A Project Report

on

Optimization of BIPV and PV Array Efficiency Under Partial Shading Conditions Using Fuzzy Logic and Perturb and Observe Method

Submitted for partial fulfilment for the degree of

Bachelor of Technology in Electrical Engineering

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Certificate

It is certified that the work contained in this thesis entitled
"**Optimization of BIPV and PV Array Efficiency Under Partial Shading Conditions Using Fuzzy Logic and Perturb and Observe Method**"
submitted by Shrayam Sarmah (2113089) and Ashmita Sutradhar (2113135) for the B.Tech. End Semester Project Examination May, 2024 is absolutely based on their own work carried out under my supervision.

Place:
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ABSTRACT

Photovoltaic (PV) arrays and Building-Integrated Photovoltaic (BIPV) modules play key roles in the solar energy revolution, each with unique benefits and challenges in providing clean, renewable energy. These technologies are transforming how electricity is generated and consumed, reflecting advancements in solar technology and the growing demand for sustainable energy.

PV arrays are made up of multiple solar panels connected together, converting sunlight into electricity through photovoltaic cells, typically made from silicon. They come in various configurations, from small residential setups to large-scale solar farms. PV arrays offer scalability, flexibility, and adaptability to meet diverse energy needs, from homes to industries. They can be installed on rooftops or open land, making them suitable for various applications. Another major advantage is cost efficiency: the price of solar panels has dropped significantly in recent years due to technological advancements and increased production, making solar energy more affordable. Additionally, PV arrays are reliable, durable, and require minimal maintenance, with lifespans often exceeding 25 years.

Building-Integrated Photovoltaic (BIPV) modules are a newer innovation. Unlike traditional PV arrays, BIPV modules are integrated directly into building materials like windows, facades, and roofs, allowing them to serve as both functional building components and electricity generators. This dual-purpose design is especially valuable in urban areas where space is limited and aesthetics matter. BIPV systems offer an efficient way to generate solar power while maintaining the architectural integrity of buildings.

This project also presents a fuzzy logic-based Maximum Power Point Tracking (MPPT) method to optimize the performance of a solar photovoltaic (PV) array under partial shading. The PV system is simulated in MATLAB/SIMULINK, using five PV modules connected in series. Under consistent solar irradiance, the power output follows a nonlinear pattern, featuring a single Maximum Power Point (MPP).However, partial shading results in multiple local maxima, complicating the identification of the true MPP.

The PV characteristics of a module or array under uniform irradiance are nonlinear, but a single Maximum Power Point (MPP) can be identified where power output is maximized. Nevertheless,The PV characteristic becomes more complex with multiple Maximum Power Points (MPPs) under varying conditions, such as partial shading or non-uniform irradiancewhen

the PV array under partially shaded conditions (PSC). This project investigates the use of the Perturb and Observe (P&O) algorithm for Maximum Power Point Tracking (MPPT). MPPT is a technique used in solar systems to ensure they operate at the optimal point to generate the maximum power. The P&O algorithm works by slightly adjusting the operating voltage and observing whether the power increases or decreases. It continues this process, changing the voltage in the direction that increases power until

the maximum is found. The method is simple and cost-effective but can cause oscillations around the maximum power point, especially under changing conditions.

Fuzzy logic is integrated into the conventional MPPT to improve the overall performance of the PV system.

Contents:

LIST OF ABBREVIATIONS

- **BIPV**: Building-Integrated Photovoltaics
- **PV**: Photovoltaic
- **PSC**: Partial Shading Conditions
- **GMPP**: Global Maximum Power Point
- **MPPT**: Maximum Power Point Tracking
- **TCT**: Total-Cross-Tied
- **QT**: Quarter-Tied
- **AC**: Alternating Current
- **DC**: Direct Current
- **I-V**: Current-Voltage
- **P-V**: Power-Voltage
- **P&O**: Perturb and Observe
- **Inc Cond**: Incremental Conductance
- **PSO**: Particle Swarm Optimization
- **W**: Lambert W-function

CHAPTER 1. INTRODUCTION:

The significant global growth in renewable energy sources has brought solar photovoltaic (PV) systems to the forefront as a solution to the current energy crisis. Known for its abundance and sustainability, solar energy holds great promise in reducing our dependence on fossil fuels and solving environmental problems. Despite their great potential, the performance of photovoltaic systems is affected by many environmental factors, making partial solar power (PSC) systems a major competition. PSC caused by clouds, buildings, trees and other obstructions can lead to power loss and poor performance in PV arrays. source of electricity demand. According to MNRE, India has a climate that can utilize abundant solar energy. India's area produces about 5,000 terawatt hours of energy each year. Almost everything takes 4-7 kWh per section. Letter from Mr. Praveen Kumar Bonthagorla Page 4 170 square meters. meters per day. Its supply is sufficient to meet the energy needs of India's urban and rural areas, such as electricity, heating and cooling. Photovoltaic energy generation is the most efficient and green energy generation among all renewable sources in India. If we use solar energy effectively, we can meet the needs of the entire country. However, there are still many areas in India that do not have access to electricity.

