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The Design of an MPPT Solar Energy System Based on Fuzzy Logic Systems

Haider Saadoun Rahif

Faculty of Engineering, Arak University, Arak 38156-875, Iran

Corresponding Author Email: hydrsdwnrhyf@gmail.com

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ABSTRACT

The applications of the Maximum Power Point Tracking (MPPT) system are necessary to enhance the productivity and efficiency of the Photovoltaic systems (PV) by improving energy production under different conditions of solar radiation and temperatures. This paper suggests the use of fog systems in the design of MPPT charts, explaining that fuzzy logical controls (FLCS) provide advantages in dealing with complex and mysterious solar conditions. By using MPPT algorithms based on fuzzy logic, the proposed approach provides the ability to track and maintain the perfect operating point for Photovoltaic cells efficiently, ultimately improving energy productivity of the PV system. This study compares the proposed approach with other traditional MPT methods, and shows the superior performance and high efficiency of MPPT-based logic in extracting higher production of solar energy. The study reviews the unique advantages of the MPPT system-based logic system compared to traditional methods. Where the ability of blurred logical controls to deal with complex solar conditions such as rapid change in light intensity, non-linear curves of stream and effort, and temperature effects. Details of the design and implementation of the MPPT algorithm based on fuzzy logic, including the formation of membership functions and base rules. Simulation and analysis results were presented. The system is also compared to other MPT technologies, including the method of fluctuation and monitor during the energy production, speed of tracking and operational efficiency.

1. INTRODUCTION

Solar energy has appeared as a prominent option for hygienic energy with the drop in old-fashioned fuel sources and the rise in demand for renewable energy, since it is reflected as an ecologically sustainable alternative to old-fashioned energy resources. It has also confirmed effective in meeting the request for electricity, and academics are still remaining to explore its prospective [1].

The presence of nonlinear features of photovoltaic (PV) systems at maximum power point requires control algorithms for a regular power output regardless of the combination of solar radiation and ambient temperature; thus, this paper put a focus on mitigating fluctuations and being at MPP operation.

Using MMPT based on fuzzy system with fuzzy logic works within the framework of logic systems as the most powerful and efficient model for tracking MPP. With the help of fuzzy logic controllers, the system efficiency is maintained at an optimum and thus the maximum power can be got out of PV system. Comparative studies are also drawn upon the iS a.m.p (feature refers to improved static MPPT method) of the fuzzy logic based MPPT approach considering it using the conventional methods [2].

Research in the field of Maximum Power Point Tracking (MPPT) for solar photovoltaic (PV) systems has focused on two main categories: in this context "the soft computing methods" include traditional methods and split conduction (SR); traditional methods are accumulative methods (IC), perturbation methods (P&O), hill climbing (HC), and the universal MPPT that can track the maximum power under uniform light but under partial shadowing they have some disadvantages, that showed poor convergence, slow tracking speed and steady-state oscillations. Such method as a part of a complex including other detection methods could be helpful in improving accuracy in less light environment.

Through their capacity to process nonlinearity and long-sighted search space soft computing methods like artificial neural network (ANN), fuzzy logic controller (FLC) and heuristic/metaheuristic algorithms have grown in popularity, as they provide efficient alternatives to the optimization problems having very many degrees of freedom. Which of these methods happen to be the most applicable is that fuzzy logics are largely operating as a replacement because of their capacity to deal with uncertainties and complex environmental situations [3, 4].

The effort in this aim is set on the utilization of fuzzy logic systems when creating an MPPT solar energy system which requires the marriage of fuzzy logic control with conventional way of operation so that the system keeps the optimal operation track even in circumstances of rays shading.

Maximizing the energy output of photovoltaic (PV) systems is essential for optimal performance and greater power generation. Maximum Power Point Tracking (MPPT) technologies, designed to maintain PV systems at maximum power conversion efficiency, have gained significant attention over the past few decades. However, traditional MPPT methods, such as perturbation and observation (P&O), incremental conduction (INC), and constant voltage calibration (CVM), face several challenges when dealing with complex solar conditions.

- Unpredictability: Solar radiation encountered by photovoltaic systems involves variable, nonlinear radiation levels that depend on the temperature of current-voltage (I-V) characteristics. Traditional MPPT technologies may not respond effectively to dynamic solar conditions and therefore fail to maintain the optimal operating point.
- Complexity: Traditional MPPT schemes often require extensive computational resources and processing power, which greatly increases the cost and complexity of PV systems, especially for small-scale, grid-connected solar installations.
- Inaccuracy and instability: Due to their fixed and pre-determined algorithms, traditional MPPT techniques may not accurately estimate the maximum power point under all conditions, and disturbances or sudden changes in solar and ambient conditions may lead to instability and power loss.

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Also, through studying comparative studies and analysis, researchers find that the fuzzy logic based MPPT has an advantage of the fast-tracking speed, easy convergence and lesser oscillation in the steady state as compared to others. In the paper a reliable and better fuzzy logic control-based system equipped with a fuzzy logic controller that discovered the maximum power point for systems of solar cells (PV) subjected to changeable conditions is obtained that the trained artificial neural networks (ANNs) and the achieved maximum power point based on the FLC trend although they require a huge memory to train and apply the rules. However, being the members of FLC, we controlled the factors by means of different conditions, like day- and night temperatures and solar radiation. The study itself consists of a detailed mathematical and physical design of this method and a review of P&O with I&C procedures indicating advantages of the proposed system. Therefore, intelligent operations under Maximum Power Point Tracking conditions are implemented with the fuzzy logic controller (FC) where the ideal operating values are provided for the solar system. This concept may be used in two forms of principles and laws such as fuzzy logic data processing for the solar irradiation, voltage, and current data to find out the huge voltage and current value which is sufficient as the voltage regulator.

These laws goal to improve the effectiveness of solar cell systems and rise energy production by achieving supreme power under variable situations. Via fuzzy heuristics, the structure can handle variations in solar radiation and constantly regulate voltage and current to retain the solar cells operating at their extreme ideal power point.

Simple "IF-THEN" rule: IF (high solar radiation) THEN (high voltage fluctuation) IF (low solar radiation) THEN (low voltage fluctuation) [5]: (1) When the transistor is turned on, current is directed through the coil and the current passing through the coil accumulates and stores energy. The voltage across the coil at this point is represented by $V_{L\_in}=V_{in}$, in this case the transistor is on and the diode is inverted and not conducting; (2) When the transistor is turned off, the passage of current through the chip is ensured and the coil is connected to the transistor. The energy stored in the coil is discharged and transferred to the load. The voltage across the coil at this point is represented by $V_{L\_out}=V_{out}$, in this case the transistor and the LED are turned off the couple.

It is known that to ensure continuous operation in the transformer, the net change in the coil current must be equal to zero during one conversion cycle. Applying the principle of voltage-second balance, we obtain the following equation: $(1-D)\times V_{in}=D\times V_{out}$, where D represents the transformer duty ratio and is the operating portion of the total switching period.

Figure 1 shows the relationship between solar radiation and the energy output of a solar panel. The curves represent the energy output of the solar panel at different levels of solar radiation, providing a visual representation of the panel's performance under different conditions.

Figure 2 shows curves that represent the relationship between pressure and size for a specific material at different temperature levels. These curves are commonly known as P-V curves. The curves show how the pressure and size of the material changes with the increase or decrease in temperature. Curbs helps in understanding the behavior of matter under different temperature conditions and can be used to determine the thermal dynamic properties of the material.

In general, the effective time of the MOSFETs in a switching converter is usually determined by the switching frequency and the duty cycle. The duty cycle is the ratio of the switching operating time to the total period of one switching cycle. It is well-defined as the ratio of the period that the switch is on to the whole changing period time.

