

Design of Photovoltaic System using Fuzzy Logic Controller

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Abstract -This paper assesses the use of Fuzzy logic Controller in a standalone Photovoltaic (PV) system. The PV system was designed and simulated using MATLAB/Simulink where an array of Sun Power SPR-440NE-WHT-D solar panels was connected to a boost DC-DC converter. The number of parallel strings along with the number of series modules in each string of the PV panel have been designed to produce an output power of 150 KW at standard testing conditions (STC). The controller was assessed in terms of dynamic response, output power efficiency, and output ripples. These variables were tested under two scenarios; the first under fixed weather conditions and the second under varying weather conditions.

Key Words: Renewable Energy, PV, MPPT, and Fuzzy Logic

1. INTRODUCTION TO FUZZY LOGIC

Fuzzy logic is considered a type of many-valued logic (MVL) otherwise called non-classical logic. They are a form of logic that do not constrain the output truth-values to only two but accept the range of values in between as well [1]. This means that it is not restricted to binary values of "0" and "1" or "True" and "False", but operates as well in the grey area in between allowing for a more accurate indication of the variable. Another unique attribute that fuzzy logic has is the use of linguistic interpretation instead of numerical, which makes it closer to the human thought process. When Lukasiewicz and Tarski introduced infinite-valued logic in 1920 and when Lotfi Zadeh perfected it and introduced fuzzy Logic in 1965, the aim was to create a new framework that is not only black and white [2].

1.1 FUZZY SETS AND MEMBERSHIP FUNCTIONS

Fuzzy logic is a unique method that transforms mathematical equations into a set of linguistic commands which is done using two crucial concepts: fuzzy sets and membership functions. Fuzzy sets are a group of sets where the numerical data gets allocated to, and by doing so it transforms numerical values into linguistic ones. Fuzzy sets are similar to the Mathematical concept of having a universe of discourse, where a universe defined as Z contains all the values and the data are grouped. A simple example of a fuzzy set would be creating three sets called low, medium, and high, used to divide and group the available numerical data into these sets using the second concept, which is the membership function. The membership function is a tool developed through the experience of the user and is used to assess the degree to which this value belongs to a certain set and is evaluated on a

scale of zero to one. As shown in Figure 1, the triangle shape represents the membership function which is bound by zero and one, where zero means that the variable does not belong to the set at all and one means that it the variable entirely belongs to the set.

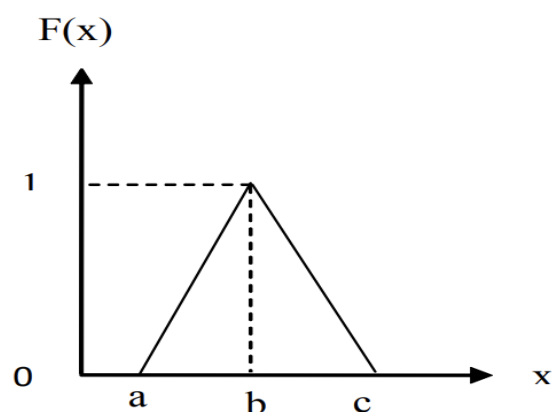


Fig -1 Membership Function Diagram [3]

1.2 FUZZY RULES AND REASONING

A fuzzy set can be adapted and tailored towards any application and that is due to the fuzzy rules that are embedded in each of the sets. A fuzzy rule is a statement developed by the user of the logic based on the knowledge of the industry experts to determine the output based on the input variables. These rules are formulated as conditional statements that utilize the "if" and "then" arguments along with some logic gates as well such as "and", "not" and "or" [4]. The rules were built in such a way to mimic the day-to-day human reasoning that is being done naturally such as "IF room temperature is low THEN switch the air-conditioning to low." In this conditioning statement, the "if" and "then" argument was used to figure out the output and input. In this case, the output is the air-conditioning fan level and the input is the room temperature. The final elements of the rule are the fuzzy sets that represent both the input and the output values, which in this case are both called low. A general fuzzy rule should look like Equation 1:

$$\text{IF } X \text{ is FS THEN } Y \text{ is FS} \tag{1}$$

Where:

X is the input measured variable.

FS is the Fuzzy Set assigned to each variable.

Y is the output measured variable.

