POWER ANALYSIS WITH MPPT ALGORITHM FOR AN ISOLATED PV SYSTEM

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Abstract:
Environmental challenges caused by heavy reliance on fossil fuels and the depletion of these resources have intensified the search for alternative energy solutions like solar power, as it is available in abundance, Photovoltaic (PV) systems are becoming more widely adopted because they offer clean renewable energy with little environmental impact. This is where Maximum Power Point Tracking (MPPT) systems are required to optimize the performance of PV panels, ensuring that they are operating at their peak power even when conditions like sunlight and temperature fluctuate. By integrating DC-DC converters in between the load and PV array energy efficiency of PV systems are enhanced. The following paper aims to explore the design and application of three different MPPT models: Gravitational Search Algorithm (GSA), Particle Swarm Optimization (PSO), and Fuzzy Logic Controller (FLC) for optimizing a standalone solar PV system operating under typical conditions of 1KW/m² irradiance and 25°C ambient temperature. These models are simulated in a MATLAB environment to continuously find the MPP of the PV array. While performance of GSA and PSO showed similar efficiency, FLC outperformed them by providing faster and more accurate MPP tracking with minimal overshoot and less fluctuation.
Keywords- *Photovoltaic Array, Maximum Power Point Tracking, DC-DC Converter, Gravitational Search Algorithm, Particle Swarm Optimization, Fuzzy Logic Controller*

Introduction:

Due to the growing energy demand and the reserves of fossil fuel being depleted, the search for alternative energy sources has become crucial. As part of this effort, extensive research has focused on renewable energy options. Among these, photovoltaic (PV) energy has attracted considerable attention because of its clean, low-maintenance, and its noise-free nature. Even though, PV systems still face two key challenges: high initial costs and relatively low efficiency [18]. To design and simulate a photovoltaic (PV) module in MATLAB/Simulink the PV cell has to be defined in a circuit-based structure. This approach has enabled a more accurate representation of the PV system's behaviour when integrated with power converters [7, 16].

Sunlight and temperature are two environmental factors that heavily impact a PV module's output energy this leads to PV modules having a specific point in which peak power gets generated, that point is called Maximum Power Point (MPP). To attain a desired voltage and current level a PV module is made up of PV cells that are connected through series configuration or parallel configuration. Under standard test conditions (STC) defined as 1kW/m² and 25°C as irradiance and ambient temperature respectively these systems can be accurately assessed for their energy production capabilities [21]. By using MPPT algorithms, not only the PV array's efficiency is maximized, but its overall cost is also minimized, making the system more effective and economical [1]. Various MPPT techniques are developed for PV systems to optimize energy output, with many techniques well-documented in the literature. These methods differ in several key factors, such as simplicity, speed of convergence, type of implementation (digital or analog), sensor requirements, cost, and overall effectiveness [6]. Commonly used techniques include Perturb and Observe (P&O) [3, 4, 15, 23], Incremental Conductance (IC) [3, 4, 9, 15, 23], Artificial Neural Networks (ANN) [24], and Fuzzy Logic Controller (FLC) [22]. Each of these approaches varies in terms of ease of use, response speed, hardware needs, and their ability to adapt to different conditions, making some more suitable than others based on the specific application.

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The field of optimization algorithms has advanced significantly, providing a range of efficient techniques to solve complex problems. One notable algorithm that has gained attention is the Gravitational Search Algorithm (GSA), known for its effectiveness in navigating challenging optimization landscapes [5]. The GSA is practical in real-world applications; however, it has challenges such as limited local search capability, but it still outperformed Particle Swarm Optimization (PSO) and other intelligent algorithms, offering a more effective solution [11]. Unlike many other optimization algorithms, PSO only requires an objective function and does not rely on gradients or differential forms of the objective. Additionally, it has very few hyper parameters making it easier to implement and adjust [17].