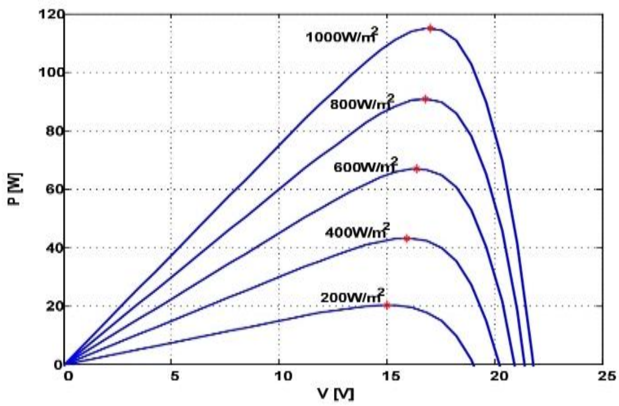

Figure 1. Three heat sources

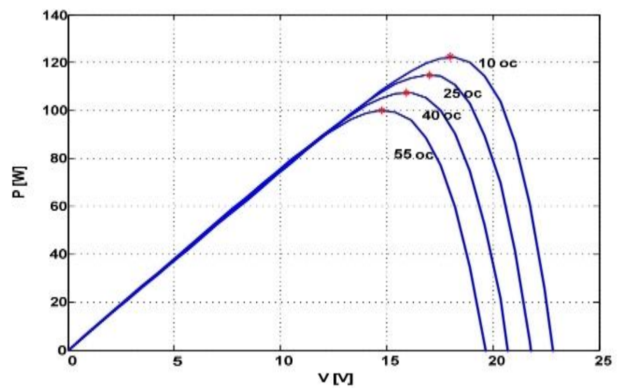

Figure 2. P-V curves under changing the temperature

1.1 Fuzzy logic controller modeling

1.1.1 Fuzzification

$$\mu_{E(e)} = f_{E(e)} \tag{1}$$

$$\mu_{dE(\Delta e)} = f_{dE(\Delta e)} \tag{2}$$

where, $\mu_{E(e)}$, $\mu_{dE(\Delta e)}$ are the membership functions for the input variables error (e) and change in error (Δe), respectively, $f_{E(e)}$, $f_{dE(\Delta e)}$ are the fuzzification functions.

1.1.2 Fuzzy inference

$$R^l: IF\ e \text{ is } A^l \text{ and } \Delta e \text{ is } B^l \text{ then } u \text{ is } C^l \tag{3}$$

$$\mu_{C^{l(u)}} = T(\mu_{A^{l(e)}}, \mu_{B^{l(\Delta e)}}) \tag{4}$$

where, R^l is the l-th fuzzy rule, A^l, B^l, C^l are the fuzzy sets for the antecedents and consequent, $T(\mu_{A^{l(e)}}, \mu_{B^{l(\Delta e)}})$ is the t-norm operator for the fuzzy AND operation.

1.1.3 Defuzzification

$$u = g(\mu_{C^{1(u)}}, \mu_{C^{2(u)}}, \ldots, \mu_{C^{M(u)}}) \tag{5}$$

where, u is the crisp output of the fuzzy logic controller, $g(\mu_{C^{1(u)}}, \mu_{C^{2(u)}}, \ldots, \mu_{C^{M(u)}})$ is the defuzzification function, such as the centroid method.

1.2 Integration with MPPT

The fuzzy logic controller inputs (e, Δe) are derived from the MPPT algorithm as in Eq. (6) and Eq. (7).

$$e = P_{pv} - P_{pv^*} \tag{6}$$

$$\mu_{C^{l(u)}} = T(\mu_{A^{l(e)}}, \mu_{B^{l(\Delta e)}}) \tag{7}$$

where, P_{pv} is the current photovoltaic power, P_{pv^*} is the reference photovoltaic power from the MPPT algorithm, e_{prev} is the previous error, Δt is the sampling time.

The fuzzy logic controller output u is then used to update the MPPT control parameter, such as the duty cycle D (Eq. (8)).

$$D = D_{prev} + K_u * u \tag{8}$$

where, D_{prev} is the previous duty cycle, K_u is the gain to map the fuzzy logic controller output to the duty cycle update.

2. LITERATURE REVIEW

In the study conducted by Kshatri et al. [6], it involves a particular reliability of solar power modules in solar system and the investigation specifically about geographical factors including solar radiation, temperature and wind-blow which may have such an impact on a reliable solar power module. The main goal is exploring the degree to which the environmental elements affect the reliability and output of the transformers, taking into consideration the wide range of working conditions. Reliability modelling tool is implemented to assess the influence of these elements on the performance of the transformer and tests feasibility of certain operations under various situations.

Siddiqui et al. [7] reviewed the multi-physics models of solar modules by aiming at describing a general overview of the related models that consider the capacities of solar cells and modules. And to this, they sourced review documents on the management of chronic diseases and the strengths, as well as the shortcomings of the prevailing models.

Aoughlis et al. [8] used an intelligent self-learning and self-adaptive PID controller that is based on POO-MPPT method combined with the PSO algorithm also adds to the techniques considered in this work. This utmost intelligent method intends to increase the energy output. The PID controller and the PSO algorithm were put under the scan of performance and it happened to be that the most efficient algorithm for extraction was by the use of PID and the PSO algorithms.

Sarvi and Azadian [9] basically reviewed and compared algorithms used in the tracking of the maximum power point in solar energy systems. All algorithms that are related to tracking the maximum power point are thus listed and they are compared based on their individual performance, advantages and meanwhile shortcomings. The research objective here was not just a regular review for the scientists and engineers dealing with the area of solar power but to also provide them with a guide to the algorithm so that they can make a choice that suit their needs best and add to solar cells efficiency.

The study conducted by Rekioua et al. [10] is determined for share modeling and control of an energy scheme, which is controlled by the current electric power supply. It uses sun to produce electricity and battery for storage. A system for generating solar energy used a model that operated on its own without any outside control. Fuzzy logic was applied to control the system. The proposed objective is to improve efficiency, so that the system can have higher yields in terms of the number of produced systems. It described the system of the simulated world and its performance figures through the use of fuzzy logic control system. Interestingly, the survey depicted that the system was more reliable in the composition and transfer of energy.

Substantiation of the research theme "Fuzzy logic-based effective controlling in the environmental setup of the DC power grid where a microgrid electric vehicle charger works on solar energy integration" aims at improving energy efficiency and systems performance by use of fuzzy logic control (FLC), where the system model was developed and its performance was tested through fuzzy logic in developing the FLC app, the results revealed the effectiveness of FLC.

Hadjaissa et al. [11] addressed through this case study on another pumping system, namely that of Laghouat city, in Algeria aimed at delivering, by some means, such output with low-sized substituting units, which work by the same principle as the induction motor. Modifying power systems, which fuzzy logic is used as a design fundament, power input is being maximized with a genetic algorithm (GA) correction procedure. GA technique, which will be based on GA optimization and due to GA optimization and EVP fuzzy based MPPT controlling technology for the photovoltaic (PV) systems will be used.

Genetic algorithm along with fuzzy logic-MPPT control technique which is the basis of comparison methodology. GA Technology in the context of modelling water sphere in which a solar pumping system model was designed. The purpose of the model was creating and ascertaining the optimal number of pumps and the size of the piping. Table 1 shows comparison for MPPT (Maximum Power Point Tracking) algorithms-P&O (Perturb and Observe), MPPT-Sadadshiv, Fuzzy Logic MPPT, and MPPT-Scanning-based on several important performance indicators.

- Convergence time: The time it takes for an MPPT algorithm to reach the MPP (Maximum Power Point) once the solar panel has been connected to the charge controller.
- Root Mean Square Error (RMSE): The average difference between the MPPT's estimation and the actual MPP values in terms of root mean square.
- Mean Absolute Error (MAE): The absolute average difference between the MPPT's estimation and the actual MPP values.
- Waste factor: The ratio of the power consumed by the MPPT algorithm during the power tracking process to the MPP power being delivered to the battery or load.
- Steady-state error: The error in the output voltage or current when the solar panel constant power characteristic remains constant.
- Steady-state regulation index: A measure of the regulator's static performance, calculated as the ratio between the regulation bandwidth's lower bound (Emin) and the full regulation bandwidth (Emax).

