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PERFORMANCE ANALYSIS OF FUZZY LOGIC AND ANFIS MPPT OPTIMIZED QUADRATIC BOOST CONVERTER FED PV SYSTEM UNDER DIFFERENT SOLAR IRRADIANCE CONDITIONS

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ABSTRACT:
This paper discusses the implementation of FLC and ANFIS to optimize MPPT for a photovoltaic system consisting of a quadratic boost converter in relation to the variable nature of solar irradiation. The operational efficiency of the PV systems is largely based on the ability to ensure proper functioning at the maximum power point, independent of variations in the environment. Quadratic boost converters are preferred due to their higher voltage gain as compared to the classical boost converters, which makes them very helpful for PV applications. So, MPPT algorithms on FLC and ANFIS are developed and implemented for enhancing the performance of the PV system. Robust rule-based tracking of the sun, including non-linear conditions, FLC tracks using ANFIS neural network flexibility coupled with inference power in fuzzy logic in order to increase tracking precision and responsiveness. Simulations test how dynamic responses, efficiency, and precision with which the tracking occurs under varied conditions of solar irradiance are compared. The results show that ANFIS outperforms FLC in tracking precision and convergence rate when the changes in irradiance are rapid, but it is more intuitive and robust if the irradiance is relatively constant. This work provides key information on advancing the design and efficiency of MPPT algorithms suitable for complex photovoltaic systems..
Keywords- Fuzzy Logic Controller (FLC), Adaptive Neuro-Fuzzy Inference System (ANFIS), Maximum Power Point Tracking (MPPT), Photovoltaic (PV) System, Quadratic Boost Converter, Solar Irradiance.

INTRODUCTION
The growing need for renewable energy sources has spurred significant advancements in photovoltaic (PV) systems. Due to their ability to harness solar power, a clean and abundant resource, these systems are increasingly being preferred [9]. However, the PV system's performance efficiency is critically dependent on its ability to operate at the Maximum Power Point (MPP), which varies dynamically with changing solar irradiance and temperature [14]-[15]. To address this problem, Maximum Power Point Tracking algorithms are used to ensure maximum extraction of power from photovoltaic (PV) systems [4].
Quadratic boost converters, however, have emerged as one promising solution in PV applications as compared to the traditional boost converters that yield higher voltage gain capability. Such an enhanced voltage gain helps quadratic boost converters better manage the wide-ranging changes in voltage encountered in a PV system, especially under the changeable solar conditions [17]. Recent studies have shown the need for integration of advanced MPPT techniques with quadratic boost converters to achieve better efficiency and stability in PV systems [25].
This work studies comparative performance analysis for Fuzzy Logic Control and Adaptive Neuro-Fuzzy Inference System when applied as the Maximum Power Point Trackers to a quadratic boost converter-based PV system. Simulations were performed to test conditions with variable levels of irradiation on solar resources to demonstrate and assess tracking capability and the steadiness of controllers. Hence, bringing benefits of quadratic boosting converters by more improved MPPTs, it

seeks to identify the issues about efficient and viable PV generation for practical applicability purposes [21].

SYSTEM CONFIGURATION

It includes a photovoltaic (PV) array, a quadratic boost converter, and two MPPT controllers-Fuzzy Logic Controller (FLC) and Adaptive Neuro-Fuzzy Inference System (ANFIS-to effectively extract solar energy under variable conditions. The PV array converts sunlight into electricity, and its output varies with the variation in solar irradiance, temperature, and load. Accurate modeling of the PV array is important for making predictions about its performance and to identify the MPP that describes the condition at which it operates most efficiently for power generation.

In boosting the low voltage of the PV array, a quadratic boost converter is implemented. The boost converter here follows the two-stage voltage conversion, with extra inductors and capacitors being used in achieving much higher voltage gain as well as efficiency than what can be achieved in a standard boost converter. Its wide-range operation also qualifies it for use over a wide range of unpredictable power input in PV applications.

The MPPT controller cooperates with the quadratic boost converter in dynamic duty cycle adjustment for the converter to ensure that the PV system runs at MPP for optimal energy conversion efficiency and the delivery of optimal power to the load or storage system. It effectively deals with low PV output voltages, especially in low irradiance conditions, by using a high-gain DC-DC converter to enhance adaptability in real-world conditions.