Equation 1 is the most general and simplified version of the fuzzy rule but as the application gets more and more complicated slight changes can be noticed on the rule such as the number of inputs, the number of outputs, and finally the number of conditions in the rule.

Now that the fuzzy rules have been explained, the next part is to understand how the user programs the set of fuzzy rules so that fuzzy logic can calculate the output from the value of the input variables. Figure 2 is what a typical set of fuzzy rules look like once the user has programmed it. The figure shows the nine rules of the fuzzy rule design of a nonlinear process that has three membership functions, two input variables and one output [5]. There are two input variables, which are the error signal and the change in the error signal. Secondly, the three membership functions represent the variables that have been transformed from numerical to linguistic state. The three membership functions are N, Z, and P respectively, which as stated in the figure refer to negative, zero, and positive. Finally, the output can be denoted by three different values, which are: small, medium, and big, or S, M, and B respectively. The output can be calculated by figuring out the intersection point between the two inputs or the intersection of the rows and columns.

		$\Delta e(t)$		
		N	Z	P
$e(t)$	N	S	M	S
	Z	M	B	M
	P	S	M	S

N-negative, Z-zero, P-positive
S-small, B-big, M-medium

Fig -2 Fuzzy Rules [4]

1.3 METHOD OF OPERATION

Figure 3 describes the method of operation of a fuzzy logic controller through the use of a flowchart. The controller starts by setting an initial value for the duty cycle and then measures the values of both the PV output voltage and current. The PV output voltage and current values are then used as input signals to the FLC MPPT controller to calculate the power output. Furthermore, the measured value of the voltage along with the calculated value of the power are used to calculate the value of the error and the change in error between the inputs of the current and previous cycles. Both the error and the change in error can be calculated by using Equations 2 and 3 shown below:

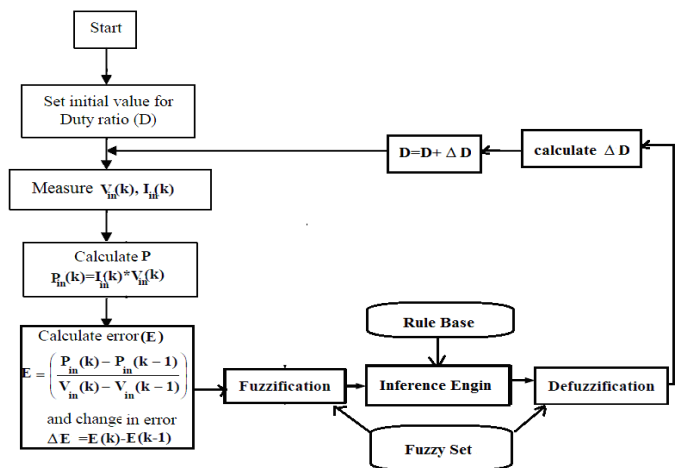


Figure -Error! No text of specified style in document. FLC Design Flowchart [6]

$$E(k) = \left(\frac{P_{in}(k) - P_{in}(k-1)}{V_{in}(k) - V_{in}(k-1)} \right) \quad (2)$$

Where:

$E(k)$ is the error signal value

$P_{in}(k)$ is the current cycle's power value

$P_{in}(k-1)$ is the previous cycle's power value

$V_{in}(k)$ is the current cycle's voltage value

$V_{in}(k-1)$ is the previous cycle's voltage value

$$\Delta E = E(k) - E(k-1) \quad (3)$$

Where:

$E(k)$ is the current cycle's error signal value

$E(k-1)$ is the previous cycle's error signal value

Once the error and the change in the error values are calculated, the fuzzy logic process shown in Figure 3 starts. The controller takes these two values in as crisp inputs and changes them into linguistic values corresponding to their fuzzy set label, which is the fuzzification process. The inference engine in the controller then calculates the output decision based on the inputs it receives from the fuzzifier and the fuzzy rules the user has installed in the knowledge base. The de-fuzzifier then transforms the received output decision from linguistic to numerical or crisp value. This numerical value is the change in the duty cycle required to have the output at the MPP. Thus, the new duty cycle is equivalent to the old duty cycle plus the change in duty cycle calculated. The change in duty cycle can either be positive or negative depending on the required final duty cycle as shown in Equation 4:

$$D(k) = D(k - 1) + \Delta D \tag{4}$$

Where:

$D(k)$ is the new cycle's duty cycle ratio ($0 \leq D(k) \leq 1$)

$D(k-1)$ is the previous cycle's error signal value

ΔD is the calculated change required in duty cycle ($-1 \leq \Delta D \leq 1$)

1.4 ADVANTAGES & DISADVANTAGES OF FLC

The popularity and usage of fuzzy logic have been increasing steadily ever since Zadeh created it in 1965. Nevertheless, Proportional Integral Derivative (PID) is still the most widely used control logic. This section will clarify this usage by presenting the advantages and drawbacks of fuzzy logic control.

