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A COMPARATIVE ANALYSIS OF BOOST CONVERTER TOPOLOGIES FOR PHOTOVOLTAIC SYSTEMS USING MAXIMUM POWER POINT (P&O) AND BETA METHODS UNDER PARTIAL SHADING

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Keywords: Photovoltaic (PV) system; Maximum power point tracking (MPPT); Dc-dc converter; Topologies; Beta method.

Photovoltaic systems have become a popular renewable energy source due to their many benefits. Optimizing PV systems requires efficiently extracting the maximum power point. This can be achieved by optimizing maximum peak power tracking algorithms or testing different PV system topologies. In this paper, different topologies of dc/dc converters with two MPPT algorithms (Beta and perturb and observe) are tested to control the duty ratio of the converters. At first, the modeling of different DC/DC converter topologies to optimize the maximum power point tracking efficiency of photovoltaic systems is achieved. The simulation results show that the Beta algorithm gives a higher accuracy and efficiency than the P&O algorithm, especially in low oscillations with fast convergence speed. According to the findings, a parallel arrangement of boost converters is usually preferable to a series arrangement, especially for following changes in irradiance.

1. INTRODUCTION

Air pollution, global warming, and other environmental challenges have afflicted the world in recent decades due to the uncontrolled huge use of oil and carbon as energy sources. As a result, clean energy sources have emerged as a viable solution to the current difficulties, and they offer inherent environmental benefits. Solar energy, acquired by photovoltaic (PV) array systems, is the most extensively used power source [1].

Photovoltaic technology is rapidly gaining attention as a viable renewable energy option worldwide. Peak power extraction from a PV system is an important task due to the nonlinear behavior of the PV output power curve. In addition, the power converter's architecture largely sets a PV system's essential properties, such as the number and arrangement of PV modules. It also calculates the effects of module mismatch and partial shading on energy output. Also, the cost and efficiency of the PV system are affected by the architecture used, leading to varying degrees of energy output and cost. Hence, understanding the various types of architecture is vital in selecting the appropriate one for a specific PV installation [2].

Moreover, the reduction of output power in PV modules can be attributed to many factors, but the most important are maximum power point (MPP) mismatch and shadows [3]. Photovoltaic module's output is very sensitive to both temperature and irradiation. So, it is important to know the behavior of the PV system under shaded conditions. However, several important considerations must be considered [4].

The effectiveness of PV solar panels might decrease if their output current and voltage decrease due to weather conditions. As a result, the PV systems need a power conversion stage to adapt the transfer of the available power to the load via a maximum power point tracking controller [5]. The MPP tracker is a necessary controller for increasing the available power from a PV system to increase the efficiency of the PV system. Several MPP methods to achieve better maximum power extraction have been proposed in the literature [6]. These algorithms aim to achieve maximum power output from solar photovoltaic systems under varying weather conditions. The MPPT algorithm can optimize the PV array output to attain optimal performance by modifying the converter's duty cycle. Several MPPT algorithms are available to achieve the best panel voltage and current combination for optimal performance. Various conventional algorithms have been suggested to enhance the efficacy of solar photovoltaic systems, including adaptive hill climbing [7], P&O [8], Incremental conductance with variable step size [9], and the conventional Beta method [10]. To address the drawbacks of traditional methods, numerous nature-inspired algorithms have been proposed in the literature, such as genetic algorithm [11], simulated annealing [12], particle swarm optimization (PSO) [13], and others [14,15].

Hybrid approaches are also used widely to achieve the maximum peak power. the data optimized by genetic algorithms have been used to train the neural network. [16,17]. A new hybrid fuzzy-neural approach is presented in [18], while a neuro-fuzzy IC variable step size approach is proposed in [19]. In addition, several research studies have been conducted to analyze different topologies of PV systems among them [20,21].

