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E-Mail :
editor.ijasem@gmail.com
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INTELLIGENT PHOTOVOLTAIC CONVERSION SYSTEM WITH CASCADED FUZZY MPPT FOR EFFICIENT DC POWER TRANSFER

RAUSHAN KUMAR¹, MD MOKIM ANSARI², KODI YOHAN³, GOLLA SATYANARAYANA⁴

¹Department of EEE, Godavari Institute of Engineering and technology (A), pandeyraushan343@gmail.com

²Department of EEE, Godavari Institute of Engineering and technology (A), ansarimdmokim1@gmail.com

³Department of EEE, Godavari Institute of Engineering and technology (A), yohankodi45@gmail.com

⁴Professor, Department of EEE, Godavari Institute of Engineering and technology (A), yohankodi45@gmail.com

ABSTRACT

Photovoltaic (PV) systems are increasingly being recognized as a crucial component in the transition towards sustainable energy. Traditional Maximum Power Point Tracking techniques, such as Perturb and Observe, Incremental Conductance, and Constant Voltage, have been widely used to optimize power extraction from PV modules. While these methods work well under stable conditions, they often struggle with dynamic environmental changes, leading to reduced performance and oscillations. In this, an intelligent photovoltaic conversion system with cascaded fuzzy MPPT for efficient DC power transfer. It features a transmitter side with Maximum Power Point Tracking (MPPT) control and a receiver side with Maximum Energy Point Tracking (MEPT) control. The system utilizes a transformer for efficient wireless energy transfer without the need for feedback communication. Key components include power electronic switches, capacitors, and inductors to enhance energy conversion and stabilization. Experimental results demonstrate improved energy efficiency and system reliability, contributing to sustainable solar energy utilization. A SEPIC-ZETA converter, which provides bidirectional voltage conversion (step-up and step-down) to maintain consistent output despite fluctuations in the PV array's input. A cascaded fuzzy MPPT algorithm dynamically optimizes the operating point for maximum power extraction under varying environmental conditions. A PWM generator produces precise switching signals for the converters, reducing switching losses and electromagnetic interference. An interleaved synchronous rectifier improves rectification efficiency by minimizing conduction losses. The PI controller regulates the system's output, maintaining voltage and current within optimal ranges.

1.INTRODUCTION

A photovoltaic (PV) system, also known as solar energy, represents a power conversion machine that converts sunlight directly into electricity through the photovoltaic effect. This process is based on the use of semiconductor materials (usually silicon) that produce electric current when burned. The concept of using solar energy is not new, but recent developments have increased the efficiency, affordability and effectiveness of photovoltaic systems and have made these systems the basis of modern electrical engineering ideas. A photovoltaic system consists of several main components: solar panels, inverter and sometimes battery storage. A solar panel or module consists of several solar cells that capture sunlight and produce direct current (DC) electricity. This power is then taken to an inverter, which converts the DC power into alternating current (AC) suitable for home and commercial use. In some installations, especially off-grid or hybrid systems, batteries are included to store excess energy for later use, providing continuous power even when the sun is out.

The evolution of photovoltaic technology has been driven by ongoing research and development, resulting in significant improvements in efficiency and cost. Early solar cells, developed in the 1950s, were relatively expensive and inefficient. However, advancements in materials science, manufacturing techniques, and system design have dramatically enhanced performance and reduced costs. Modern PV systems are capable of converting a larger fraction of sunlight into electricity, with some high-efficiency modules achieving conversion rates above 20%. Additionally, the cost of solar energy has decreased substantially, making it competitive with traditional fossil fuels and accelerating its adoption worldwide. As technology advances and costs continue to fall,

photovoltaic systems are set to become an even more integral part of our energy landscape, driving us toward a future powered by renewable resources.