There are numerous advantages to using fuzzy; however, the main one that stands out is the user-friendly logic. The concept that fuzzy logic was built on was to mimic the human thinking process, which is why fuzzy logic transforms numbers into language and the rule base is configured by sentences instead of mathematical equations. Thus, making it not only much more convenient for the users but also faster to program. Another major advantage is that unlike other controllers, fuzzy logic has the ability to work with imprecise mathematical models or ones that are approximated and still provide an efficient output. Fuzzy logic is consistent and robust even during frequently fluctuating applications such as the weather condition with solar panels. Finally, fuzzy logic is capable of working in parallel with other control techniques such as PID or state feedback [7].

On the other hand, like any other control technique, fuzzy has its drawbacks. Firstly, compared to other commonly used methods, FLC is much more complex. The common techniques require the usage of one or more sensors and thus they are simpler to use. Moreover, higher complexity translates into higher cost of implementation. Another drawback is when an accurate mathematical model of a complex project is available; it tends to be easier and quicker to use a controller that utilizes this model instead of re-writing the model to conditional statements. In this case fuzzy would not be the optimum choice

2. PV SYSTEM DESIGN

The PV system design as shown in Figure 4, starts with a Ramp-up/down module that controls and fluctuates the value of the temperature and the irradiance to simulate real-life conditions. These values are fed to the PV array block, which produces a certain voltage and current depending on the

specific values of the temperature and irradiance. The voltage and current values taken from the PV array are used as inputs to the MPPT controller while the output of the array is connected to a DC-DC Boost converter. The MPPT controller uses the input PV voltage and current value to continuously calculate the duty cycle, which is then fed to the boost converter. The boost converter controls the voltage level according to the duty cycle to continue tracking the Maximum Power Point at all times. Finally, the output of the

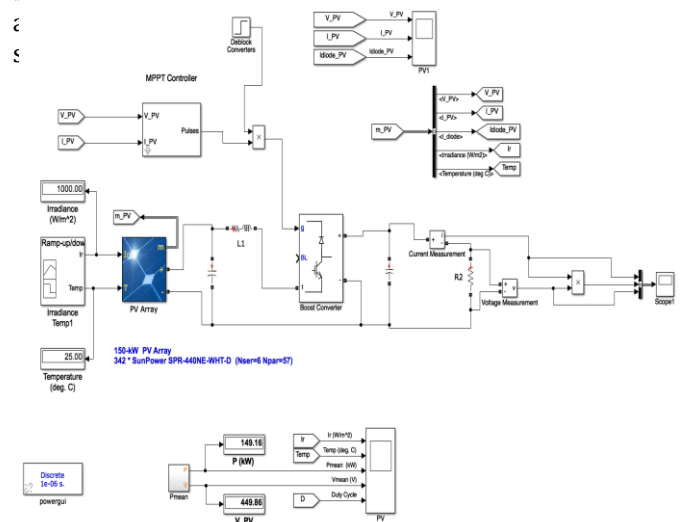


Figure -Error! No text of specified style in document. PV Solar System Design on MATLAB [8]

2.1 FUZZY LOGIC CONTROLLER DESIGN

This controller is designed in a unique way as it utilizes linguistic rules and functions instead of mathematical models. Figure 5 shows the proposed MATLAB design of the fuzzy logic controller used in this paper. The fuzzy logic controller has two inputs, which are the error and the change in error as calculated using Equations 2 and 3 and has one output, which is the duty cycle.