In this research paper, we aim to compare two MPPT algorithms – Beta and perturb and observe (P&O) – that they regulate the duty cycle of dc/dc converters with different topologies, including series and parallel. We aim to identify the most effective MPPT method that provides the required performance characteristics, such as high precision, low steady-state fluctuations, high dynamics, and fast maximum power point (MPP) monitoring. We will also determine which option is the most cost-effective.

The results show that the Beta MPPT technique outperforms the P&O approaches in tracking the MPP with minimal oscillations and quick speed, even when the irradiation changes suddenly. This method's potential in terms of dynamic response speed and tracking factor has yet to be fully realized. The original beta approach must be improved by determining the ideal scaling factor and identifying the parameter range for various weather circumstances.

Several photovoltaic (PV) system topologies are studied using the MATLAB/Simulink software. Partially shaded PV systems are discussed, and output voltage, current, and power graphs are shown. The results of this study can be

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used to make well-informed decisions about the optimal location for a solar system and the optimal maximum power point tracking (MPPT) method to employ.

This paper is organized into the following sections. In section 2, the methodology used and the mathematical models of both the PV module and the dc/dc boost converter will be presented. Section 3 will detail the implementation of the MPPT technique employed. Section 4 will introduce various topologies proposed for testing and selecting the most suitable one for our PV system. Section 5 will present the simulation outcomes and provide a comparative analysis between different dc/dc converter topologies with MPPT regulators, utilizing both the Beta and P&O methods, under partial shading. Finally, the last section will provide the conclusions.

2. METHODOLOGY

We aim to compare two MPPT algorithms for different dc/dc converter topologies to extract the maximum peak power. Hence, the adopted methodology is represented in Fig. 1. We used a converter series configuration consisting of two photovoltaic (PV) modules and two dc/dc converters interconnected in series, with each converter model identical to the string converter model. An MPPT controller governed the system – the same methodology of steps in parallel configuration.

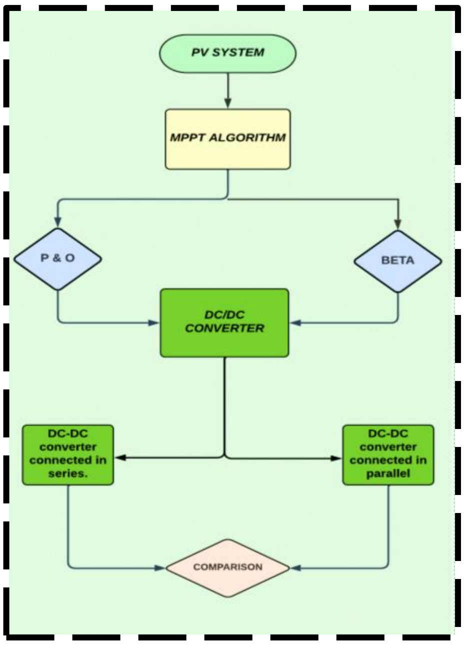

Fig. 1 – Flowchart of the proposed methodology for PV systems.

2.1. PV MODULE

A simplified equivalent circuit model can be used to model a PV cell, where the practical model of a photovoltaic cell includes the addition of resistances R_{sh} and R_s to the circuit, as shown in Fig. 2. The single diode PV model is the preferred choice in this study due to its simplicity, characterized by a reduced number of equations and parameters in comparison to the more complex two-diode PV model [22,23]. The current generated by the PV panel is expressed as [24,25]:

$$I = I_L - I\,[\exp\left(\frac{q(V+R_s\ I)}{K.T}\right) - 1] - \frac{(V+R_s\ I)}{R_{sh}}. \qquad (1)$$

The current flowing through the diode can be expressed as

$$I_D = I\,[\exp\left(\frac{q(V+R_s\ I)}{KT}\right) - 1]. \qquad (2)$$

The current output of the solar cell can be expressed as:

$$I = I_L - I_D - I_{sh}. \qquad (3)$$

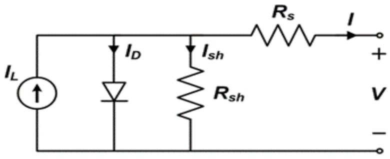

Fig. 2 – The electrical equivalent circuit model of a single-diode PV cell.