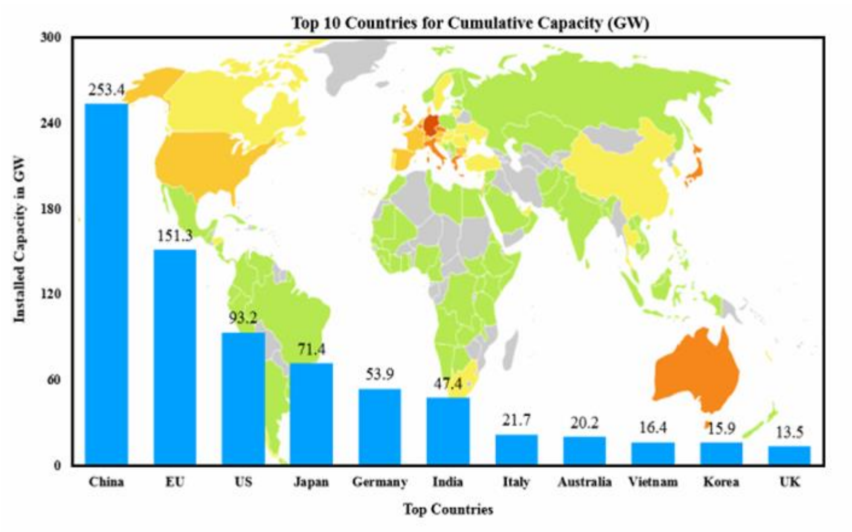

Figure 1.1: Global Annual PV Installed Capacity

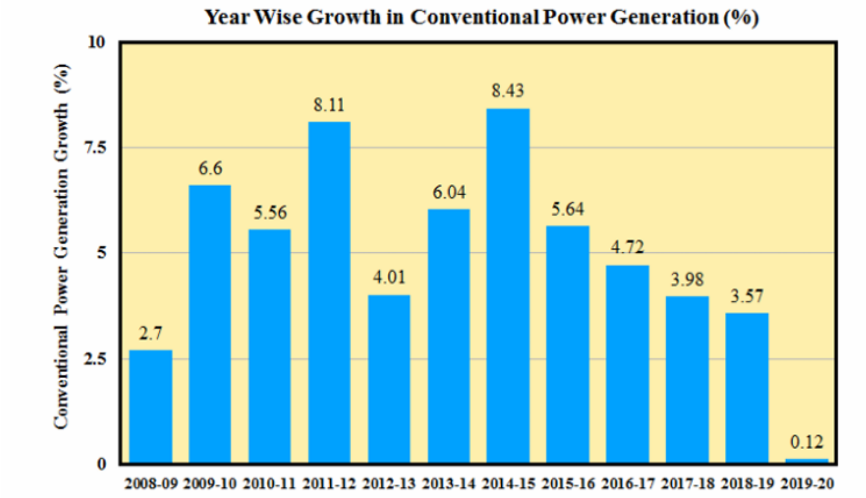

Figure 1.2: Annual India's growth in Conventional Power Generation

1.1. Introduction

1.1.1. Sustainability

Solar energy is a renewable source that helps reduce greenhouse gas emissions and mitigates climate change.

1.1.2. Energy Independence

Solar systems provide energy security by reducing dependence on external energy sources.

1.1.3. Business Support

The decreasing cost of solar technology and availability of incentives make it profitable for many users. These advantages establish solar energy as the foundation for a future transition to sustainable and powerful energy solutions.

1.2. Effect of Partial Shading (PSC)

Partial shading conditions significantly impact photovoltaic (PV) system performance. Shadows can arise from:

1.2.1. Natural Obstacles

Shadows caused by weather or climate changes lead to variations in power output.

1.2.2. Object Obstructions

Structures like buildings, antennas, and other objects cast shadows that affect PV array performance.

1.2.3. Trees

Vegetation growth can create shading that reduces electricity production. Inconsistent shading (e.g., a shadow from a hand) acts as a barrier, diminishing overall energy output. Understanding and controlling these effects is critical for maintaining PV system efficiency.

1.3. Photovoltaic Array Configurations

To address shading issues and optimize performance, PV arrays use various interconnection schemes:

1.3.1. Grid-Tied Systems

These systems connect to the grid, allowing surplus energy export. While improving energy management and financial returns, their benefits can be overshadowed by potential grid-related conflicts.

1.3.2. Off-Grid/Standalone Systems

Used in isolated locations, these systems offer energy independence but are sensitive to shading due to the lack of grid connection for output stabilization.

1.3.3. Hybrid Configurations

Hybrid systems combine grid-connected and off-grid features to balance benefits while minimizing inefficiencies caused by shading.

1.3.4. Microgrid Systems

Microgrids operate independently or integrate with larger grids, providing local solutions to mitigate shading effects and improve energy management.

1.4. Advances in Photovoltaic Technology

Innovations in PV technology focus on enhancing efficiency and addressing shading challenges:

1.4.1. Hybrid Configurations

Innovations include advanced string configurations and control strategies to improve efficiency under shading conditions.

1.4.2. Advanced Modeling Technology

Computer simulations and machine learning algorithms predict and control shading effects, optimizing system performance.

1.4.3. Building-Integrated Photovoltaic Systems (BIPV)

BIPV integrates PV technology into building materials (e.g., windows and facades), addressing urban limitations while introducing unique design challenges.

1.4.4. Flexible, Transparent Photovoltaic Technologies

Developments in flexible, transparent PV materials enable applications on unconventional surfaces, reducing shading impacts.

1.4.5. Energy Storage Integration

Combining PV systems with energy storage solutions, such as batteries, improves reliability and mitigates shading-induced energy disruptions.

1.5. Research Objectives

1.5.1. Performance Evaluation

Evaluate the performance of TCT (Triple-Connected) and QT (2x2 Quadrant-Connected) configurations under different shading scenarios.

1.5.2. Maximizing Power Output

Identify configurations that maximize power output under shading conditions by considering factors such as shading duration and utilization. This includes minimizing mismatch losses and enhancing overall system efficiency, reliability, and validity.

1.6. Methodology

Configurations are simulated to predict performance under varying shading scenarios. Advanced diode modeling techniques analyze shading effects on individual PV cells and their contribution to overall array performance.

1.7. Expected Results

1.7.1. Recommendations

Provide insights into the optimal PV array configurations for shading conditions. Develop guidelines for designing robust PV systems that maintain efficiency despite shading challenges.

1.7.2. Contribution to Future Research

Deliver research outcomes that inform future advancements in PV system optimization and shading control strategies.

CHAPTER 2. LITERATURE SURVEY

2.1. Introduction

Solar photovoltaic (PV) technology, including photovoltaic arrays and integrated photovoltaic (BIPV) modules, plays an important role in the development of new, more cost-effective energy solutions. Photovoltaic arrays consist of interconnected solar panels designed to maximize energy output and efficiency by converting sunlight into electricity. Research in the field of optoelectronics is increasingly focused on optimizing different configurations to improve performance, especially in difficult situations such as partial shading.

Grid-connected and off-grid PV systems are some of the most sought-after installations for efficient and effective energy storage, despite environmental issues such as shadowing by clouds, buildings, or facilities. Most importantly, these challenges affect the power of the photovoltaic system, creating too many local maximum power points (MPP) in the power-voltage (P-V) curve, which in turn complicates the task of finding the global maximum power point (GMPP). Effective materials that reduce losses from partial shading and innovations in advanced panel design allow photovoltaic systems to operate more efficiently in real-world environments. These systems save space and aesthetically appeal by capturing solar energy in areas such as roofs, facades, or windows.

However, these systems often face challenges from buildings such as chimneys, air conditioning units, or nearby structures. Research into BIPV systems is focused on seamlessly integrating solar modules into building designs while controlling shading and optimizing performance. This research provides an overview of ongoing efforts aimed at improving the performance of photovoltaic and BIPV systems by focusing on shading reduction and overall system optimization.

2.2. Data Analysis

2.2.1. Photovoltaic Array Interconnection Scheme for Power Maximization Under Varying Irradiance Conditions

Abstract: This study investigates various photovoltaic array designs such as series, series-parallel, bridge, cellular, and total cross-tied (TCT) under different partial shading conditions. MATLAB/Simulink simulations show that the total cross-tied arrangement consistently achieves the highest power and performance, providing maximum power and efficiency with minimal degradation, especially under shading conditions. The configuration demonstrates lower power loss compared to other configurations.

