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Optimizing The Maximum Power of Photovoltaic System Using Modified Incremental Conductance Algorithm Operating Under Varying Dynamic Climatic Conditions

I. M. Elzein[1], M. Kurdi[2], Y. Harrye[3]

[1,3]Faculty of Telecommunications and Network Engineering, University of Doha for Science and Technology, Doha, Qatar
[2] Faculty of Engineering and Information Technology, City University, Tripoli, Lebanon

Corresponding author: 60101973@udst.edu.qa

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Abstract: In a photovoltaic system the challenge is to contentiously searching for the maximum power point to generate the maximum power (Pmax) within the system. In this study a hybrid maximum power point tracking module (MPPT) consisting of a well-known incremental conductance algorithm (INC) is being adapted to operate along with fuzzy logic controller (FLC). The new design focused on applying variable voltage step size estimations based on analyzing the degree of incremental and decremental of power to voltage relation. To achieve this, five effective regions were introduced around the maximum PV power point and FLC controlled the tunning and accurate adjustments of the duty ratio cycle step size by relying on the inputs of fuzzy logic controller to reach a zero oscillation around the MPP point. To adjust the duty cycle step size, fuzzy logic is established based on the position of the fuzzy input points which are derived from the current and voltage proportions and their derivatives, whereas the membership functions and rules are shaped. Matlab simulations were used under different irradiance levels to test the efficiency of tracking the maximum power. Based on the simulated results, the integration of fuzzy logic controller with incremental conductance algorithm provided enhanced performance in tracking the Pmax, and notable fast convergence time and provided the least oscillation around the maximum power point and thus maintained the overall tracking accuracy, and applying the proper step size to drive the operating point at the P-V curve in reaching Pmax under the effects of various environmental dynamic changes in temperature and irradiance.

Keywords: *Incremental conductance, Fuzzy logic, Adaptive step size, PV system, Intelligent control system, dc-dc converter*

1. Introduction

Solar energy is getting more popular and of interest at the level of renewable energy source category because photovoltaic (PV) modules and systems have low maintenance costs, and quiet in terms of the noise and can range in size from large kilo-watts to very few milli- watts allowing for efficient integration into our current environment [1],[2],[3]. As a result, the PV energy's amounts generated and produced are rising and getting a noteworthy part for both the industrial and domestic subdivisions.

In fact, the limitation to the spreading of PV power systems comes to many reasons however not to count the cost only, but the in-ability of PV cells in transforming/converting the energy of solar radiation into electrical power. Currently, conversion in the energy and its efficiency is close by and about twenty percent, assuming that the solar cells are working at their maximum rate [4], [5].

PV cell output power (Pout) to its operating voltage has the characteristics of a non-linear function with respect to each other's. Such an identified function has an MPP equivalent to a certain voltage value; similarly, the PV array performance would rely on different other factors such as voltage operation, shading, irradiance and temperature [6], [7].

The main goal sought in PV solar panels and systems is to track and reach the MPP. To achieve this goal, an extra module shall be implemented. This would be achieved through a power converter [8], [9]. The converter shall be connected to the PV output's module; this inverter drives the PV module output voltage to reach the optimal value considering the aforementioned atmospheric conditions and their versatilities that affect the overall performance of the system.

In the most recent years, many approaches were addressed to reveal their capability of controlling converters while looking to address tracking the MPP through applying different MPPT algorithmic methods

E-mail: 60101973@udst.edu.qa, m.al-kurdi@cityu.edu, 60102147@udst.edu.qa

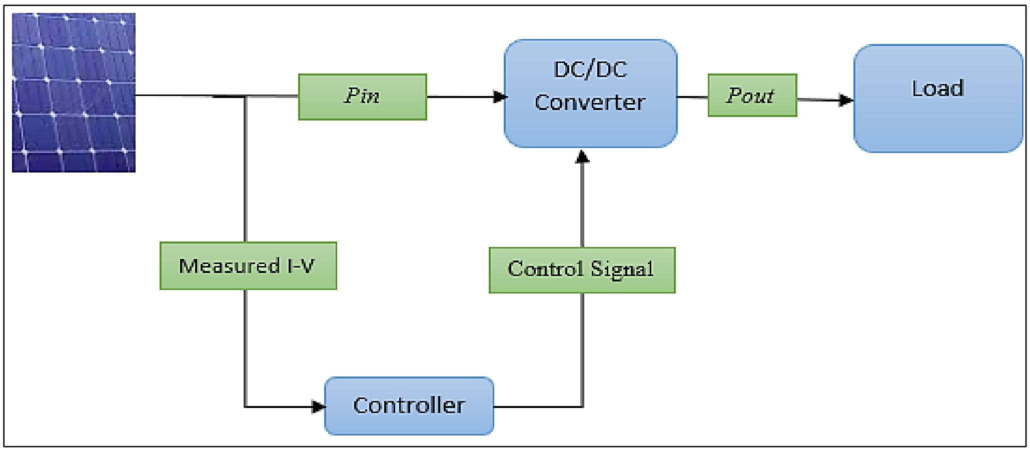

Figure 1. MPPT block diagram

[10]. Those are currently recommended and their assessment is presented in several set of articles. The main block diagram of MPPT is shown in Figure 1 [11].

In fact, two well know algorithms have been studied by many researchers in regards of tracking and extracting the MPP and those are the Perturb and Observe (P&O) as well as the Incremental Conductance (INC) methods [12], [13].

Numerous MPPT systems have been addressed as per the literature. Along of that some techniques are uncomplicated, relying on voltage/current feedback. However, they necessitate sporadic interruption of the PV modules for measuring the V_{oc} or the I_{sc} for reference, leading to increased losses in power (Liu et al).

The (P&O) algorithm (Abdul et al), hill climbing (HC) and incremental conductance (IC) algorithms (Kiesh et al.) are more improved in tracking the MPP however they require more complicated settings. The incremental conductance algorithm works on the principle of applying at the PV's module operating voltage a perturbation. The HC algorithm applies a perturbation at the DC-DC converter's duty cycle which makes it more favorable since its control structure is simple to adapt (Alaj et al.).

The development of MPPT controllers utilizing neural network and FLC techniques resulted in faster tracking speed of the MPP and more accurate performance in extracting the Pmax of a PV system (B. Salh and Oali et al.). In particular, FLC have demonstrated superior performance compared to other control methods, and are able to maintain good performance even under varying atmospheric conditions (Isram et al.).

Most of the well know algorithms and precisely the INC, relies on a fixed step size perturbation when applied in a direct control. However, this conventional practice has several disadvantages, that can be listed as follow; the convergence speed is very slow in reaching the operating point at the optimal level and this is due to the fact that the fixed step size perturbation is applied [14], [15]. Further in the steady state, the oscillation of the driven operating point to reach the MPP or around it using a conventional INC algorithm leads to a major loss in energy (overall extracted power) [16]. In addition, INC algorithm cannot track the MPP at severe climatic conditions due to the use of pre-determined and fixed step size perturbation [17], [18].

The operating voltage of PV system relies on MPP location to keep updating it by tuning and changing the power converter duty ration cycle through a series of fixed step sizes [19], [20]. In the past studies of the most recent tracking algorithms, it has been well known that the P&O is easier to implement when compared to an INC method. However, it degrades from its lower accuracy results when tracking the MPP, regardless of the testing environmental conditions whether being constant or non-constant [21], [22]. On the other hand, the INC method can provide better accuracy as compared to the P&O algorithm however for the price of being more complex mechanism and slower convergence time. Such complexity is capable of providing an ultimate and reasonable performance for rapid changes in atmospheric conditions [23], [24], [25], [26].

The curve of the current-to-voltage (I-V) and its characteristics under the normal test conditions is depicted in Figure 2. This curve denotes a particular characteristic of a PV array. It provides a description of the conversion in the solar energy efficiency [27], [28]. Once the I-V characteristics for solar cell is known it will be essential in the determination of the efficiency of solar system and the PV overall output performance [29], [30], [31].

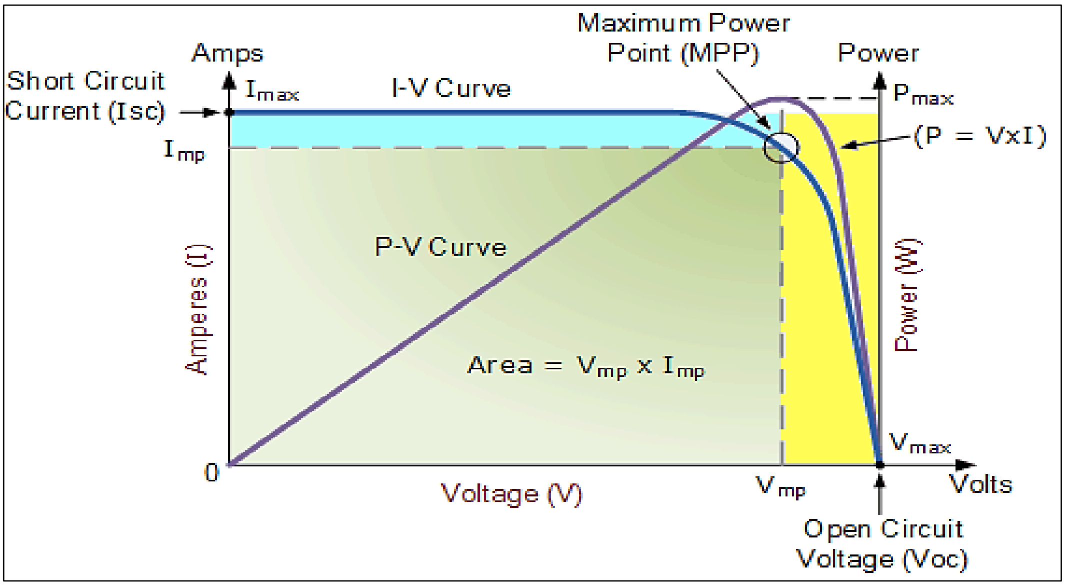

Figure 2. General characteristic current-voltage curve

At the stage of the open-circuit state, the voltage (V_{oc}) is obtained through the maximum voltage (V_{max}) and vice versa, the (I_{max}) is being attained through the short circuit state (I_{sc}).

A PV array operational point is lying always between the above mentioned two states, denoted by (0, V_{oc}) and (I_{sc}, 0). The combinational product of both the current and voltage is going to be at the maximum. Hence, that point is normally denoted as the maximum power point (MPP).

Once we refer to the MPP, the current and voltage are represented by (V_{mp} and I_{mp}). As per solar panels, when we operate them at the operating points that are not guided or directed to reach the MPP, then the power extraction from that PV module will be degraded and hindered in extracting the maximum power [32], [33].

The PV system operating point is found on the characteristic curve and its location is not constant due to n the changes associated with the irradiance and temperature at certain given time period. To harvest the Pmax at different temperature levels and irradiances, the operating point of the system must reach the maximum peak of the P-V curve. Once this condition is satisfied, that point is called the maximum power point denoted as (MPP). To extract this MPP out of the module it will be essential to drive the current operating point to operate at the peak level of the MPP of the P-V curve [34], [35].

Along this research we will implement a type of hybrid MPPT consisting of two schemes: incremental conductance control (INC) and novel fuzzy logic (FLC) control. This approach seeks and tracks the maximum power point (MPP) under a different set of dynamic solar irradiances. Additionally, it will precisely adjust the duty ratio cycle of a DC-DC converter to speed up the tracking process of MPP [36]. Simulation analyzes are performed to test the tracking accuracy and overall performance of the suggested approach in this research study. The obtained testing simulations and results were promising in regards to the tracking scheme of MPPs under varying irradiances and diminished the oscillation around the maximum power point of the PV non-linear curve [37], [38].

For this proposed work, a photovoltaic system is used, which consists of many interconnected photovoltaic sets of cells and apply a conversion from sunlight form to an electricity form. The load impedance will determine both the current and voltage through which PV module operates [39], [40].

To recap, in this research a proposed modified INC variable step size perturbation based FLC controller is implemented to overcome the degradations of power losses of the conventional fixed step size technique, where the adaptation of variable step using an FLC intelligent controller provided the following positive outcomes based on the simulation results [41], [42], [43]. The below points were addressed, investigated and tested through the course of investigating the proposed system [44], [45], [46];
(1) The PV operational conditions are subject to changes due to the changes of temperature and irradiance. To address these variations effectively, FLC was employed in this research study to adjust the step size in the INC algorithm dynamically, enabling real-time adaptation to the evolving conditions. (2) Utilization of variable step sizes based on fuzzy logic improved the overall MPPT efficiency as demonstrated in the simulation results there were obtained from Matlab Simulink. (3) INC based on FLC intelligent control was able to adjust the step sizes based on the changes of the systems' dynamic weather parameters that minimized the oscillation factor around the MPP, permitted the system to converge more faster at the MPP level, and demonstrated a major reduction in the response time of driving the operating point on the P-V curve towards the optimal MPP [47], [48]. (4) Applying FLC provided the advantage of operating and making decisions simultaneously based on different sets of changing input parameters (i.e., the current and voltage) and this was revealed through the set of pre-defined FLC rules to

generate the optimal output power of the designed PV system [49], [50].