The solar cell's output current (I) is dependent on various factors, including the diode saturation current I_D, solar cell series resistance (R_s), electron charge (q), Boltzmann's constant (K), cell temperature (T), light-generated current (I_L), solar cell's output voltage (V), and shunt resistance (R_{sh}). This paper examines the SPR-305E-WHT-D solar panel and its performance under standard testing conditions (STC) of 25 °C and 1 KW/m2, as shown in Table I.

The Photovoltaic module's *P-V* and *I-V* characteristics were measured at various irradiance levels and 25°C, as illustrated in Fig. 3.

Table 1

The characteristics of the PV module.

Information	Value
Maximum power	305.226 W
Current at MPP	5.58A
Voltage at MPP	54.7V
Short circuit current	5.96A
Open circuit voltage	64.2V
Parallel strings	66
Series-connected modules per string	5

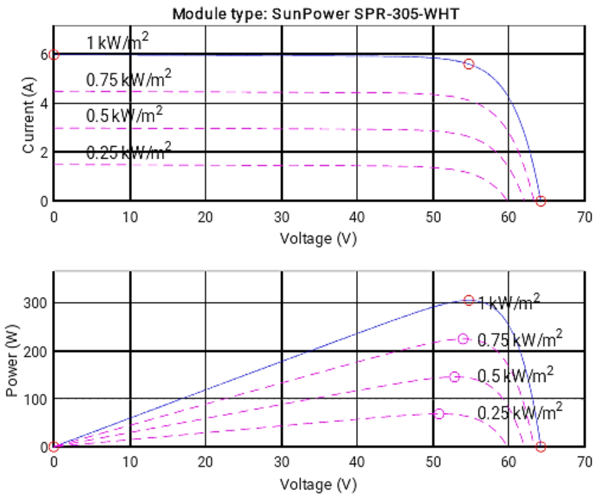

Fig. 3 – The *P-V* and *I-V* photovoltaic module's characteristics were measured at 25 °C and different levels of irradiance.

2.2. DC/DC BOOST CONVERTER

2.2.1. ANALYSIS OF DC/DC CONVERTER

The boost converter is a fundamental type of DC/DC converter that can electronically adjust the transformation ratio by changing the duty cycle between 0 and 1. Its design is founded on the standard relationship between the input signal, output voltage, and duty ratio. The output power is given in eq. (1)

$$V_{out} = 1/(1-\alpha) \times V_{in}, \qquad (4)$$

where V_{in} is the voltage supplied to the input of the converter; V_{out} is he voltage supplied to the output of the converter, and α is the duty cycle of the 's' switch. Figure 4 illustrates the electrical circuit diagram of the boost converter.

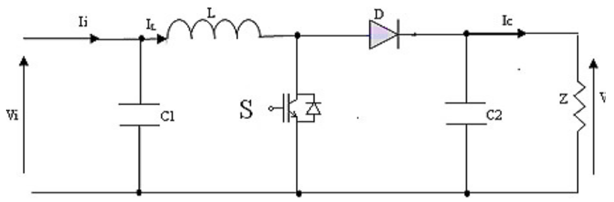

Fig. 4 – Electrical configuration of the boost power converter [20].

A dc-dc power switching converter is commonly used in solar systems for converting direct current power between different voltage levels. It is also commonly used in maximum power point trackers to optimize the energy conversion process.

2.2.2. CONTROL OF DC/DC CONVERTER

The dc-dc converter control strategy is determined by computing the optimal input voltage reference to extract maximum power from the PV array. An MPPT algorithm is employed to set the voltage reference. It detects the changes in PV array power to determine the appropriate voltage reference. These systems are installed near the PV module and distribute the energy extracted from it. Forecasting studies are conducted for photovoltaic applications.