2. LITERATURE SURVEY

This literature survey provides a comprehensive overview of the current state of research on intelligent photovoltaic conversion systems with cascaded fuzzy MPPT for efficient DC power transfer. It highlights the advantages of using fuzzy logic control in MPPT and discusses recent trends and future directions in this field. Photovoltaic (PV) systems are widely used for converting solar energy into electrical energy. However, the efficiency of PV systems is highly dependent on environmental factors such as solar irradiance, temperature, and shading. To maximize the power output from PV systems, Maximum Power Point Tracking (MPPT) techniques are employed. MPPT algorithms ensure that the PV system operates at its maximum power point (MPP) under varying conditions.

Mohammadreza Aghaei *et al* [2022] have proposed Simulations of Luminescent Solar Concentrator Bifacial Photovoltaic Mosaic Devices Containing Four Different Organic Luminophores.

Robin Grab *et al* [2022] have proposed Modelling of Photovoltaic Inverter Losses for Reactive Power Provision.

William P. Lamb *et al* [2022] have proposed Real Time Anticipation and Prevention of Hot Spots by Monitoring the Dynamic Conductance of Photovoltaic Panels.

J. C. Colque *et al* [2023] have proposed Fault-Tolerant Strategy for the MMC-Based PV System With Faults Detection and Converter Reconfiguration Using Permutation Algorithms.

Hyunjae Lee *et al* [2024] have proposed Sensor less MPPT Considering Power Loss Factors for DPP Structure in Photovoltaic Generation System.

Stefano Cerutti *et al* [2024] have proposed Modelling and Design of a Zero-Voltage Switching Battery Charger for Photovoltaic Applications.

3. PHOTOVOLTAIC SYSTEM

Photovoltaic (PV) systems, also known as solar power systems, represent a ground-breaking advancement in the quest for sustainable and renewable energy. At their essence, PV systems convert sunlight directly into electricity through the photovoltaic effect, utilizing semiconductor materials such as silicon. This technology, though rooted in scientific principles that date back over a century, has evolved dramatically in recent decades, enabling it to become a cornerstone of modern energy solutions. To fully appreciate the significance and complexity of photovoltaic systems, it's essential to delve into their components, principles, technological advancements, environmental impacts, challenges, and future prospects. The fundamental operation of a photovoltaic system begins with solar panels, or modules, which are composed of multiple solar cells. Each solar cell is made of a semiconductor layer that produces an electric current when exposed to sunlight. The most common material is silicon, which comes in two types: single crystal and polycrystalline.

Monocrystalline silicon cells are made from a single continuous crystal and are therefore more plentiful but also more expensive. Polycrystalline silicon cells, made from multiple silicon crystals, are less costly but have slightly lower efficiency. Each type has its advantages and disadvantages, and the choice between them depends on various factors including cost, space, and efficiency requirements. Monocrystalline silicon cells are highly efficient photovoltaic cells made from a single, continuous crystal structure. They exhibit better performance than polycrystalline cells, especially in low-light conditions. Their efficiency ranges from 15% to 22%, making them one of the most efficient solar technologies. Monocrystalline cells also have a long lifespan, typically lasting over 25 years. Despite their higher cost, they are widely used in residential and commercial solar installations due to their superior energy output and space efficiency.



Figure 1:Photovoltaic system

The environmental benefits of photovoltaic systems are significant. Solar energy is a clean, renewable resource that produces electricity without generating electricity or other pollutants. This is in contrast to fossil fuel-based energy production, which is a major source of air pollution and carbon emissions. Photovoltaic systems help reduce climate change and improve air quality by reducing reliance on fossil fuels. Solar energy also requires less water for cooling than traditional power plants, which typically use more water. This makes photovoltaic systems particularly useful in arid regions where water is scarce. Some PV systems, especially those designed for off-grid use or for energy independence, include batteries to store excess energy. These solutions make energy available during periods when there is no sunlight, such as at night or on cloudy days. The environmental benefits of photovoltaic systems are significant. Solar energy is a clean, renewable resource that generates electricity without generating electricity or other pollutants. This is in stark contrast to fossil fuel-based energy production, which is a major source of air pollution and carbon emissions.