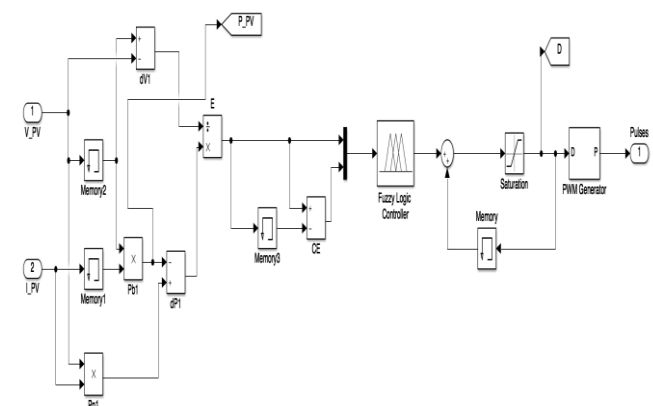


Figure -5 Simulink/MATLAB Fuzzy Logic MPPT Controller

3. DISCUSSION AND RESULTS

This section will highlight the performance of the Fuzzy Logic controller under two separate scenarios. In the first scenario, the panel will be subjected to a constant solar irradiance of 1000 W per square meter and will have a constant internal temperature of 25 degrees Celsius as shown in Figure 6. This allows for a simple and reliable demonstration of the algorithms' performance in terms of accuracy and speed to get the desired power output, which is 150 kW.

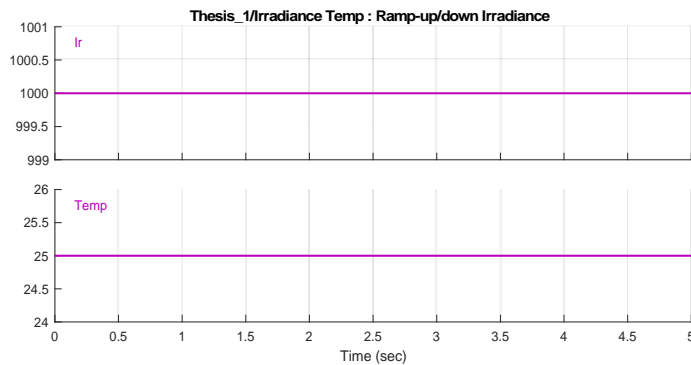


Figure -6 Constant Irradiance and Temperature Signals

Figure 7 illustrates the second scenario where the panel is subjected to variable irradiance and variable temperature to document the behavior of each algorithm when experiencing conditions similar to those in real life. The irradiance will vary from 1000 W per square meter to 250 W per square meter and the temperature will vary from 25 degrees Celsius to 50 degrees Celsius. There is also a period of time where the temperature is constant and the irradiance is changing and vice versa and the reason behind that is to capture the effect of each of these variable on the output power separately. Period A represents a fixed value of irradiance and temperature at 1000 W per square meter and 25°C respectively. In Period B the temperature remained unchanged, however, the irradiance dropped from 1000 to 250 W per square meter and remained this way from the 1.7-second mark until 2.5 seconds. Period C commenced after the 2.5 second mark, increasing the voltage back to 1000 W per square meter. Finally, in period D, the first change in the temperature is witnessed from 25 °C to 50 °C with an irradiance of 1000 W per square meter.