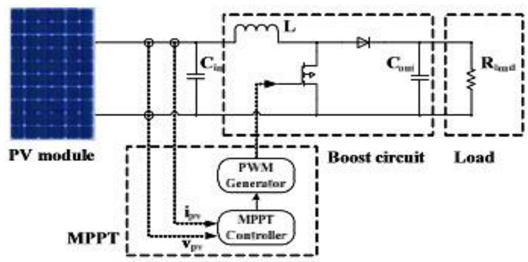

Fig. 5 – PV array with MPPT control [26].

3. **MPPT TECHNIQUES**

The MPPT may be implemented in several ways, each with its own pros and cons related to speed, cost, and efficiency. In this paper, two MPPT algorithms are examined, namely the P&O and the Beta techniques. To maximize power point tracking, the system's suggested algorithm immediately modifies the dc/dc converter's duty cycle based on successive current and voltage measurements. These metrics impact the control system's precision and performance.

3.1. PERTURB AND OBSERVE METHOD

The "perturb and observe" method is an algorithm used in MPPT for photovoltaic systems.

The algorithm works by perturbing the converter's duty cycle and observing the effect on the output power. The duty cycle is then adjusted in the direction that increases the output power until the MPP is reached. The algorithm continues to adjust the duty cycle in small increments until the MPP is achieved and then maintains the duty cycle at that point. This method is widely used due to its simplicity and effectiveness in extracting maximum power from photovoltaic systems under varying environmental conditions. While the P&O method is simple and easy to implement, it has some limitations. For example, it may fail to track the MPP accurately under partial shading conditions and suffer from oscillations and steady-state errors in rapidly changing weather conditions.

3.2. CONVENTIONAL BETA METHOD

Jain and Agarwal [5] originally suggested the Conventional Beta technique. The fundamental tenet of this technique is to monitor an intermediate variable β_a, regardless of a change in power. The equation below can be used to represent the intermediate variable β_a

$$\beta_a = \ln(I_{pv}/V_{pv}) - c \times V_{pv}. \tag{5}$$

The output voltage of the PV module is denoted by V_{pv}, and its output current is denoted by I_{pv}. A constant diode c can be expressed as follows:

$$c = q\ (N_s AKT), \tag{6}$$

where $q = 1.6\times10^{19}$ C is the charge of an electron; $K = 1.38\times 10^{-23}$ J/K is Boltzmann's constant, A is the diode's ideality factor; N_s is the PV module cell number, and T is the p-n junction's temperature (in Kelvin).

The Beta method involves two stages: the transitory and steady-state stages, which adjust to the variable and fixed step sizes. To implement the Beta method, the ranges of β_{min} and β_{max} must be identified, and the algorithm should calculate β_g itself. First, a PV module's voltage and current output are measured, then the actual values are continuously calculated. If β_a falls between (β_{min}, β_{max}), the Beta method enters the steady-state stage, and the P&O method is implemented. Otherwise, the Beta method enters the transient stage, where a guiding parameter β_g) is used to compute the variable step size ΔD, expressed as:

$$\Delta D = N \times (\beta_a - \beta_g). \tag{7}$$

The parameter range (β_{min}, β_{max}) and the parameter β_g are determined using the scaling factor N, where the range of β is dependent on the environmental conditions of the PV module, such as the irradiance and temperature.

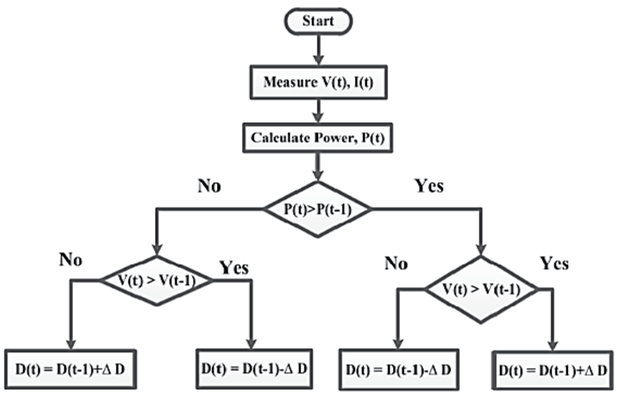

Fig. 6 – Flowchart for P&O method [27].