3.1 COMPONENTS OF PHOTOVOLTAIC SYSTEM

Photovoltaic (PV) systems consist of several components that work together to capture sunlight and convert it into usable electricity. Each component plays a key role in ensuring the efficiency, effectiveness, and longevity of the system. Here are the key terms, their functions, and their importance:

SOLAR PANELS: STRUCTURE, FUNCTION, AND TYPES

Solar cells: The core component of a solar panel, made from semiconductor materials like silicon. They are arranged in layers to absorb sunlight.

Encapsulation: Solar cells are sandwiched between layers of protective material, usually ethylene-vinyl acetate (EVA), which protects them from environmental damage.

Frame: Solar panels are typically encased in a durable aluminum frame to provide structural support and allow for mounting on rooftops or ground-based systems.

Glass cover: The front of the solar panel is covered with tempered glass, allowing sunlight to pass through while protecting the internal components from harsh weather conditions.

Back sheet: A protective layer on the rear of the panel that helps prevent moisture and environmental contamination from entering the system.

Function: Solar panels convert sunlight into direct current (DC) electricity using the photovoltaic effect. When sunlight hits the PV cells, electrons are knocked loose from the atoms in the semiconductor material, generating an electric current. The electricity generated by these panels is then sent to an inverter for conversion to alternating current (AC), the form of electricity used in homes and businesses.

3.2 TYPES OF SOLAR PANELS:

Monocrystalline Solar Panels: Made from a single continuous crystal structure, these panels are known for their high efficiency and space-saving design, but they are typically more expensive.

Polycrystalline Solar Panels: Composed of many fragments of silicon crystals melted together, these panels are less efficient than Monocrystalline but more affordable.

Thin-Film Solar Panels: These panels use layers of photovoltaic materials that are much thinner than crystalline silicon cells. They are flexible and lightweight, making them ideal for certain applications, though they have lower efficiency and shorter lifespans.

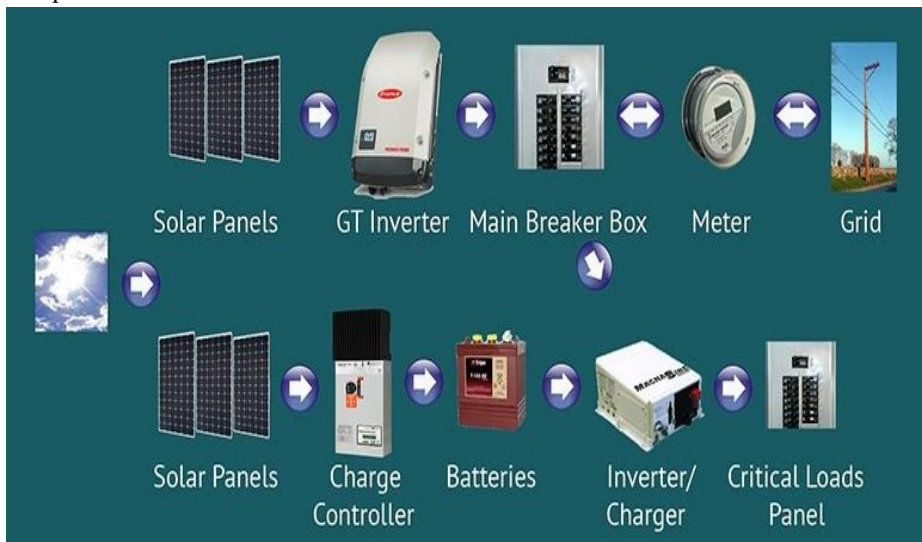


Figure 2: Components of photovoltaic systems

3.3 INVERTERS: DC TO AC CONVERSION

Role of Inverters: Inverters are a crucial component in any PV system. They convert the direct current (DC) electricity generated by solar panels into alternating current (AC), which is the type of electricity used by most household appliances and for grid distribution. Without an inverter, the electricity produced by the solar panels cannot be used directly by the electrical grid or most electronic devices.

