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Design and Implementation of MPPT Techniques on PV Systems using Fuzzy Logic controller, ANN, and Genetic Algorithm

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Abstract*: This paper presents the design and implementation of Maximum Power Point Tracking (MPPT) techniques for Solar Photovoltaic (PV) systems using Fuzzy Logic, Neural Networks, and Genetic Algorithm (GA). Efficient energy harvesting from solar PV systems is essential to optimize performance under varying environmental conditions, such as changes in solar irradiance and temperature. The proposed approach combines intelligent control methods—Fuzzy Logic and Neural Networks to adaptively adjust the operating points of the PV system to track the maximum power point (MPP). Moreover, a Genetic Algorithm enhances the optimization process by adjusting the duty cycle of the DC-DC converter for efficient energy extraction. The Fuzzy Logic controller fine-tunes the duty cycle based on predefined membership functions and rules, while the Neural Networks approach uses training data for real-time adaptation. The Genetic Algorithm optimizes the duty cycle to maximize power output. Simulation results demonstrate the hybrid system's superior performance, especially in handling rapid environmental changes, compared to conventional MPPT methods.*

Keywords: Solar PV, Boost converter, fuzzy logic controller, ANN controller, Genetic algorithm

I. INTRODUCTION

The rapid escalation in global energy demand has underscored the necessity for transitioning toward renewable energy sources, with solar photovoltaic (PV) systems emerging as a pivotal solution for clean and sustainable energy production. However, the efficiency of PV systems is significantly influenced by dynamic environmental factors such as irradiance and temperature variations, necessitating advanced optimization techniques to ensure maximum power output. In this context, MPPT algorithms play a crucial role in enhancing energy harvesting efficiency by continuously adapting the operational parameters of PV systems to their optimal conditions. Traditional MPPT techniques, including those based on Fuzzy Logic Controller (FLC) and Artificial Neural Network (ANN), have garnered considerable attention for their adaptability and capability to optimize energy extraction under varying environmental conditions [1-3]. Flcsoffer a rule-based approach that leverages expert knowledge, while ANN-based controllers employ data-driven models to predict and regulate the system's performance. Despite their effectiveness, these methods are often constrained by challenges such as increased complexity in rule management (for FLC) and time-intensive training processes (for ANN), as highlighted in prior studies [4].

To address these limitations, the integration of evolutionary computation techniques like the Genetic Algorithm (GA) presents a promising alternative. GA, inspired by the principles of natural selection and genetics, offers a robust framework for solving complex optimization problems. Its ability to explore a wide search space and converge toward optimal solutions makes it highly suitable for MPPT applications in PV systems [5-7], where dynamic and nonlinear characteristics demand precise and adaptive control mechanisms. This paper critically evaluates the performance of MPPT techniques implemented using FLC, ANN, and GA. Through a comparative analysis, it aims to demonstrate the superior efficiency and adaptability of GA-based controllers over conventional methods, particularly under diverse

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environmental scenarios. By showcasing the advantages of GA in overcoming the limitations of FLC and ANN, this study contributes to advancing the state of the art in renewable energy technologies and paves the way for more efficient and reliable solar energy systems [8-10].

The organization of the following paper contains: Section II provides a comprehensive system description. Section III introduces the proposed method, focusing on the implementation of the GA controller for enhanced voltage regulation. In Section IV, the simulation results and discussions are presented, demonstrating a performance of proposed method under several operational conditions. Finally, Section V concludes the paper with key findings and suggests avenues for future research.

II. SYSTEM CONFIGURATION

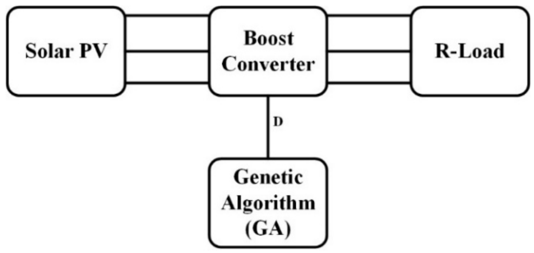

Fig.1 Block diagram

The system under consideration integrates a photovoltaic (PV) generator as the primary energy source, connected to a load through an intermediary DC-DC converter. The core functionality of the system is orchestrated by a MPPT controller, which ensures the PV generator operates at its optimal power output under varying environmental conditions [11-13]. The PV generator, responsible for converting sunlight into electrical energy, inherently experiences fluctuations in its output due to changes in solar irradiance and temperature which is shown in fig.1. To mitigate these variations and maximize energy extraction, the DC-DC converter dynamically adjusts the system’s operating point. This converter plays a pivotal role by regulating the voltage and current supplied to the load, thereby aligning with the MPP of the PV array [14-16].

