates the highest power that can be extracted from photovoltaic system at different conditions of irradiance and temperature. Figures (11 - 13) demonstrate the input power and output power of PV system at different irradiance and temperature depending on the change of duty cycle of dc-dc converter.

Table (3): Optimum duty cycle at different values of input current & voltage.

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

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Table (4): 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

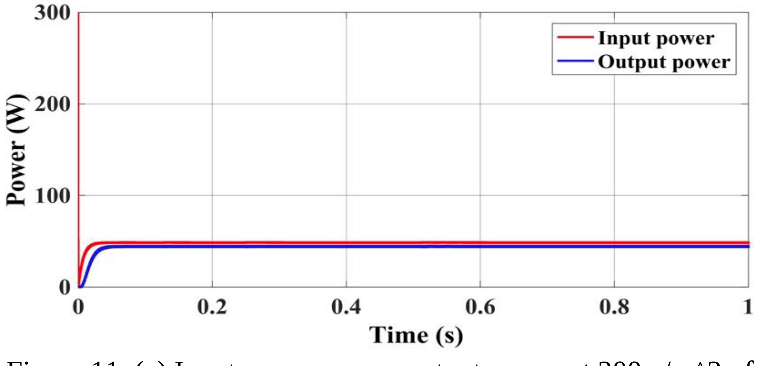

Figure 11. (a) Input power versus output power at 200w/m^2 of irradiance.

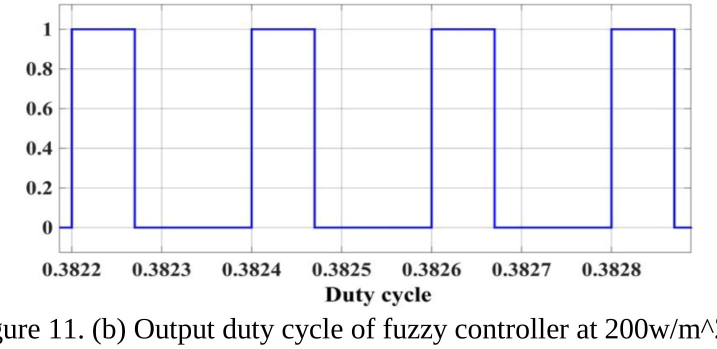

Figure 11. (b) Output duty cycle of fuzzy controller at 200w/m^2 of irradiance

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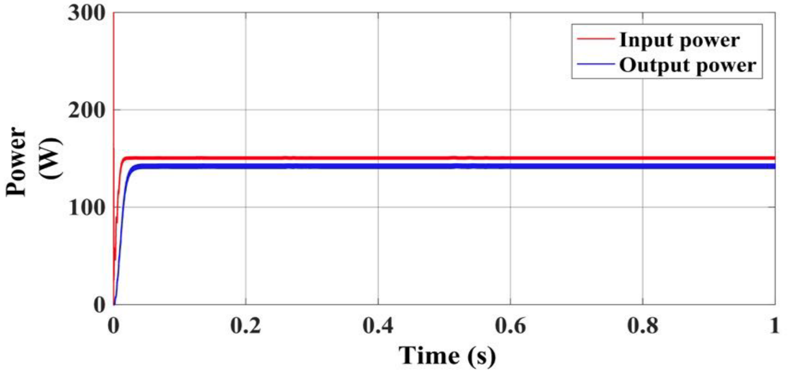

Figure 12. (a) Input power versus output power at 600w/m^2 of irradiance.

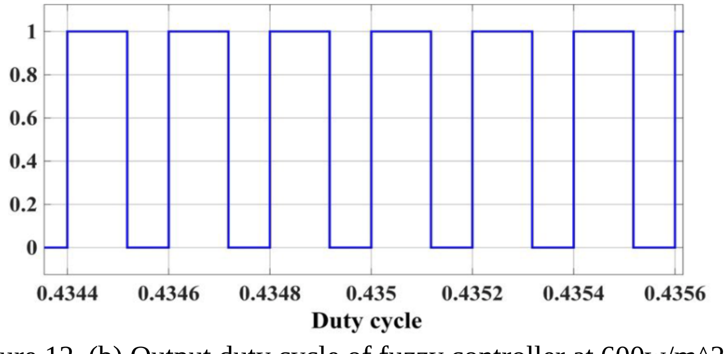

Figure 12. (b) Output duty cycle of fuzzy controller at 600w/m^2 of irradiance.

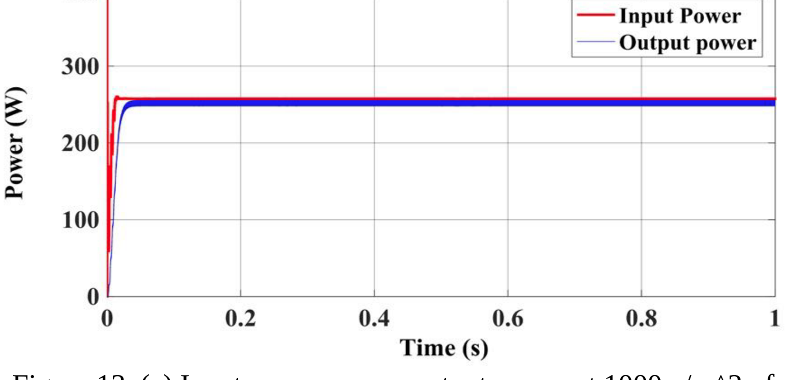

Figure 13. (a) Input power versus output power at 1000w/m^2 of irradiance.

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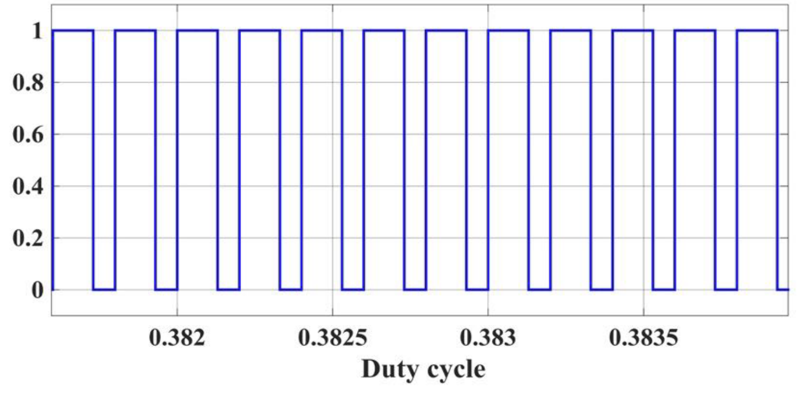

Figure 13. (b) Output duty cycle of fuzzy controller at 1000w/m^2 of irradiance.

7. Conclusion

In this paper, A Fuzzy controller for tracking maximum power point of photovoltaic source was proposed and simulated in Simulink/MATLAB. The controller was based on the basic blocks offuzzy system, which are (Fuzzification, Inference, and Defuzzification). These blocks read inputsof fuzzy and program the process of the inputs and convert the program into output action respectively. The trapezoidal shapes of inputs and output membership functions were proposed in this controller and Mamdani's fuzzy inference method and centroid method as aDefuzzification process were chosen for this controller as well. The whole system includes PV, buck-boost converter, fuzzy controller, and load was modeled and simulated under differentchanges ofirradiance. The results indicate that the proposed fuzzy controller performed well and able to maintain output power of solar panels at its maximum point.

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