Types of Inverters:

String Inverters: These inverters are connected to a series of solar panels (a string). They are cost-effective but can suffer efficiency losses if one panel underperforms (due to shading or damage), as the performance of all panels in the string is affected.

Microinverters: Installed at the individual panel level, microinverters optimize the power output of each solar panel independently. This improves overall system performance, especially in cases of shading or panels facing different directions.

Hybrid Inverters: These inverters work with both solar energy and battery storage, allowing systems to store excess energy and use it when needed.

4. MOUNTING STRUCTURES AND TRACKING SYSTEMS

Mounting Structures:

Roof-mounted systems: Solar panels can be mounted on roofs using various brackets and frames. The tilt angle and orientation of the panels are adjusted to maximize exposure to sunlight.

Ground-mounted systems: These systems are installed on the ground and are often used for large-scale solar farms or when roof space is insufficient. Ground-mounted systems allow for greater flexibility in panel positioning and are easier to maintain.

Tracking Systems:

Fixed-tilt systems: Panels are installed at a fixed angle, optimized for the location's latitude to maximize sunlight exposure throughout the year.

Single-axis trackers: These systems allow the panels to follow the sun's path from east to west during the day, increasing energy capture by up to 20-30%.

Dual-axis trackers: These systems adjust the panels to follow both the sun's horizontal and vertical movements, capturing even more sunlight. However, they are more expensive and have higher maintenance requirements.

Significance of Mounting and Tracking Systems: Mounting structures provide stability and ensure the panels are positioned correctly for maximum exposure to sunlight. Tracking systems further enhance energy capture by allowing panels to follow the sun, especially in areas with high solar radiation.

5. RESULTS AND DISCUSSIONS

OVERALL SIMULATION DIAGRAM:

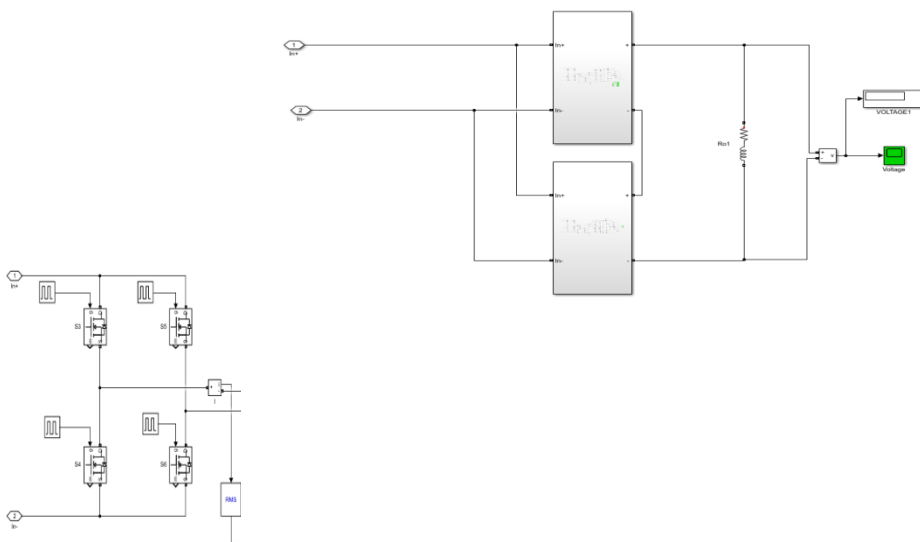
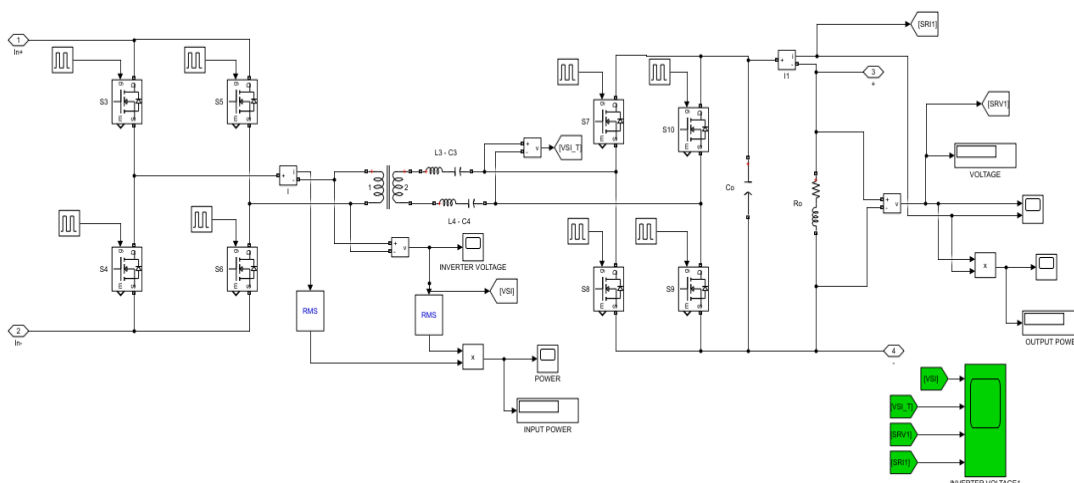