Further, a new MPP Tracker which used a fuzzy set theory was proposed to enhance efficiency of energy conversion. The FLC's algorithm relies on linguistic based rules that represent the control strategies of an operator and is used to manage a boost converter. Key linguistic variables in the FLC are carefully chosen to regulate the DC-DC converter. This approach offers several advantages, including quick response times and better performance in minimizing fluctuations [8]. Fuzzy logic systems were able to reach the MPP more quickly under varying loads or changing weather conditions because of its adaptable and lenient calculation nature of FLC. This allows for improved efficiency of the system when compared to other methods. This system uses two key inputs: change in power and voltage. The output from the FLC adjusts the duty cycle, ensuring optimal performance of the system [2] The FLC, used to adjust converter's duty cycle, operates with two input parameters: error (E) and change in error (ΔE). Based on the PV panel inputs, the FLC calculates an optimal duty cycle for any converter, adapting for various operating conditions. In this setup, a design of a PV system consisting of a solar panel, a resistive load, a fuzzy MPPT, and a boost converter is simulated. Fuzzy logic controllers are favoured for their simple and easy implementation, as these don't require detailed knowledge of the system's mathematical model [12, 19]. However, many MPPT techniques inherently use PWM to control the duty cycle of DC-DC converters, which is often discussed in conjunction with DC-DC converters in MPPT implementations [10]. After studying the most common MPPT methods that are used [20], this paper compared and analysed the maximum power optimization of the GSA, PSO, and FLC models.

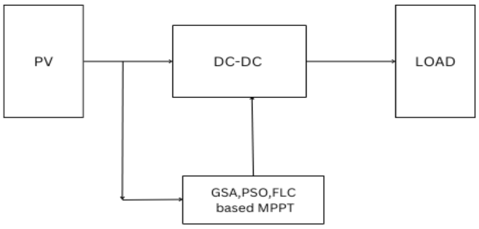

Fig 1. Block diagram with GSA, PSO, and FLC based MPPT of PV System

PV ARRAY MODEL:

PV arrays are integral components in solar energy systems, composed of interconnected solar cells that convert sunlight into electrical energy. The performance of any PV array is highly dependent on environmental factors like temperature and solar irradiance, leading to fluctuations in power output. Accurate modeling and simulation of PV arrays are crucial for optimizing their efficiency and understanding their dynamic behavior under varying conditions.

Solar-Cell and PV Array Module Design

PV panels are composed of multiple solar cells that work in unison to convert sunlight into electrical energy. Each solar cell generates a small amount of electricity through the PV effect, where sunlight excites electrons in the cell's semiconductor material. When these cells are assembled into a module, they can produce a substantial amount of power, making PV panels a viable solution for renewable energy.

Solar cell consists of a p-n junction created by applying semiconductor-based PV technologies, designed for capturing solar radiation and transforming it into electrical energy. However, one single solar cell generates only a limited output voltage. So, to achieve the desired voltage or current levels, multiple solar cells are interconnected in series configuration and parallel configurations to form PV modules.

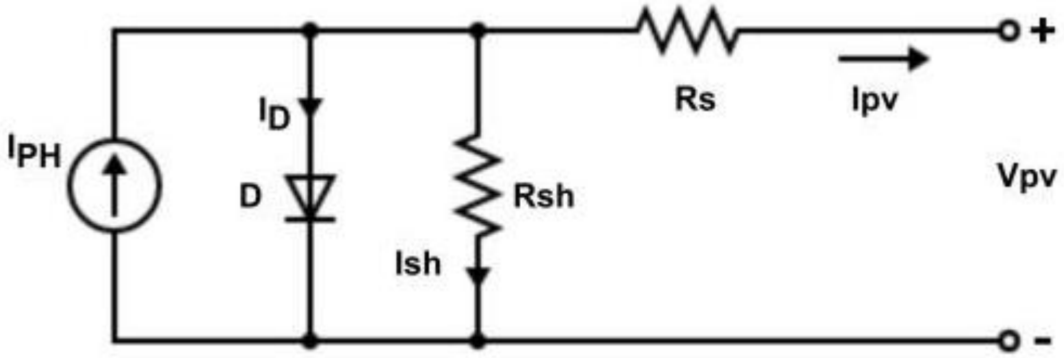

Fig 2. Equivalent circuit model of a solar cell

The equivalent circuit of a solar cell shown in Fig. 2 includes elements like a current source for the photon-generated current (I_{ph}), a diode for the diode current (I_D), and a shunt resistor for the shunt current (I_{sh}).