The MPPT controller, which incorporates advanced algorithms to continuously monitor and adjust the operational parameters of the PV generator. Specifically, the controller utilizes both Fuzzy Logic (FL) and ANN algorithms to intelligently adapt to changing conditions. The FL component relies on a set of predefined rules and membership functions to make real-time adjustments, while the ANN module leverages its trained architecture to predict the optimal duty cycle for the converter based on input variables such as voltage and current [17]. The integration of these intelligent algorithms enhances the system's adaptability and ensures superior performance. By leveraging the strengths of FL and ANN, the controller is able to achieve precise and consistent tracking of the MPP, leading to increased energy efficiency [18]. The combination of these techniques not only maximizes power output but also ensures robust performance under rapidly changing environmental conditions, such as fluctuating irradiance or partial shading [19-20].

1) Implementation of Controller Strategies

Effective implementation of MPPT strategies is crucial to optimize the energy output of solar PV systems under varying environmental conditions. This work evaluates and compares three MPPT techniques: FLC, ANN, and Genetic Algorithm (GA), emphasizing their implementation methodologies and performance.

A) Fuzzy Logic Controller

The FLC uses a rule-based approach to optimize the duty cycle of the DC-DC converter, enabling maximum energy extraction from the photovoltaic system. It consists of three main components. The Fuzzy Inference System (FIS) processes input variables, such as the error (rate of change of power with respect to voltage) and the change in error, using fuzzy logic principles to derive meaningful decisions. The Rule Base defines a set of linguistic rules that map the input variables to desired output adjustments, with terms like Negative Big (NB), Zero (ZE), and Positive Small (PS) used to describe control logic. Finally, the Defuzzification process converts the fuzzy output into a precise value, ensuring accurate adjustments to the duty cycle of the DC-DC converter for optimal performance.

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The FLC implementation involves defining membership functions for the input variables and constructing a rule base. However, challenges include increased complexity with additional rules and reduced computational efficiency in large-scale applications.

B) Artificial Neural Network (ANN)

ANN-based MPPT adopts a data-driven methodology to determine the optimal duty cycle for the DC-DC converter. The neural network architecture includes an input layer, which receives parameters such as PV voltage and current; multiple hidden layers, responsible for complex feature extraction and pattern recognition; and an output layer, which computes the precise duty cycle required to achieve maximum power point tracking.

The implementation process involves Data Collection Gathering training data under various irradiance and temperature conditions. Network Design Configuring the architecture, including the number of layers, neurons per layer, and activation functions. Training Employing supervised learning algorithms, such as the Levenberg-Marquardt algorithm, to minimize error and optimize network weights.

Although ANN demonstrates superior adaptability and response speed, its dependence on extensive training data and computational resources can pose practical challenges.

C) Genetic Algorithm (GA)

The Genetic Algorithm (GA) employs an evolutionary approach to MPPT by mimicking the process of natural selection. Its implementation begins with the initialization phase, where an initial population of solutions is generated, with each individual representing a potential duty cycle value. This is followed by the fitness evaluation step, where the fitness of each individual is assessed based on the PV system's power output. Finally, genetic operators such as selection, crossover, and mutation are applied to iteratively evolve the population toward the optimal solution, ensuring efficient and adaptive maximum power point tracking.

Unlike FLC and ANN, GA does not rely on predefined rules or training. Instead, it iteratively explores the search space, ensuring global optimization. This reduces the risk of getting trapped in local optima and makes GA more robust in handling highly nonlinear and dynamic PV characteristics.

2) Comparative Insights

While FLC and ANN offer effective MPPT solutions, their reliance on either rules or training data limits their scalability and adaptability. In contrast, GA provides a more flexible and efficient approach, adapting dynamically to diverse environmental conditions without the need for extensive reconfiguration. This positions GA as a superior alternative for MPPT implementation in modern PV systems.

III. PROPOSED METHOD

The proposed method integrates a GA-based MPPT system with a boost converter for optimizing energy harvesting in solar PV systems. This method enhances the traditional architecture by replacing conventional controllers (e.g., FL and ANN) with a GA-driven control mechanism. This integration ensures precise and dynamic tracking of the MPP under varying environmental conditions while leveraging the advantages of the boost converter for voltage regulation and efficient energy transfer.