2. CHARACTERISTICS OF I-V AND P-V CURVE

To gain an enrich insight of the operational and performance as we address solar panels, it is essential to examine the characteristics perspective of both the I-V and P-V curves in a photovoltaic environment [51], [52].

Those curves are needed to assist in detecting the degradation level and the sort of low performance causing a solar panel to function under its expected output level [53], [54], [55].

Figures 3 and 4 demonstrating the I-V and P-V respectively, with a different range of irradiance values and temperature [56], [57]. As per Figure 3, an I-V nonlinear curve is shown with different ranges of irradiances. Normally this curve represents in a graphical means the solar array's operation and therefore addressing the current and voltage relationship at a set of irradiance level value [58], [59], [60], [61].

Climate factors, like temperature and irradiance, have a direct impact on the I-V curve of a PV module, leading to deviations in its maximum power point (MPP) [62], [63]. Considering that, practical PV systems operate in dynamic conditions where these factors are continuously fluctuating, it becomes essential to continuously adjust the operating point of the PV module to match the new MPP [64], [65].

This curve gives the necessary information during the configuration of a PV system to make it operating at the optimal maximum power point (MPP). In addition, this curve depends on the quantity of irradiance hitting the solar panel modules [66], [67].

When an increase in irradiance (during peak hours of the day) takes place, this will lead to increase the current at the vertical axis as shown in Figure 3. For instance, when the irradiance increases from 400w/m^2 to 1000w/m^2 we observe that the effect of irradiance on the short circuit current (I_{sc}) is linear and thus it increases linearly and proportionally with the solar irradiance level [68].

As per the effects of the open circuit voltage (V_{oc}), when the irradiance increases the V_{oc} will also increase. However, in this scheme the V_{oc} is ranging between 1.3 and 1.5 volts (due to irradiance changes) and thus the solar irradiance effects on the V_{oc} are not that significant [69], [70].

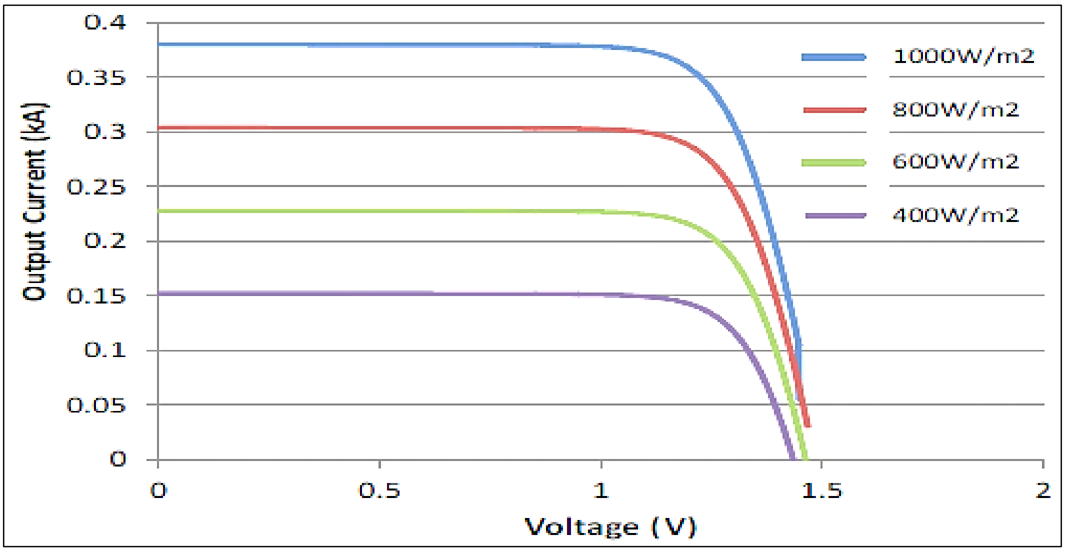

Figure 3. PV module I-V curve for various irradiances

As per Figure 4, it represents a PV solar panel with a 60W power efficiency. The P-V curve is analyzed under varying temperature levels [71], [72]. It is noted that the temperature and power are inversely proportional in this scheme where the power will decrease when an increase in temperature occurs [73], [74].

In fact, both the output power and voltage of the solar array is decreasing when the operating temperature of the solar cell is increasing [75].

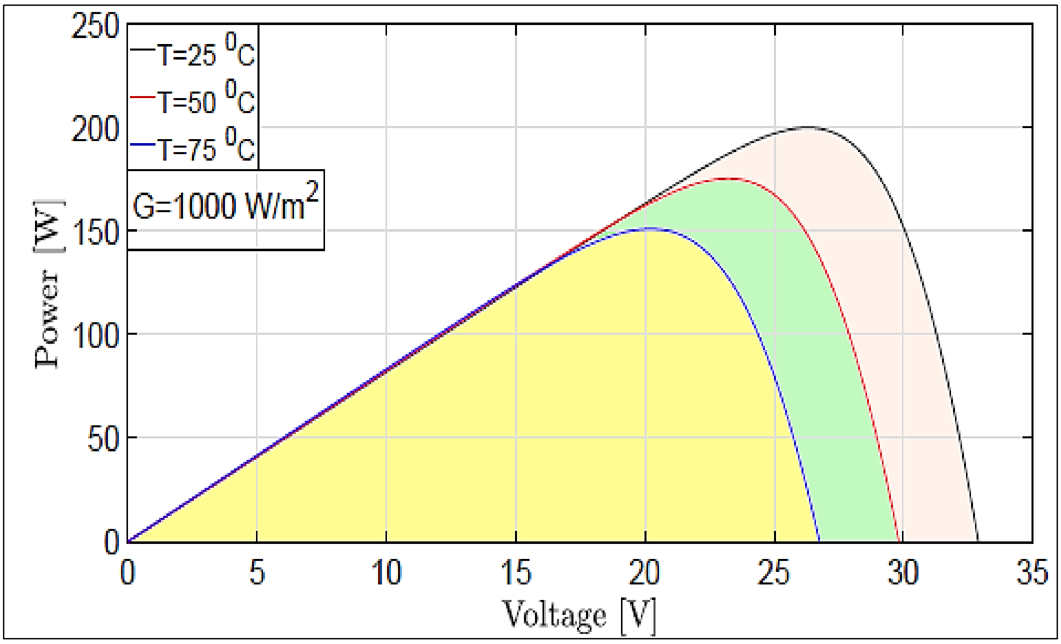

Figure 4. P-V characteristics curve with varying temperatures

From the above illustrations we notice that many parameters affect a PV array which reveals a non-linear characteristic in term of either I-V or P-V curves whether there was a change in irradiance levels or temperature values. This will lead to loss of the system's energy and eventually degradation in tracking the maximum power point (Pmax) of the PV system. To overcome this optimal power loss and to affirm PV solar arrays are operating at the Pmax under the above versatile parameters' conditions, a maximum power point track mechanism is crucial to be incorporated. It diminishes the oscillations around the Pmax on the P-V curve and maximize the overall energy of the system [76].

To summarize, the efficiency of photovoltaic systems is typically affected by climatic conditions, including solar radiation denoted as (G or S) and temperature (T).

3. MPPT TRACKING THROUGH THE IMPLEMENTATION OF INCREMENTAL CONDUCTANCE ALGORITHM

MPPT is an algorithm utilized to enhance the efficiency of a PV module. Multiple MPPT systems are designed to seek and track the MPP. In general, a decent and reliable range of such algorithms are available to line-up the PV module to operate at the full power extraction point MPP [77].

In general, we have a variety of different types of MPPT algorithms. The most well-known for instance, would be the perturb and Observe(P&O) and the incremental inductance (INC). These algorithms used to tack the MPP, and can be integrated with different variety of controllers, such as, fuzzy logic controller (FLC) [78].

The P&O algorithm, operates in the sense of perturbing the voltage and observing the power in a path of keep monitoring and driving the operating point (current direction) to move it towards the MPP and reaching it. Technically speaking, the P&O continuously has a role of targeting the current location of the operating point and move it to the desired location on the P-V curve [79].

Consequently, and back to the PV module, when the operating point moves away and not aligning with the MPP, the voltage will be perturbed (adjusted) in the reverse direction. Many researchers addressed the P&O in their research papers, along with the Hill Climbing (HC).

The above mechanisms and approaches, unfortunately, will have a negative impact due to causing the operating point on the P-V curve fluctuating around the MPP. This oscillation around the MPP is normally due to environmental climatic conditions that changes drastically, as well as, when the load is changing.

The incremental conductance (INC), operates in another and different way as compared to P&O, where (INC) function and operates through a special and unique mechanism. It concentrates on the PV power slope rather than the voltage curve. Through this functionality approach, it's capable to optimize reaching the ultimate and most desired MPP at zero (This is the location where the maximum power extraction occurs).

INC has a special characteristic where it utilizes a fixed iteration step size. Dealing with fixed iteration step size has proved to have many performances limitation according to many researches when it was used in tracking the MPP [80].

Our proposed approach deals with integrating the INC algorithm along with one of the most known controllers, the fuzzy logic control (FLC).

The direction of this study in this paper is to work on reducing the shortcomings of the conventional INC algorithm. In addition, the anticipated module is designed to minimize and reduce the oscillation that is taking place and re-occurring around the MPP.

Furthermore, another achievement of the proposed hybrid tracker to improve the steady-state performance as well.

In addition, through this investigated theme, we recommend an improved INC algorithm established on the approach of utilizing a variable step size versus the fixed step control where the variable step size improves both dynamic (sudden irradiance fluctuations) and stability of the overall functionality and the system's performance of the photovoltaic module during extracting the Pmax [81].

4. IMPLEMNTATION OF MPPT ALGORITHM USING INCREMENTAL CONDUCTANCE

As one of the most popular algorithms in tracking the MPP, the incremental conductance (INC) would serve its purpose as an MPPT algorithm. It depends on the most important two parameters in a photovoltaic system, namely the PV voltage and current. The maximum power point tracking (MPPT) has enhanced the overall performance of a PV module especially under dynamic climatic changes. The INC as compared to P&O has overcome the optimization to the PV system.

In an incremental conductance, the method used to find and track the MPP is relying on comparing the incremental conductance to the instantaneous conductance. Since the MPP is determined when the change of power to voltage (ΔP/ΔV) is set to zero; using the product/chain rules we can deduce the following [82];

$$\frac{dp}{dv} = \frac{d}{dV}(VI) = 1 + \frac{VdI}{dV} = 0 \qquad (1)$$

Applying the method of approximating to the (dI/dV) through selecting small step size with a small value, then we may assume that the $\Delta I/\Delta V \approx dI/dV$, and this would lead to get:

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \qquad (2)$$

This in conclusion would stress that the operating point is at MPP under the condition when the incremental conductance is approximated as the conductance of the instantaneous conduciveness. In the same manner, when the incremental conductance is falling smaller than the instantaneous conductance; hence in such state, the operating point shifts to the left of MPP; i.e., operating voltage must increase and vice versa.

To work on reaching the MPP, stated in equation (1), INC algorithm apply a searching operation in tracking that point through accessing and applying a control structure of the (V_{ref}) to duty cycle (D), knowing that V_{ref} is the reference voltage in this case.

When the MPP state is not satisfied, INC exerts continuous searching to satisfying that state. Knowing that MPP state is reached as the left side (1) is equal to zero. Consequently, when left side (1) > zero, in this case V_{ref} increases.

When the left side (1) is < zero, V_{ref} decreases. This situation is designated in Figure 5, where the left side shows that the instantaneous conductance and the incremental conductivity summation are greater than zero [83].