Generally, the system architecture is structured to achieve a balance among simplicity, efficiency, and adaptability. It optimizes power extraction from the photovoltaic array besides ensuring consistent and stable performance across a wide range of environmental conditions..

PHOTOVOLTAIC SYSTEM

As part of this paper, a standalone PV system is taken into account. A PV panel, a quadratic boost converter, a MPPT controller, and a resistive DC load make up the components of the system, as shown in Figure 1. The system contains different parts, which will be developed in the following paragraphs.

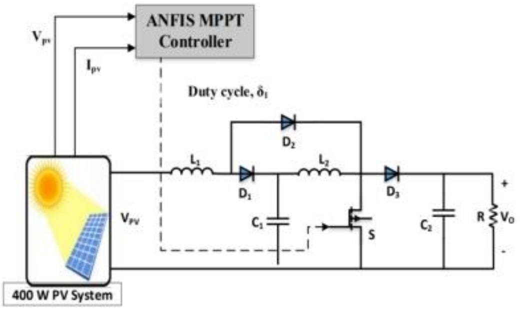

Figure. 1. Block diagram of the proposed system.

A PV system module consists of PV array which is arranged in series and parallel configuration to achieve the desired power. A single diode model of the PV system is shown in Figure 2. The PV module's parameter requirements determine the PV system's output.

The PV system's output is dependent on temperature and solar radiation. The following are the fundamental IPV-VPV properties of the PV panel that are used to generate the mathematical modeling of the PV system. The output voltage (*Vpv*) and output current (*Ipv*) of PV system are defined as,

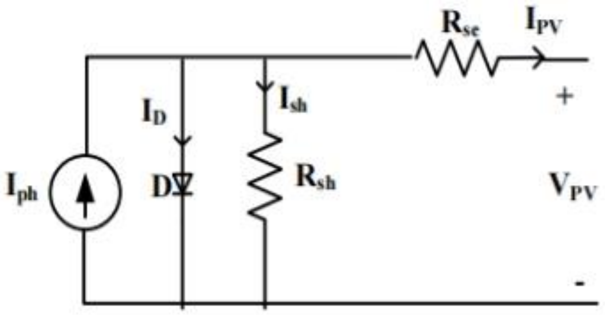

Figure. 2. Block diagram of the proposed system.

$$V_{pv} = \frac{\eta KT}{q} \ln\left(\frac{I_{ph}}{I_{pv}} + 1\right) \tag{1}$$

$$I_{pv} = I_{ph} - I_{pvrsc}\left(e^{\frac{q(V_{pv}+I_{pv}R_s)}{\eta KT}} - 1\right) - \frac{V_{pv} + I_{pv}R_{se}}{R_{sh}} \tag{2}$$

where, K is Boltzmann's constant (1.381 *10-23J/K) and q is elementary charge (1.603*10-19 C) Writing the shunt current as I_{pvrsc}= (V + IRS) / R_{sh}. R_{se} : series resistance (Ω) R_{sh} : shunt resistance (Ω). I_{ph} represents Phase current (A) and T represents Temperature (^{o}C). The modelling parameters of PV system are avalibale in literature for different irradiance and temperature [16]-[19].

CONVERTER ANALYSIS

A quadratic boost converter is a high-gain DC-DC converter designed to provide a significantly increased output voltage compared to traditional boost converters. Its architecture incorporates an additional energy storage stage, typically achieved by cascading two inductors, capacitors, and diodes in a specific configuration [13].

This design allows the converter to achieve a quadratic relationship between the input and output voltages, resulting in much higher voltage gain. The enhanced voltage conversion capability makes it particularly suitable for applications like photovoltaic (PV) systems, where the input voltage from the PV array is often low and requires substantial amplification to meet load or grid requirements.

The converter configuration of contemplated QBC for high voltage transfer gain in 400 W PV systems is shown in Figure. 3. It comprises of control switch S, three diodes of D_1, D_2 and D_3, two capacitors C_1 and C_2 and inductors of L_1 and L_2 with a load resistance of R.

