Optimized Power Extraction Techniques for Solar Photovoltaic Arrays

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Abstract: Due to the high initial investment and relatively low energy conversion efficiency of Solar Photovoltaic (SPV) systems, it becomes crucial to operate these systems at their Maximum Power Point (MPP) to ensure optimal energy extraction. This paper explores methods for maximizing power output from SPV arrays (SPVA), particularly under conditions where some solar cells are partially shaded and do not receive uniform sunlight. It also examines the impact of array reconfiguration and load tracking on enhancing power generation efficiency.

Key words- Solar Photovoltaic, Maximum Power Point,

I. INTRODUCTION

The primary aim of this study is to explore the design and implementation of an innovative approach for detecting faults and analyzing degradation in photovoltaic (PV) systems. Although a range of fault detection techniques have been developed for PV installations, they generally rely on multiple system parameters such as voltage, current, power output, and the series resistance of PV modules. In addition, these methods often require environmental inputs like ambient temperature and solar irradiance. However, such comprehensive data is not always accessible at many PV installation sites. Therefore, there is a need to enhance current fault detection methodologies to function effectively with limited PV and environmental data [1].

This research addresses that gap by focusing on algorithms that utilize only key electrical parameters—specifically voltage and power ratios—for identifying faults. Unlike previous studies that were based solely on controlled laboratory experiments, this work aims to provide insights that are applicable to real-world scenarios by using long-term, field-based measurements from PV modules deployed at different locations. The paper is structured in two main parts. First, it introduces the development of various PV fault detection strategies, categorized into three primary groups: (i) mathematical and statistical models, (ii) fuzzy logic-based systems, and (iii) artificial neural network (ANN)-based approaches. The second major contribution of this work is the development of novel techniques for mitigating hot spots in PV systems [2].

I.1 ACTIVE POWER FILTERS (APF) PHOTOVOLTAIC ENERGY SYSTEM

The output generated by a solar photovoltaic (PV) cell is direct current (DC). The magnitude of the current depends on both the cell's surface area and the intensity of the incident sunlight. Each individual silicon PV cell typically produces a voltage of about 0.5 volts. To achieve a usable voltage level, multiple cells are connected in series to form a module.

PV systems are commonly utilized in three primary areas:

- Satellite Applications – Solar panels supply power to satellites in space.
- Off-Grid Applications – Solar power is used in remote areas that lack access to the electrical grid.
- Grid-Connected Applications – Solar energy is used to serve both local loads and feed into the public electricity grid.

At the core of any solar PV power management system is the DC-DC converter. In applications like satellite or telecom systems—where the goal is to charge batteries or stabilize a DC bus—a DC-DC converter alone is sufficient, as illustrated in Figure 1.

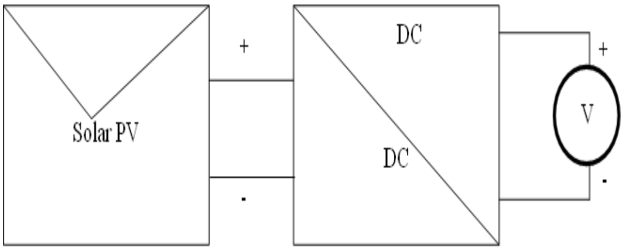


Figure 1: Basic element of power conditioning system

The efficiency of solar photovoltaic (PV) systems used in space satellites largely hinges on the performance of the DC-DC power conditioning stage. To ensure optimal power transfer and system reliability, it is critical to design a highly efficient DC-DC converter that suits solar PV applications. However, the inherent non-linear behavior of the DC-DC converter, particularly when used in Maximum Power Point Tracking (MPPT) systems, can degrade the overall performance of the PV system, causing unstable and inefficient operation. Moreover, for reliable operation, the converter must maintain a stable input voltage even under fluctuations in source voltage or changes in solar irradiance. Motivated by these challenges, this research focuses on a PV-powered MPPT system utilizing a DC-DC Ćuk converter. The primary objectives of the study are as follows:

- To develop a fault detection technique for identifying defective bypass diodes in PV modules.
- Although bypass diodes are widely incorporated into PV modules to improve power output during partial shading conditions, there is a significant research gap in identifying faults in these diodes.
- This work introduces a fuzzy logic-based classification system for detecting bypass diode faults, which relies on analyzing parameters such as voltage drop (V_{drop}), open-circuit voltage (V_{oc}), and short-circuit current (I_{sc}) derived from the I-V characteristics of the PV module under inspection.