By applying Kirchhoff's Current Law (KCL), the output current (I_{pv}) of PV cells is:

$$I_{pv} = I_{ph} - I_d - I_{sh}$$

Parameter	Value
Cells / module N_{cell}	20
Open circuit voltage (V_{oc})	21.7 V
Short-circuit current (I_{sc})	4.8 A
The voltage at max power point (V_{mp})	15 V
Current at max power point I_{mp}	3.7 A
Temp coefficient of V_{oc}	-0.33641
Temp coefficient of Isc	0.102
Max power	55.5

Table 1. Parameters of the PV Array

This detailed modeling enables the accurate simulation of the PV module under different solar irradiation conditions, which is crucial for analyses of performance of MPPT methods. The table 1 shows the parameters of the PV array. Fundamental components like diodes, capacitors, inductors, and resistors along with the Power MOSFET which functions as the DC-DC Converter receiving input as duty cycle from the MPPT controller, are attached to the PV array element to form the PV system. The parameters of the fundamental components are as follows:

Parameter	Value
Parallel Capacitance to PV Array	0.00047 F
Load capacitance	0.000047 F
Series Inductance	0.0012 H
Load Resistance	58 Ohms

Table 2. Parameters of Components of the PV Array

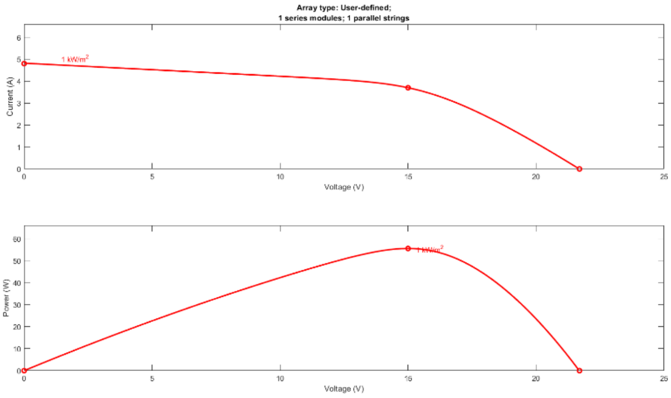

Fig 3. The V-I and P-V Characteristics of the PV module are obtained for a temperature constant of 25^{o}C and 1000W/m^2 of Irradiance

MPPT CONTROLLER:

An MPPT controller is a main component in solar power systems which help to maximize energy production. It's essentially a smart DC-DC converter which is placed between the PV array and the load, working to make sure the panels always operate at their peak efficiency. By adjusting the system's electrical settings based on current temperature and sunlight, the MPPT controller allows the solar panels to deliver the most power possible at any given time.

The MPPT controller continuously monitors the system and tracks the optimal power point, ensuring the solar panels generate as much energy as possible, even with changing weather conditions like sunlight and temperature. Using sensors and control systems, it makes precise adjustments to keep the system operating at its highest efficiency.

MPPT is a smart technology used in solar systems to maximize the output energy from solar panels. Think of it as an intelligent controller that constantly adjusts the settings of the panels to ensure they're always generating the most power possible, even when conditions like shading or cloud cover change.

MPPT acts like a flexible system that continuously monitors and fine-tunes the panels to keep them operating at their best. This is especially important in solar charge controllers, grid-tied inverters, and other solar applications where efficiency matters. By optimizing the panels, MPPT helps the system to capture the effective amount of energy from the solar sun.

1. GSA ALGORITHM

GSA works by simulating the gravitational pull between objects, where larger masses exert stronger attraction forces. In this case, each potential solution is treated as a "mass," and the best solutions (those closer to the MPP) have a stronger influence on the others. By using this gravitational behavior, the algorithm helps the system quickly and efficiently track the MPP, extracting more energy from the solar panels. The improved version of GSA fine-tunes this process even further, making it more effective in adapting to changing sunlight conditions.

By allowing the best solutions to guide the search, GSA makes it easier to adjust to changing conditions and improve energy capture. GSA improves the accuracy of tracking the MPP by simulating gravitational interactions between agents, making it highly suitable for real-time solar energy applications.

GSA Implementation

The MATLAB environment was used to implement the GSA to optimize the duty cycle in a MPPT system. Inspired by the principles of physics, GSA works by simulating gravitational attraction and mass interactions to explore different possibilities and guide the system towards the best solution, which here it is finding the MPP of a solar PV system. The MATLAB function closely follows the steps of the GSA algorithm to ensure effective optimization and here's how it works:

- Mass Representation: Each possible solution is treated as a "mass" in the search space.

- Gravitational Force: The attraction between two masses depends on their size (or quality of the solution) and the distance between them. Larger masses have stronger attraction, while those farther apart experience weaker forces.
- Acceleration: This gravitational force determines how quickly each mass moves within the search space, influencing its direction and speed.
- Position Updates: Each mass adjusts its position based on its acceleration, and this process repeats iteratively, helping the algorithm zero in on better solutions over time.