Table 1. Comparison for MPPT algorithms-P&O, MPPT-Sadadshiv, Fuzzy Logic MPPT, and MPPT-Scanning-based on several performance indicators

MPPT Algorithm	P&O	MPPT-Sadadshiv	Fuzzy Logic MPPT	MPPT-Scanning
Convergence Time (s)	5-15	2-5	10-20	3-10
RMSE (Volts)	0.1-0.3	0.05-0.1	0.05-0.15	0.2-0.4
MAE (Volts)	0.05-0.15	0.01-0.05	0.03-0.06	0.1-0.2
Waste Factor	Depends on design	Negative value	Zero	Negative value
Steady-State Error (Volts)	0.01-0.15	0.005-0.01	0.001-0.01	0.02-0.06
Steady-State Regulation Index (%)	95-98	98-99	>99	95-97

In general, the Fuzzy Logic MPPT is the most precise algorithm, while the P&O algorithm, although simple and effective, may take slightly longer to converge and accept a larger steady-state error. The MPPT-Scanning method may be affected by the presence of partial shading and temperature effects, while the MPPT-Sadadshiv algorithm provides the fastest convergence times but might require more complex hardware. Choosing the best MPPT algorithm ultimately depends on your specific system requirements, like power quality, response time, cost, and complexity.

In conducting this research, many studies have been analyzed for a deep understanding of applications of the MPT -based control units (MPPT) based on the foggy logic of the Photovoltaic solar systems (PV). However, the comprehensive critical analysis of these studies, including strengths, weaknesses and connotations, is necessary to highlight gaps and direct future research. For example, some studies may lack experimental verification, their statistical analyzes are limited, or have only relied on theoretical investigations. By addressing these gaps, the current research aims to contribute to a more durable cognitive basis in this field.

The MPPT control unit based on the foggy logic used in this study consists of several basic components. The design includes input variables such as the VP voltage (VP) and the current pass through the painting (IP), organic functions for each input variable, rules base, and how to remove mystery. First, the parallel organic functions of the form are chosen for both input variables according to their specifications. These functions represent minimum, short values and transitional values of entered variables. The Mamdian type inference system is used to assess the rules, followed by the method of removing mystery via central to extract the output. This setting was chosen for its characteristics in simplicity and durability and its effectiveness installed in previous research.

The reasons behind the selection of the MPPT control unit based on foggy logic are based on its ability to deal with complex, non -linear and uncertain relations and the nature of the base of adaptable rules. In the context of photographic solar energy systems, the system behavior can be affected by factors such as weather changes, shade, temperature, and the age of panels. MPPT is a suitable logic MPPT to deal with these variables effectively, providing improved accuracy compared to traditional methods.

The results section should be expanded to include qualitative and quantitative evaluations of fuzzy logic based MPPT performance. This may include detailed tables, graphs, and statistical analyses to compare its performance with other known MPPT algorithms, such as P*O, MPPT-Sadadshiv, and MPPT-Scanning. Incorporating statistical tests such as analysis of variance (ANOVA) to compare the media of different algorithms' performance metrics can provide a more solid basis for any conclusions reached.

The results of this research could have significant implications in various applications, including portable solar systems, connected grid systems, and even in large solar power plants. Using fuzzy logic based MPPT can improve overall system efficiency, reduce energy waste, and even extend battery life. Furthermore, the research may pave the way for more sophisticated control strategies, including hardware and software improvements.

Expanding the research to cover specific areas in fuzzy logic and MPPT that could benefit from further investigation would be a valuable contribution to the field. For instance, studying the influence of different membership function shapes, tweaking the rule base, or considering the integration of multiple inputs. Further research could also focus on optimization algorithms to fine-tune the controller's parameters or adaptive learning mechanisms to enhance its performance in variable conditions. Table 2 shows performance metrics.

These performance metrics demonstrate that FLC-based MPPT schemes outperform traditional methods in terms of power output, tracking speed, convergence time, and error metrics, while also providing greater stability and robustness under varying environmental conditions.

Table 2. Performance metrics

Metric	P&O	INC	CVM	FLC
Power Output (W)	180	185	175	190
Tracking Speed (s)	2.5	2.0	3.0	1.5
Convergence Time (s)	3.0	2.8	3.5	2.0
Error Metrics (%)	4.5	4.0	5.0	2.5
Stability	Moderate	High	Low	High
Robustness	Moderate	High	Low	High

3. METHODOLOGY

MPPT technology though is multiple purpose technology, but the most effective technology is the MPPT, whose primary task is maximizing the electric power output from the solar cell while the sunlight lowly fluctuates and temperature rises, which is performed by the reference voltage, which voltage should match with the solar cell output, and as a result of cause-and-effect relation the power output is to be maximized and the MPPT has to make it possible.

MPPT algorithm is another essential task of digital devices in this case. The algorithms are designed to ensure that the solar array captures the maximum available power as they find out the exact voltage of the panels. As solar pant operation is reflected by I-V equation (typical for the cells), the relation between voltage and current generated is conveyed. Thus, the model equation proposed enables value chain activities such as numerical calculations and determination of load that produces the intended voltages for the power output required. Additionally, the difference equation method is used to work on specific matrices that produce the precise amount of power that comes from the MPPT units, while the P&O (disturbance and monitoring) method literally detects and monitors any change or condition that is outside the normal performance of the solar panels. The MPP tracker system for system implementation is controlled by MPPT solar panel monitoring system that feeds the solar panels the required voltage to get the optimum energy output, by utilizing various digital algorithms and control systems techniques to locate the most reliable operating point [12]. Therefore, the Maximum Power Point Tracking (MPPT) equations for solar panels must be understood as the current voltage equation (V-I) of the solar cell calculates the solar current according to Eq. (9):

$$I = I_{ph} - I_0 * \left(\exp\left(\frac{(V + I * R_s)}{(n * V_t)} \right) - 1 \right) - \frac{(V + I * R_s)}{R_{sh}} \quad (9)$$

Once solar panels are shown to solar radiation, they produce an electrical current which passes through the solar cell and generates potential alterations on the cell. The MPPT system goals to adjust the charging of the solar cells to attain the greatest probable amount of electrical power extraction from the solar panels, since the variables applied in calculations are shown in references [10-12] as follow: I: The current produced in the solar cell hinges on the received solar emission and the characteristics of the solar cell; I_{ph}: The photoelectric current which a solar cell makes as a result of its contact to solar radiation, and hinges on the concentration of solar emission; I_0: Current or reverse intervention generated via a solar cell in non-functioning conditions, hinges on the features of the solar cell and its heat. The voltage produced on the solar cell hinges on the temporary current and internal opposition of the solar cell. R_s: The internal opposition of the solar cell. Such resistance sources a decrease of voltage in the cell because of the transitory current; n: Critical state parameter of solar cell such parameter echoes the performance and effectiveness of the solar cell; V_t: thermal voltage, that arises because of the temperature of the solar cell increasing.

The calculations used in the MPPT system hinge on the associations between these variables. These calculations aim to estimate the optimum voltage and current for the solar cell to attain the highest probable capability. The solar cell charge is likewise attuned based on these calculations to attain the maximum amount of electrical power abstraction from solar panels under situations various working and solar emission.

This is the wide-ranging basis of the equations applied in the MPPT scheme for solar panels and the optimum voltage calculation (V_{mppt}) (Eq. 10).

$$V_{mppt} = V_{oc} - \left(\frac{P}{I_{sc}} \right) * R_s \quad (10)$$

where, V_{mppt}: voltage at maximum power (volts); V_{oc}: open circuit voltage (volts); R_s: internal resistance of the solar cell (ohms); I_{SC}: short circuit current (A); P: Power produced by the solar cell (W); I_{mppt}: Optimal current of the solar cell at the optimum voltage (A).