The GA is embedded into the MPPT controller, where it continuously monitors the PV panel’s output voltage and current to maximize power extraction. The GA operates by encoding potential solutions (duty cycle values of the boost converter) as chromosomes in a population. Using genetic operators such as selection, crossover, and mutation, the algorithm evolves the population over successive generations to identify the duty cycle that yields the highest power output. This optimized duty cycle is fed to the boost converter, which adjusts its switching operation accordingly, ensuring the PV array operates consistently at its MPP. In this architecture, the boost converter plays a crucial role by stepping up the PV panel’s variable voltage to meet the load’s requirements. The GA dynamically determines the optimal duty cycle, allowing the boost converter to adapt to real-time changes in solar irradiance and temperature. This integration significantly improves system efficiency and response time compared to fixed or heuristic controllers.

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Moreover, it eliminates the need for extensive rule bases (as in FL) or training datasets (as in ANN), making the system more scalable and computationally efficient.

IV. SIMULATION RESULTS AND DISCUSSION

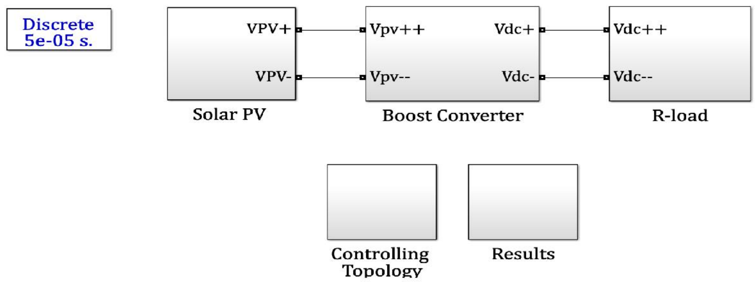


Fig.1 Simulation model

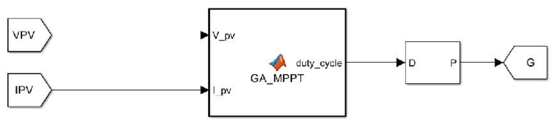
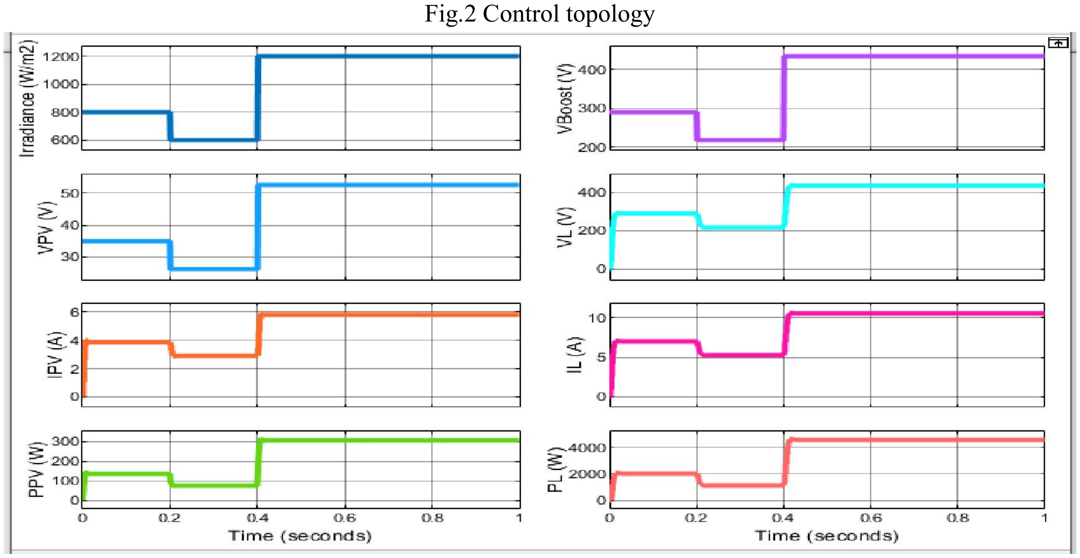


Fig.2 Control topology



Irradiance, Solar PV Voltage, Current and Power, Boost Converter Voltage, Load Voltage, Current and Power
Fig:3 Simulation results obtained using GA based MPPT at varied Irradiance

This figure illustrates the performance of the GA-based MPPT under varied solar irradiance conditions, highlighting its effectiveness in dynamically tracking the maximum power point. The Solar PV Voltage plot demonstrates GA's adaptability as it adjusts the voltage to reach the optimal operating point for power output. Changes in irradiance directly impact the PV voltage, but GA's ability to adapt ensures it remains near the maximum power point, minimizing losses. The Solar PV Current plot reflects the current fluctuations due to irradiance, showing how GA's adjustments in voltage yield corresponding current variations that aim to maximize power. The Solar PV Power graph is particularly revealing of GA's effectiveness, displaying a near-optimal power output even as irradiance changes, and validating its efficiency in maintaining high power extraction. Boost Voltage is controlled to ensure consistent output to the load by adjusting it according to the varying PV power, providing stable voltage. Finally, Load Voltage, Current, and Power demonstrate the end-result stability. The GA-based MPPT successfully tracks and maintains power under dynamic

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irradiance, yielding stable load parameters—critical for real-world applications where reliable power delivery is essential, despite environmental changes.