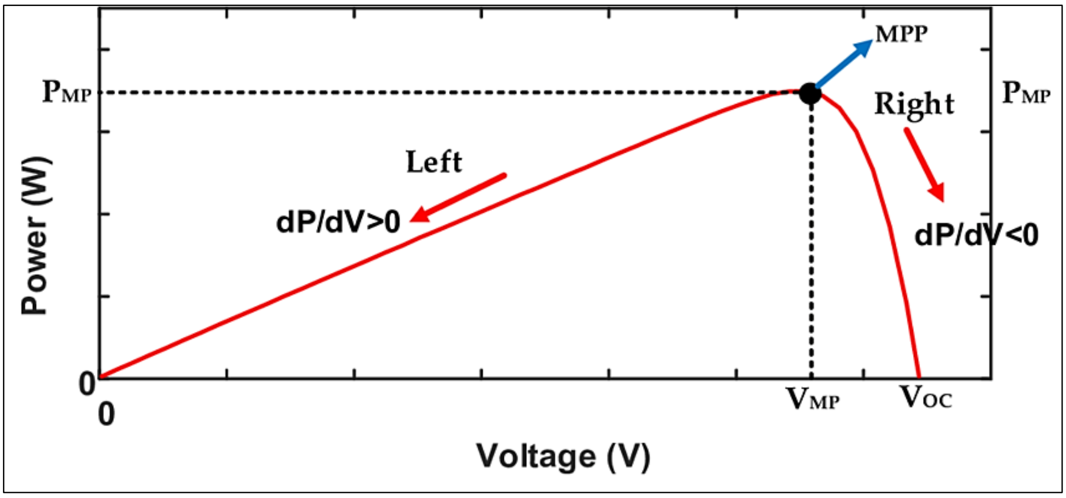

Figure 5. Operating MPP point location on P-V curve

On the contrary, and as we discuss the other side which is the right section of the curve, it reveals that the instantaneous conductance and the incremental conductivity summation is < zero.

In Figure 6 INC flowchart operation is being exhibited. Normally, the control signal output of INC algorithm works on the adjustment of the photovoltaic $V_{ref.}$ This is achieved by the increase and decrease of the constant value denoted as (ΔV) to the prior reference voltage. Note that in this mechanism the tracking is done through a series of fixed step size regardless of the operating point location versus its optimal power point Pmax on the P-V curve.

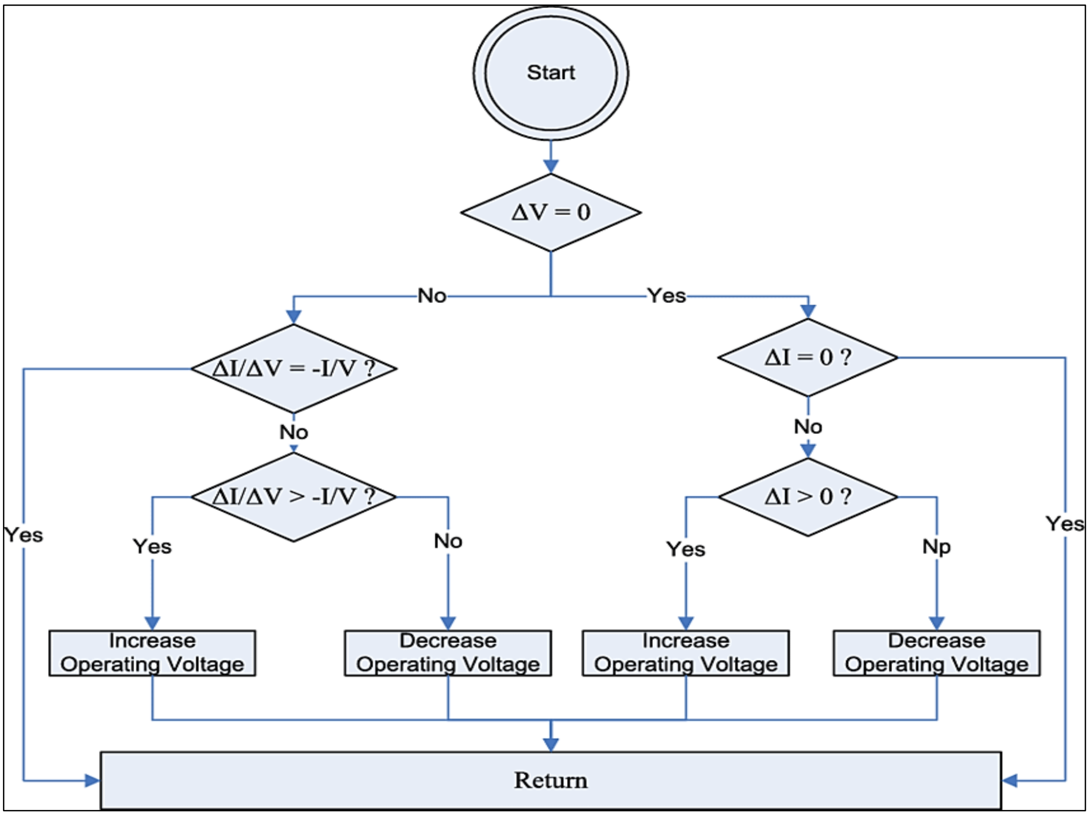

Figure 6. Incremental conductance operational flowchart

Reaching the $\frac{dP}{dV} = 0$ slope is not a normal reached case. To align and track the non-zero slope, we need to get a minimal marginal error, and that error's value will rely on the requisite sensitivity of MPPT. This error can be determined through the following equation [84].

$$e = \frac{dI}{dV} + \frac{I}{V} \quad (3)$$

Three cases are noted in regards to the error at three different stages;

- Case 1: when the error is greater than zero (e > 0); Here operating point to the left of the maximum power point (MPP)
- Case 2: when the error is equal to zero (e = 0); Ultimate extraction of power at this stage where the operating point is at MPP
- Case 3: when the error is less than zero (e < 0); In this scenario we conclude the operating point is located at the right of MPP.

To summarize, in the below table it shows the three cases as seen from the incremental conductance perspective.

Table 1 is drafting the three cases of detecting our best location for the maximum power point (MPP).

Table1. The INC three cases of tracking MPP

Right [of MPP]	$(dp/dv)<0$	$(\Delta I/\Delta V)<-I/V$
At [MPP]	$(dp/dv)=0$	$(\Delta I/\Delta V)=-I/V$
Left [of MPP]	$(dp/dv)>0$	$(\Delta I/\Delta V)>-I/V$

Having revealed some strengthens of the INC algorithm however, it has a definite disadvantage:
The need and requirement to perform excessive and additional more complex calculations, as well as it has a negative drawback in consuming the memory of the system.

5. VARIABLE STEP SIZING PROPOSED FLC CONTROL FOR MPPT ALGORITHM

With an applied incremental conductance (IC) algorithm and during a change in the solar irradiance level from lower to higher level, the traditional incremental conductance algorithm would inaccurately respond in the first step size changing at the converter duty cycle.

However, with the new modified incremental conductance algorithm it can deliver a more precise values as the level of solar irradiance increases. This will lead to provide a zero oscillation at MPP that eventually allow a full extraction of power from the PV module. [85].

Fuzzy logic controller (FLC) considered as a branch of intelligent controllers. FLC theory is attained by imitation and acquisition of human behavior. In addition, FLC never depends on a complex mathematical model calculations as other controllers would require; however, it deals with imprecise input and this drive the authors of this research to implement it in extracting the Pmax of PV system.

Although the literature has discussed various methods for tracking the operational optimal point, however, the utilization of artificial intelligence, specifically fuzzy logic, has been selected to enhance the performance of the controller to achieve the maximum power point. This is conducted through a set of MATLAB SIMULINK simulations and a design modeling of FLC based MPPT control system [86].

FLC methodology design is based on the nonlinearity of the PV system comprises the following components as shown in Figure 7A.

FLC essentially includes, three different processes through a fuzzification process, knowledge base (inference rules) and defuzzification process. This is depicted in Figure 7B and Figure 7C.

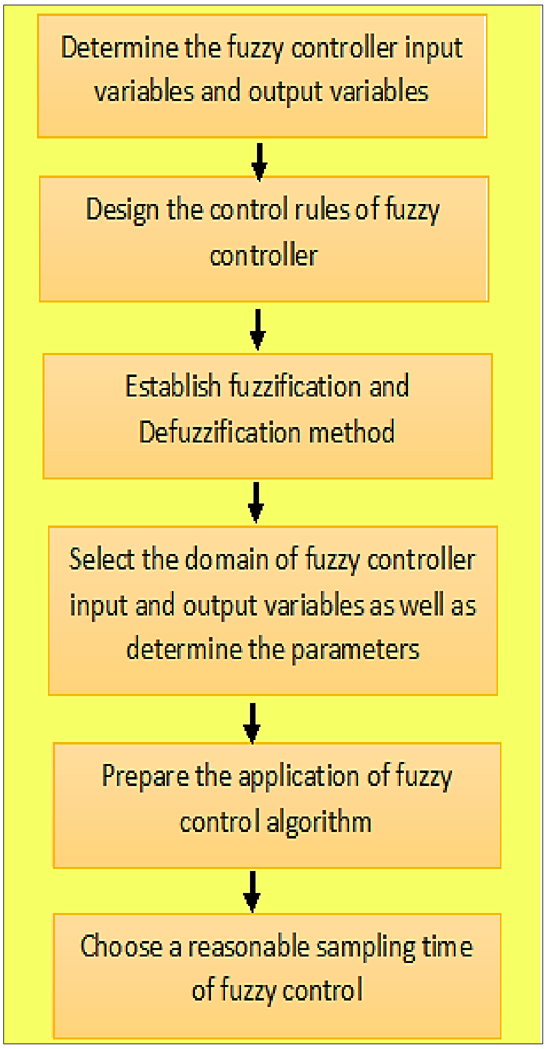

Figure 7A. Methodology of FLC design

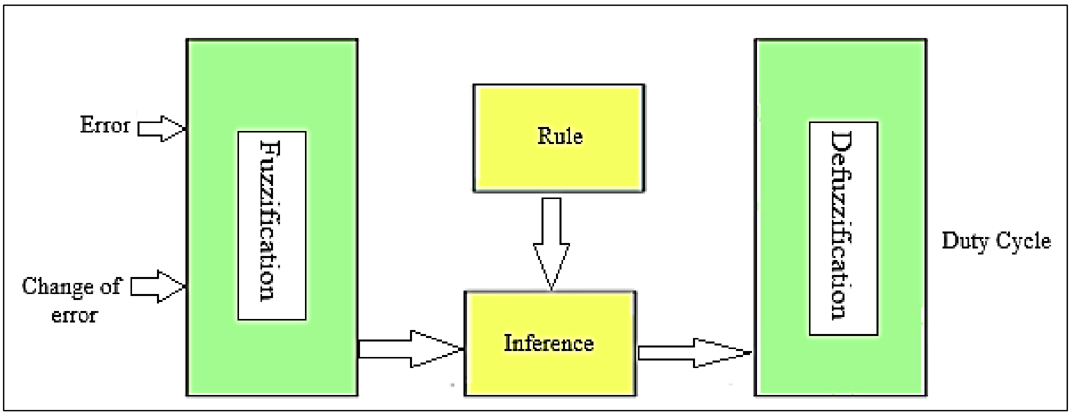

Figure 7B. Block diagram of fuzzy logic controller

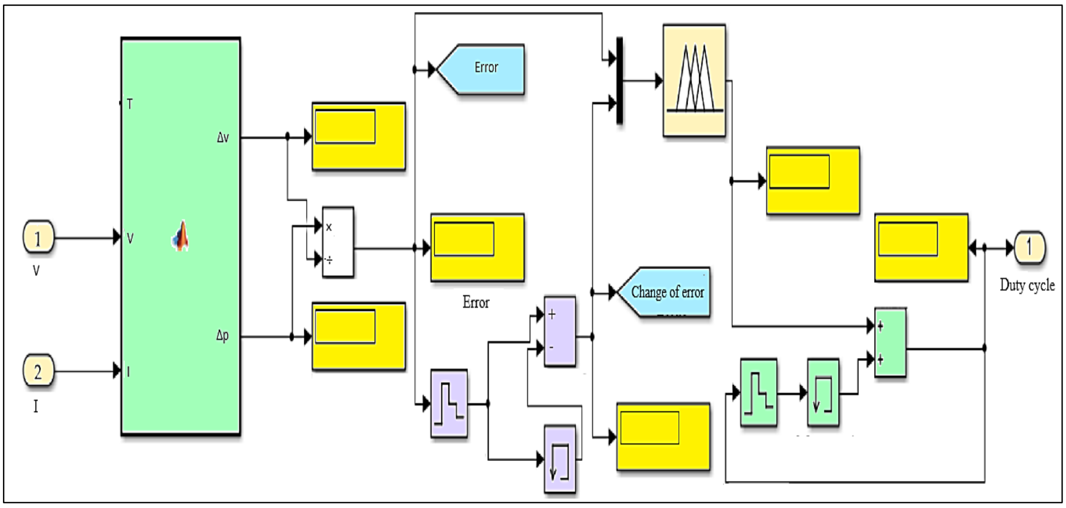

Figure 7C. Block diagram of Matlab FLC circuit

At the fuzzification process the numerical input variable of the change of power to the change of voltage is converted to a crisp values represented by a set of membership functions.