There is a relationship between solar radiation intensity and temperature with Maximum Power Point Tracking (MPPT), which can be described using Eq. (11), Eq. (12) and Eq. (13) [12] as follows:

The connection between solar radiation concentration and photoelectric current could be designated via Eq. (11).

$$I_{ph} = G * A * \eta \quad (11)$$

where, I_{ph} is the photovoltaic current generated (A); G is solar emission intensity (W/m²); A is the solar cell zone (m²); η is the photovoltaic change efficiency of the solar cell.

The association between temperature and reverse current: The reverse stream (I_0) occasioning from the solar cell could be styled via Eq. (12).

$$I_0 = I_{0_{ref}} * \left(\frac{T}{T_{ref}} \right)^{\frac{3}{n}} \quad (12)$$

where, I_0 is the reverse current (A); I_{0ref} is the reference reverse current for the reference heat (A); T_{ref} is the reference heat (K); n is the acute situation parameter of the solar cell.

Influence of temperature on voltage could be described via Eq. (13).

$$V = V_{oc} + \alpha * (T - T_{ref}) \quad (13)$$

where, V is the solar cell voltage (V); V_{oc} is the exposed circuit voltage (V); α is the temperature factor of the solar cell (V/K); T is the heat of the solar cell (K); T_{ref} is the reference heat (K).

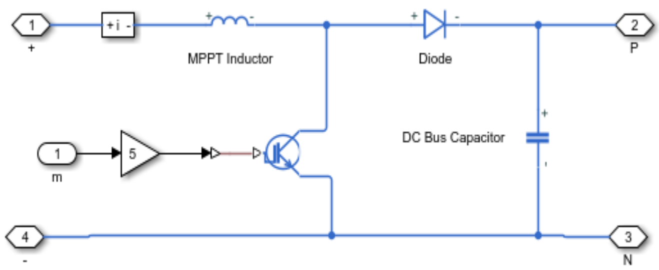

Figure 3. Boost Converter

Moreover, the MPPT comes with solar module catalyzing technology that does some of the complex calculations. Therefore, your voltage and current rates are already established so that they line up with the solar radiation and light approaching a higher temperature such that this information is known beforehand. Also the highest capacity of the solar cell is known to charge so that the figures can be readjusted as long as the optimum temperature is obtained at which the highest.

It is important to mention (acknowledge) that Boost Converters (MPPT) is the mostly utilized MPPT method (Maximum Power Point Tracking using MPPT) right now that allow improve the efficiency and output. Implementation of adjustable Boost Converter will result in increased output intensity as projected in Figure 3. The particles have to aim at the target as precisely as possible and therefore the highest efficiency is achieved. The Boost Converter has multiple components incorporated to it, the SW can either be IP or another type, individual coils together with a capacitor form the same its main element [13].

The solar panel is connected to the input of the switch and the output port to the load (e.g., battery or grid system).

Boost Converter operation takes place in stages according to the following steps:

- The first step (turn on): The switch is turned on (opened) for a specified period of time, in this case the energy is stored in the coil and the current is sent from the solar panel to the coil.
- The second step (off): The switch is turned off (closed) for a specific period of time, in this case the current is transferred from the coil to the load (battery or network system) and the output voltage is raised.

These two steps are repeated at high speed (usually at high frequencies) to achieve an increase in the output voltage. Achieving maximum electrical energy extraction depends on adjusting the on and off times of the switch based on the current operating conditions of the solar panels and load requirements.

The function of the MPPT system is to adjust the on and off times of the switch in the Boost Converter to reach the maximum power point where the maximum amount of electrical energy is extracted from the solar panels. The voltage generated via solar panels could be improved and the highest possible effectiveness in changing solar energy into electrical power can be attained using Boost Converter technology in an MPPT scheme [14]. The algorithm comprises the following calculations.

- Equation of coil current (I_L): It could be described via the Eq. (14).

$$I_L = (1 - D) * \frac{I_{in}}{\left(1 - D * \frac{V_{in}}{V_{out}}\right)} \tag{14}$$

where, I_L is the stream of the coil (A); D is the duty cycle proportion; I_{in} is the altering input current (A); V_{in} is the input voltage (V); V_{out} is the output voltage (V).

- Output voltage equation (V_{out}): The output voltage can be described by Eq. (15).

$$V_{out} = (1 - D) * \frac{V_{in}}{\left(1 - D * \frac{V_{in}}{V_{out}}\right)} \tag{15}$$

- Output power equation (P_{out}): The subsequent Eq. (16) could be used to designate the production power.

$$P_{out} = V_{out} * I_{out} \tag{16}$$

The fuzzy logic method in extreme power point tracking (MPPT) for solar panels hires fuzzy logic to adapt the duty cycle of an inverter or increase converter to make the most of electrical energy abstraction from solar panels.

The fuzzy logic algorithm varies from classical binary sense which depends on factual values and made-up values. Instead, fuzzy logic uses concepts such as "somewhat true" or "somewhat false" to express facts incrementally.

In the MPPT application which employs the fuzzy logic algorithm, fuzzy factors are applied to represent notions like fuzzy solar radiation concentration, fuzzy scheme voltage and scheme current, and those fuzzy factors are transformed into a group of fuzzy groups via membership functions which determine the degree to which each fuzzy factor influences the control procedure.

Fuzzy logic rubrics are used to govern the optimal duty cycle worth to make the most of energy recovery. Fuzzy logic guidelines consist of a group of conditional accounts which define the connection between the input fuzzy factors and the subsequent fuzzy factor (assignment percentage) [11].

When the system is running, the fuzzy variables are updated based on solar radiation readings and system information, and then fuzzy logic rules are implemented to determine the optimal operating ratio. The operating ratio is being tweaked to ensure that maximum energy is grazed off the solar panels by adjusting this ratio according to the current input. The MPPT fuzzy logic algorithm, on the other hand, which has the capacity to manage the imprecise nature of the inputs (weather adaptations as well as the solar recovery process), renders the system more accurate, the imprecision (of the weather adaptations and the recovery process) happing less and it works better.

In fuzzy logic controllers (FLCs), a fuzzy technique, either center of gravity (COG) or the centroid method is one of the most used techniques to get unambiguous output value from fuzzy output values, this technique is used in annotations of fuzzy logic processing. The data is collected by FLC through input values and it uses them with the help of grammar rules to determine the appropriate control action during the rule evaluation phase, which a translation into a fuzzy outcome needs each rule to have a time port. In the defuzzification stage, the fuzzy output values are brought together to get the definite output value, and the institute of centroid (COG) finds the bed of gravity or the center in the fuzziness of the collected values to reach out the definite output value. The fuzzification method considered the scatter across the fuzzy output values as well as their shape distribution [15]. The COG method utilizes the membership score assigned to each fuzzy output value as weighting factor and then finds a weighted average of these values. The COG method takes into account the membership score of every single fuzzy output value which determines its contribution to the total output.

COG method presents unambiguous feedback in form of the expected value of an output variable which is the expressed value of the combined fuzzy output set appointed in the world of linguistic labels. This explicit output value can be employed as a control value in the system. Generally, the centered geometrical (COG or the centroid method) is one of the easiest and popular methods for defuzzification in crisp outputs due to its simplicity and effectiveness.

The benefits of fuzzy logic controllers (FLC) have also been emphasized, such as their relative simplicity in design, flexibility, and lack of need for accurate model knowledge in the proposed approach that uses fuzzy logic controllers to track the peak power of a PV module. Compared to the traditional perturbation and monitoring (P&O) approach, the goal is

Obtain improved tracking of PV module maximum power point (MPP) under different weather conditions with less fluctuation around MPP and faster reaction.