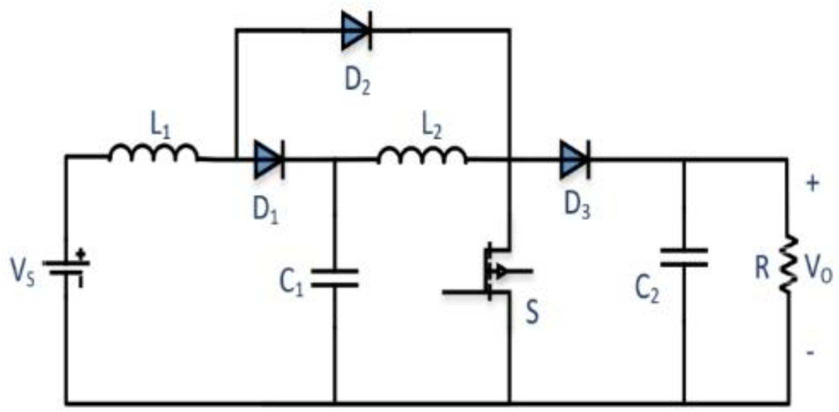

Figure. 3. Quadratic Boost Converter Topology

The voltage transfer gain of QBC is given in Eq. (1)

$$G = \frac{V_o}{V_s} = \frac{1}{(1-\delta)^2} \tag{3}$$

The modeling of parameters of QBC is as follows

$$V_o = \frac{V_i}{(1-D)^2} \tag{4}$$

Where, V_O and V_i are the output voltage and input voltage respectively. D refers to the duty cycle. The inductors are selected as follows,

$$L_1 = \frac{V_{i\min}}{2 * \Delta I_{L1} * f_s} * D \tag{5}$$

$$\Delta I_{L1} = \frac{I_o}{(1-D)^2} \tag{6}$$

$$L_2 = \frac{V_{i\min}}{2 * \Delta I_{L2} * f_s} * D \tag{7}$$

$$\Delta I_{L(n)} = \frac{I_o}{(1-D)} \tag{8}$$

The capacitors in QBC are selected as,

$$C_{dc} = \frac{I_o * D}{(1-D)\Delta V_{c1} * f_s} \tag{9}$$

$$V_{c1} = \frac{V_i}{(1-D)} \tag{10}$$

$$C_o = \frac{I_o * D}{\Delta V_{c2} * f_s} \tag{11}$$

$$V_{c2} = \frac{V_{c1}}{(1-D)} \tag{12}$$

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High voltage gain, the quadratic boost converter offers improved efficiency and reduced component stress compared to other high-gain configurations. By distributing the voltage step-up process over two stages, the converter minimizes switching losses and voltage spikes, enhancing reliability and performance. The designed parameter values of QBC for 400 W PV system are listed in Table. 1.

Table 1. QBC Design parameters

Parameter Specifications	**Values**
Power Rating	400 W
Input Voltage	18V
Output Voltage	335V
Switching frequency	20kHz
Inductor, L1	4.3mH
Inductor, L2	4.75mH
Capacitor, C1	17.23µF
Capacitor, C2	5.75 µF
Load resistor, R	358.4 Ω

MPPT Control Strategies:

Radiation and temperature changes have an impact on solar arrays' non-linear voltage characteristic. An MPPT controller is required to acquire the most power in order to solve this issue. Figure 1 illustrates how MPPT regulates the boost converter. The controller receives voltage and current samples as inputs. The use of algorithms as MPPT control logic for PV systems has been studied in the literature [4].The MPPT controller determines the duty cycle of the boost converter's power electronic switch using the voltage Vpv and current Ipv samples from the PV array as input. As a result, the output voltage of the power electronic circuit will be raised to the required level while the MPPT controller continually monitors the MPP of the PV array. The effectiveness and speed of various techniques for determining the MPP of solar modules differ. Here, the three most popular methods are examined.