H. H. Khaing et al. [1] introduced a variable step-size incremental conductance MPPT method for photovoltaic (PV) systems, designed to optimize power extraction by dynamically adjusting the step size to accurately track the maximum power point (MPP) of the PV array. In a separate study, Y. Zhao et al. [9] presented a methodology for the modeling and emulation of PV module clusters. Meanwhile, M. Z. S. El-Dein et al. [10] showed that conventional buck and boost converters are inadequate for replicating the complete I–V characteristics of PV generators. Further work by Y. Zhao et al. [11] involved the development of a PV charger system using a SEPIC converter, with both modeling and control strategies addressed. Additionally, Y. Zhao et al. [12] conducted a bifurcation analysis on a current-controlled Luo converter operating in continuous conduction mode, employing a continuous-time modeling approach.

II. PROBLEM FORMULATION

There are various types of solar photovoltaic (PV) cells, but the most widely used and commercially available ones include monocrystalline, polycrystalline, and amorphous silicon cells. According to PV Magazine (2021), the energy conversion efficiency of these technologies typically falls within the following ranges:

- Monocrystalline cells: 13% to 25%
- Polycrystalline cells: 10% to 20%
- Amorphous silicon cells: 6% to 13%

Silicon photovoltaic (PV) cells generally generate around 0.5 volts each. To achieve a higher voltage suitable for practical use, multiple cells are connected in series, forming a PV module. When several of these modules are linked in series, they create what is known as a PV string. Multiple PV strings are then combined to form a PV array. The configuration of the modules within a string is based on the desired output voltage of the array, while the number of strings determines the current capacity. To protect the system and improve reliability, most PV arrays include bypass diodes. These diodes are typically installed in parallel with individual modules or groups of modules to prevent power loss and damage during shading or faults. This diode functions to allow current flow when one or more modules are either damaged or partially shaded. Additionally, a blocking diode is typically installed in series with each string to stop reverse current flow and safeguard the modules. The configuration of the PV array is illustrated in Figure 2.

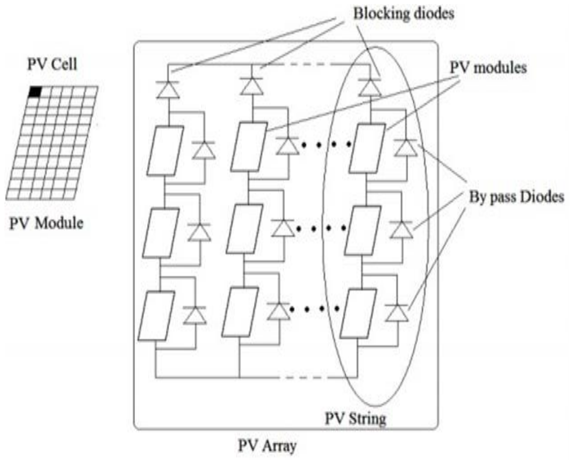


Figure 2: PV Array configurations

The P-V and I-V characteristic curves of the PV module under different values of solar irradiation and temperature are shown in Figures 3.

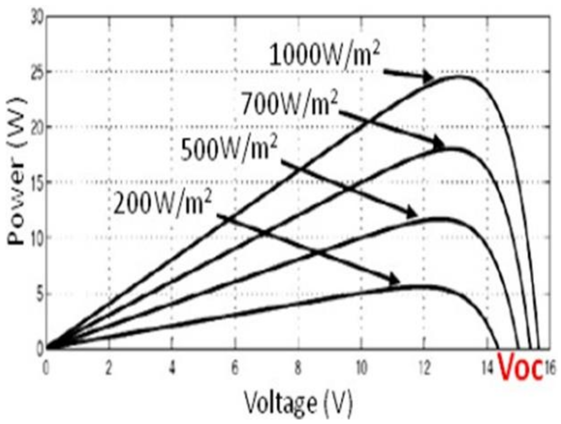


Figure 3: The P-V and I-V characteristics curve at different irradiation levels and a constant temperature (250C) condition

The electrical performance of a photovoltaic (PV) cell is primarily influenced by the amount of solar irradiance it receives and its operating temperature. Figure 4 illustrates how the cell's electrical behavior varies with different irradiance levels while maintaining a constant temperature. It is evident that variations in irradiance significantly impact the short-circuit current (Isc) and the cell's output power, whereas the open-circuit voltage (Voc) remains largely unaffected.