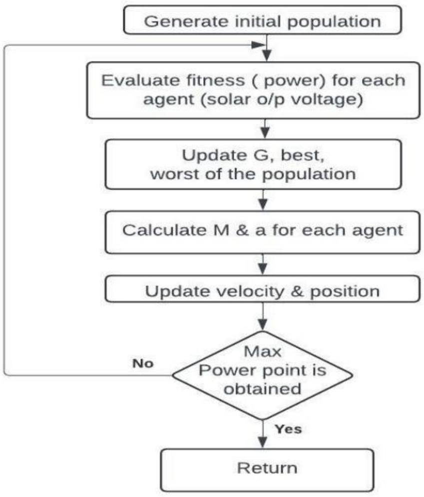

Fig 4. Flow of the GSA Algorithm

It begins by initializing the positions of agents (potential solutions) randomly within the search space. These agents iteratively move through the search space, evaluating their performance based on a fitness function, such as power output. The algorithm updates each agent's position and velocity by calculating gravitational forces between them, with stronger-performing agents exerting a greater pull. As the iterations progress, the gravitational constant decreases, helping the agents converge toward optimal solutions.

2. PSO ALGORITHM

PSO is an algorithm influenced by nature, designed in finding solutions to complex optimization and search problems. It mimics the behavior of birds flocking or fish schooling, where individuals (or particles) in a group work together to find the best solution. PSO has been applied to various problems, such as optimizing functions, fine-tuning parameters, and even training neural networks, showing its versatility and effectiveness.

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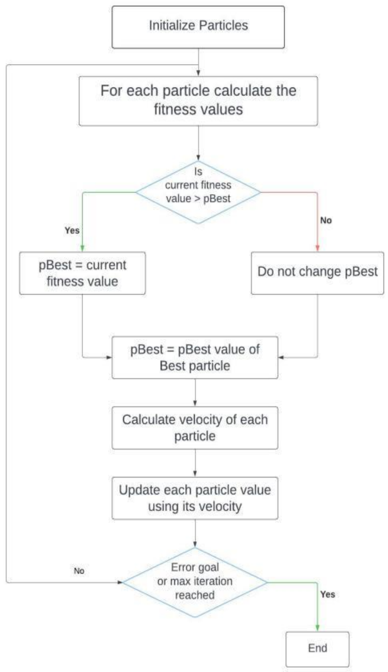

Fig 5. Flow of the PSO Algorithm

When the PSO function is called, it first checks if key variables are initialized (such as global best). If not, it sets up several persistent variables to store the state of the algorithm between iterations. These include:

- local best: the best position found by each particle.
- global best: The overall best position found by any particle in the swarm.
- k: A counter to track the number of iterations.
- p: Stores the best power output found by each particle.
- dc: holds the duty cycle values for each particle.
- P_{best}: The highest power output found by the algorithm so far.
- P_{prev}: The power output from the last iteration.
- $d_{current}$: The current duty cycle being used by the system.
- u: An index used to loop through each particle.
- v: stores the velocity of each particle.
- Temp: A flag used as a conditional variable in the algorithm.

In the PSO algorithm for MPPT, the process begins with the current duty cycle set, followed by a series of checks. If a precondition (tracked by a variable) isn't met, the function pauses before proceeding. As the loop iterates, it updates the best power output found so far (P_{best}) and continues as long as the iteration count remains under a set limit, typically 3000. If minimal change in power is detected, suggesting the possibility of being stuck in a local optimum, the algorithm re-randomizes the duty cycles to explore new areas. Each particle updates its personal best and overall best position (global best) based on its performance. The algorithm adjusts the particle's velocity using a mix of its inertia, the distance to its personal best, and the global best, with random elements for exploration. The particle's position is updated based on this new velocity, keeping the duty cycle within valid limits (0 to 1). The variable dcurrent starts with an initial value of 0.5, which is also used as the starting point for global best. This setup ensures that each particle begins its search with diverse starting points, helping the algorithm find the optimal solution efficiently. By the end of each cycle, the duty cycle corresponding to the best solution is used to adjust the system's performance, ensuring the MPPT system steadily approaches the optimal power point of the PV system. The algorithm

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refines this process over multiple iterations, similar to the gravitational interaction approach in the GSA, enhancing energy extraction efficiency.