Fuzzy logic (FL) technique:

In order to potentially minimize power losses, fuzzy logic control can do nonlinear computations for erroneous inputs and is highly appropriate for a variety of climatic variations without the requirement for temperature and light intensity sensors. Figure 4 illustrates the fuzzy logic control process, which consists of de-fuzzification and fuzzification of all relevant rules in the rule base.[27]

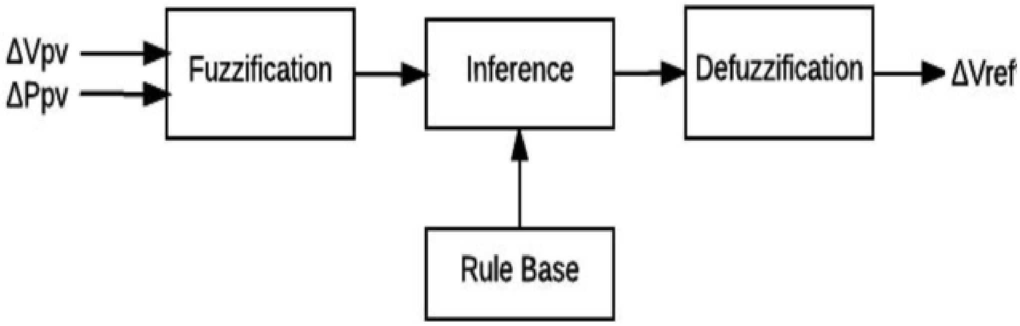

Figure-4 Architecture fuzzy logic Controller

The first part is fuzzification, which converts input variables with true values into a fuzzy set, the second part is called the fuzzy inference engine, which states fuzzy IF-THEN rules, and the third part is De-fuzzification which converts a fuzzy set to a real variable [10]-[19].

The behavior of the photovoltaic system must be fully understood in order to construct a fuzzy controller and choose fuzzy rules. The fuzzy control MPPT technique has two input variables, namely change in voltage (ΔV) and change in power (ΔP), and one output variable, duty cycle (D), during the fuzzification stage. [10] The crisp input and output variables are converted into linguistic variables based on the membership functions (MFs) [17].

$\Delta V = V(k) - V(k-\Delta k)$ (13)

$\Delta P = P(k) - P(k-\Delta k)$ (14)

ANFIS MPPT Controller: The Adaptive Neuro-Fuzzy Inference System (ANFIS), illustrated in Figure 5, is a hybrid framework consisting of five layers, each designed to perform a specific function within the fuzzy inference process. This layered structure enables ANFIS to seamlessly integrate neural network learning capabilities with fuzzy logic reasoning, making it a robust and efficient system for complex decision-making tasks. Each layer contributes uniquely to the overall inference mechanism, facilitating precise and adaptive control [13].

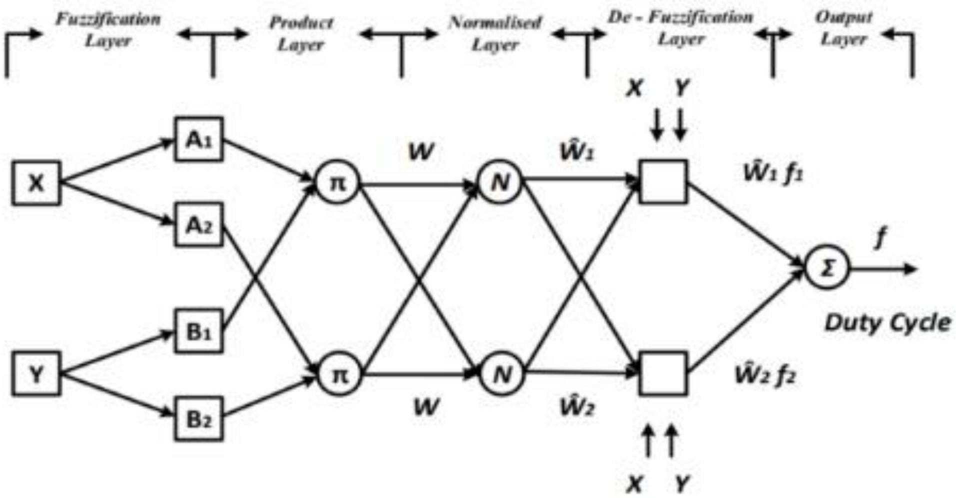

Figure. 5. Structure of ANFIS controller

The roles of the five layers in the fuzzy inference system are described as follows