Such a controller has been configured to have two inputs and one output. The two inputs are the error (E) and the change of error (CE). Note that, these variables are fed for processing purposes, to an inner inference system and a set of rules [87].

These conditions are implemented to generate the fuzzy logic output. The last process in the fuzzy logic control is the process of defuzzification.

At this stage the output is denoted by the fuzzy duty cycle ratio change (ΔD). During the defuzzification process, crisp value will be set back to the original state which is converted back to a numerical value and fed in the photovoltaic system.

In Figure7D, the algorithm of the INC based FLC measures how far the distance of the current operating point from the MPP and based on the current step size the adjustment of ΔV is applied to improve the response time in regards to tracking the MPP and this is achieved through the implementation of FLC. In addition, the direction of the operating point on the P-V curve is determined during that process (either to the right or left of the curve).

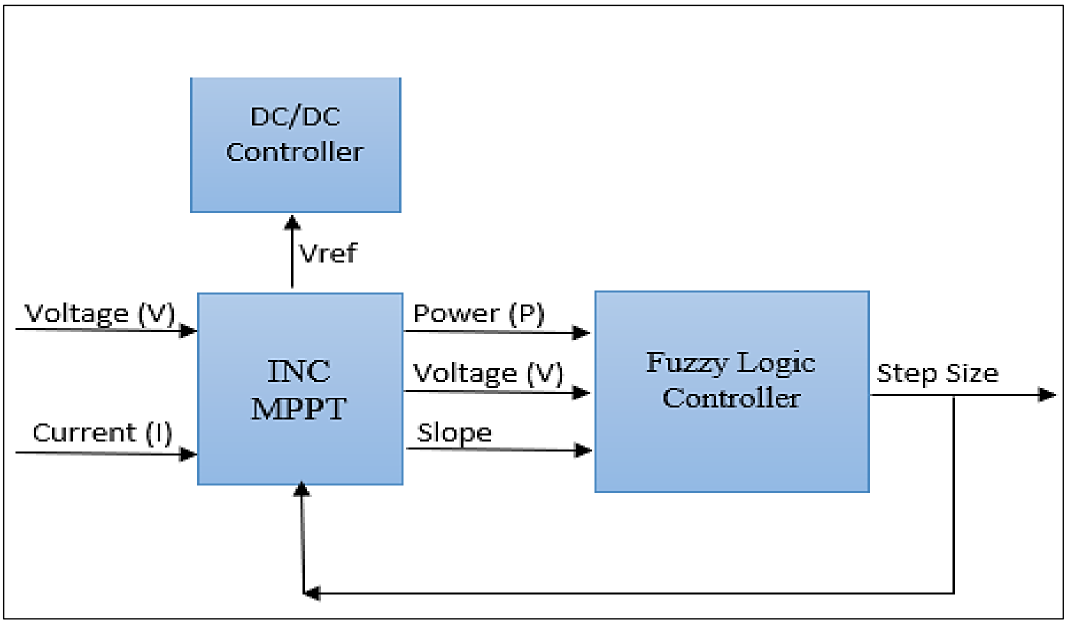

Figure 7D. FLC integration in ΔV step size

The distance of the current operating point is governed through the slope calculations of the current PV operating point.

When the operating point is closely approaching the MPP, the slope derives a small step value size and vice versa for an operating point that is far away from the MPP point.

In the next discussions we will address the applied membership functions of the two inputs and one output. Those MF functions are created using linguistic variable such as "Negative big", "negative small", "zero", "positive big", "positive small", etc.

The FLC control consists of five membership function (MF) at every individual input of the universe of discourse. This would generate through the controller a set of 25 rules. Knowing that FLC depends on these rules to initiate the control of the PV system in term of adjusting the step sizes of the operating point during the tracking and seeking of the optimal MPP [88].

In FLC a collection of rules that govern the relationship between its input variables against its output actions. The rules in an FLC's rule base generally follow an "if-then" structure and employ linguistic variables to define the system's behavior. The formation of these rules is dependent on an expert knowledge or experiential observations to drive the decision-making process of the controller.

As per this research the fuzzy rules are applied to minimize the system's error and reach what's called "zero error state" through the maximum power point (MPP) steady state. Further those 25 rules are forcing through the FLC controller the operating point of the PV system to move towards the MPP [89].

This is achieved by adjusting the duty ratio cycle (increasing or decreasing) based on the current location of the operating point and its position from reaching MPP.

As a result, when the operating point is at a very close by distance from MPP, then a smaller step size needs to be applied and the duty cycle will be decreased or increased slightly and vice versa when the operating point is far away from the MPP where the duty cycle will be decreased or increased in a larger scale to reach MPP.

In Figure 8 the FLC based MPPT tracking algorithm is introduced. This block structure consists of two inputs denoted as the error (E), the change of error (CE), and an output representing the change of duty cycle (ΔD) [90].

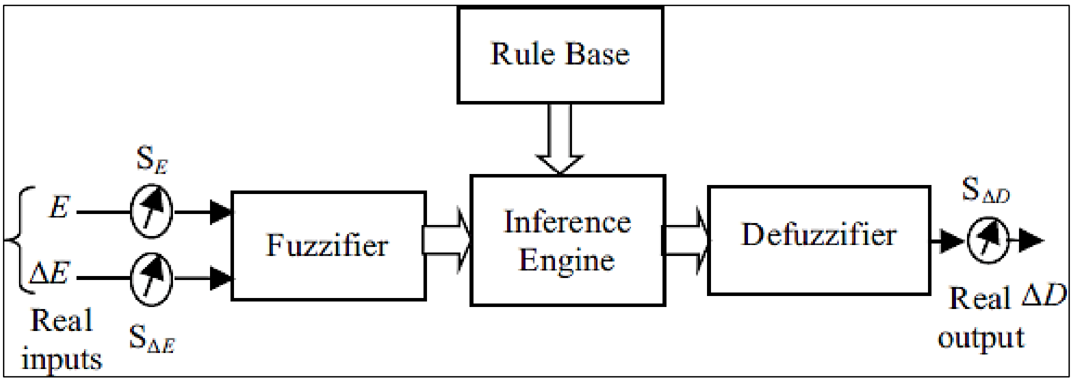

Figure 8. FLC controller with 2 inputs and 1 output

The above-mentioned two inputs and one output at the block diagram of the adaptive FLC controller are addressed by the following equations at "k" sampling instant [91];

$$E(k) = \frac{[P(k) - P(k-1)]}{[V(k) - V(k-1)]} \quad (4)$$

$$\Delta E(k) = E(k) - E(k-1) \quad (5)$$

$$D(k) = D(k-1) + \Delta D(k) \quad (6)$$

Where;

P(k) = Output power of PV system
V(k) = Voltage at k^{th} sampling time
ΔD = Change in duty ratio cycle

The change of duty cycle ΔD acts as the Fuzzy logic controller's output where it is used to compute the DC-DC converter's real duty cycle (D(k) at the k^{th} sampling and this will adjust according to the inputs applied the step size required to drive an operating point accordingly towards the MPP. E(k) is representing the error at the P-V curve slope.

Knowing that, the E(k) input of the FLC designate the operating point's position at a k^{th} instance of time whether being located at the right or the left of the maximum power point (MPP) at the PV system's P-V curve.

The second input of the FLC denoted as $\Delta E(k)$ determines in which direction the operating point shall move; i.e., the moving direction of the operating point on the photovoltaic systems' P-V curve (left or right of the curve).

The Matlab Simulink was used to create and construct the membership functions of the first input of the FLC controller, the input error (E) as shown in Figure 9.

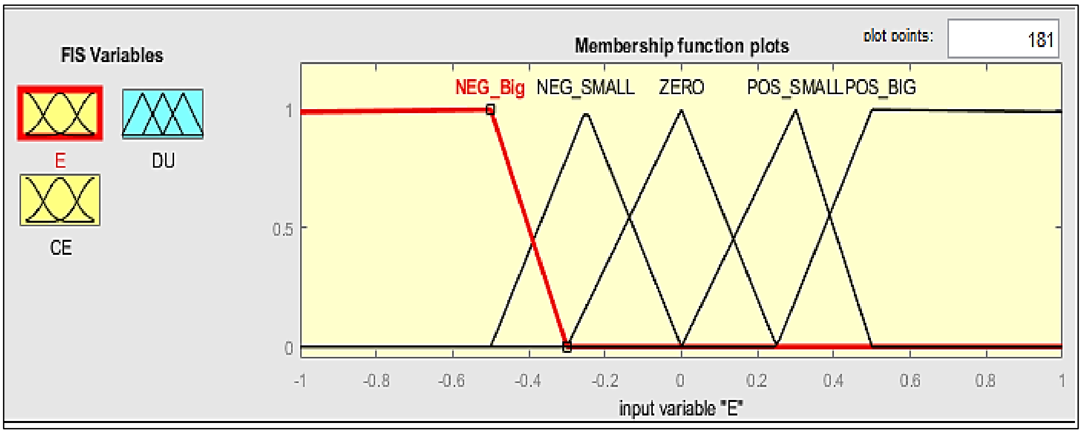

Figure 9. Construction of FLC input Error (E) membership functions

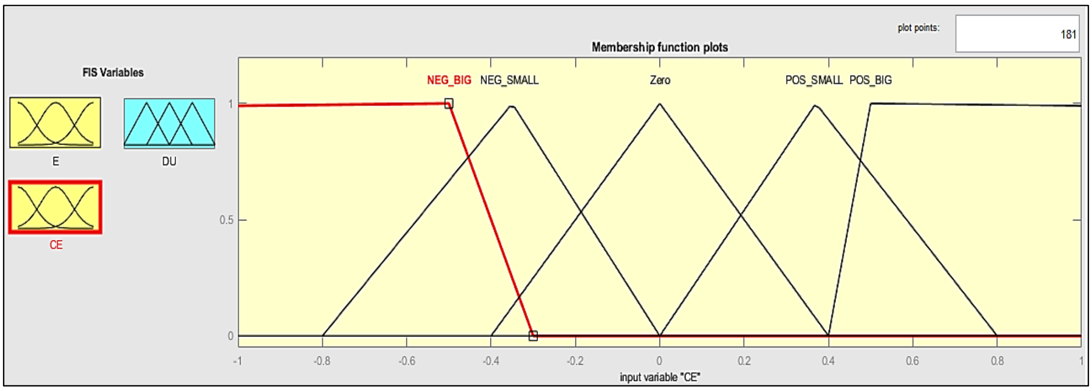

Figure 10. Construction of FLC input Change of Error (CE) MF

Similarly, Figure 10 depicts the change of error at a k^{th} sampling time.

Figure 11 depicts the duty ratio cycle output of the fuzzy logic which plays an essential part in determining the tunning of the applied step size perturbation to move the operating point on the photovoltaic system P-V curve towards the MPP.

By analyzing the changes in (V) and (P) of PV system, FLC will be capable of generating the duty cycle of the DC-DC converter. Significantly, the duty cycle can range from 0 to 1. The FLC MPPT algorithm sends the signal representing the change in duty cycle to the pulse width modulation (PWM) module, which then switches the IGBT transistor to update automatically the converter's duty cycle. This dynamic adjustment has the advantage of extracting the maximum power (Pmax) from PV module.

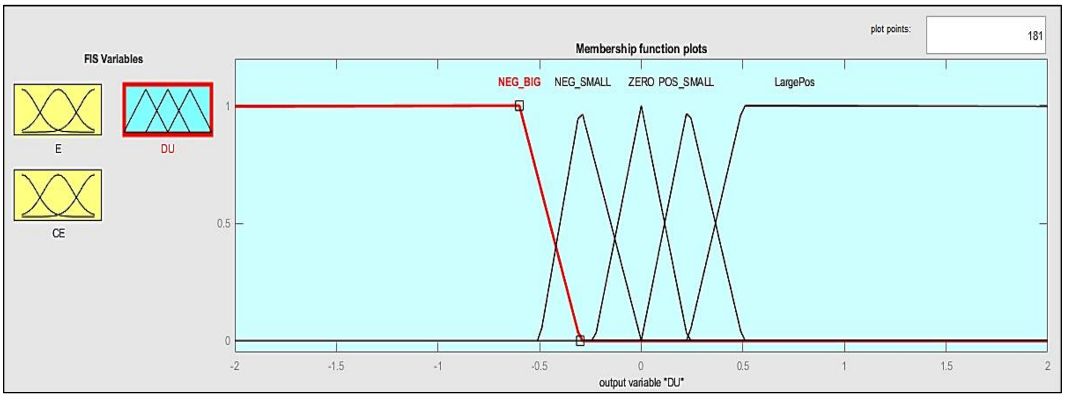

Figure 11. Construction of MF for duty ratio cycle (ΔD)

Note that the purpose of an FLC rule editor is to provide a software graphical user interface that enables the seamless creation or rules, tunning them and apply proper adjustments and modify them according to the systems' parameters.