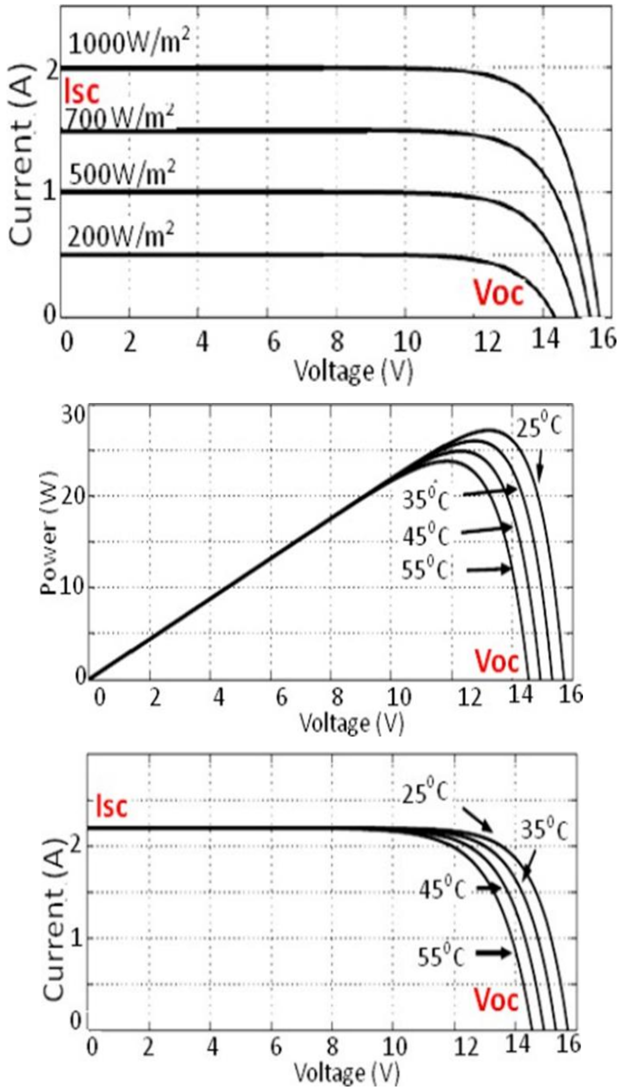


Figure 4: The P-V and I-V characteristics curve at different temperature levels and a constant irradiation (1000 W/m2) condition

III. METHODOLOGY

A boost converter, also known as a step-up converter, is a type of DC-to-DC power converter that increases the input voltage to a higher output voltage. It belongs to the switched-mode power supply (SMPS) category and typically includes at least two semiconductor devices—usually a diode and a transistor—along with one or more energy storage components, such as inductors, capacitors, or a combination of both. To minimize output voltage ripple, filtering components—often capacitors and sometimes inductors—are added to the converter's output stage.The diode blocks the flow of current and so the load current remains constant which is being supplied due to the discharging of the capacitor. The model is shown in Figure 5.

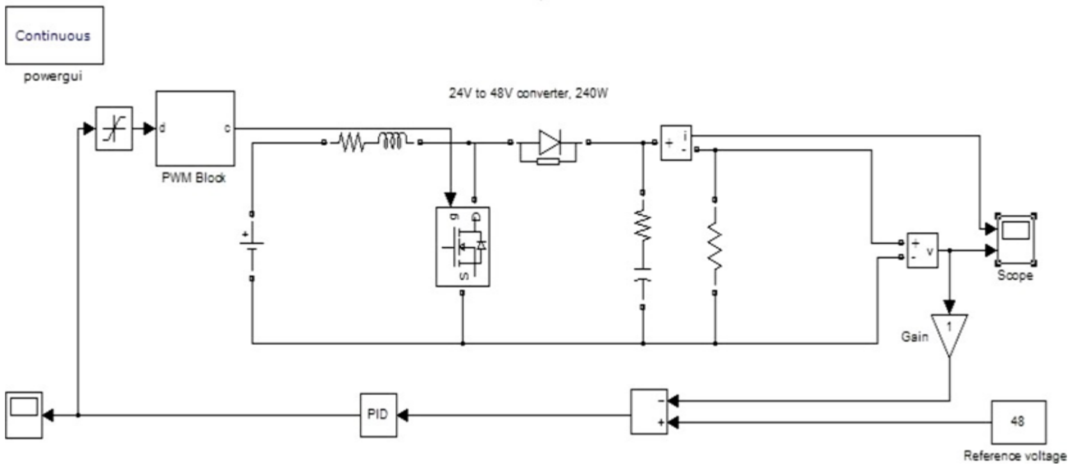


Figure 5: Simulation Model of Closed Loop Boost Converter

The switch is open and so the diode becomes short circuited. The energy stored in the inductor gets discharged through opposite polarities which charge the capacitor. The load current remains constant throughout the operation.