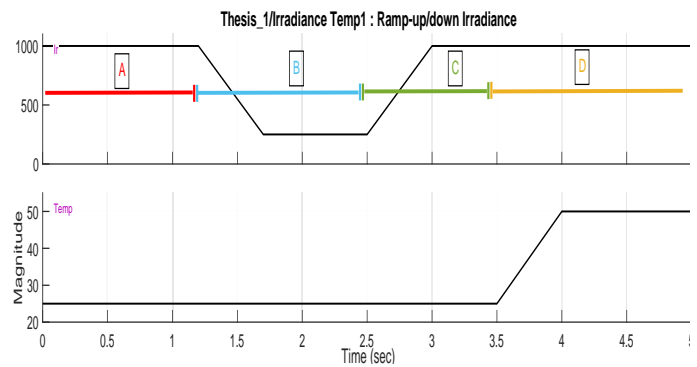


Figure -7 Varying Irradiance and Temperature Signals

3.1 SCENARIO 1: CONSTANT IRRADIANCE AND TEMPERATURE

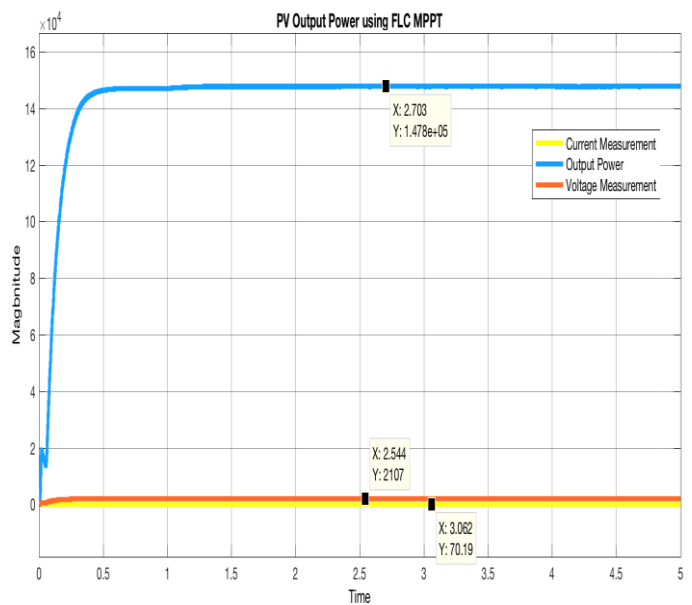


Figure -8 Output Power Under Constant Conditions Using FLC MPPT

The step response of the output power using fuzzy logic controller in Figure 8 results in a rise time of the output power of about 0.198 seconds and settling time of about 0.26 seconds. Moreover, the output power reaches a maximum value of about 148,100 W at time 4.675 seconds. However, the mean value of the output power is 148,000 W and when compared to the targeted output power, which is 150,000 W, results in an output efficiency of about 98.66% for the FLC.

Figure 9 is divided into 5 plots under constant weather conditions, which are: the duty cycle (DC), the PV output voltage, PV output current, system output voltage, and current on the load side. The first three graphs oscillate at the very beginning until they reach their steady state value at time of about 0.3 seconds. The steady state values are: 0.9 for the DC, 452 Volts for the PV voltage, 326.2 Amperes for the

PV current, 2106 Volts for the output system voltage, and 70.2 Amperes for the output system current.