3. FLC

Fuzzy logic-based MPPT is presented as an effective alternative to traditional methods like Perturb and Observe (P&O) for maximizing power output from PV systems. The FLC uses a rule-based approach, which makes it adaptable to both linear and non-linear variations in temperature and solar radiation.

Overall, the FLC-based MPPT is shown to provide faster tracking, with fewer overshoots and smoother performance than P&O, making it ideal for optimizing energy output in changing environmental conditions.

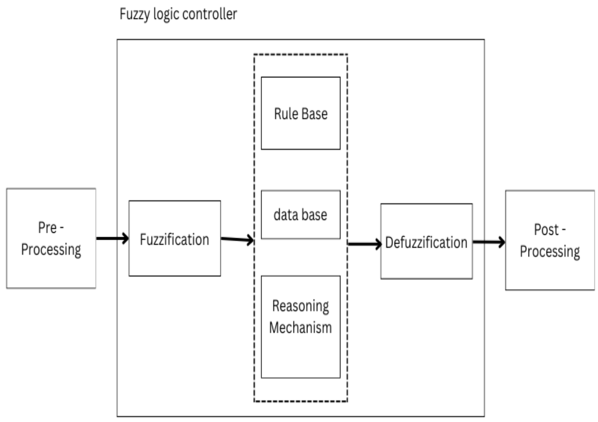

Fig 6. Block diagram of FLC system

The FLC continuously monitors the output power of the PV system at each time interval (denoted as time k) and calculates how power changes with respect to voltage (dp/dv). If this value is positive, the controller adjusts the pulse width modulation (PWM) duty cycle to increase the voltage until maximum power is reached, or until dp/dv equals zero. If the value is negative, the controller reduces the voltage by changing the PWM duty cycle to approach the maximum power.

The FLC operates with two key inputs: **error** and **change in error**. These inputs are used to adjust the duty cycle of the PWM, which in turn controls the DC-to-DC converter, ensuring that the system stays optimized for maximum power output.

The controller uses the **Mamdani method** for fuzzy inference to manage the MPPT. The FLC is composed of three main components.

i. Fuzzification

In the **fuzzification** stage of the FLC, numerical input values are converted into linguistic terms through the use of a membership function. These linguistic terms help the controller interpret changes in voltage and power. The system is designed with five fuzzy categories: PB (Positive Big)**,** PS (Positive Small)**,** ZE (Zero)**,** NS (Negative Small)**, and** NB (Negative Big)**.**

The inputs to the system, changes in voltage and power, are used to determine the appropriate output, which is the adjustment of the duty cycle. The membership functions for each of these variables guide how the system interprets and responds to fluctuations. These limits and ranges are set based on prior knowledge and system behavior, ensuring the controller responds accurately to changing conditions.

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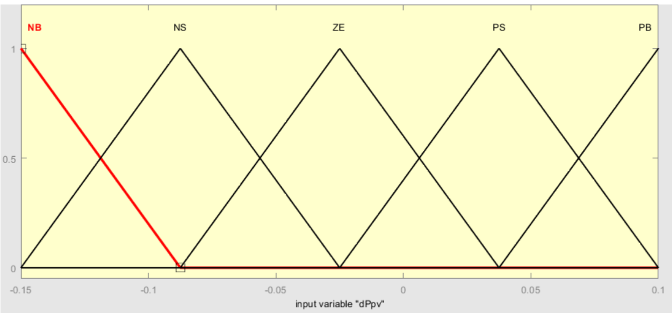

Fig 7. Membership function representing change in power

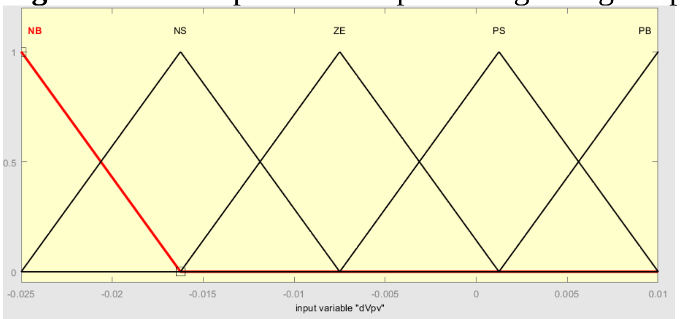

Fig 8. Membership function representing change in voltage

ii. Inference System**:**

The fuzzy algorithm organizes a series of control rules in a specific order, to guide the system towards achieving optimal performance. These rules are built on expert insights about the system. The **fuzzy inference** process, based on the **Mamdani method**, works by using a max-min composition to evaluate the rules.