Layer 1: The nodes in the first layer is defined as a square node which is represented as,

$$N_{1,i} = \mu_{X_{i(a)}}\ for\ i = 1,2$$
$$N_{1,i} = \mu_{Y_{i(b)}}\ for\ i = 3,4 \quad (15)$$
$$N_{1,i} = \mu_{Z_{i(c)}}\ for\ i = 5,6$$

Layer 2: This layer consists of circular nodes, which multiply all incoming inputs and generate a product as the output,

$$N_{2,i} = \phi_i = \mu_{X_{i(a)}}\mu_{Y_{i(b)}}\mu_{Z_{i(c)}} \quad (16)$$

Layer 3: In this layer, the circular nodes calculate the normalized firing strengths. These firing strengths are determined using successive relationships between the inputs.

$$N_{3,i} = \bar{\phi_i} = \frac{\phi_1}{\phi_1+\phi_2} \quad (17)$$

Layer 4: This layer consists of square nodes, which are defined and operate based on the function outlined below,

$$N_{4,i} = \bar{\phi_i} f \quad (18)$$

Layer 5: The final layer in the structure consists of a circular node that sums up all the inputs from the previous layer to produce the overall output,

$$N_{5,i} = \sum_i \phi_i f_i(ANFIS) \quad (19)$$

In order to meet the load requirement in all weather circumstances and maintain a constant dc voltage, the rule system generates an ideal duty cycle. The rules and input parameters determine the duty ratio of the bi-directional DC/DC converter. There will be two inputs in the controller system and one output for ANFIS.

Simulation Results and Discussions

A 400 W photovoltaic (PV) system is modeled in MATLAB/Simulink using the parameters of the Kyocera KD135GX-LP module, as detailed in Table 2. The proposed system, which includes a Quadratic Boost Converter (QBC) integrated with an MPPT controller and a PWM generator, is designed and simulated in the MATLAB/Simulink environment, as illustrated in Figure 6.

Table 2. PV System rating and specifications

PV Parameters	Specifications at STC
Module type	Kyocera KD135GX-LP
Series connected modules per string	2
Parallel strings	9
Open circuit voltage, V_{oc}	22.099 V
Short circuit current, I_{sc}	8.369 A
Voltage at maximum power point, V_{mp}	17.7 V
Current at maximum power point, I_{mp}	7.629 A
Series resistance, R_s	0.105 ohm
Parallel resistance, R_p	142.84 ohm
Saturation current, I_{sat}	$9.845e^{-7}$ A
Phase current, I_{ph}	8.37 A

Figure 7 illustrates the P-V and I-V characteristics of the 135 W Kyocera KD135GX-LP PV module. Figure 10 presents the P-V and I-V characteristics of the 400 W PV system, which is constructed using the Kyocera KD135GX-LP modules. This system is configured by connecting one module per string in series and three such strings in parallel.

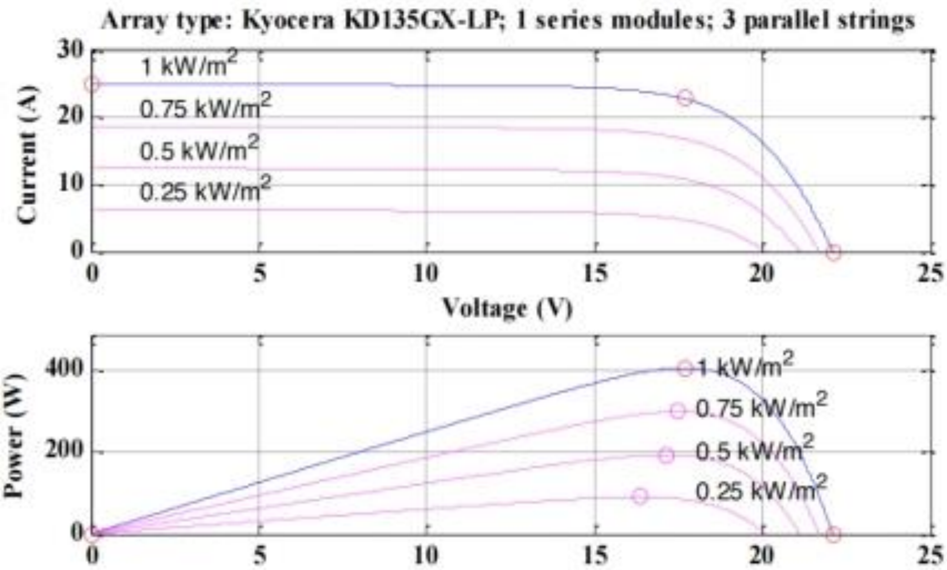

Figure.7. 400 W PV system P-V & I-V characteristics of Kyocera KD135GX-LP.