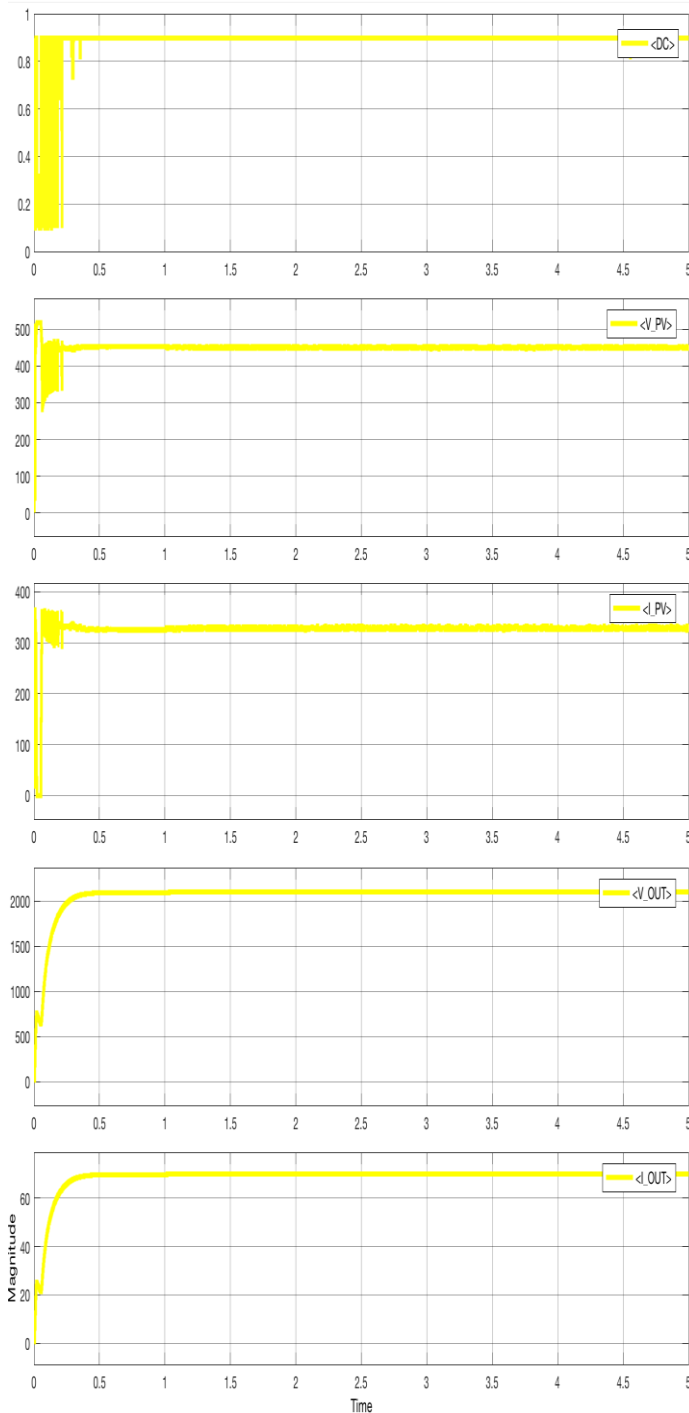


Figure -9 FLC DC, Voltage, and Current Diagrams Under Constant Conditions

3.2 SCENARIO 2: VARYING IRRADIANCE AND TEMPERATURE

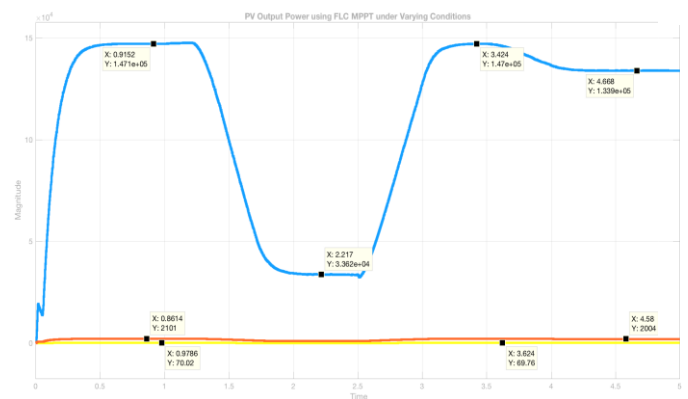


Figure -10 Output Power Under Varying Conditions Using FLC MPPT

In Figure 10, period A is where the irradiance is 1000 W per square meter and the module temperature is 25 °C. The output power curve increases here from zero to 147,600 W of power. It then drops down to about 33,770 W in period B when the irradiance drops to 250 W per square meter and the temperature is kept constant. In part C, the irradiance increases again to 1000 W per square meter and thus the power output is close to that in part A, which is 147,200 W. Part C is done in preparation for part D, where the irradiance is kept constant at 1000 W per square meter and the temperature increases from 25 to 50 °C. This results in a power output drop from 147,200 W to 133,900 W.

As expected, the drop in the irradiance causes the most deterioration in output power where the change from 1000 W per square meter to 250 W per square caused a 77.2% drop in the output power. On the other hand, the increase in temperature from 25 °C to 50 °C causes a percentage drop in power by about 9%.

Table 1 demonstrates the efficiency levels calculated using Equation 5.1, which are: 98.0% in period A, 92.43% in period B, 97.74% in period C, and 98.97% in period D. FLC achieved staggering efficiency percentages across all four periods.

Table -1: FLC Efficiency Percentages of each Period

Period	Irradiance Value (W/m ²)	Temperature Value (°C)	Actual Output Power (W)	Theoretical Output Power (W)	Efficiency Percentage %
A	1000	25	147,600	150,600	98.00
B	250	25	33,700	36,460	92.43
C	1000	25	147,200	150,600	97.74
D	1000	50	133,900	135,300	98.97

Figure 11 shows the Duty cycle values, PV output voltage and current, and the system output voltage and current. Regarding the PV's voltage and current response, the current is highly affected by the drop in irradiance from 326 Amperes to about a mean value of 75 Amperes and no change is observed during the increase in temperature. However, the PV voltage does not seem to be affected much by either change but is affected more by the temperature where it drops from 453 Volts in period A to 451 Volts in period B and 401 Volts in period D. The two final curves are of the load side voltage and current which react in the same manner they start at with values of 2101 Volts and 70.04 Amperes respectively in period A, dropping to 1006 Volts and 33.5 Amperes in period B, increasing back up to 2101 Volts and 70.03 Amperes in period C, and finally slightly dropping to 2005 Volts and 66.8 Amperes in period D.