The FLC's inference system can be broken down into three key components:

1. **Rule Base**: This consists of several **If-Then** rules that govern the controller's operation. The "If" part (antecedent) sets the condition, while the "Then" part (consequence) defines the action. These rules mimic human decision-making and use linguistic input variables from the fuzzification stage.
2. **Database**: This contains all the user defined membership functions that are referenced in the rules.
3. **Reasoning Mechanism**: This component processes the rules and determines the output based on the current conditions and rules applied.

The controller evaluates these control rules through an inference mechanism to deliver the appropriate result based on the system's needs.

ΔVpv*[o/p]	ΔVpv[i/p]					
ΔPpv[i/p]		**NB**	**NS**	**ZE**	**PS**	**PB**
	NB	PS	PB	NB	NB	NS
	NS	PS	PS	NS	NS	NS
	ZE	ZE	ZE	ZE	ZE	ZE
	PS	NS	NS	PS	PS	PS
	PB	NS	NB	PB	PB	PS

Fig 9. MPPT Fuzzy controller rule base

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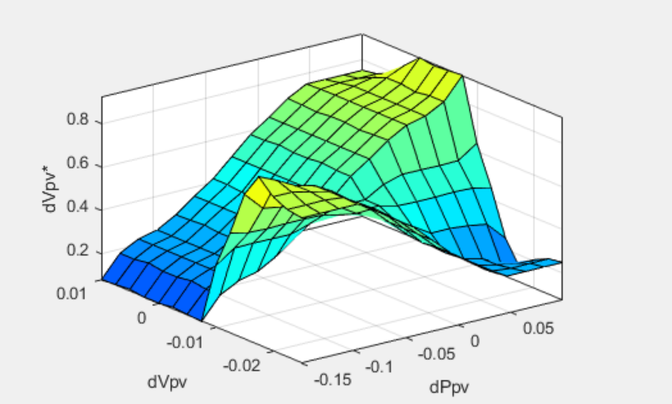

Fig 10. FLC Rule Surface

iii. Defuzzification:

While there are different methods for defuzzification, the two most common are the centroid of area and the bisector of area methods. In this model, the defuzzification process in the FLC uses the centroid method to calculate the output, which in this case is the duty cycle (D).

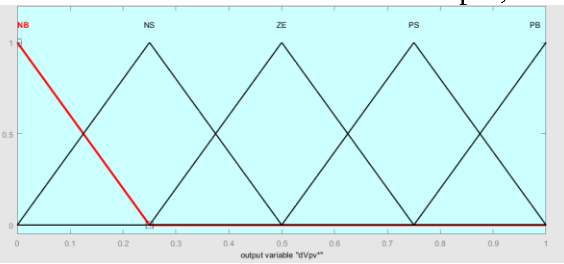

Fig 11. Membership function for change in duty cycle ratio

DC-DC CONVERTER:

A DC-DC converter is an electronic circuit designed to adjust a direct current (DC) voltage from one level to another, either stepping it up or stepping it down. Because of this function, it's often referred to as the DC equivalent of a voltage transformer. Another common name for this type of converter is "chopper."

Beyond changing voltage levels, one of the key roles of a DC-DC converter is voltage regulation. Typically, the power supply delivers an unregulated AC voltage, which is then rectified into a DC value. However, this DC voltage often fluctuates due to variations in the input. A switch-mode chopper regulates this fluctuating DC input into a stable, controlled DC output.

In the context of a MPPT system, the DC-DC converter is a critical component. It regulates the input voltage at the MPP, ensuring the system operates efficiently by matching the load and maximizing the transfer of power from the PV module. The converter which used here in this work is a boost converter

Boost DC-DC Converter:

A boost converter is a type of DC-DC power converter which increases (or "steps up") the input voltage while reducing the current as it delivers power to the load. It operates as a switched-mode power supply (SMPS), utilizing components like diodes and transistors, along with energy storage elements like inductors and capacitors. To manage voltage ripples and ensure a smooth output, filters made of capacitors and inductors are typically used. These filters are added both on the supply side and the load side to stabilize the voltage.

A step-up boost DC-DC converter takes a DC voltage input (Vs) and uses key components like an inductor (L), which is often called the boost inductor, a capacitor (C) acting as a filter, a diode (D), and a switching element (S), typically an IGBT or a MOSFET. The converter supplies power to the load at a higher voltage than the input.