By simplifying the process of defining rules, MFs, and their relationships, and the linguistic variables, it facilitates for the designer the fine-tuning of the fuzzy logic controller rule base.

In Figure 12 we constructed the (rule editor) that consists of twenty-five rules.

A fragment of the twenty-five rules is shown using the fuzzy IF-THEN rules [91].

As mentioned earlier the FLC is consisting of five rule-based membership functions (MF); the universe of discourse is divided into five fuzzy sets to represent the five MF FLCs [91].

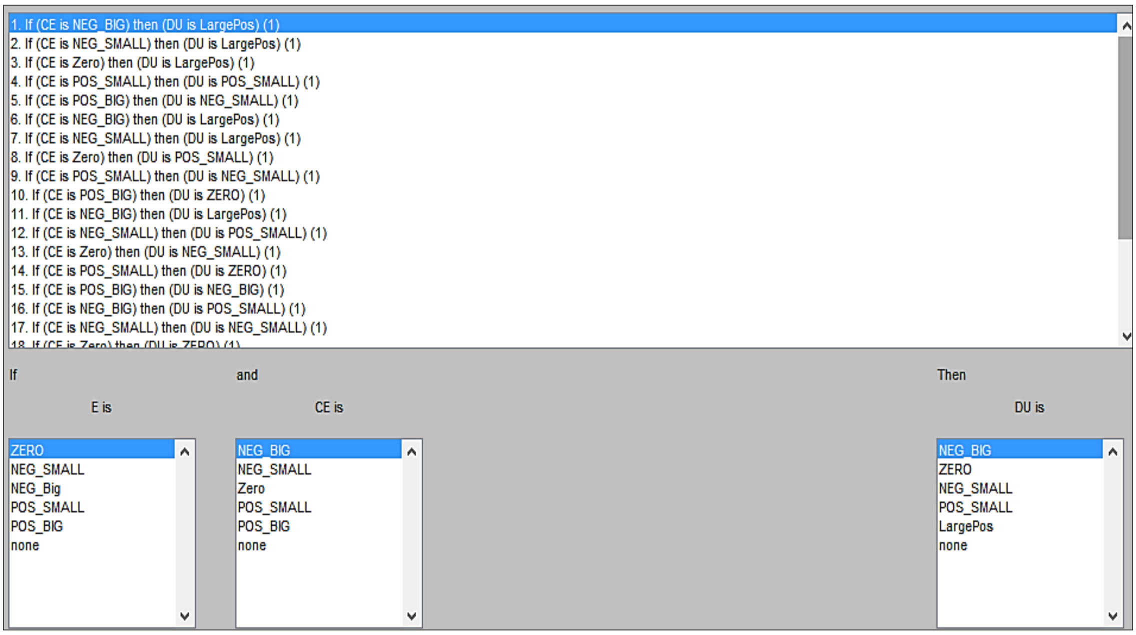

Figure 12. Rule Editor in Fuzzy logic tool box

6. SIMULATION AND DISCUSSION OF RESULTS

In this section a series of discussions will take place in regards to the findings and results obtained for the enhanced fuzzy logic-incremental conductance adaptive model.

Starting by the module manufacturing data, Figure 13 depicts the technical specifications of the tested solar panel; "Sharp-ND-62" parameters.

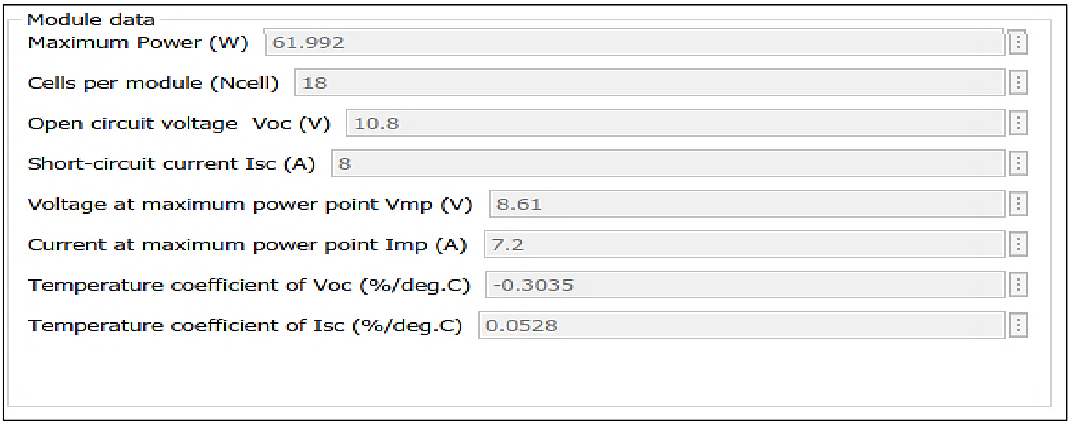

Figure 13. The manufacturer data sheet for Sharp solar

The general power, voltage and current curves are shown in Figure 14 for a 60 watts solar panel used in this research where the values form the technical graph shows the expected outputs of the power, voltage, and current of this solar cell module and those can be verified with the obtained results through the simulations using variable step size adaptive INC based FLC.

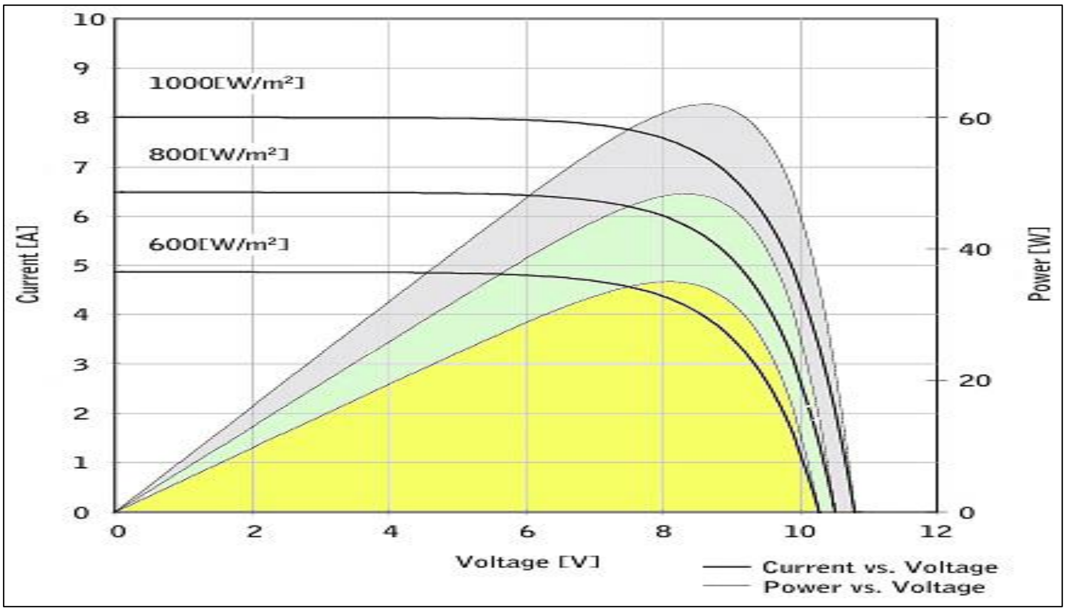

Figure 14. The Sharp-ND-62 graphical specifications

The output maximum power is set around 60 Watts when taken into consideration the standard test conditions (STC) with an irradiance of 1000w/m^2 and temperature at 25C^o.

Our simulations of power, voltage and current are being tested at different set of irradiance levels ranging between 500, 800 1000 and again back to 500 w/m^2.

This represents how the optimal MPP varies in accordance with the variations in the irradiance at a constant test temperature condition.

The calculated power, voltage, and current through the simulation that we ran at the different ranges of irradiances (500, 800, and 1000 w/m^2) after being fed with the appropriate inputs are shown in Figures 15, 16, and 17 respectively.