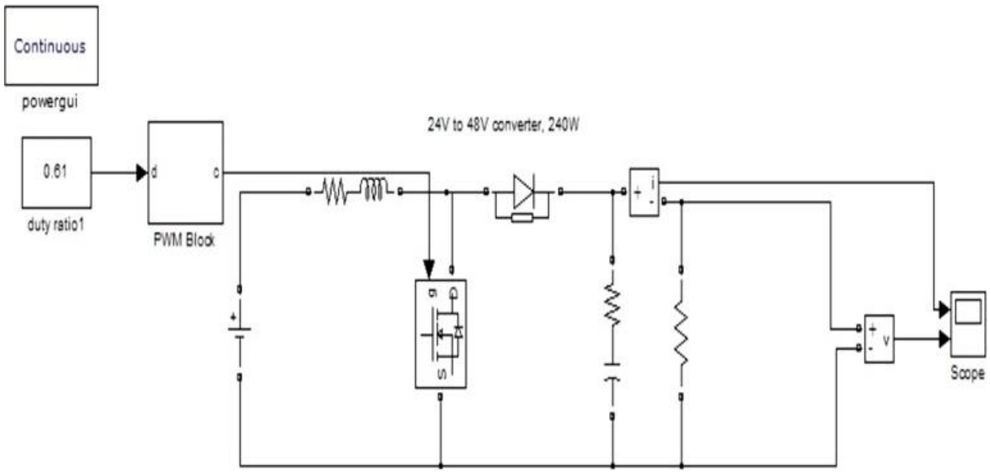
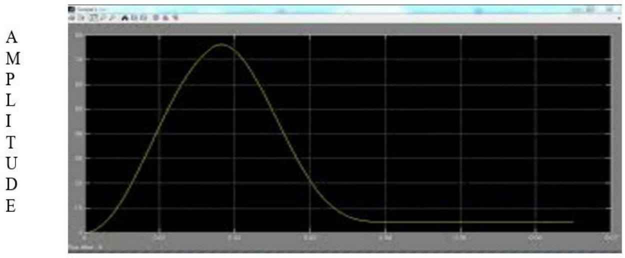


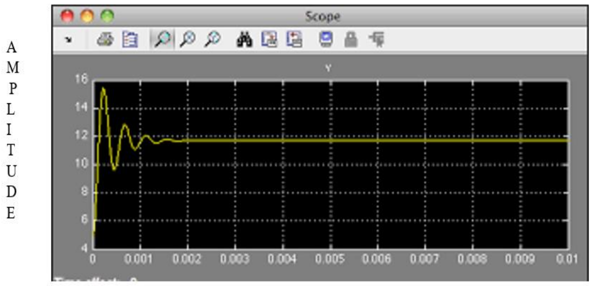
Figure 6: Simulation Model of Open Loop Boost Converter

IV. RESULTS AND ANALYSIS

In Figures 7 and 8, the key factor limiting the highest possible output voltage of a boost converter is the maximum voltage rating of components like the MOSFET and the diode. These ratings are clearly mentioned in their datasheets and should be among the first considerations when selecting a suitable converter for any application. However, from a practical standpoint, another important constraint is the maximum duty cycle the converter can support. The duty cycle refers to the ratio of the MOSFET's on-time to the entire switching period. In all types of DC/DC converters, the output voltage is directly influenced by this duty cycle.



Voltage



Current

Figure 7: Open Loop Control Characteristics of Boost Converter

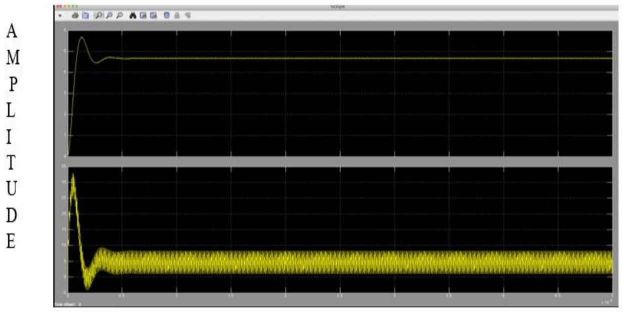


Figure 8: Closed loop control characteristics of Boost Converter

A single solar cell typically generates a low voltage of about 0.5 volts. To obtain a higher and usable output, multiple solar cells are connected in series and parallel configurations. When some parts of the array are shaded, diodes are often used to prevent reverse current flow, which could damage the system. Additionally, proper ventilation is maintained behind the solar panels to help dissipate heat, as high temperatures can reduce their efficiency.

V. CONCLUSION

This study introduces a fault detection approach for identifying defective bypass diodes in photovoltaic (PV) modules. The proposed method utilizes a Mamdani-type fuzzy logic system, which analyzes key parameters—namely the voltage drop (Vdrop), open-circuit voltage (Voc), and short-circuit current (Isc)—derived from the I-V characteristics of the PV module under test. The fuzzy logic system operates based on three input variables: the percentage voltage drop (PVD), the percentage of open-circuit voltage (POCV), and the percentage of short-circuit current (PSCC). With this framework, the system is capable of diagnosing up to 13 distinct fault types related to both functional and faulty bypass diodes.

The detection system demonstrated high accuracy during the validation phase. Furthermore, the fuzzy logic-based approach was tested on two distinct PV modules installed at the University of Huddersfield. Lastly, the temperature variations of the PV modules were analyzed under conditions involving faulty bypass diodes and partial shading.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

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