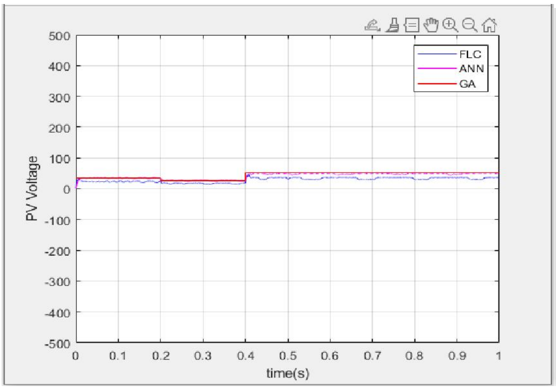

Fig.4 Solar PV Voltage

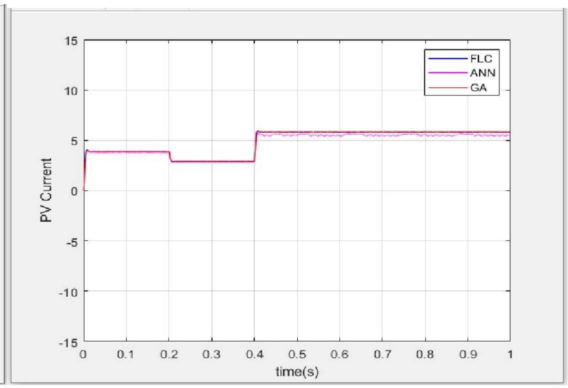

Fig.5 Solar PV Current

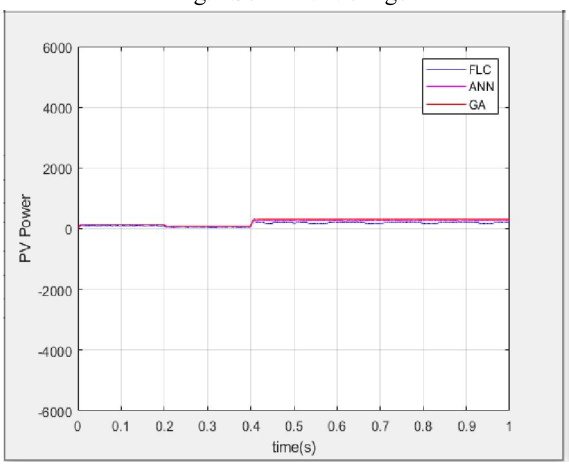

Fig.6 Solar PV Power

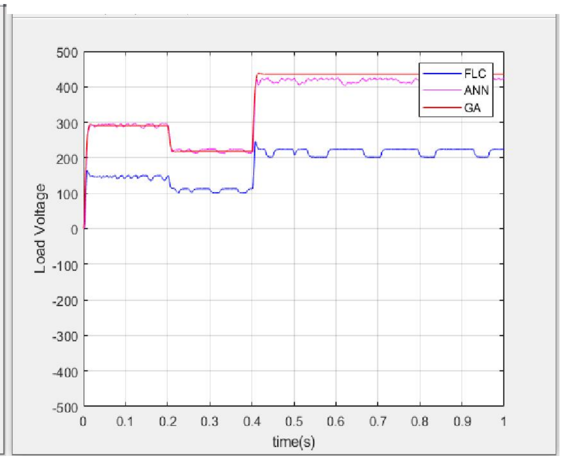

Fig.8 Load Voltage

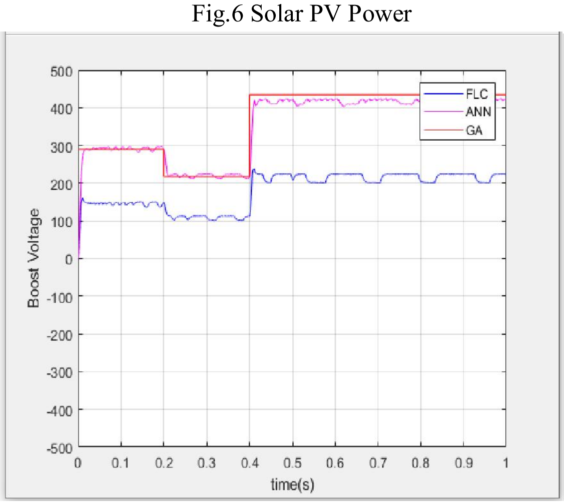

Fig.7 Boost Voltage

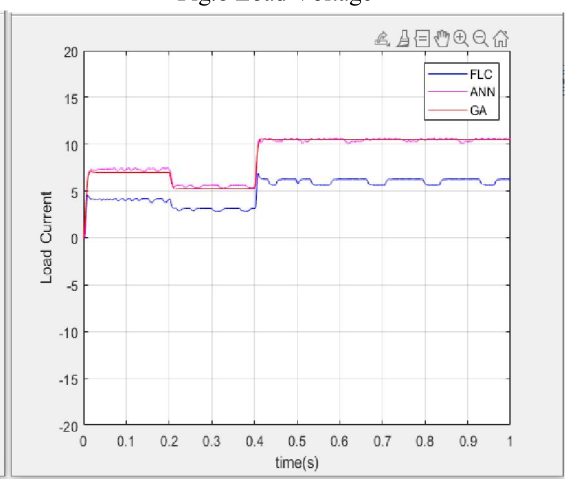

Fig.9 Load Current

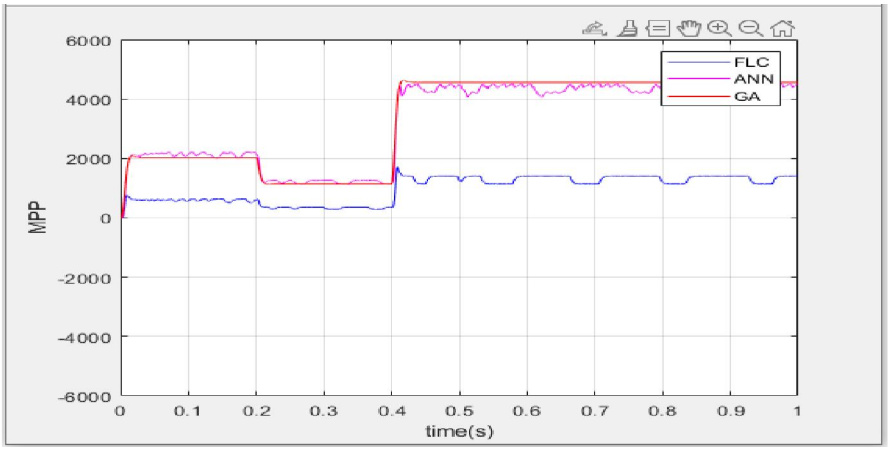

Fig.10 Comparison of ANN and FUZZY

This comparative figure contrasts the performance of GA, ANN, and FLC MPPT techniques in optimizing power extraction from solar PV under similar conditions. GA-based MPPT demonstrates a rapid and precise convergence to the maximum power point, displaying an advantage in speed and adaptability over the other methods, especially under changing irradiance. This is evident in the PV voltage, current, and power plots, where GA maintains a steady output closer to the theoretical maximum compared to ANN and FLC. ANN MPPT exhibits a reasonably effective tracking performance but may require extensive training and can have a slightly slower response time when sudden irradiance changes occur. ANN’s tracking capability is beneficial but can be less precise without significant training data, as minor variations from optimal are possible. FLC MPPT is also effective but shows some limitations under dynamic conditions, as its rule-based approach may not fully capture complex irradiance variations, potentially resulting in less stable power outputs in the plots. Overall, GA shows superior adaptability and precision, providing robust performance in maintaining maximum power, making it a valuable choice for fluctuating conditions in real-world solar applications.

IV. CONCLUSION

This study successfully demonstrates the design and implementation of advanced MPPT techniques for Genetic Algorithm (GA). By integrating intelligent control strategies, the approach achieves efficient energy extraction under varying environmental conditions, such as changes in solar irradiance and temperature. The Genetic Algorithm complements these techniques by optimizing the duty cycle to maximize power output. Simulation results validate the hybrid system's superior tracking accuracy and faster response compared to traditional MPPT methods. The proposed framework not only enhances the overall energy harvesting efficiency of solar PV systems but also offers a robust solution for handling rapid environmental changes. This work establishes a foundation for future advancements in intelligent MPPT systems, emphasizing their potential for improving renewable energy utilization.

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