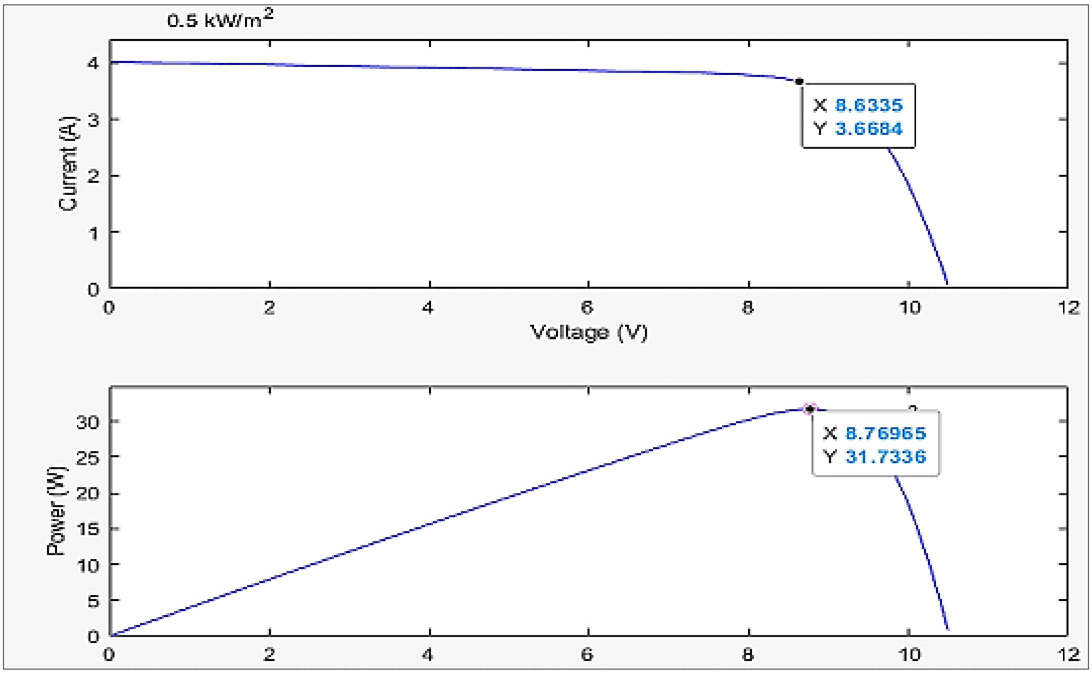

Figure 15. I-V and P-V curves at 500w/m^2

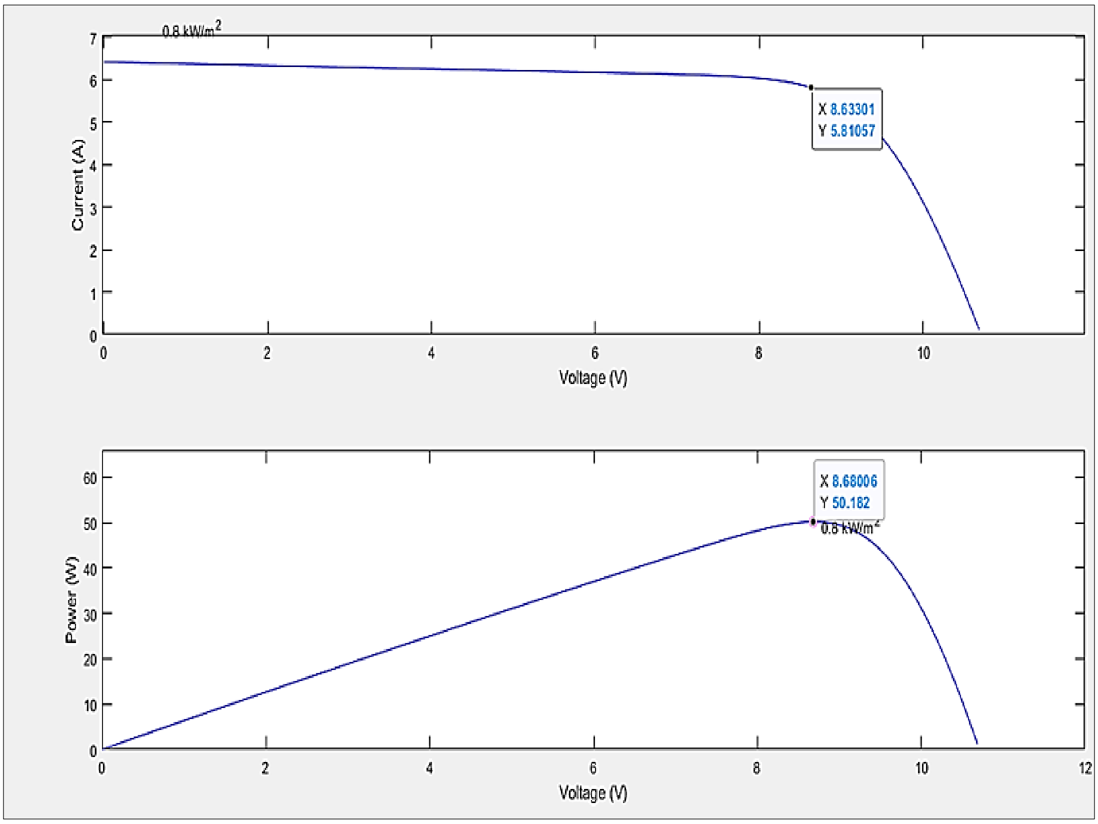

Figure 16. I-V and P-V curves at 800w/m^2

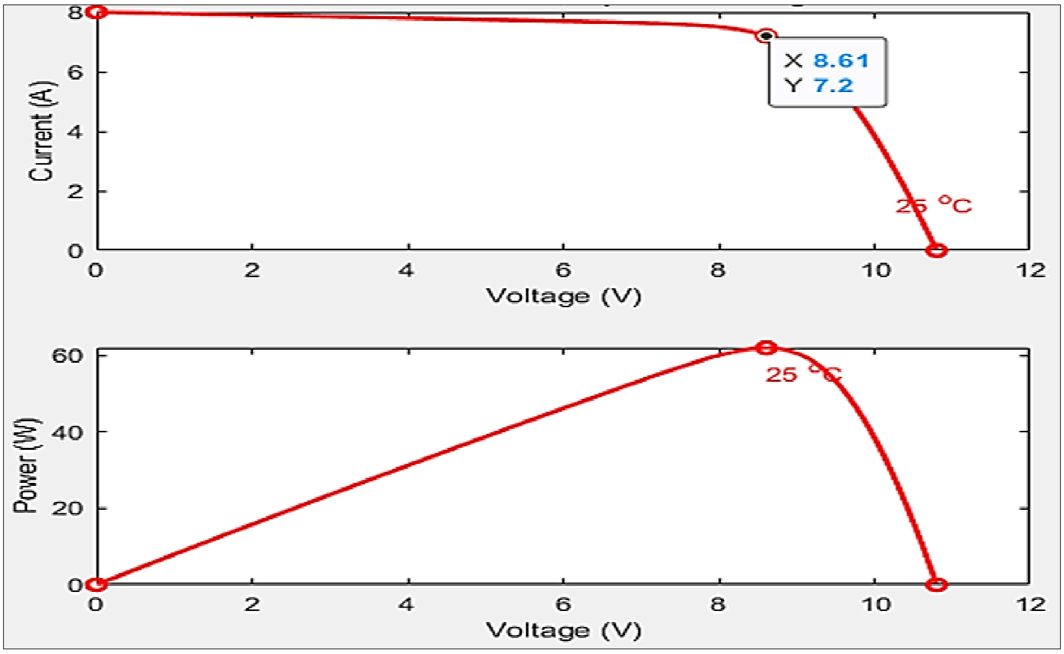

Figure 17. (I-V) and (P-V) curves at 1000w/m^2

Table 2 concludes the results that shall be obtained after applying the adaptive fuzzy logic based incremental conductance with various step size.

The irradiance levels are shown in Figure 18 with respect to a sampling set of time.

Table 2. Effective measurement of P, V, and I at different irradiance levels

Irradiance (G)W/m^2	Power (P)	Voltage (V)	Current (I)
500	31.75	8.63	3.68
800	50.18	8.63	5.81
1000	62	8.61	7.2

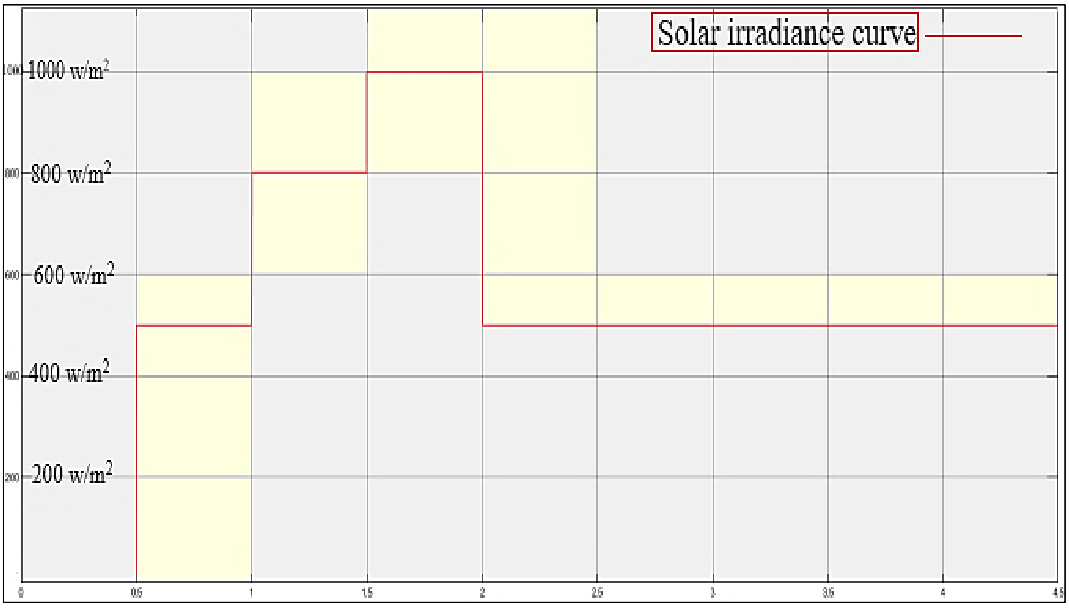

Figure 18. Step size of irradiances at different levels (0 to 1000 w/m^2)

These varying steps are being tested against their effects on the Pmax, Vmax and Imax to verify the effective implementation of fuzzy logic control with incremental conductance in extracting the maximum power at different weather conditions.

As per Figure 19 the simulation output tests for the current (I) were based on adaptive fuzzy-incremental conductance variable step size model.

The results obtained were very close to those in table 1 (the theoretical calculations).

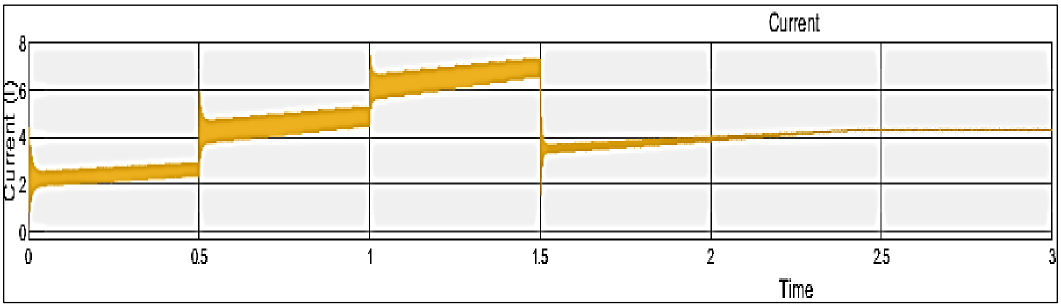

Figure 19. Simulation of current I at different irradiance levels (500, 800, and 1000 w/m^2)

We analyzed the obtained current values versus the levels of applied irradiances (at the 500, 800 and 1000 w/m^2).

Back to the 500 w/ m^2 and by referring to table 1, the theoretical calculated current is 3.68A, and the simulated result was outputting a current of 3.3A.

At 800 w/ m^2 the current calculated in table 1 is 5.81A and the obtained simulated result was 5.8A. At the 1000 w/m^2 Table 1 current was calculated 7.2A and the simulated output current at this irradiance level was close to 7.15A.

Figure 20 shows the voltage obtained at the different irradiances levels and those were tested for 500, 800, and 1000 w/m^2).

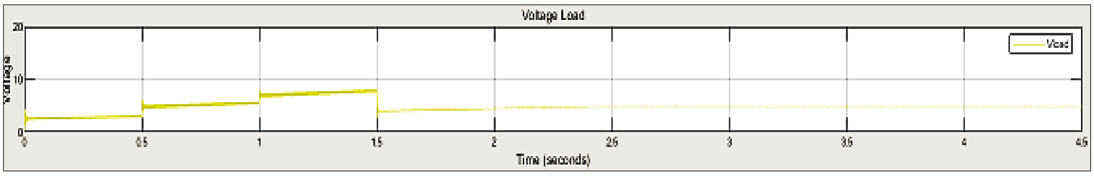

Figure 20. Simulated voltages at different irradiance levels

As per the voltage theoretical calculation versus results obtained from the simulated model, we may record the following;

At 500, 800, and 1000 w/m^2, the calculated voltages were 8.63V in accordance to the three different irradiances.

In Figure 20 the simulated results obtained were as follows; at the 500 w/m^2 the voltage was 7.8V, at 800 w/m^2 the voltage obtained was 8.61V, and at the standard test condition (1000 w/m^2) the voltage obtained was 8.68V.

In the following discussion we will analyze the obtained results with reference to the maximum power extracted from the PV module structure.

Before commencing the discussions, we will get a closer look at Figure 21 which is representing the measured values of power at the different irradiance levels.

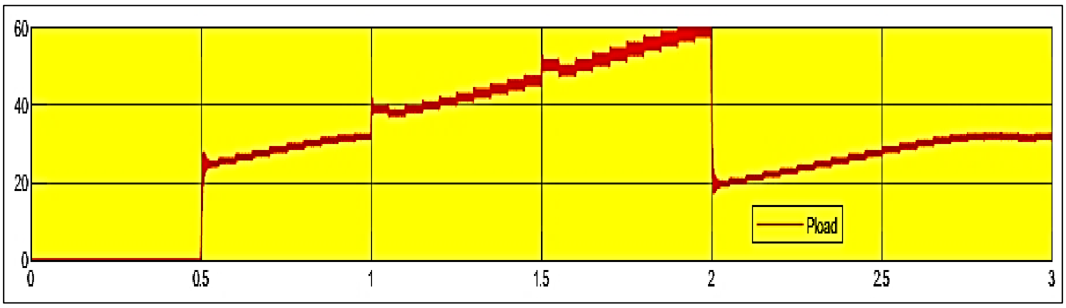

Figure 21. Maximum power extraction under varying irradiance levels

At the 500 w/m^2 irradiance level the calculated maximum power was 31.73 watts, and this value as it can be observed from Figure 21 the incremental conductance fuzzy logic with variable steps was able to reach that value at 0.76s, with a very satisfactory stable signal free of any oscillation, with a satisfactory climbing towards the maximum power point. At 800 w/m^2 the calculated maximum power was 50.18, and as compared to the one obtained from the simulation, we can conclude that the simulated result was close to 49.56 at 1.23s. During the testing of the standard test condition (STC) which represents the temperature at 25^o C, along with an irradiance of 1000 w/m^2, the calculated maximum power was 62 watts. The system was able to detect and reach that value at 1.82s time for the 1000 w/m^2 where the power

extraction reached 60 watts. Further we tested the system in a drastic shift from 1000 w/m^2 to 500w/m^2 to test the overall response in shifting at a sudden change in irradiance to verify the tracking of the P_{max} in accordance with the FLC controller's efficiency versus such irradiance changes, and the result obtained was as follows; at 1.5s we decided to apply a sudden change in irradiance to verify how the system will behave and testing the time required to reach the Pmax while the system is tracking it.
As shown in Figure 20, at 1.82s the system tracked the maximum power for the value of 30.95w (calculated is 31.73 watts) within a 0.32 s time. This testing proved that the system was robust and efficient to work with any sudden changes in irradiances and getting the ability to reach and track the optimal power.

To conclude the above discussions and results, the below tables were used to compare the overall performance of the modified system in comparison of the calculated versus the simulation results of the maximum current (Imax), the maximum voltage (Vmax) and the maximum power (Pmax) of the photovoltaic system using a 62 watts sharp solar panels.

It is noted that the efficiency of the modified INC based variable step size FLC controller was able to accurately and in a faster response time to track the MPP at different irradiance levels. This conclude that the efficiency of the modified INC based FLC control was reaching more than 99.2 %.

In table 3, the maximum current (Imax) at the different applied irradiances was achieved with an average accuracy rate of more than 99.95%. As per table 4, the maximum voltage (Vmax) at the different applied irradiances was achieved with an average accuracy rate of more than

99.43 %, and through table 5, the maximum power (Pmax) at the different applied irradiances was achieved with an average accuracy rate of more than 99.12%.

In general, the simulation and experimental results specifies that the efficiency of the MPPT tracking system based FLC was achieved at a rate of more than 99.95% and further as per the simulation results the tracking response time and the convergence speed were at the minimal level where for instance to track the Pmax at;
500 w/m^2 it took 0.76 seconds, and at 800 w/m^2 the tracking time was 1.23 second and eventually at 1000 w/m^2 it took the modified MPPT system 1,82 seconds to reach Pmax of the solar panel system.