2.2.2. Improving GMPP, Reducing Power Peaks, and Overlap Losses Using a New Hybrid BIPV Array Setup

Abstract: This paper describes the setup of a hybrid BIPV array to improve global maximum power point (GMPP) tracking during low power peaks and overlaps. MATLAB/Simulink simulations show significant improvements in power output and performance under various shading scenarios. The hybrid BIPV array configuration effectively reduces mismatch loss and improves GMPP reach, resulting in better power and system efficiency under partial shading conditions.

2.2.3. Reducing Mismatch Power Loss Through Optimal Photovoltaic Array Configurations Under Partial Shade Conditions

Abstract: This study aims to determine the optimal photovoltaic array configuration to maximize power draw under partial shade conditions. Various topologies were simulated and compared for power output, loss, and efficiency. The research proposes a configuration that reduces energy loss and improves overall performance.

Conclusion: The optimal photovoltaic array configuration found in this study improves energy extraction and provides practical solutions for the operation of photovoltaic systems by minimizing losses in partial shading.

2.2.4. Analyzing the Performance of Conventional and Hybrid PV Array Configurations in Grid-Connected Standalone PV Systems

Abstract: This study compares the performance of hybrid and conventional PV array topologies in grid-connected standalone systems. The study investigates the effects of different configurations of electronic devices and physical activity under various conditions. Hybrid designs show better performance and reliability compared to conventional configurations.

Conclusion: This study provides a detailed analysis of static BIPV array configurations under partial shading. Using experimental methods, it evaluates the ability of various configurations to minimize losses and maximize energy output, providing a good option for improving power generation capacity.

2.2.5. Increasing Power with Hybrid BIPV Arrays Having Fewer Peaks and Lower Mismatch Losses During Partial Shading

Abstract: This study introduces a hybrid BIPV array configuration designed to reduce power peaks and mismatch losses during partial shading. Simulations show that the proposed setup outperforms traditional configurations in overall performance.

Contribution: The research presents a hybrid BIPV array design that significantly reduces power peaks and mismatch losses, enhancing power output under partial shading conditions.

Summary: The hybrid BIPV array configuration achieves better performance by lowering power peaks and mismatch losses, surpassing conventional setups in shaded environments.

2.2.6. Examining the Performance of Conventional and Hybrid PV Array Setups for Grid-Connected Standalone PV Systems

Abstract: The performance of hybrid and traditional PV array topologies in grid-connected standalone systems is examined in this research. The impact of different configurations on power output and system efficiency is assessed. The findings suggest that hybrid designs provide better performance and reliability compared to traditional setups.

Contribution: The study compares hybrid and traditional PV array topologies, finding that hybrid setups offer higher power production and efficiency, improving system reliability in shaded areas.

Summary: Hybrid PV array topologies show improved performance and reliability in grid-connected standalone systems, effectively addressing shading challenges and increasing power output and system efficiency.

2.2.7. Mitigating Mismatching Power Losses to Extract Maximum Power Under Partial Shading Conditions Through Optimal PV Array Configuration

Abstract: This study aims to determine the best PV array arrangement for maximizing power extraction in situations where partial shading occurs. A range of topologies is simulated, and their power output, mismatch losses, and efficiency are compared.

Contribution: The authors determine the optimal PV array configuration for maximizing power extraction in partial shading conditions, significantly reducing mismatch losses and improving system efficiency.

Summary: The study's optimal PV array arrangement outperforms others in terms of power extraction and mismatch loss minimization in partial shading conditions, providing a practical way to increase PV system efficiency in shaded areas.

2.3. Research Gaps and Motivation

2.3.1. Identified Research Gaps

1. **Need for Improved Modelling of BIPV Module Circuits**: Existing models for BIPV modules often lack the precision needed to accurately represent their electrical characteristics, leading to suboptimal performance predictions and design inefficiencies. More advanced and detailed modelling techniques are required to better understand the interaction between BIPV modules and building materials, along with varying environmental conditions.
2. **Limitations of Conventional PV Array Configurations**: Traditional PV array configurations, such as series, series-parallel, and grid-tied setups, often suffer from reduced power output, high losses, and increased costs, particularly under partial shading conditions. These conventional designs are often inadequate in handling the complexities of shading patterns, leading to lower system efficiency and higher operational costs.
3. **Challenges with Total-Cross-Tied (TCT) Configurations**: While the Total-Cross-Tied (TCT) configuration minimizes mismatch losses and improves overall efficiency, it requires extensive wiring. This added complexity can result in increased electrical losses and suboptimal performance under certain shading conditions. The trade-off between reduced mismatch losses and increased wiring-related inefficiencies needs to be further explored to improve the practical applicability of TCT configurations.

2.3.2. Motivation

1. **Partial Shading in Large PV Systems**: Large-scale PV systems often experience partial shading due to environmental factors like clouds, nearby structures, or vegetation. This shading creates complex P-V curves with multiple peaks, making it difficult to extract the maximum power and optimize system performance.

2. **Space Constraints and Shading Issues in BIPV Systems**: BIPV systems aim to address the challenge of limited space in urban areas by integrating solar modules directly into building materials. However, these systems are also vulnerable to shading from architectural features and nearby obstructions, negatively impacting their efficiency and overall performance.
3. **Need for Optimized Array Configurations**: There is a critical need for improved PV array configurations that minimize mismatch losses, reduce wiring requirements, and maximize power output, particularly under partial shading conditions. Developing such configurations will be essential for enhancing the efficiency and cost-effectiveness of both traditional PV and BIPV systems.

CHAPTER 3. WORK DESCRIPTION:

3.1. Review of the Literature

3.1.1. Current State-of-the-Art in PV Array Configurations

Significant advancements in photovoltaic (PV) array configurations focus on mitigating partial shading effects to enhance energy output and efficiency. PV arrays are optimized to maintain power generation despite shading by employing advanced configurations and control strategies.

3.1.1.1. Conventional Configurations

Traditional PV array setups, such as Series and Series-Parallel configurations, exhibit significant performance degradation under partial shading. The Series configuration is simple but susceptible to the shading of individual panels, causing power losses. The Series-Parallel configuration offers improved shading tolerance by combining series and parallel connections, but its performance diminishes when multiple panels are affected.

3.1.1.2. Advanced Configurations

The Total-Cross-Tied (TCT) configuration interconnects all panels to reduce mismatch losses and improve shading tolerance. Its uniform distribution of power generation ensures better performance under partial shading. For this work, a 2x2 TCT configuration is used, which balances complexity and practical implementation, offering robust simulation capabilities for shading analysis.