Figure 3:Overall Simulation Diagram



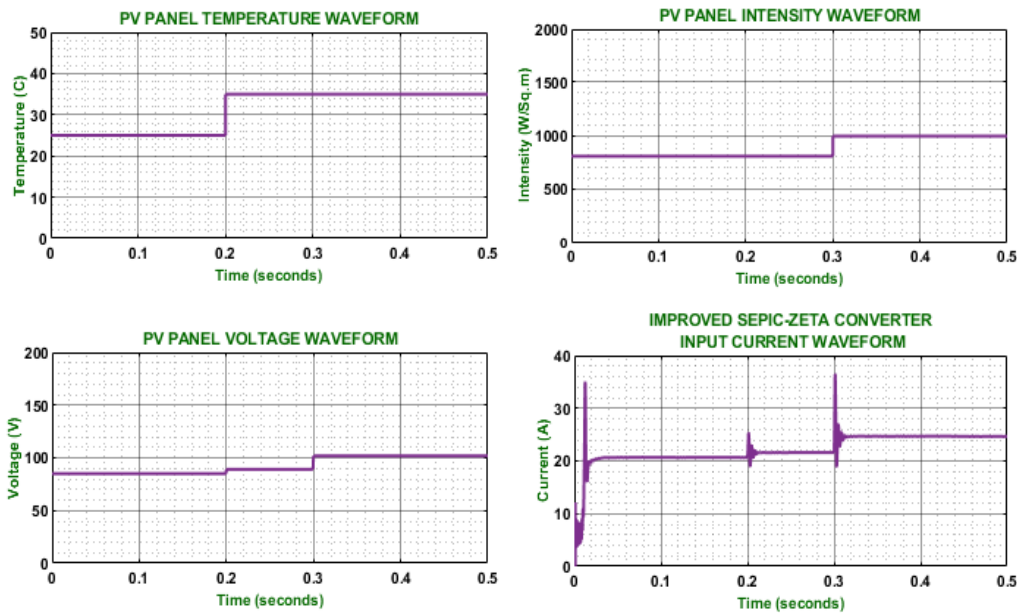


Figure 4: PV Panel Performance Waveforms

Figure 4: represents distinct waveforms related to photovoltaic (PV) panel performance. The top left graph illustrates the temperature of the PV panel over time, while the top right shows the intensity measured in watts per square meter. The bottom left graph represents the voltage output of the PV panel, indicating its electrical potential. Finally, the bottom right graph depicts the input current waveform of an improved SEPIC-Zeta converter. Together, these graphs provide insights into the operational dynamics of the PV system under varying conditions.