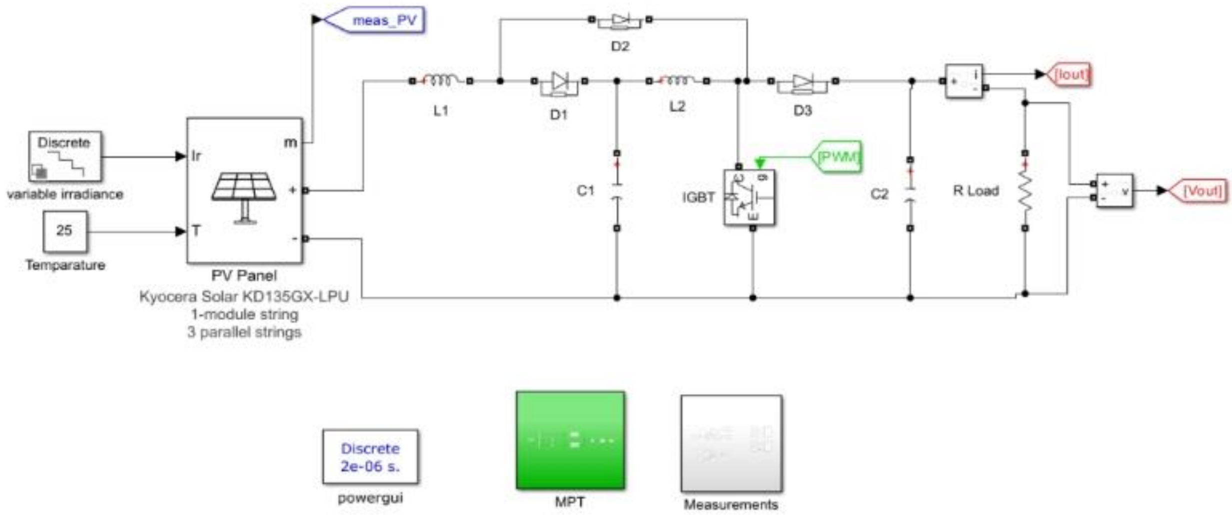

Figure 6. Proposed Design and simulation of PV connected Quadratic boost converter

The simulation of the PV system integrated with a quadratic boost converter and various MPPT controller methods was conducted using the MATLAB/Simulink environment shown in the figure-6. The corresponding results from these simulations are shown in figure-8,9 and discussed as follows.

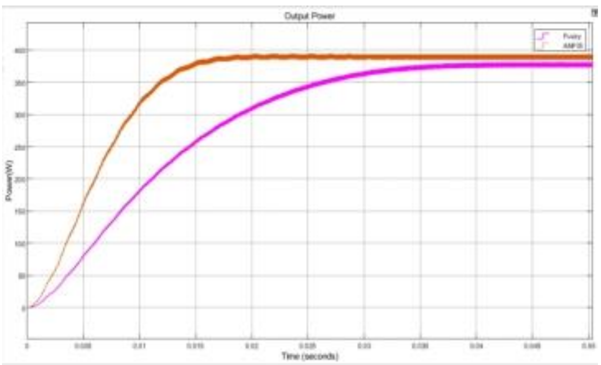

Figure 8. Response Time of Output Power

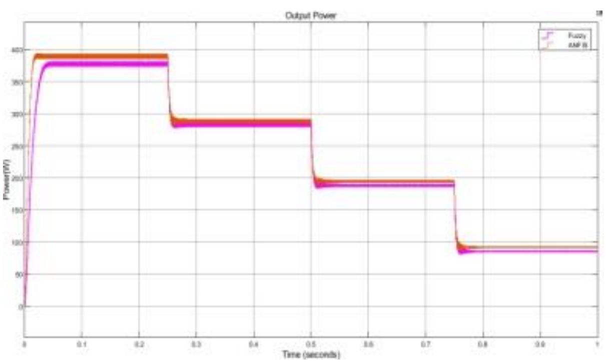

Figure 9. Output Power of PV system

Table 3: MPPT efficiency under various irradiance.