Table 3. Calculated VS simulated "Imax" at different irradiance levels

Irradiance	Calculated current value	Simulation current value
500 w/m^2	3.68 A	3.3 A
800 w/m^2	5.81 A	5.8 A
1000 w/m^2	7.2 A	7.15 A

Table 4. Calculated VS simulated "Vmax" at different irradiance levels

Irradiance	Calculated voltage value	Simulation voltage value
500 w/m^2	8.63 v	7.8 v
800 w/m^2	8.63 v	8.61 v
1000 w/m^2	8.7 v	8.68 v

Table 5. Calculated VS simulated "Pmax" at different irradiance levels

Irradiance	Calculated power value	Simulation power value
500 w/m^2	31.75 w	25.74 w
800 w/m^2	50.14 w	49.93 w
1000 w/m^2	62.64w	62.06 w

7. CONCLUSION

The conducted research has been applied in accordance of using an incremental conductance modified through an adaptive variable step size fuzzy logic controller. The design approach was to modify the INC MPPT algorithm to move from the conventional fixed step size perturbation into a variable step size modified MPPT using FLC by decrementing and incrementing of the DC-DC converter duty cycle. This has been implemented through a defined five membership functions (MFs) of the FLC inputs. Our applied testing was not only at the standard test conditions but went further to different irradiance levels to verify and stress out the modified system in testing its efficiency that reached in an overall bench mark efficiency of more than 99.5%. The tracking system was able to provide an overall high operational power efficiency (during the extraction of this power) along with a minimal/suppressed oscillation around the maximum power point, and a very fast response time in tracking the MPP at the different irradiances applied. The simulation tested many parameters associated with a PV module, ranging from the maximum voltage (Vmax), and maximum current (Imax), to tracking the maximum power (Pmax) at the varying tested irradiance levels. From the discussions conducted we can conclude that the results were well optimized to those calculated (theoretically) with respect to the tested parameters (Vmax, Imax, and Pmax) and the modified system was able to track the power at a fast response time as the irradiance was changing from one level to another, improved the DC output power, and minimized the convergence time for reaching the steady-state as switching through the various irradiance levels.

REFERENCES

[1] Pandey, Nirmal Kumar, et al. "Asymmetrical interval Type-2 Fuzzy logic controller based MPPT for PV system under sudden irradiance changes." Materials Today: Proceedings 80 (2023).

[2] Lokanadham, Metta, and K. Vijaya Bhaskar. "Incremental conductance based maximum power point tracking (MPPT) for photovoltaic system." International Journal of Engineering Research and Applications (IJERA) 2.2 (2012): 1420-1424.

[3] Swanepoel, Nathan Chris, et al. "Experimental Investigation of Incremental Conductance-based MPPT for PV Arrays." 2020 IEEE PES/IAS PowerAfrica. IEEE, 2020.

[4] Elzein I. Maximum Power Point Tracking System for Photovoltaic Station: A Review. Journal of System Analysis and Applied Information Science, Minsk, Vol.3, 2015, pp.15-20. Universal Decimal Classification (UDC) 620.92+502.174.3.

[5] Boubii, Chaymae, et al. "A Comparative Study Between Optimization Algorithms of MPPT Algorithms (P&O and Incremental Conductance Method)." International Conference on Digital Technologies and Applications. Cham: Springer Nature Switzerland, 2023.

[6] Pathak, Pawan Kumar, et al. "Modified incremental conductance MPPT algorithm for SPV-based grid-tied and stand-alone systems." IET Generation, Transmission & Distribution 16.4 (2022): 776-791.

[7] Alaas, Zuhair, et al. "Analysis and enhancement of MPPT technique to increase accuracy and speed in photovoltaic systems under different conditions." Optik 289 (2023)

[8] Ali, Majid, et al. "Maximum power point tracking for grid-connected photovoltaic system using Adaptive Fuzzy Logic Controller." Computers and Electrical Engineering 110 (2023).

[9] Sun, Chunhu, Jing Ling, and Jing Wang. "Research on a novel and improved incremental conductance method." Scientific Reports 12.1 (2022): 15700.

[10] Elzein I, Y. N. Petrenko. Fuzzy Logic Controller Implementation for photovoltaic station. System Analysis and Applied Informatics: International scientific and technical journal. Vol. № 4. pp. 44 - 48. 2014. Universal Decimal Classification (UDC): 620.92 + 502.174.3. https://rep.bntu.by/handle/data/12197

[11] Abutaima, Khaleel Abed, and Ramizi Mohamed. "Design of Improved Incremental Conductance with Fast Intelligent (FI) Based MPPT Technique for Solar PV System." Jurnal Kejuruteraan 34.6 (2022): 1093-1104.

[12] Ez-Zghari, Mohamed, et al. "Optimized Energy Output from a PV System Using a Modified Incremental Conductance Algorithm for Rapidly Changing Insolation." International Conference on Digital Technologies and Applications. Cham: Springer International Publishing, 2022.

[13] Abdellatif, Walid SE, et al. "A Fuzzy Logic Controller Based MPPT Technique for Photovoltaic Generation System." International Journal on Electrical Engineering & Informatics 13.2 (2021).

[14] Elzein I, M. Kurdi. Integrating a P&O Through a Variable Steps Fuzzy Logic Control for a Photovoltaic System to Track the Maximum PowerPoint. International Conference on Advances in Computing and Technology (ICACT 2020). Proceeding of the University of Kelanyia, Nov. 28, 2020, Srilanka.

[15] Siva, Harshini, and Sujatha Balaraman. "Step Incremental Conductance MPPT for Solar PV System Based on Fuzzy Logic Controller." Journal of Trends in Computer Science and Smart Technology 4.1 (2022): 23-29.

[16] Narayana, Meniga Venkata Lakshmi, et al. "A Novel Variable Step Incremental Conductance Maximum Power Point Tracking Algorithm based on ANFIS Controller for Grid Photovoltaic Systems." 2023 Second International Conference on Electrical, Electronics, Information and Communication Technologies (ICEEICT). IEEE, 2023.

[17] Chowdhury, Saptaparna Basu Roy, Alok Mukherjee, and Pritam Kumar Gayen. "Maximum power point tracking of photovoltaic system by Perturb & Observe and Incremental Conductance methods under normal and partial shading conditions." 2021 Innovations in Energy Management and Renewable Resources (52042). IEEE, 2021.

[18] Barkat, Noman, and Aamer Iqbal Bhatti. "A Comparative Study of Different Modified Incremental Conductance MPPT Algorithms Under very Fast-Changing Atmospheric Conditions for Solar Charging Station." 2021 16th International Conference on Emerging Technologies (ICET). IEEE, 2021.

[19] Maheswari, N. V. U., and L. J. S. Shanthi. "Implementation of Modified Incremental Conductance MPPT Algorithm in Grid Connected PV System Under Dynamic Climatic Conditions." Indian Journal of Science and Technology 15.17 (2022): 819-828.

[20] Lorenzini, Giulio, Mehrdad Ahmadi Kamarposhti, and Ahmed Amin Ahmed Solyman. "Maximum power point tracking in the photovoltaic module using incremental conductance algorithm with variable step length." Journal Européen des Systèmes Automatisés 54.3 (2021): 395-402.

[21] Mokhlis, Mohcine, et al. "Comparative study between the different MPPT techniques." 2020 5th International Conference on Renewable Energies for Developing Countries (REDEC). IEEE, 2020.

[22] Shang, Liqun, Hangchen Guo, and Weiwei Zhu. "An improved MPPT control strategy based on incremental conductance algorithm." Protection and Control of Modern Power Systems 5 (2020): 1-8.

[23] Liu, Xiao Dong. "Photovoltaic MPPT Control Strategy Based on Improved Conductance Increment Method." Journal of Physics: Conference Series. Vol. 2527. No. 1. IOP Publishing, 2023.

[24] Feroz Mirza, Adeel, et al. "Advanced variable step size incremental conductance MPPT for a standalone PV system utilizing a GA-tuned PID controller." Energies 13.16 (2020): 4153.

[25] Ananda, M. H., et al. "An Improved Fuzzy Logic Control Algorithm of Photovoltaic MPPT Incremental Conductance Methodology." 2023 World Conference on Communication & Computing (WCONF). IEEE, 2023.

[26] Alrajoubi, Hamza, and Selim Oncu. "A golden section search assisted incremental conductance MPPT control for PV fed water pump." Int. J. Renew. Energy Res 12.3 (2022).

[27] Usman Khan, Fahad, et al. "Variable step size fractional incremental conductance for MPPT under changing atmospheric conditions." International Journal of Numerical Modelling: Electronic Networks, Devices and Fields 33.6 (2020): e2765.

[28] Riahi, Jamel, et al. "Fuzzy Logic based MPPT Control Strategies of PV Systems." 2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). IEEE, 2023.

[29] Kawde, P., and D. S. Muley. "Mppt incremental conductance technique for PV systems." Int. J. Eng. Appl. Sci. Technol 5.11 (2021).

[30] Siva, Harshini, and Sujatha Balaraman. "Step Incremental Conductance MPPT for Solar PV System Based on Fuzzy Logic Controller." Journal of Trends in Computer Science and Smart Technology 4.1 (2022): 23-29.

[31] Ali, Mahmoud N., et al. "An efficient fuzzy-logic based variable-step incremental conductance MPPT method for grid-connected PV systems." Ieee Access 9 (2021).

[32] Ali, A.; Almutairi, K.; Padmanaban, S. Investigation of MPPT Techniques Under Uniform and Non-Uniform Solar Irradiation Condition—A Retrospection. IEEE Access 2020, 8, 127368–127392.

[33] Ali, Ahmed Ismail M., et al. "An Efficient MPPT Technique-Based Single-Stage Incremental Conductance for Integrated PV Systems Considering Flyback Central-Type PV Inverter." Sustainability 14.19 (2022): 12105.

[34] Giurgi, Gavril-Ionel, Lorant Andras Szolga, and Danut-Vasile Giurgi. "Benefits of fuzzy logic on MPPT and PI controllers in the chain of photovoltaic control systems." Applied Sciences 12.5 (2022).

[35] Jalali Zand, Sanaz, et al. "Improvement of self-predictive incremental conductance algorithm with the ability to detect dynamic conditions." Energies 14.5 (2021): 1234.

[36] Assem, Houria, et al. "Adaptive Fuzzy Logic-Based Control and Management of Photovoltaic Systems with Battery Storage." International Transactions on Electrical Energy Systems 2023 (2023).

[37] Harrison, Ambe, Njimboh Henry Alombah, and Jean de Dieu Nguimfack Ndongmo. "A new hybrid MPPT based on incremental conductance-integral backstepping controller applied to a PV system under fast-changing operating conditions." International Journal of Photoenergy 2023 (2023).

[38] Hebchi, Mohamed, Abdellah Kouzou, and Abdelghani Choucha. "Improved Incremental conductance algorithm for MPPT in Photovoltaic System." 2021 18th International Multi-Conference on Systems, Signals & Devices (SSD). IEEE, 2021.

[39] Abouobaida, Hassan, et al. "Performance optimization of the INC-COND fuzzy MPPT based on a variable step for photovoltaic systems." Optik 278 (2023).

[40] Singh, Priyanka, Nitin Shukla, and Prerna Gaur. "Modified variable step incremental-conductance MPPT technique for photovoltaic system." International Journal of Information Technology 13 (2021): 2483-2490.

[41] Siddula, Sundeep. "Analysis of fuzzy logic based MPPT using Incremental Conductance technique for PV cell." 2020 International Conference on Smart Technologies in Computing, Electrical and Electronics (ICSTCEE). IEEE, 2020.

[42] Reddy, K. Hareesh, R. Vijayasanthi, and K. RamaSudha. "Modeling and Performance Analysis of Perturb and Observe (P&O) Incremental Conductance (IC) Fuzzy Logic and Model Predictive MPPT Controllers Using a Boost Converter." International Journal of Innovative Science and Research Technology 5.12 (2020): 59-67.

[43] Reddy, Allugari Sowmya, et al. "Simulation of Comparative Analysis Of Maximum Power Point Tracking Techniques for Photo Voltaic System." 2023 4th International Conference for Emerging Technology (INCET). IEEE, 2023.

[44] Singh, Priyanka, Nitin Shukla, and Prerna Gaur. "Modified variable step incremental-conductance MPPT technique for photovoltaic system." International Journal of Information Technology 13 (2021): 2483-2490.

[45] Hai, Tao, Alireza Rezvani, and Binh Nguyen Le. "Improved design and analysis of MPPT technique for photovoltaic power systems to increase accuracy and speed under different conditions." Environment, Development and Sustainability (2023).