3.1.2. Best Practices and Constraints

Maximum Power Point Tracking (MPPT) algorithms ensure efficient tracking of the Global Maximum Power Point (GMPP), even under partial shading.

3.1.2.1. MPPT Algorithms

- **Perturb and Observe (P&O):** Simple but struggles under dynamic conditions and may fail to locate GMPP.
- **Incremental Conductance (IncCond):** Uses power-voltage derivatives for GMPP tracking, improving performance in dynamic conditions.
- **Fuzzy Logic-Based MPPT:** A rule-based algorithm that employs fuzzy logic to adaptively adjust the operating point. It offers superior GMPP tracking by handling complex shading patterns efficiently.

3.2. Modeling and Simulation in MATLAB

3.2.1. Simulation Setup

The study employs MATLAB/Simulink to simulate a 2x2 TCT array under various partial shading scenarios. The simulation includes:

- **PV Array Model:** Implements the 2x2 TCT configuration.
- **Fuzzy Logic MPPT:** Integrates a fuzzy logic controller to dynamically track GMPP.
- **Shading Patterns:** Models real-world shading conditions such as moving clouds or nearby obstructions.

3.2.2. Analysis of Shading Impacts

Shading scenarios are applied to the simulated 2x2 TCT array, generating P-V and I-V curves for evaluation. The performance of the fuzzy logic MPPT controller is analyzed by tracking the GMPP under non-uniform irradiance conditions.

3.3. Performance Assessment

3.3.1. Performance Metrics

Key metrics for evaluating the proposed system include:

- **Relative Power Gain:** Improvement in power output over conventional configurations.
- **Fill Factor:** Comparison of actual and theoretical power output.
- **Mismatch Losses:** Reduction of losses caused by uneven panel performance.
- **GMPP Tracking Efficiency:** Validation of the fuzzy logic MPPT's ability to maintain optimal power extraction.

3.3.2. Comparative Analysis

Simulation results of the 2x2 TCT array are compared with conventional configurations, highlighting the advantages of fuzzy logic MPPT. Statistical analysis, including mean power output and efficiency, confirms the superiority of the proposed method.

3.4. Experimental Validation Through Simulation

All modeling and validation are performed within MATLAB/Simulink. Experimental setups for testing were replicated in simulation to ensure practical applicability. Simulated results verify the consistency and reliability of the fuzzy logic MPPT with the 2x2 TCT configuration under varying shading conditions.

Conclusion

This study demonstrates that the MATLAB-based 2x2 TCT PV array coupled with fuzzy logic MPPT effectively mitigates shading impacts, ensuring efficient power generation and robust system performance

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CHAPTER 4. DIODE MODELLING AND ALGORITHMS

4.1.1. Modeling of PV Array

This section explains the modeling of a photovoltaic (PV) array using the one-diode model. To understand the behavior of a PV cell, it can be visualized as a solar-powered pump converting sunlight into electricity. Similar to how a pump generates flow, a PV cell generates current under light, known as the photogenerated current (I_pv). However, the current flow faces resistance, characterized by:

- **Series Resistance (R_s):** Analogous to friction in a pipe, caused by metal contacts and semiconductor layers that hinder electricity flow.
- **Parallel Resistance (R_p):** Similar to leaks in a pipe, representing leakage current across the p-n junction bypassing the intended current path.

The Shockley diode equation describes the current-voltage relationship of a PV cell, akin to calculating water flow by considering resistance and potential difference. Multiple PV cells are connected in series or parallel to form a module, increasing voltage or current, as required. For instance, five series-connected PV cells form a PV array supplying higher voltage to a load.

4.1.2. MPPT Algorithm

To maximize power output from the PV array, Maximum Power Point Tracking (MPPT) algorithms are employed. MPPT acts as a smart manager adjusting PV system operating conditions to extract maximum power.

- **Perturb and Observe (P&O):**
  This algorithm perturbs operating voltage and observes power changes, akin to finding the highest point on a hill by taking steps uphill or reversing when descending. It involves:
  - Measuring voltage and current at two intervals.
  - Calculating power and comparing to determine whether to increase or decrease voltage.

While effective, P&O may cause oscillations around the maximum power point when perturbation size is large.

4.1.3. Fuzzy Logic in MPPT

Fuzzy logic enhances the P&O algorithm by dynamically adjusting perturbation size based on real-time conditions, reducing oscillations. It employs linguistic variables for decision-making, similar to human reasoning based on experience.

- **Advantages:**
  - Faster tracking of maximum power point.
  - Reduced oscillations and stabilized operating voltage.
  - Efficient adaptation to varying environmental conditions.

Combining the simplicity of P&O with the adaptability of fuzzy logic creates a robust MPPT system for efficient and stable operation under dynamic conditions.

4.2: Integration of Fuzzy Logic with P&O Algorithm

4.2.1. Overview of the P&O Algorithm
The P&O algorithm adjusts PV array voltage to track the maximum power point (MPP) by:

- Increasing voltage when power rises and reversing when it decreases.
- Limitations:
  - **Small Perturbation:** Slow tracking of MPP.
  - **Large Perturbation:** Excessive oscillations causing instability.

4.2.2. Improving P&O with Fuzzy Logic
Fuzzy logic dynamically adjusts perturbation size based on the rate of power change (dp/dv) and power difference (dp).

- **Advantages:**
  1. **Faster Tracking:** Larger perturbations accelerate tracking when far from MPP, while smaller ones fine-tune closer to MPP.
  2. **Minimum Oscillations:** Dynamic adjustment stabilizes voltage after MPP identification.
  3. **Adaptive Control:** Real-time adaptation to changes in irradiance and temperature.

4.2.3. Fuzzy Maximum Power Point Tracking (FMPPT)
Integrating fuzzy logic with P&O results in FMPPT, offering:

- **Flexibility:** Real-time perturbation adjustment for varying conditions.
- **Efficiency:** Quick convergence to MPP with reduced transient time.
- **Stability:** Minimized oscillations ensuring consistent power generation.
- **Performance:** Optimal tracking under fluctuating environmental factors, improving system resilience and efficiency.

4.2.4. Advantages of Fuzzy Logic in MPPT

- **Dynamic Adjustment:** Real-time perturbation adjustment enhances responsiveness.
- **Improved Convergence:** Faster MPP tracking reduces delays.
- **Enhanced Stability:** Stabilized voltage minimizes power fluctuations.

Conclusion
Fuzzy Maximum Power Point Tracking (FMPPT) effectively combines the strengths of P&O

and fuzzy logic. It adapts to changing conditions, minimizes inefficiencies, and ensures maximum efficiency, making it an optimal solution for real-world photovoltaic system applications.