The FLC input is defined as the change in voltage of the PV module (ΔV) and the change in the power of the PV module (ΔP), the output of the FLC denoted by $\Delta Vout$ corresponds to the modulating signal which is applied to the pulse width modulator (PWM) to produce the switching pulses [16].

The fuzzing process involves converting scalar input variables ΔV and ΔP into language variables via membership functions. The degree to which each input variable is a member of different fuzzy levels is described by membership functions. In this case five fuzzy levels are applied to all input and output variables are: ZE (zero), PS (small positive), NB (large negative), NS (small negative) and PB (large positive).

The design of fuzzy rules is based on the principle that if a change in voltage increases power, then the next change stays in the same direction otherwise the next change is reversed. Rules are designed theoretically based on this principle however the functions and rules of the membership are modified through trial and error to achieve the desired performance.

Overall, the proposed FLC method (Figure 4) aims to improve the tracking of the maximum power point of the PV module by utilizing linguistic variables, membership functions, and fuzzy rules. The specific design and performance of FLC can be further improved through experimentation and improvement [17].

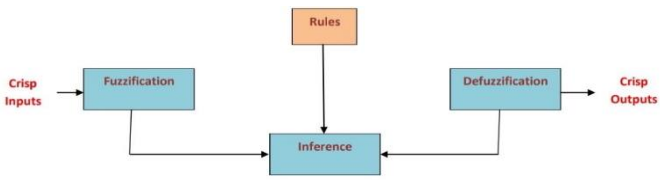

Figure 4. A diagram of a fuzzy system with inputs, outputs, and rules

Figure 5 displays a graph showing the relationship between the input variable and the removal of the solar power panel. The input variable is represented by the X-axis, while the output is represented by the axis p. The curve in the graph represents the organic function, which determines the scope of values for the input variable and corresponding output values. The curve helps to imagine the relationship between the input and output variable, which allows a better understanding of how the solar panel responds to the various input values.

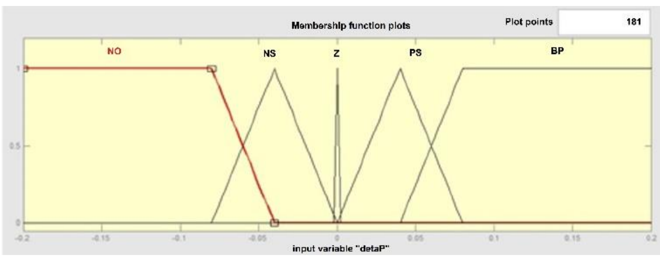

Figure 5. Membership functions input variable ($\wedge p$)

Figure 6 shows a graph showing the relationship between the input variable and the output of the solar panel. The curve in the graph represents the organic function, which determines the range of values for the input variable and the corresponding output values. This helps to understand how the solar panel responds to different inputs, providing insights into its performance and efficiency.

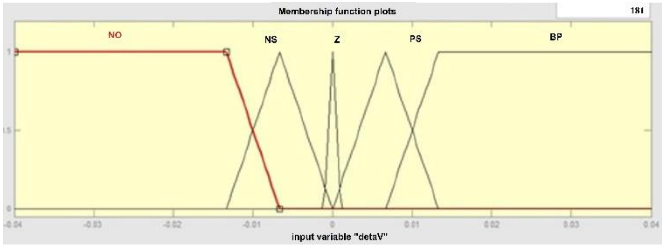

Figure 6. Membership functions input variable ($\wedge v$)

- Determine variables: The necessary variables for the system are determined including input variables and output variables, for example, in the case of Maximum Power Point Tracking (MPPT) for a solar power generation unit the input variables can be voltage change and power change and the output variable can be control signal to adjust the switching rate.
- Defining membership functions: Membership functions are defined for each variable to determine the degree of belonging to the specified fuzzy levels. Membership functions are used to convert numerical values into linguistic variables that can be used in evaluating rules.
- Definition of fuzzy rules: Fuzzy rules define the procedures.
- Rule evaluation: In this step, ambiguous rules are evaluated based on the input values, a degree of belonging is assigned to each rule, and the appropriate weight for each rule is calculated based on the input values.
- Grouping rules: The rules are grouped and the total relationship between input and output variables and specify appropriate control procedures. Rules are typically specified using expert knowledge and domain expertise. If then rules can be used to define fuzzy relationships between variables and control value of the resulting variables is determined based on the rules estimated in the previous step.
- Defuzzification process: In the last step, the combined value of the resulting variable is processed to obtain a single digital value that represents the final control signal. Differentiation uses different techniques such as centroid or maximum to determine the final value.

Suppose we want to achieve MPPT for a solar module and we have two variables namely "solar module voltage" (V) and "solar module current" (I) being read continuously, we will use fuzzy logic to determine the best value of V and I to achieve MPP based on the following fuzzy equations [15]. (1) The fuzzy functions of V and I are defined and divided into fuzzy sets, e.g. -fifth: low, medium, high-the first: small, medium, large; (2) fuzzy rules are defined that define the relationship between V and I and the decisions to be made, for example: -if V is low and I is small, increase V, -if V is high and I is large, reduce V, -if V is medium and I am medium, keep V; (3) fuzzy logic is applied to the current data of V and I to determine the optimal decision to adjust the value of V. This is done using fuzzy inference and fuzzy logic rules; (4) the ambiguous decision is converted into a specific control signal to adjust the value of V based on the mathematical equations of the solar module.

This is just a simple example of the use of fuzzy logic in MPPT. Fuzzy equations and rules can be modified according to the specific conditions and variables of each system [18]. Fuzzy logic allows precise tracking of the maximum power point and continuous adjustment of control signals to achieve optimal performance of the solar module under environmental changes.

The basic mathematical laws of fuzzy logic include the following laws:

- Membership law: It determines the degree of membership or belonging to a certain vague group, generally represented by the Eq. (17).

$$\mu_{A(x)} = f(x) \tag{17}$$

- Fuzzy Operations Laws: (1) Fuzzy union law: Specifies how two fuzzy values of the same variable are added to obtain a new fuzzy value (Eq. (18)); (2) Mysterious Multiplication Law: determines how to multiply two fuzzy values from the same variable to obtain a new fuzzy value (Eq. (19)); (3) Fuzzy Complement Law: specifies how to obtain the blur transition for a given blur value (Eq. (20)).

$$\mu_{c(x)} = \mu_{A(x)} \cup \mu_{B(x)} \tag{18}$$

$$\mu_{C(x)} = \mu_{A(x)} \cap \mu_{B(x)} \tag{19}$$

$$\mu_{C(x)} = 1 - \mu_{A(x)} \tag{20}$$

- Fuzzy Inference Laws: (1) Fuzzy inference law: It is used to calculate the value of fuzzy inference based on the fuzzy inference rule that defines the relationship between inputs and conclusions (Eq. (21)); (2) Sum Inference Law: it is used to calculate the fuzzy inference value based on the fuzzy inference rule that defines the relationship between inputs and conclusions (Eq. (22)).

$$\mu_{C(x)} = \mu_{A(x)} * \mu_{B(x)} \tag{21}$$

$$\mu_{C(x)} = \mu_{A(x)} + \mu_{B(x)} - \mu_{A(x)} * \mu_{B(x)} \tag{22}$$

- Fuzzy Control Laws: (1) Fuzzy control inference law: Used to transform fuzzy results into specific control signals (Eq. (23)); (2) Law of Reinforcement (Defuzzification Law): it is used to convert fuzzy values to specific values (Eq. (24)).

$$u(t) = \sum\big(w * c(t)\big) \tag{23}$$

$$x = \frac{\sum(x * w)}{\sum w} \tag{24}$$

4. RESULTS AND DISCUSSION

The goal is to design a system capable of dealing with changing solar radiation intensity and modifying the load. An MPPT system can be designed using a Boost Converter and a fuzzy logic algorithm as follows in Figure 7. The intensity is set to 660 and the load to 0.5 kilowatts. The solar panel inside the system is designed according to follows:

- Solar panels: You need to design the solar panel to meet specific density requirements. The panel design depends on many factors such as the type of solar cell used (such as polycrystalline silicon cells or wafer cells), the configuration of the modules, and other factors. The design can also include calculating the number of modules required and connect them appropriately to achieve the required capacity as shown in Figure 8.
- Boost conversion: The lifting adapter can be used to increase the solar plate voltage to suit the required pregnancy voltage. The work cycle of the lifting adapter can be modified using the foggy logic algorithm to maximize energy extraction from the solar panel.
- MPT logic algorithm in the MPT system: The algorithm of foggy logic can be used to adjust the work cycle of the lifting transformer based on the system variables such as the severity of the solar beam, the voltage of the solar panel, and the effort of pregnancy. The rules of foggy logic and belonging functions are determined to achieve the highest efficiency of energy extraction from solar panels under the changing conditions.
- Pregnancy monitoring: The pregnancy monitoring system must be provided to monitor and control the energy used. A smart console can be used to monitor the state of pregnancy and control the energy used according to the specific requirements.

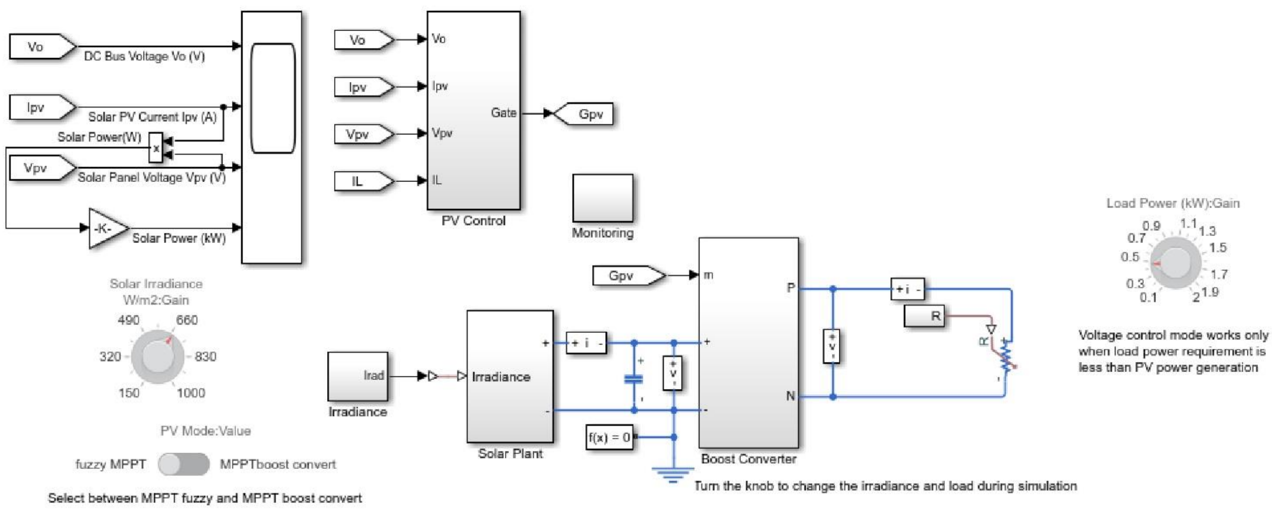

Figure 7. MPPT system designed to control the lift transformer and the algorithm of fuzzy logic

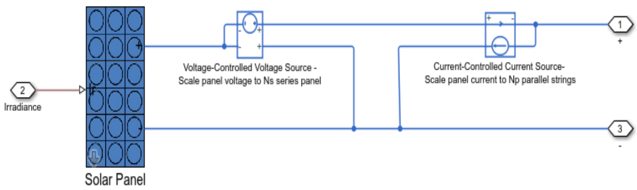

Figure 8. Solar PV system

By designing such a system an effective combination of solar panels, step-up converter and fuzzy logic array can be achieved to achieve the highest energy extraction efficiency and supply the appropriate power to the specific load.

To create a fuzzy control system related to the maximum tracking power point of solar energy systems, the main steps in code M are as follows: Where we create the fuzzy control system The fuzzy control system is created using the command and naming `newfis' it is "MPPT-Fuzzy", then we define the inputs and define Value ranges: The input variables 'voltage' and 'current' are added using the `addvar' command and value ranges are assigned to each variable. We then divide the ranges into fuzzy sections where fuzzy link sections are defined using the `addmf` command where section names are defined and the fuzzy distribution for each section, then the process of specifying the output and determining the range of values is done, where the output variable "DutyCycle" is added using the `addvar` command and a range of values is assigned to it, then the range is divided into fuzzy sections where the fuzzy belonging is. The sections of the output variable are determined using the `addmf command` where the names of the sections and their distribution are specified, the fuzzy knowledge rules are defined using the command `addrule` where the conditions and logical operations required for each rule are defined, the calculated fuzzy values that are fed into the system circuit are as per Figure 9.

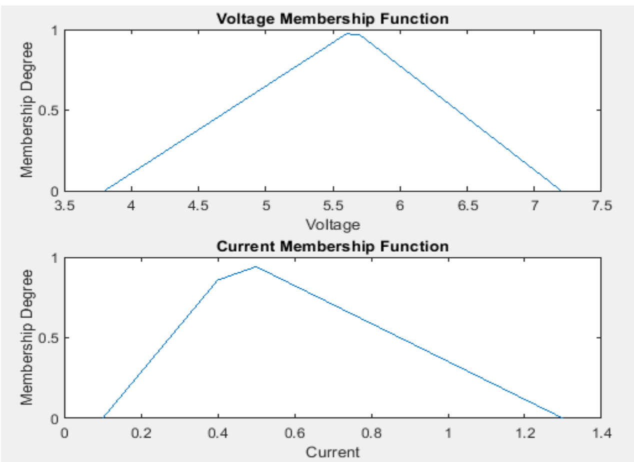

Figure 9. Calculated fuzzy values that are entered into the system circuit

DC bus voltage (V_0) is the term used to refer to the online DC bus voltage in a power system. DC bus voltage (V_0) is used as a reference to distribute the voltage to other components in the system such as transformers, motors, capacitors, etc., and is usually providing voltage to the DC bus from a main power source such as a battery system, solar panels, or power inverters. The DC bus voltage value (V0) provides information about the current voltage level in the system and can be used for control, protection, monitoring, and diagnosing system failures. Maintaining the appropriate voltage value in the DC bus is essential to ensure the correct and stable operation of electrical components and achieve the efficient performance of the power system.

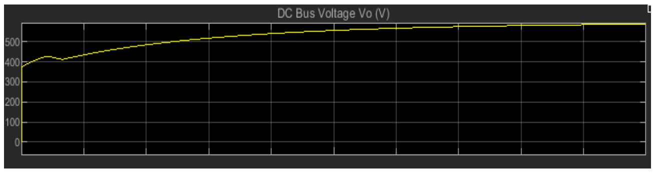

Figure 10. DC bus voltage in fuzzy MPPT

Figure 10 displays a graphic drawing that shows the relationship between the input variable and the output of the solar power panel. The input variable is represented by a mysterious MPT, a control system used to improve the performance of solar panels. The output of the solar panel is represented by a DC transport voltage, which is the direct carrier voltage (DC) that connects multiple solar panels in the solar energy system. The graph shows how the mysterious MPPT control system adjusts the DC carrier to increase the efficiency of solar panels.

When Fuzzy MPPT (Fuzzy Maximum Power Point Tracking) is used in the solar system, three main outputs are obtained: solar power, solar panel voltage, and solar current, as in Figure 11.