[46] El Ouardi, Hind, et al. "A Novel MPPT Technique Based on Combination between the Incremental Conductance and Hysteresis Control Applied in a Standalone PV System." Eng 4.1 (2023).

[47] Maddikari, Jagadeshwar, and Dushmanta Kumar Das. "Incremental Conductance based Adaptive Poleplacement MPPT Controller Design for Solar Photo Voltaic System." 2020 IEEE Applied Signal Processing Conference (ASPCON). IEEE, 2020.

[48] Khademi, Reza, and Mohammad Ali Mohammadi. "Maximum Power Point Tracking of the Photovoltaic System Based on Adaptive Fuzzy-Neural Method." Energy Engineering& Management 6.4 (2023).

[49] Saleh, Ameer L., et al. "Modeling and Simulation of A Low Cost Perturb& Observe and Incremental Conductance MPPT Techniques In Proteus Software Based on Flyback Converter." IOP Conference Series: Materials Science and Engineering. Vol. 881. No. 1. IOP Publishing, 2020.

[50] Qureshi, Muhammad Ahmed, et al. "A Novel Adaptive Control Approach for Maximum Power-Point Tracking in Photovoltaic Systems." Energies 16.6 (2023).

[51] Hebchi, Mohamed, Abdellah Kouzou, and Abdelghani Choucha. "Improved Incremental conductance algorithm for MPPT in Photovoltaic System." 2021 18th International Multi-Conference on Systems, Signals & Devices (SSD). IEEE, 2021.

[52] Mishra, Jyotismita, et al. "A novel auto-tuned adaptive frequency and adaptive step-size incremental conductance MPPT algorithm for photovoltaic system." International Transactions on Electrical Energy Systems 31.10 (2021): e12813.

[53] Ghatak, Aditya, et al. "Comparative Analysis of Maximum Power Point Tracking Algorithms for Standalone PV System Under Variable Weather Conditions." Distributed Generation & Alternative Energy Journal (2023).

[54] Mirza, Adeel Feroz, et al. "Advanced variable step size incremental conductance MPPT for a standalone PV system utilizing a GA-tuned PID controller." Energies 13.16 (2020): 1-25.

[55] Shengqing, Li, et al. "An improved MPPT control strategy based on incremental conductance method." Soft computing 24 (2020): 6039-6046.

[56] Tian, Luyu, et al. "Online Evolutionary Maximum Power Point Tracking for Photovoltaic Grid-connected System." 2023 IEEE 6th International Electrical and Energy Conference (CIEEC). IEEE, 2023.

[57] Mishra, Praveen Kumar, and Prabhakar Tiwari. "Incremental conductance MPPT in grid connected PV system." International Journal of Engineering, Science and Technology 13.1 (2021): 138-145.

[58] Al-Mohamade, Mohammed S., and Hussein D. Al-Majali. "Comparison between Fuzzy-logic MPPT and the Exciting Incremental Conductance Method under Fast Varying of Irradiance." Journal of Hunan University Natural Sciences 48.12 (2021).

[59] Atia, M., N. Bouarroudj, and A. Ahriche. "Design of a Fuzzy Logic Controller based on Incremental Conductance Algorithm for Maximum Power Point Tracking for a Photovoltaic System." ICREATA'21: 110.

[60] Pilakkat, Deepthi, and S. Kanthalakshmi. "Study of the importance of MPPT algorithm for photovoltaic systems under abrupt change in irradiance and temperature conditions." WSEAS Trans. Power Syst 15 (2020): 8-20.

[61] Hamoodl, Ali N., Safwan A. HAMOODI, and Farah I. HAMEEDI. "Enhancing the Solar PV Plant Based on Incremental Optimization Algorithm." Przeglad Elektrotechniczny 2023.10 (2023).

[62] El Halim, Ahmed A., and Ehab HE Bayoumi. "Using a New Combination of P&O and ICM Methods for the Experimental Validation of MPPT Efficacy." Journal Européen des Systèmes Automatisés 54.6 (2021).

[63] Deepu, V., et al. "Adaptive Multiple-Step Size Incremental Conductance MPPT Algorithm with Zero Oscillation for Solar PV Applications." International Conference on Intelligent Solutions for Smart Grids & Smart Cities. Singapore: Springer Nature Singapore, 2022.

[64] Yang, Xuejie. "Improvement of Voltage Collapse of MPPT Single-stage Photovoltaic Grid-connected based on Conductance Increment Method." Highlights in Science, Engineering and Technology 15 (2022): 89-93.

[65] Akin, Ercan, and Mustafa Ergin Şahın. "Investigation of Incremental Conductance MPPT Algorithm in MATLAB/Simulink Using Photovoltaic Powered DC-DC Boost Converter." 2023 22nd International Symposium on Power Electronics (Ee). Vol. 1. IEEE, 2023.

[66] Ngo, Sy, et al. "A novel approach based incremental conductance method for MPPT strategy of PV systems considering partial shading conditions." Electric Power Components and Systems 49.16-17 (2021): 1348-1362.

[67] Eluri, Hima Bindu, and M. Gopichand Naik. "Energy management system and enhancement of power quality with grid integrated micro-grid using adaptive fuzzy logic controller." iInternational Journal of Renewable Energy Research (ijrer) 13.1 (2023): 144-154.

[68] Kumar, Pradeep, and Islavatu Srikanth. "Power quality performance enhancement by PV-based distribution static compensator under incremental conductance maximum power point tracking algorithm." Cleaner Energy Systems 4 (2023): 100062.

[69] Ounnas, Djamel, et al. "Design and hardware implementation of modified incremental conductance algorithm for photovoltaic system." Advances in Electrical and Electronic Engineering 19.2 (2021): 100-111.

[70] Asif, Rao Muhammad, et al. "Modified fuzzy logic MPPT for PV system under severe climatic profiles." Pakistan Journal of Engineering and Technology 4.2 (2021): 49-55.

[71] Bennia, Rachid, Cherif Larbes, and Faiza Belhachat. "Maximum Power Point Tracking Under Fast Changing Irradiance Using Hybrid Fuzzy-PO Algorithm." Artificial Intelligence and Heuristics for Smart Energy Efficiency in Smart Cities: Case Study: Tipasa, Algeria. Springer International Publishing, 2022.

[72] Hong, Ying-Yi, and Peter Mark P. Buay. "Robust design of type-2 fuzzy logic-based maximum power point tracking for photovoltaics." Sustainable Energy Technologies and Assessments 38 (2020): 100669.

[73] Ibrahim, Nagwa F., et al. "A new adaptive MPPT technique using an improved INC algorithm supported by fuzzy self-tuning controller for a grid-linked photovoltaic system." Plos one 18.11 (2023).

[74] Nam, Nguyễn Bình, Nguyễn Văn Tấn, and Trương Đình Minh Lê Thành Bắc. "An evaluation of effectiveness of P&O, INC and Fuzzy logic MPPT algorithms in photovoltaic systems." Tạp chí Khoa học và Công nghệ-Đại học Đà Nẵng (2020): 20-25.

[75] Pattnaik, Manasi, Manoj Badoni, and Yogesh Tatte. "Design and analysis of adaptive neuro-fuzzy inference system based MPPT technology." 2021 IEEE 18th India Council International Conference (INDICON). IEEE, 2021.

[76] Isknan, Ismail, et al. "Benchmarking of the conductance increment method and its improved versions." ITM Web of Conferences. Vol. 43. EDP Sciences, 2022.

[77] Pawar, Aarti S., and Mahesh T. Kolte. "A Comprehensive Evaluation of Traditional MPPTS and Fuzzy Rule-Based Algorithms at Varying Solar Irradiance Levels." Sustainable Communication Networks and Application: Proceedings of ICSCN 2021. Singapore: Springer Nature Singapore, 2022. 575-592.

[78] Kandemir, Ekrem, Numan Sabit Cetin, and Selim Borekci. "Single-stage photovoltaic system design based on energy recovery and fuzzy logic control for partial shading condition." International Journal of Circuit Theory and Applications 50.5 (2022): 1770-1792.

[79] Lupangu, C., et al. "Critical performance comparison between single-stage and two-stage incremental conductance MPPT algorithms for DC/DC boost-converter applied in PV systems." Electric Power Components and Systems 50.4-5 (2022): 207-222.

[80] Loukil, K., et al. "Design and implementation of reconfigurable MPPT fuzzy controller for photovoltaic systems." Ain Shams Engineering Journal 11.2 (2020): 319-328.

[81] Chowdhury, Suman, Dilip Kumar Das, and Md Sharafat Hossain. "Power Performance Evaluation of a PV Module Using MPPT with Fuzzy Logic Control." Journal of Engineering Advancements 2.01 (2021): 07-12.

[82] Prasad, Dinanath, Narendra Kumar, and Rakhi Sharma. "Grid interfaced solar-wind hybrid power generating systems using fuzzy-based TOGI control technique for power quality improvement." Journal of Intelligent & Fuzzy Systems 42.2 (2022): 1127-1139.

[83] Benchikh, Salma, et al. "Design of an Adaptive Neuro-Fuzzy Inference System for Photovoltaic System." The International Conference on Artificial Intelligence and Smart Environment. Cham: Springer International Publishing, 2022.

[84] Babu, Narendra, et al. "A novel adaptive fuzzy-based controller design using field programmable gate arrays for grid-connected photovoltaic systems." Advances in Smart Grid Power System. Academic Press, 2021. 331-364.

[85] Alhasnawi, Bilal Naji, and Basil H. Jasim. "A new energy management system of on-grid/off-grid using adaptive neuro-fuzzy inference system." J. Eng. Sci. Technol 15 (2020).

[86] Ganesan, Prakash, and S. Gunasekaran. "Modelling and Simulation of Incremental Conductance Algorithm for Solar Maximum Power Point Tracker." 2022 IEEE Delhi Section Conference (DELCON). IEEE, 2022.

[87] Atik, Lotfi, Ghalem Bachir, and Michel Aillerie. "Implementation of Fuzzy Logic MPPT in high-efficiency Double Boost DC-DC Converter Dedicated to Photovoltaic Sources." Journal of Electrical Systems 17.3 (2021).

[88] Krishnaprasad, M., and Vijay Raviprabhakaran. "Maximizing Power Yield from Mismatched Environment in Grid-Connected PV

System by Fuzzy Logic Control." CVR Journal of Science and Technology 22.1 (2022): 63-69.

[89] Narne, Dharani Kumar, T. A. Ramesh Kumar, and RamaKoteswaraRao Alla. "Evaluation of series-parallel-cross-tied PV array configuration performance with maximum power point tracking techniques under partial shading conditions." Clean Energy 7.3 (2023): 620-634.

[90] Kouser, Sanam, G. Raam Dheep, and Ramesh C. Bansal. "Maximum Power Extraction in Partial Shaded Grid-Connected PV System Using Hybrid Fuzzy Logic/Neural Network-Based Variable Step Size MPPT." Smart Grids and Sustainable Energy 8.2 (2023): 7.

[91] Hasan, Mashhood. "A Soft Computing Intelligent Control Algorithm to Extract Maximum Energy from Solar Panel." International Journal of Mathematical, Engineering and Management Sciences 8.3 (2023): 464.

I. M. Elzein is an electrical and electronics engineer who pursued his undergraduate and graduate level degrees in Electrical and computer engineering from Wayne State University, Michigan, USA in 2004. Currently, Dr. Elzein is holding an academic lecturing role in the department of telecommunication and networking engineering at the University of Doha for Science and Technology. Dr. Elzein has more than 70 research papers in multi-international conferences and journals as well being a reviewer committee member and technical program committee. His research profile is mainly in the fields of electrical and electronic engineering with a concentration on (PV) photovoltaic systems, robotics design, renewable energy and information technology. Dr. Elzein is a technical consultant for multi-international industries.

M. Kurdi is a computer and electrical engineer who graduated in Computer and Electrical engineering from Beirut Arab University, Lebanon in 2002 and Ph.D. in System Analysis and Data Processing from Belarusian National Technical University, Belarus, in 2018. Currently, Dr. Kurdi is the campus director (City University – CITYU - Tyre – Lebanon). He has more than 10 years of teaching experience in the fields of computer, software and networking engineering. Dr. Kurdi is member of IEEE and published 50 research works. His current research interests include multi-functional robotics, thermography, smart systems, data mining, and image watermarking.

Y. Harrye received his Ph.D. degree in Electrical Engineering from the University Aberdeen in the United Kingdom in 2017, Msc, from University of Surrey in Guidford, United Kingdom and BEng (Hons) in Electrical and Electronics engineering from Brunel University, West London, United Kingdom. He is currently an assistant professor with the University of Doha for science and technology. His main research interests include high power electronic converters, AI tools for power electronic systems and Electric vehicle drive trains.