4.3. Flowcharts and tables for P-O MPPT method & Fuzzy logic based MPPT Control:

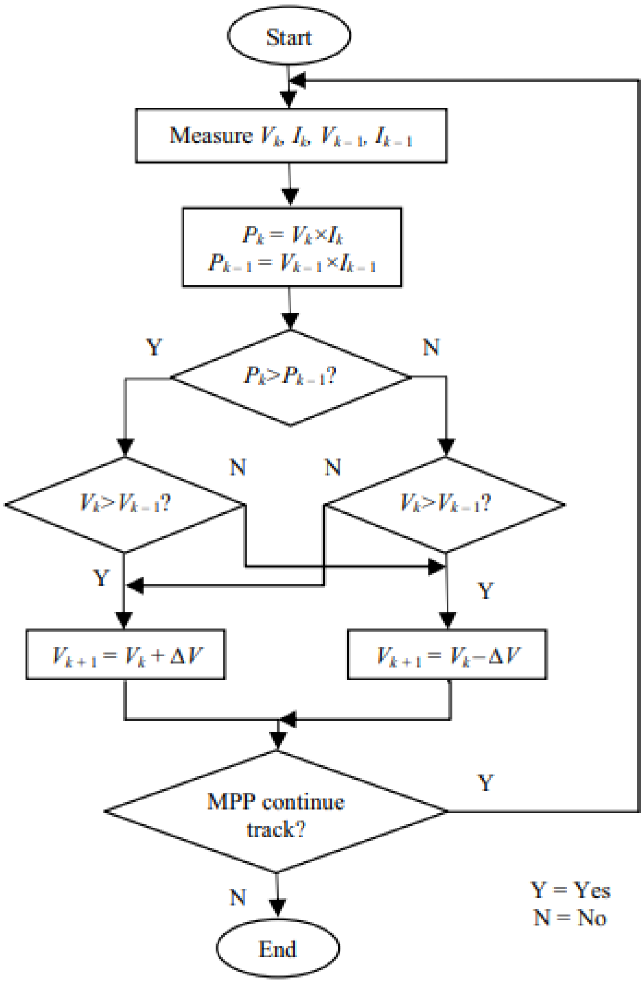


Fig. 3. Flowchart of P&O operation.

TABLE CONDITIONS FOR THE OPERATION OF P&O ALGORITHM

Case	Condition	Action on PV array
Case I	$P_k > P_{k-1}$ and $V_k > V_{k-1}$	Operating voltage is increased by ΔV
Case II	$P_k > P_{k-1}$ and $V_k < V_{k-1}$	Operating voltage is decreased by ΔV
Case III	$P_k < P_{k-1}$ and $V_k > V_{k-1}$	Operating voltage is decreased by ΔV
Case IV	$P_k < P_{k-1}$ and $V_k < V_{k-1}$	Operating voltage is increased by ΔV

CHAPTER 5. OBSERVATIONS:

This chapter presents the observations of **Maximum Power Point Tracking (MPPT)** methods: **Perturb and Observe (P&O)** and **Fuzzy Logic Controller (FLC)**. The conditions for observation are:

- **Irradiance**: 1000 W/m² and 500 W/m² (shaded condition)
- **Temperature**: 25°C

5.1 Perturb and Observe (P&O) Method

5.1.1 Observations

The **MPPT** is achieved by perturbing the operating point and observing the effect on output power. The system adjusts the duty cycle until the **maximum power point** is achieved.

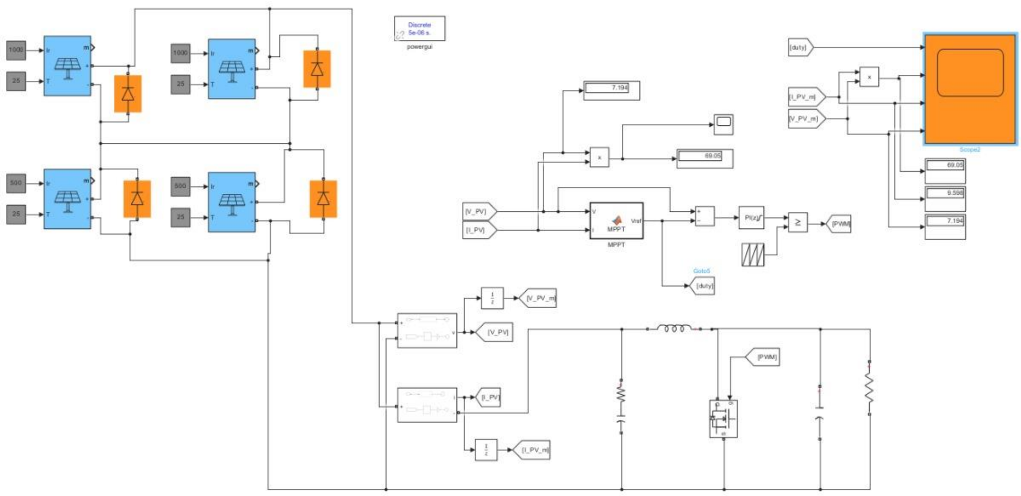
Conditions:

- **Irradiance**: 1000 W/m² and 500 W/m²
- **Temperature**: 25°C

Results:

- For **1000 W/m²**, the voltage, current, and duty cycle stabilize near their **optimal values**.
- For **500 W/m²**, reduced power output is observed due to **shading**.

Fig : PO method simulation



5.1.2 Blocks Used in Simulink

The following blocks are used for implementing th e **P&O method**:

- **PV Array**: Simulates the photovoltaic panels.
- **Diodes**: Represents bypass diodes.
- **MPPT Controller**: Implements the P&O algorithm.
- **PI Controller**: Ensures stable control of duty cycle.
- **PWM Generator**: Produces the required switching signal.
- **DC-DC Converter**: Boosts the PV voltage.
- **Load**: Represents the connected electrical load.
- **Scopes**: Visualizes voltage, current, and power waveforms.

5.2 Fuzzy Logic Controller (FLC) Method

5.2.1 Observations

The **MPPT** is achieved by applying **fuzzy logic rules** to dynamically adjust the duty cycle for maximizing power output.