Irradiance (W/m^2)	Power from PV Arrays (Watts)	Fuzzy MPPT Output (Watts)	Fuzzy Efficiency (%)	ANFIS MPPT Output (Watts)	ANFIS Efficiency (%)
1000	405	381.6	94.22%	393.7	97.21%
750	307	285.4	92.96%	291.2	94.85%
500	206	190.7	92.57%	196.1	95.19%
250	102	86.3	84.6%	92.5	90.6%

The comparison of the performance of ANFIS-based MPPT and fuzzy logic-based MPPT controllers demonstrates that the ANFIS controller's higher power production and efficiency at different levels of solar irradiation. With comparable converter outputs of **393.7 W** and **381.6 W**, respectively, the ANFIS controller achieves an efficiency of **97.21%** at full irradiance (1000 W/m2), while the Fuzzy controller achieves an efficiency of **94.22%**. The efficiency difference between the two controllers widens as irradiance drops, with ANFIS continuing to have a greater efficiency as shown in table -3, especially at **250 W/m2**, where it registers **90.6%** efficiency compared to the fuzzy controller's **84.6%**. In comparison to their settling time underscores the superiority of ANFIS over Fuzzy Logic Control. With a settling time of **0.025 seconds**, ANFIS demonstrates faster convergence to the maximum power point compared to the **0.045 seconds** of the Fuzzy Logic Controller is shown in figure 8. ANFIS is a more efficient MPPT solution for PV systems because of its steady performance, which shows how flexible and accurate it is at obtaining the most power possible even in difficult situations. Throughout the simulation, the ANFIS-controlled MPPT demonstrated superior control over efficiency compared to FUZZY controllers as shown in figure.9.

CONCLUSION

In this paper, a PV array model is constructed along with various MPPT approaches. First, the PV module has been mathematically analyzed. Two MPPT algorithms have also been examined. In particular, the ANFIS controller and fuzzy logic control have been studied.
The results demonstrate that, in spite of non-linear characteristics and quick irradiance variations, both FLC and ANFIS MPPT algorithms successfully track the maximum power point (MPP) of PV systems. But when it comes to tracking speed and adaptability, ANFIS performs better than FLC. ANFIS's lower settling time guarantees that the photovoltaic system runs faster and closer to its full efficiency while minimizing energy losses during transient situations. ANFIS can learn and adjust to a variety of environmental variables by utilizing the combined advantages of fuzzy logic and neural networks.This adaptability results in superior performance under dynamic conditions such as sudden irradiance changes and extracting maximum power available in the PV system.

Future research may focus on connecting the PV system under study to the electric grid. A DC-DC converter, a DC-AC inverter, and a control unit are necessary to supply an AC voltage that satisfies the grid's connection and synchronization requirements,[23]as seen in Figure. 10.

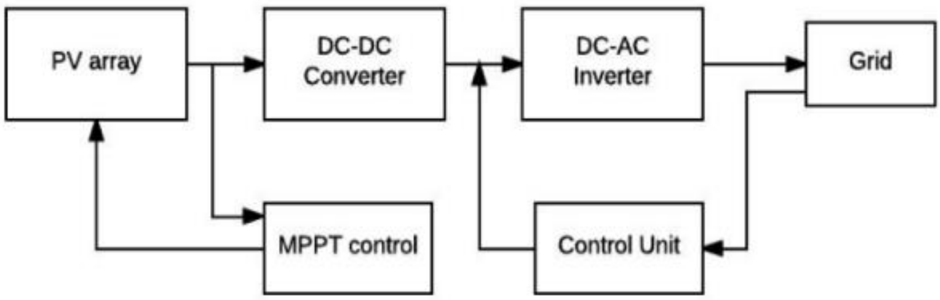

Figure. 10. Block diagram of a basic grid-connected PV system

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DECLARATION

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