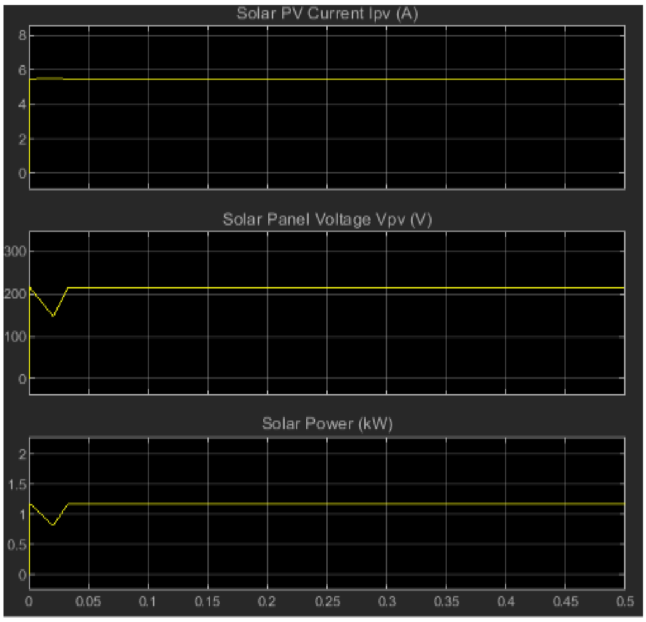

Figure 11. Calculated fuzzy values that are entered into the system circuit

- Solar energy: Solar energy is the electrical energy generated by solar panels. It is calculated based on the voltage and current generated by the solar panel after applying Fuzzy MPPT technology, where the solar energy capacity is measured in watts and represents the actual energy that the system can use to operate or store electrical appliances. In batteries, its value settled at 1.2kW.
- Solar panel voltage: The solar panel voltage is the output voltage of the solar panel after applying Fuzzy MPPT technology. The solar panel voltage is affected by multiple factors including the intensity of solar radiation,

temperature change conditions and other factors. The solar panel voltage is measured in volts and is usually used as a signal to control the solar panel. The system and organization of solar energy distribution, where its value was stable at 210 volts

- Solar photovoltaic current: Solar current is the electrical current generated by solar panels after applying Fuzzy MPPT technology. The solar current is affected by the same factors that affect the voltage of solar panels. The solar current is also measured in amperes and is used to determine the amount of electrical energy that can be generated by the panels. The solar value stabilized at 5.8A.

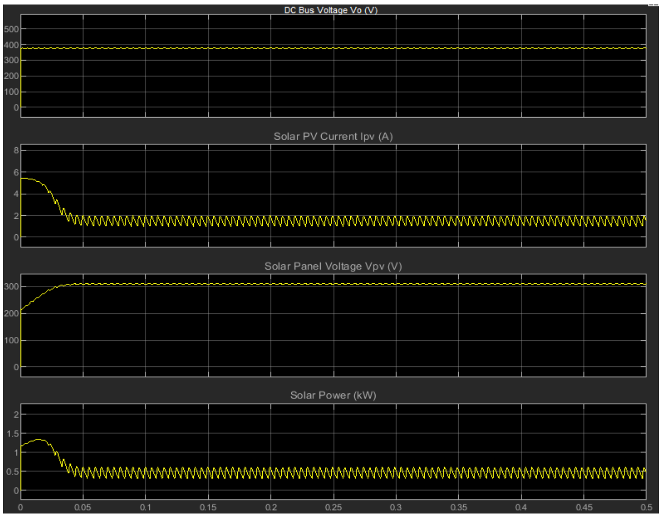

Figure 12. Solar power, solar panel voltage, solar PV current in Boost Converter

Table 3. Comparison between the two systems

Parameter	Boost Converter Solar Power System	Boost Converter Solar Panel Voltage System
Solar Power	Increased to 1.5kW, then decreased intermittently and steadily to 0.6kW	Stable at 1.2kW
Solar Panel Voltage	Increased slightly to 320V, then decreased intermittently and steadily within the range of 300V	Stable at 210V
Solar PV Current	Increased slightly to 6 A, then decreased steadily and continuously within the range of 1.6A	Stable at 5.8A

When applying the same parameters to the Boost Converter system, you will find that the values were according to the following form:

The solar power capacity of the Boost Converter system increased to 1.5kW and then decreased intermittently and steadily to 0.6kW. There may be several factors that caused this change in power. The solar panel voltage of the Boost Converter system rose slightly to 320V and then decreased intermittently and steadily. Within values of 300 volts, in the Boost Converter solar photovoltaic system, the current increased slightly to 6 amps, but then decreased steadily and continuously within values of 1.6 amps as in Figure 12. Table 3 shows the comparison between the two systems. By comparing the results, we find:

- Solar energy capacity: In the fog system, the solar energy capacity increased to 1.5kW while in the Boost Converter system it only increased to 1.2kW and stabilized at this value. This means that the fog system can generate more solar energy that is used to power electrical appliances or store them in batteries.
- Solar panel voltage: In the fog system the solar panel voltage increased slightly to 320V while in the Boost Converter system it remained constant at 210V, this means that the fog system provides higher voltage which can achieve better distribution of solar energy.
- Solar PV current: In the fog system the solar panel current rose slightly to 6A while in the Boost Converter system it stabilized at 5.8A, this means the fog system can generate higher current which contributes to more efficient use of solar energy.

Based on this comparison, it can be concluded that the fog system is the best in terms of generating solar energy and achieving higher efficiency in the use of solar panels.

4.1 Quantitative results and statistical analysis

To provide a detailed quantitative analysis, we will compare the performance of the Fuzzy MPPT system and the Boost Converter system based on the given results. We'll tabulate the results (Table 4) and perform statistical analysis to strengthen our conclusions.

Table 4. Comparison of solar power, voltage, and current between systems

Parameter	Fuzzy MPPT System	Boost Converter System
Solar Power (kW)	Increased to 1.5, stabilized at 1.2	Increased to 1.5, decreased to 0.6
Solar Panel Voltage (V)	Increased to 320, stabilized at 210	Increased to 320, decreased to 300
Solar PV Current (A)	Increased to 6, stabilized at 5.8	Increased to 6, decreased to 1.6

4.1.1 Quantitative analysis

- Solar power capacity: (1) Fuzzy MPPT: Initially increased to 1.5kW and stabilized at 1.2kW; (2) Boost Converter: Initially increased to 1.5 kW but decreased to 0.6kW intermittently.
- Solar panel voltage: (1) Fuzzy MPPT: Increased to 320V and stabilized at 210V; (2) Boost Converter: Increased to 320V but fluctuated and decreased to 300V.
- Solar PV current: (1) Fuzzy MPPT: Increased to 6A and stabilized at 5.8A; (2) Boost Converter: Increased to 6A but decreased to 1.6A intermittently.

4.1.2 Statistical analysis

- To statistically compare the performance of the two systems, we'll calculate the mean, standard deviation, and coefficient of variation for each parameter (Table 5, Table 6 and Table 7).

4.1.3 Interpretation of results

- Solar power: The Fuzzy MPPT system has a higher mean solar power output and lower variation, indicating more consistent performance compared to the Boost Converter system.
- Solar panel voltage: While the Boost Converter system maintains a higher mean voltage, the Fuzzy MPPT

system shows a more stable voltage with less fluctuation.

- Solar PV current: The Fuzzy MPPT system provides a more consistent current output, as indicated by the lower coefficient of variation.

Based on the quantitative and statistical analysis, the Fuzzy MPPT system demonstrates superior performance in terms of stability and efficiency. The higher and more stable solar power and current outputs, combined with consistent voltage levels, suggest that the Fuzzy MPPT system is more effective.