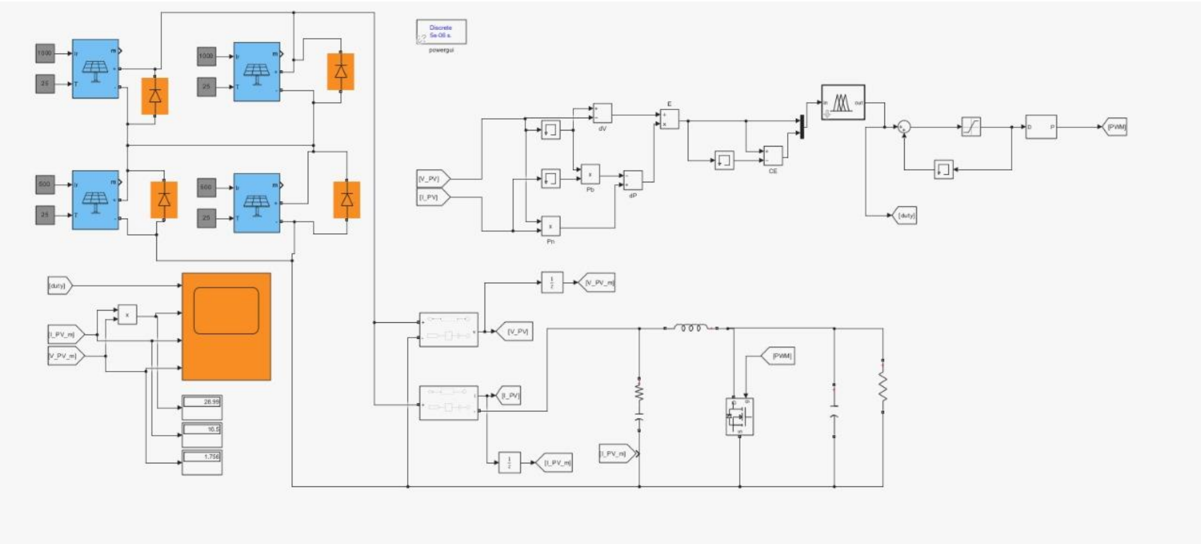
Conditions:

- **Irradiance**: 1000 W/m² and 500 W/m²
- **Temperature**: 25°C

Results:

- For **1000 W/m²**, faster convergence to the **maximum power point** compared to **P&O**.
- For **500 W/m²**, better performance in handling **shading effects**.

Fig : Fuzzy Logic Implementation in Simulation



5.2.2 Blocks Used in Simulink

The following blocks are used for implementing the **FLC method**:

- **PV Array**: Simulates the photovoltaic panels.
- **Diodes**: Represents bypass diodes.
- **Fuzzy Logic Controller**: Implements fuzzy rules for duty cycle adjustment.
- **PI Controller**: Refines the duty cycle signal.
- **PWM Generator**: Produces the required switching signal.
- **DC-DC Converter**: Boosts the PV voltage.
- **Load**: Represents the connected electrical load.
- **Scopes**: Visualizes voltage, current, and power waveforms.

5.3 Graphs Obtained:

Graph for the single pv module

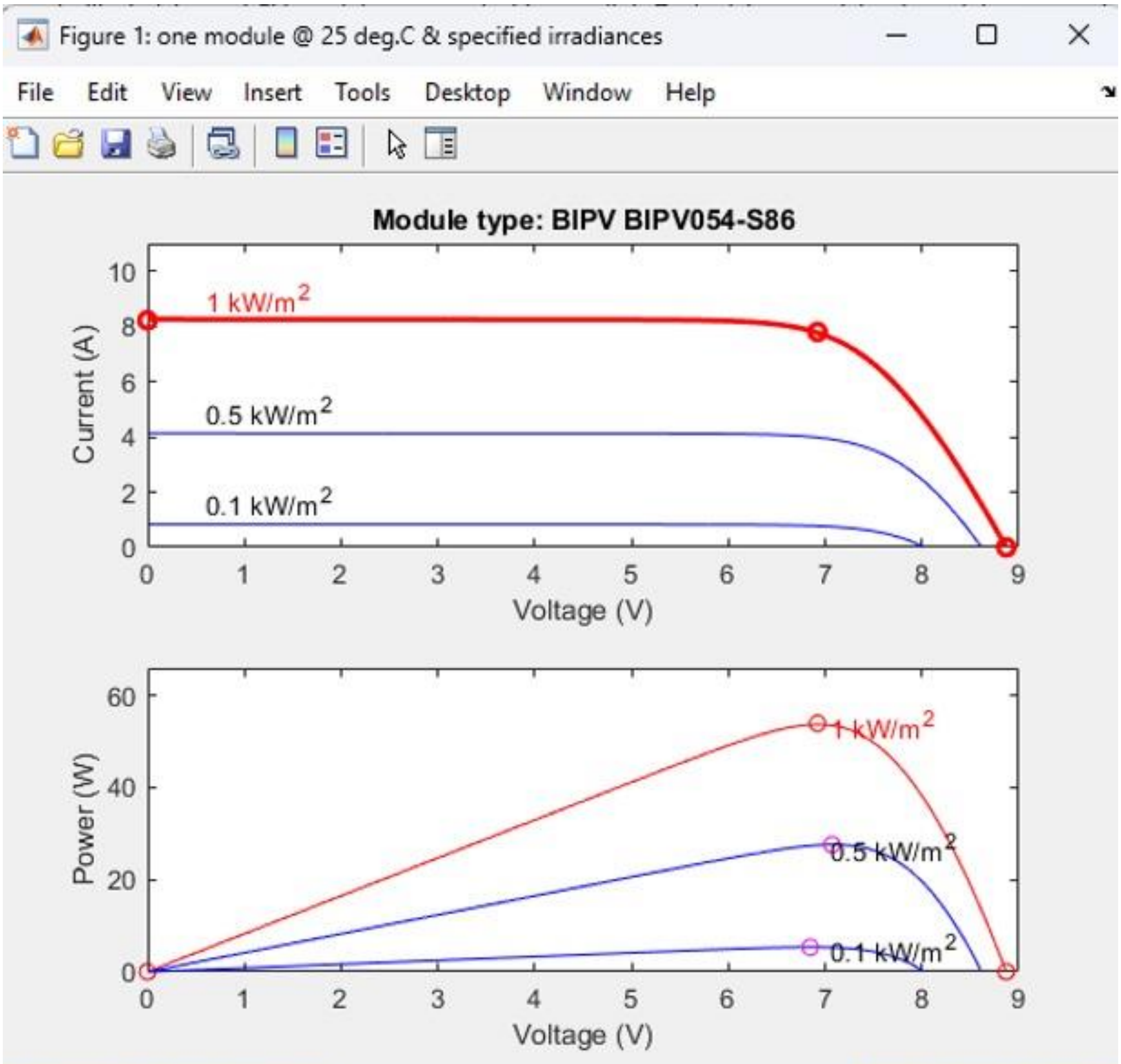


Fig: Graphs For the unshaded panel

Graph for the obtained Simulations:

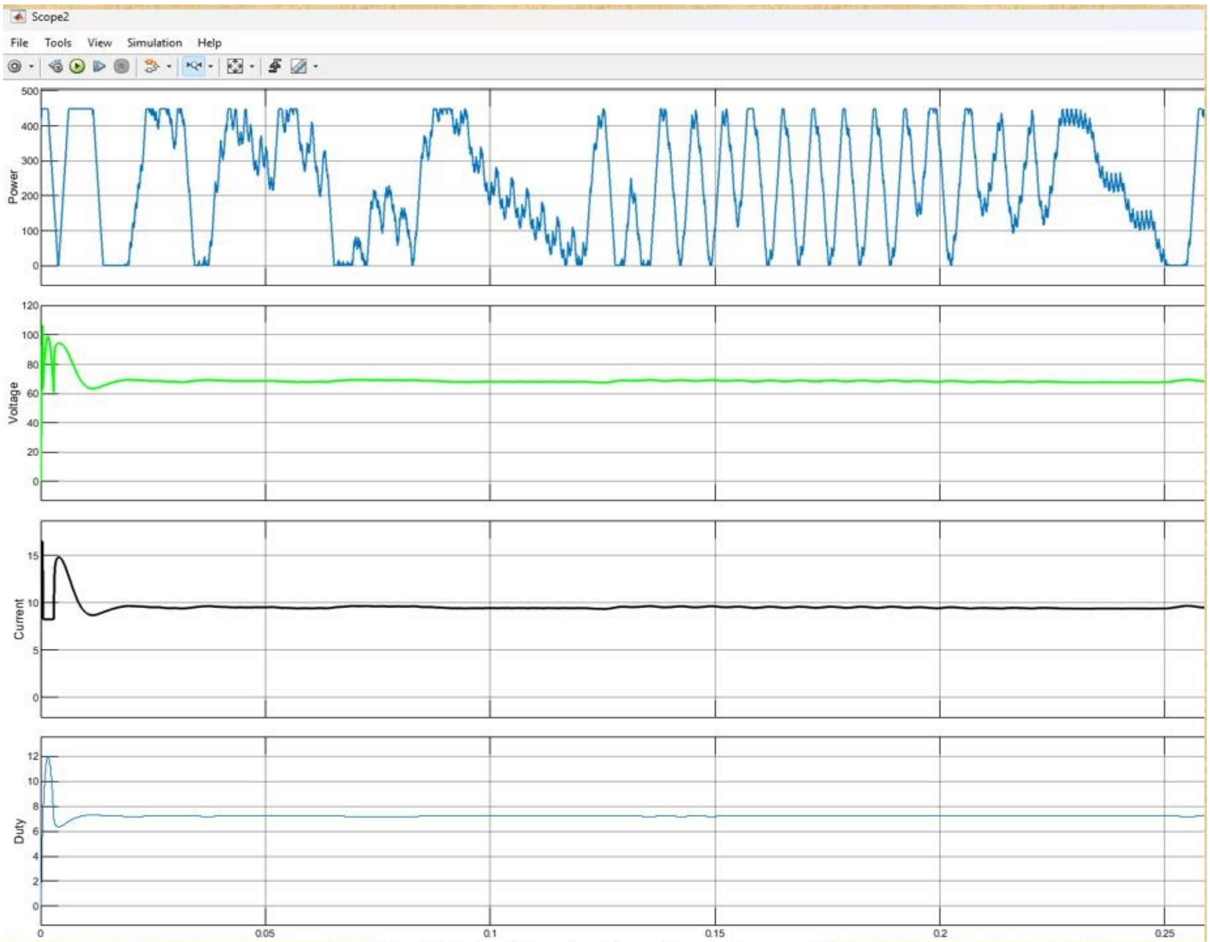


Fig: Obtained Graphs From simulation model

CHAPTER 6. RESULTS AND DISCUSSIONS:

This chapter presents the results and discusses the performance of **Flexible Maximum Power Point Tracking (FMPPT)** compared to **traditional MPPT** methods with fixed perturbation sizes (0.5V and 1.0V) under varying environmental conditions.

6.1 Results

6.1.1 FMPT and MPPT (0.5V and 1.0V)

- **Stage 1 (80% of PV array at 60% Partial Shading Condition (PSC)):**
  - **FMPPT** tracks MPP in **15 seconds**, settling at MPP by **65 seconds**.
  - **MPPT** with **1.0V** perturbation size takes **20 seconds**, settling at MPP by **65 seconds**.
  - **MPPT** with **0.5V** perturbation size takes **39 seconds**, settling at MPP by **65 seconds**.
- **Stage 2 (80% of PV array at 40% PSC):**
  - **FMPPT** tracks MPP in **161 seconds**.
  - **MPPT** with **1.0V** perturbation size tracks MPP in **181 seconds**.
  - **MPPT** with **0.5V** perturbation size tracks MPP in **166 seconds**.

6.1.2 Tracking Time Savings

- **Stage 1:**
  - **FMPPT** minimizes tracking time by **25%** compared to MPPT with a **1.0V** perturbation size.
  - **FMPPT** saves **61.5%** tracking time compared to MPPT with a **0.5V** perturbation size.
- **Stage 2:**
  - **FMPPT** saves **31.3%** and **64.5%** of tracking time compared to MPPT with **1.0V** and **0.5V** perturbation sizes, respectively.

6.1.3 Voltage Fluctuation

- **FMPPT** results in the smallest voltage fluctuation (**0.8V**).
- MPPT with perturbation sizes of **0.5V** and **1.0V** experience fluctuations of **1.0V** and **2.0V**, respectively.
- **FMPPT** reduces voltage fluctuation by **20%** and **60%** compared to MPPT with **0.5V** and **1.0V** perturbation sizes.

6.1.4 Precise MPP Control

- **FMPPT** achieves a more precise operating voltage at the **maximum power point (MPP)** with an MPP voltage of **47.8V**, which lies within the fluctuation range of MPPT with **0.5V** and **1.0V** perturbation sizes.

6.1.5 Perturbation Size Selection

- **FMPPT** dynamically adjusts the perturbation size based on environmental changes:
  - **Large perturbation (1.5V):** Used when environmental conditions change significantly (e.g., at **50s** and **150s**) to minimize tracking time.
  - **Small perturbation (0.09V):** Selected when approaching MPP to reduce voltage fluctuation.

6.2 Discussion

6.2.1 Tracking Performance

- **FMPPT** provides **faster tracking** of the MPP, significantly reducing tracking time compared to traditional MPPT methods with fixed perturbation sizes (**0.5V** and **1.0V**).
- In both stages of shading, **FMPPT** outperforms MPPT, with notable improvements in the speed of reaching the **global MPP**.

6.2.2 Voltage Stability

- **FMPPT** offers improved stability in maintaining the operating voltage near the global MPP with minimal fluctuation, resulting in **more consistent power generation**.