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The switching element, which could be either an IGBT or MOSFET, controls the converter's operation by adjusting the duty cycle. A boost converter works in two main modes: charging and discharging

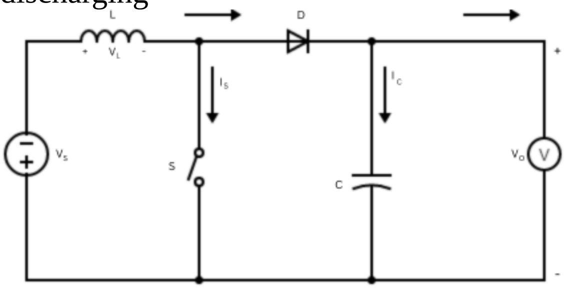

Fig 12. Basic circuit diagram of BOOST Converter

SIMULATION AND RESULTS:

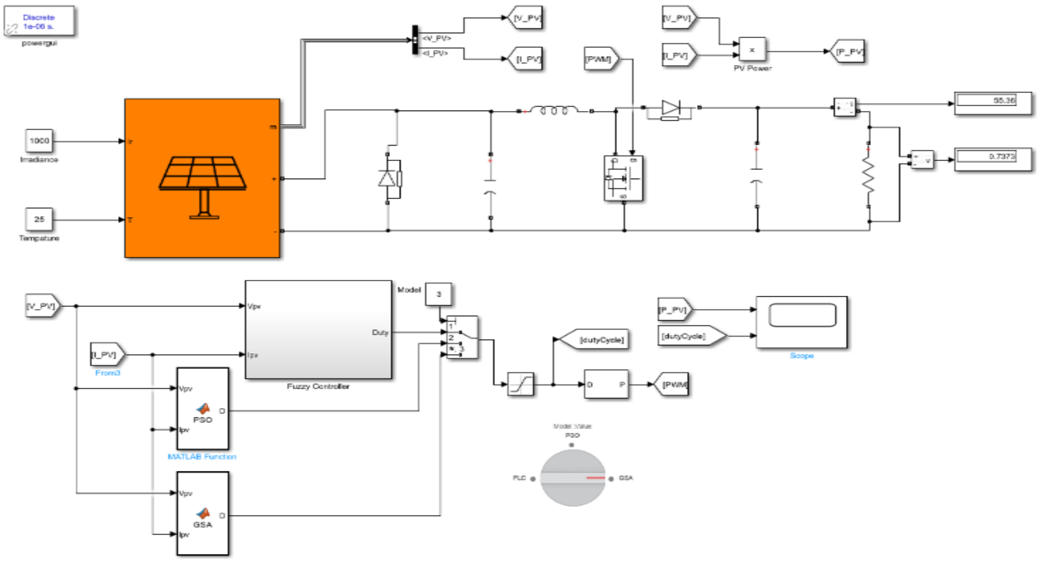

Fig 13. Isolated PV Array model with GSA, PSO & FLC based MPPT systems in Simulink

The PV Array, MPPT model and a DC-DC Converter are constructed and simulated in MATLAB Simulation as shown in Fig 13. The input parameters for the PV Array simulation are 1 kW/m² irradiance and 25°C ambient temperature. The MPPT controller is designed to have GSA and PSO algorithms and FLC as three separate function blocks receiving input parameters from the PV array and giving the output of the duty cycle. The algorithm to be employed in the simulation can be selected using a rotary switch that has been linked to a multi-port switch for ease of access. The duty cycle is then converted into Pulse Width Modulation (PWM), which then is sent to the MOSFET in the PV system as shown in the below Fig. 13 The MPPT System based on FLC is designed and constructed in Simulink as shown the Fig 14.

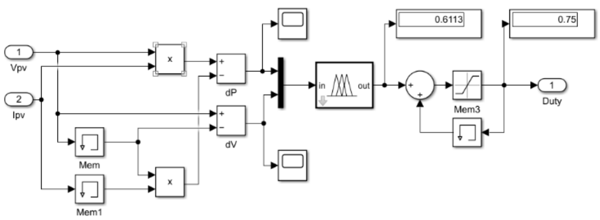

Fig 14. Model of Fuzzy Logic Controller (FLC) -based MPPT system in Simulink

MATLAB simulations are performed to test the three MPPT systems one by one, the Performance comparison of output power along with duty cycle of MPPT Controllers (represented in graph as

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shown in fig 16,17,18) are done based on several control system parameters like efficiency, settling time, max power output and off-shoot as shown in table 3.