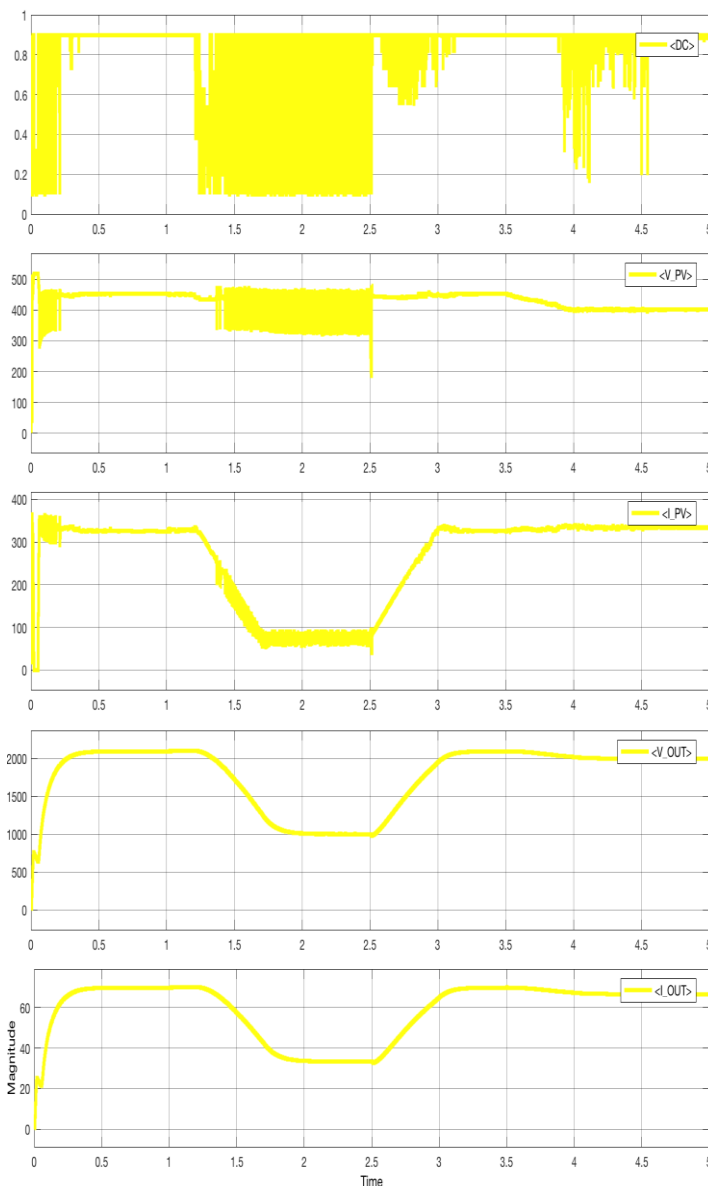


Figure -11 FLC DC, Voltage, and Current Diagrams Under Varying Conditions

4. CONCLUSION

This paper presented a Fuzzy Logic approach to modeling and simulating a photovoltaic system with a maximum power point controller. Fuzzy Logic was used because it is considered to be a high level controller. The PV system was designed and simulated using MATLAB/Simulink to generate a power output equivalent to 150 kW. Results of the modeling and simulation show a rise time of 0.198 seconds, settling time of 0.26 seconds, and a mean efficiency of 98.66%. The controller was subjected to four conditions of varied irradiance and temperature. Throughout Periods A to C, the temperature was kept constant at 25 degrees Celsius while the irradiance was varied. In Period D, the temperature is varied from 25 °C to 50 °C. Results of the four conditions show that the maximum efficiency was reached in Period D, followed by Periods A, C, and finally B.

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BIOGRAPHIES



Mohamed Khallaf Born in 1996. Graduated with a BSc in Electrical Engineering and a minor in Computer Engineering from the American University of Sharjah in 2016. Currently pursuing MSc in Electrical Engineering (in Control Systems) at RIT Dubai.

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