6.2.3 MPPT vs. FMPPT Efficiency

- Traditional MPPT with smaller perturbation sizes (**0.5V**) shows **less fluctuation** but requires longer tracking times and is **less responsive** to environmental changes.
- **FMPPT** balances both **fast response** and **low fluctuation** by dynamically adjusting the perturbation size, making it more efficient in partially shaded conditions.

6.2.4 Overall Performance

- **FMPPT** enhances the overall performance of the PV system under **partially shaded conditions**, improving both the tracking speed and the precision of the operating voltage near the **MPP**.

CHAPTER 7. CONCLUSION;

This project analyzed and compared the performance of traditional **Maximum Power Point Tracking (MPPT)** methods with fixed perturbation sizes and the innovative **Fuzzy Maximum Power Point Tracking (FMPPT)** algorithm in photovoltaic (PV) systems. The study highlights the superiority of the FMPPT approach in enhancing tracking efficiency and overall system stability, particularly under challenging environmental conditions such as partial shading.

Traditional MPPT methods rely on fixed perturbation sizes, which inherently limit their performance. Smaller perturbation sizes offer lower voltage fluctuations but take longer to track the maximum power point (MPP), while larger perturbation sizes achieve faster tracking at the cost of greater voltage instability. This trade-off demonstrates the rigidity of fixed-perturbation methods, which struggle to adapt to rapidly changing environmental conditions, such as variable irradiance or shading.

The **FMPPT algorithm**, leveraging the principles of fuzzy logic, addresses these limitations by dynamically adjusting the perturbation size based on real-time conditions. This adaptability allows FMPPT to optimize both tracking speed and voltage stability. During significant environmental changes, FMPPT applies larger perturbations to quickly locate the MPP. As the system approaches the MPP, it reduces the perturbation size, ensuring precise and stable operation with minimal fluctuations. This dynamic adjustment enhances the tracking efficiency and ensures better performance under partial shading conditions.

In addition to superior tracking speed, the FMPPT algorithm demonstrated improved voltage stability, maintaining smaller fluctuations around the MPP compared to traditional MPPT methods. This stability ensures consistent power generation, minimizing energy losses and enhancing the reliability of the PV system. By combining fast response times with precise control, FMPPT effectively bridges the gap between speed and stability, which traditional MPPT methods struggle to balance.

Overall, this project underscores the value of intelligent control systems in renewable energy applications. The FMPPT algorithm not only enhances the operational efficiency of PV systems but also contributes to the broader goal of making solar energy more reliable and sustainable. Its ability to adapt to dynamic environmental conditions ensures optimal energy harvesting, even in challenging scenarios like partial shading. These findings highlight the potential of fuzzy logic-based approaches to improve the efficiency and reliability of renewable energy technologies, paving the way for more advanced and intelligent energy management systems.

CHAPTER 8. REFERENCES :

[1] K. Ishaque, Z. Salam, A. Shamsudin and M. Amjad, "A direct control based maximum power point tracking method for photovoltaic system under partial shading conditions using particle swarm optimization algorithm," Applied Energy, vol. 99, 2012, pp. 414 422.

[2] V. Salas, E. Olias, A. Barrado and A. Lazaro, "Review of the maximum power point tracking algorithm for stand-alone photovoltaic systems," Solar Energy Materials & Solar Cells, vol. 90, 2005, pp. 1555 1578.

[3] Syafaruddin, E. Karatepe and T. Hiyama, "Polar coordinate fuzzy controller based real-time maximum-power point control of photovoltaic system," Renewable Energy, vol. 34, 2009, pp. 2597 2606.

[4] R. Ramaprabha, M. Balaji and B. L. Mathur, "Maximum power point tracking of partially shaded solar PV system using modified Fibonacci search method with fuzzy controller," Electrical Power and Energy Systems, vol. 43, 2012, pp. 754 765.

[5] M. G. Villalva, J. R. Gazoli and F. E. Ruppert, "Modeling and circuit based simulation of photovoltaic arrays," Brazillian Journal of Power Electronics, vol.14, 2009, pp. 35 45.

[6] Y. J. Wang and P. C. Hsu, "Analytical modelling of partial shading and different orientation of photovoltaic modules," IET Renewable Power Generation, vol. 4, 2009, pp. 272 282.

[7] R. Ramaprabha and B. Mathur, "Effect of shading on series and parallel connected solar PV modules," Modern Applied Science, vol. 3, no. 10, 2009, pp. 32 41.

[8] C. S. Chin, P. Neelakantan, S. S. Yang, B. L. Chua and K. T. K. Teo, "Effect of partially shaded conditions on photovoltaic array's maximum power point tracking," International Journal of Simulation Systems, Science & Technology, vol. 12, no. 3, 2011, pp. 52 59.

[9] Y. H. Ji, D. Y, Jung, J. G. Kim, J. H. Kim, T. W. Lee and C. Y. Won, "A real maximum power point tracking method for mismatching compensation in PV array under partially shaded conditions," IEEE Transaction on Power Electronics, vol. 26, 2011, pp. 1001 1009.

[10] C. S. Chin, P. Neelakantan, H. P. Yoong and K. T. K. Teo, "Fuzzy logic based MPPT for photovotaic modules influenced by solar irradiance and cell temperature," Computer Modelling and Simulation, UKSim, Cambridge, 2011, pp. 376 381.

[11] S.-M. Chen, T.-J. Liang, L.-S. Yang, and J.-F. Chen, "A safety enhanced, high step-up dc–dc converter for ac photovoltaic module application," IEEE Transactions on power electronics, vol. 27, no. 4, pp. 1809–1817, 2012.

[12] Y.-M. Chen, A. Q. Huang, and X. Yu, "A high step-up three-port dc dc converter for stand-alone pv/battery power systems," IEEE Transactions on Power Electronics, vol. 28, no. 11, pp. 5049–5062, 2013.

[13] B. Poorali, A. Torkan, and E. Adib, "High step-up z-source dc–dc converter with coupled inductors and switched capacitor cell," IET Power Electronics, vol. 8, no. 8, pp. 1394–1402, 2015.

[14] Salas V, Olı´as E, La´zaro A, Barrado A. Evaluation of a new maximum power point tracker (MPPT) applied to the photovoltaic stand-alone systems. Sol Energy Mater Sol Cells 2005; 87:807–15.

[15] Kawamura T, Harada K, Ishihara Y, Todaka T, Oshiro T, Nakamura H, Imataki M. Analysis of MPPT characteristics in photovoltaic power system. Sol Energy Mater Sol Cells 1997; 47:155–6

[16] P. K. Bonthagorla and S. Mikkili, "Performance analysis of PV array configurations (SP, BL, HC and TT) to enhance maximum power under non-uniform shading conditions," Eng. Reports, May, 2020.