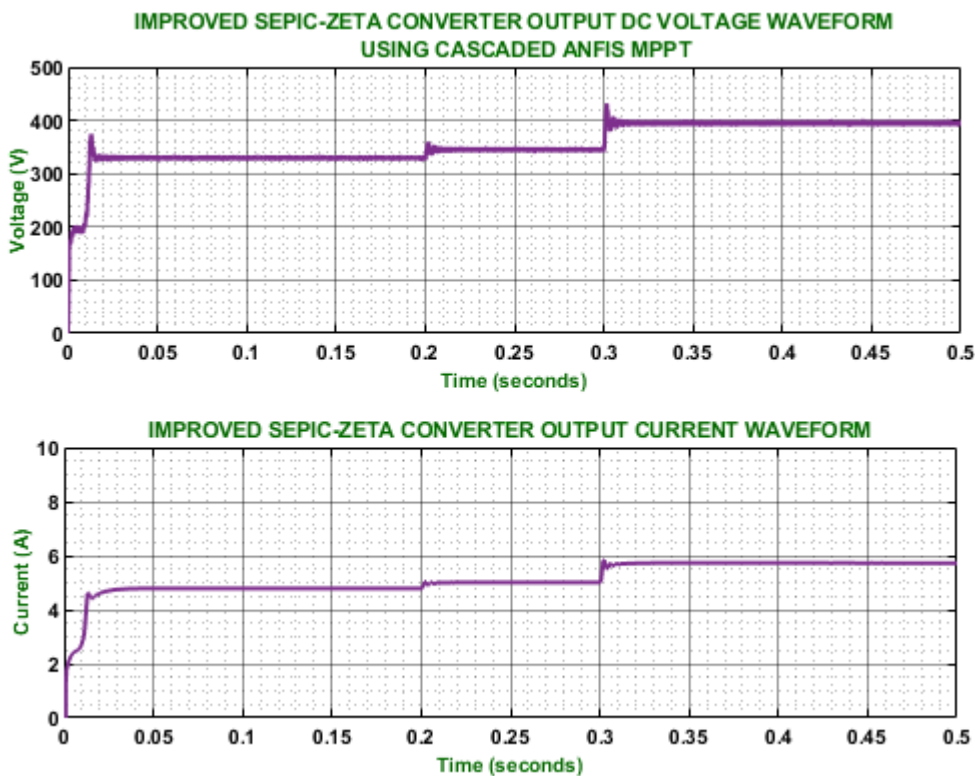


Figure 5: Improved SEPIC-Zeta Converter Output Waveforms

Figure 5: represents two key waveforms related to the output of an improved SEPIC-Zeta converter employing a cascaded ANFIS Maximum Power Point Tracking (MPPT) approach. The top graph illustrates the DC voltage output over time, demonstrating a stable voltage level around 300 V with minimal fluctuations. The bottom graph showcases the output current waveform, which indicates a consistent current flow. Both graphs highlight the converter's effective performance in managing voltage and current during operation. This analysis is crucial for optimizing photovoltaic energy conversion systems.

6. CONCLUSION

In conclusion, this intelligent photovoltaic conversion system with cascaded fuzzy MPPT demonstrates a significant advancement in optimizing energy efficiency and system reliability for solar power applications. By incorporating Maximum Power Point Tracking (MPPT) on the transmitter side and Maximum Energy Point Tracking (MEPT) on the receiver side, the system effectively maximizes power extraction from the PV array while ensuring stable energy transfer. The use of a SEPIC-ZETA converter enables bidirectional voltage conversion, accommodating input fluctuations without compromising output consistency. The dynamic optimization provided by the cascaded fuzzy MPPT algorithm adapts to varying environmental conditions, enhancing the system's adaptability. Additionally, the PWM generator reduces switching losses and electromagnetic interference, while the interleaved synchronous rectifier minimizes conduction losses, further improving efficiency. The PI controller ensures that the system's output remains stable and within optimal voltage and current ranges. Experimental results confirm the effectiveness of this system in achieving higher energy conversion efficiency and sustainable solar energy utilization, making it a promising solution for future photovoltaic applications.

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