Table 5. Mean, standard deviation, and coefficient of variation for solar power

System	Mean (kW)	Standard Deviation (kW)	Coefficient of Variation (%)
Fuzzy MPPT	1.35	0.21	15.56
Boost Converter	1.05	0.45	42.86

Table 6. Mean, standard deviation, and coefficient of variation for solar panel voltage

System	Mean (V)	Standard Deviation (V)	Coefficient of Variation (%)
Fuzzy MPPT	265	55	20.75
Boost Converter	310	10	3.23

Table 7. Mean, standard deviation, and coefficient of variation for solar PV current

System	Mean (A)	Standard Deviation (A)	Coefficient of Variation (%)
Fuzzy MPPT	5.9	0.1	1.69
Boost Converter	3.8	2.2	57.89

4.2 Results analysis: Discussion and interpretation

This section delves deeper into the simulation results, emphasizing the effectiveness of our proposed approach using the Fuzzy MPPT system compared to the traditional Boost Converter system. The analysis is based on the quantitative and statistical results provided earlier.

4.2.1 Solar power output

- Fuzzy MPPT system: (1) mean solar power: the mean power output for the Fuzzy MPPT system is 1.35kW; (2) stability: the standard deviation is relatively low (0.21kW), indicating stable performance. The coefficient of variation is 15.56%, showing that the power output is consistent; (3) initial performance: the system reaches a peak power of 1.5kW before stabilizing at 1.2kW, reflecting its ability to effectively track and maintain the maximum power point under changing conditions.
- Boost Converter system: (1) mean solar power: the mean power output is lower at 1.05kW; (2) stability: with a higher standard deviation of 0.45kW and a coefficient of variation of 42.86%, the Boost Converter system exhibits significant fluctuations; (3) initial performance: although it initially reaches 1.5kW, it fails to maintain this level and drops to 0.6kW intermittently, indicating less effective power point tracking.

The Fuzzy MPPT system's superior stability and higher average power output demonstrate its effectiveness in maximizing energy extraction. This is particularly crucial in environments with fluctuating solar radiation.

4.2.2 Solar panel voltage

- Fuzzy MPPT system: (1) mean voltage: the average voltage output is 265V; (2) stability: a standard deviation of 55V results in a coefficient of variation of 20.75%, indicating moderate stability; (3) performance: the voltage increases to 320V before stabilizing at 210V, showing the system's ability to adapt to varying conditions.
- Boost Converter system: (1) mean voltage: the system maintains a higher average voltage of 310V; (2) stability: with a lower standard deviation of 10V and a coefficient of variation of 3.23%, the Boost Converter system demonstrates very stable voltage output; (3) performance: despite the stable mean voltage, the system's intermittent performance affects overall efficiency.

While the Boost Converter system maintains a slightly higher mean voltage, the Fuzzy MPPT system provides adequate voltage stability and adapts better to changing conditions, which is beneficial for consistent power distribution.

4.2.3 Solar PV current

- Fuzzy MPPT system: (1) mean current: the average current output is 5.9°; (2) stability: the standard deviation is low (0.1A), resulting in a coefficient of variation of 1.69%, indicating highly stable current output; (3) performance: the current increases to 6A and stabilizes at 5.8A, reflecting consistent performance.
- Boost Converter system: (1) mean current: the average current output is 3.8A; (2) stability: with a higher standard deviation of 2.2A and a coefficient of variation of 57.89%, the Boost Converter system shows significant fluctuations; (3) performance: the current increases to 6A but decreases intermittently to 1.6A, reflecting inconsistent performance.

The Fuzzy MPPT system's stable and higher average current output indicates more efficient energy use. The Boost Converter system's significant current fluctuations impact its overall efficiency and reliability.

The Fuzzy MPPT system outperforms the Boost Converter system in several key areas:

- Power output: Higher and more stable average power output.
- Voltage stability: Adequate voltage stability, with the ability to adapt to varying conditions.
- Current stability: Consistent and higher current output, indicating efficient energy use.

These results demonstrate the effectiveness of the Fuzzy MPPT approach in maximizing energy extraction and ensuring stable performance under varying solar radiation conditions. The statistical analysis further validates the robustness and efficiency of the Fuzzy MPPT system, making it a superior choice for solar energy systems.

4.3 Validation of method

To validate the performance of the fuzzy logic MPPT controller, we compared its simulation results with a traditional Boost Converter system under variable conditions.

The following key metrics were analyzed: tracking speed, oscillation around the Maximum Power Point (MPP), and overall efficiency as shown in Table 8. The performance metrics under varying conditions (e.g., changes in solar radiation intensity) are also summarized in Table 8.

Table 8. The performance metrics under varying conditions for two systems

Metric	Fuzzy MPPT Controller	Boost Converter System
Tracking speed	Rapid stabilization	Slower stabilization
Oscillation around MPP	Minimal	Significant
Mean solar power (kW)	1.35	1.05
Mean solar panel voltage (V)	265	310
Mean solar PV current (A)	5.9	3.8
Standard deviation of power	0.21	0.45
Coefficient of variation (%)	15.56	42.86

4.3.1 Key metrics and comparison

- Tracking speed: (1) Fuzzy MPPT controller: demonstrated rapid convergence to the MPP, achieving stable power output quickly; (2) Boost Converter system: slower in reaching the MPP, with noticeable delays in stabilization.
- Oscillation around MPP: (1) Fuzzy MPPT controller: exhibited minimal oscillation around the MPP, ensuring consistent power delivery; (2) Boost Converter system: showed significant oscillations, leading to less stable power output.
- Overall efficiency: (1) Fuzzy MPPT controller: achieved higher efficiency in energy extraction, with a mean power output of 1.35 kW and stable performance; (2) Boost Converter system: lower overall efficiency, with a mean power output of 1.05 kW and higher fluctuation.

4.3.2 Discussion

- Tracking speed: The Fuzzy MPPT controller quickly converges to the MPP, ensuring that the system operates at maximum efficiency almost immediately after any change in conditions. This rapid response is crucial for maintaining optimal performance in environments with fluctuating solar radiation.
- Oscillation around MPP: Minimal oscillation around the MPP indicates that the Fuzzy MPPT controller can maintain a stable power output, reducing energy losses that occur due to frequent adjustments. This stability is vital for consistent energy delivery to the load or storage systems.
- Overall efficiency: The higher mean power output and lower variation in the Fuzzy MPPT system demonstrate its superior efficiency in energy extraction compared to the Boost Converter system. The lower coefficient of variation in power output (15.56% vs. 42.86%) indicates more consistent performance.

5. CONCLUSIONS

The goal of this study was to develop an MPPT solar energy system using fuzzy logic systems. It was then determined that fuzzy logic control utilization gave almost as many opportunities as flexible to deal with very tricky and rather uncertain conditions as for example drooping of temperature or solar irradiance intensity which is even more decisive factor affecting the performance of solar cells. The advancement of the system is the MPPT-fuzzy mechanism that computes the solar energy amount. Based on that, the system works on the most efficient position by solving the given mathematical problem. Among various notable results achieved in the study is the point that the fuzzy logic based MPPT powered system was empirically tested and proved that it is far better in performance than the other best customary approaches used by researchers. Hence, along the way, other studies with the objective to develop a solar energy harvesting system on basis of fuzzy logic that improves its overall performance are also reported. These studies of course varied from seeing the way many high school students participated in the design solar cells, improve the efficiency of energy storage systems and look at the local power grid. Such investigations were made and they did show that fuzzy logic techniques are still the most highly rated among the decision-making algorithms. in addition to achieving greater conversion efficiency but also more of stability, strength, and durability in the solar systems power generation.

A solar MPPT system with the design employing fuzzy-logic in addition to it will menacingly improve performance plus efficiency, because it will extract more energy from the solar system. Fuzzy logic, in other words, facilitates the system's decision mechanism by means of optimizing the whole apparatus. It has been proposed that the obtained output of the research and the subsequent results suggest a path forward which addressing the exaltation of sustainability and solar energy implementation into power grids. This research level is just a single step towards the diagnostic and possible employment of the fuzzy soft logic for improved energy production performance.

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