A. As shown in the fig.15 the max output power for the GSA MPPT model reaches 53 W after a settling time of 0.12sec with an efficiency of 95.49 % and 3.29 W offshoot.

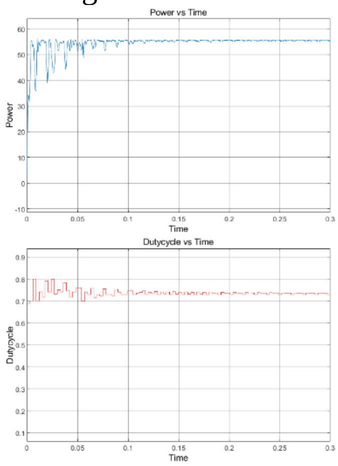

Fig 15. Output of GSA MPPT

B. As shown in Fig. 16 the max output power for PSO MPPT model reaches 52W after a settling time of 0.11sec with an efficiency of 93.69 % and 4.33W offshoot.

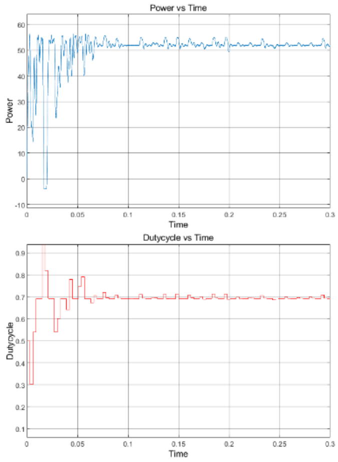

Fig 16. Output of PSO MPPT

C. As shown in Fig. 17 the max output power for FLC MPPT model reaches 54W after a settling time of 0.03sec with an efficiency of 97.29 % and 1W offshoot.

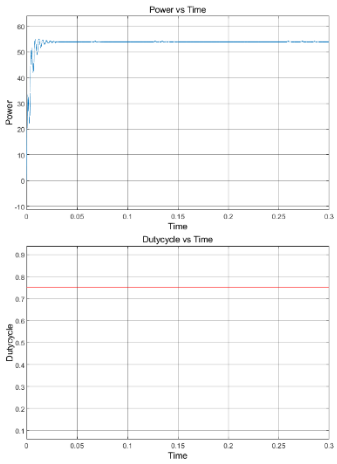

Fig 17. Output of FLC MPPT

This analysis focuses on comparing MPPT controller performance based on key parameters, including efficiency, time that is taken to reach the MPP, oscillations, overshoot, and settling time. Each parameter provides insight into how effectively the controller tracks and maintains optimal power output, with a special emphasis on minimizing power fluctuations and stabilizing output quickly.

$$Efficiency = \frac{Power\ tracked\ by\ MPPT\ controller}{Max\ power\ output\ of\ PV\ panel} * 100$$

Each algorithm brings its strengths and limitations to optimizing MPPT systems, emphasizing the need to select the right method based on the specific goals and requirements of the application. Table 3 helps in understanding each MPPT model output specifications.

MPPT Technique	Settling Time (s)	Maximum Power (W)	Off-shoot (W)	Efficiency (%)
GSA	0.12	53	3.29	95.49
PSO	0.11	52	4.33	93.69
FLC	0.03	54	1	97.29

Table 3. Comparison analysis of MPPT models

CONCLUSION:

In this paper, MATLAB/Simulink is employed to model and analyze the voltage-current (V-I) characteristics and power-voltage (P-V) characteristics of a PV module under standard conditions of 25°C ambient temperature and 1000 W/m² irradiance, and this study examines the performance of three MPPT techniques: GSA, PSO, and FLC. Simulation results are provided to highlight and compare how effectively each method tracks the MPP, contributing to improved solar energy efficiency.

From the simulation results, characteristics such as max Power and efficiency of GSA and PSO are similar to FLC, but when it comes to settling time, fluctuations and off-shoot FLC shows efficient operating conditions over the other two models therefore, FLC based MPPT Controller is preferable for drawing stable max power through PV Array.

This study aspires to be a useful resource for advancing research in MPPT optimization. With the growing demand for efficient renewable energy systems, these findings provide a basis for future exploration into hybrid approaches, tuning algorithm parameters, and examining the flexibility and adaptability of these methods across diverse MPPT configurations. Such efforts can drive further improvements in the effectiveness and efficiency of renewable energy systems.

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