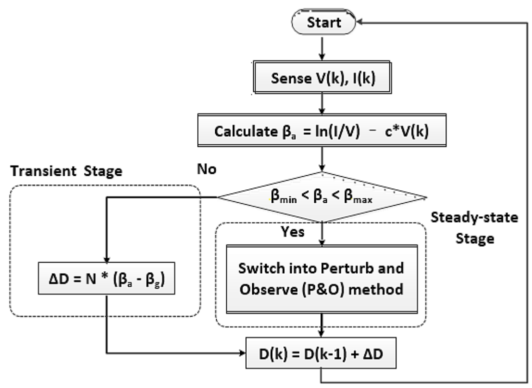

Fig. 7 – Flowchart of conventional Beta method [28].

4. **DC/DC TOPOLOGIES**

The interactive utility system, although consisting of a limited number of components, can be adapted to suit its intended function and improve its efficiency by adding further components. Two distinct categories of designs can be created by combining different structures: series and/or parallel converter topology. These connections enhance the converter's power transmission capabilities, connecting in series increases the voltage, while connecting in parallel increases the current. Such arrangements enable the achievement of new functions that would not have been possible with a single converter.

4.1. CONTROL STRATEGY FOR A DC-DC CONVERTERS CONNECTED IN SERIES.

The topology of the dc-dc converter system, presented in this paper utilizes Boost converters connected in series. A single dc-dc converter is connected to each panel., and the voltages are combined through the series connection to generate a higher output voltage. While the investigation of PV converters connected in series is gaining momentum, Nowadays, parallel connections are still used, and various writers have proposed new advancements to find the best structure for such configurations.

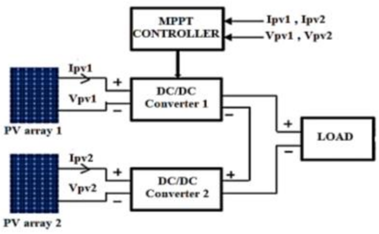

Fig. 8 – The simplest block diagram of a typical energy conversion chain (converters connected in series).

4.2. CONTROL STRATEGY FOR A DC-DC CONVERTERS CONNECTED IN PARALLEL.

Parallel connections between converters can be used to connect a wide range of converter architectures, such as inverters and dc-dc converters. However, selecting the most appropriate paralleling strategy necessitates a good comprehension of the benefits and drawbacks of each option, taking into account factors such as complexity, cost, modularity, and reliability. To ensure stable and reliable operation with good dynamic performance, it is necessary to consider various interactions between converter modules when designing the control architecture and integrating the system. One key advantage of such parallel connections is that they reduce thermal and electrical stress on the components, allowing for the transfer of a larger power charge without increasing stress on any one component. This increased distribution of load enhances the system's overall robustness and reliability.

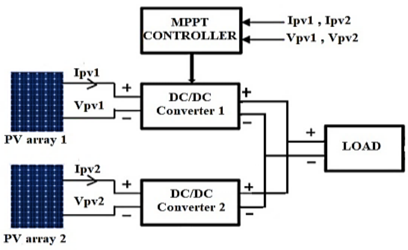

Fig. 9 – The simplest block diagram of a typical energy conversion chain. (converters connected in parallel).

5. **RESULTS AND DISCUSSIONS**

The aim of this paper is to compare different topologies under different MPPT approaches. To achieve this goal, simulations were performed using the MATLAB/ Simulink to model the overall system as shown in Fig. 10.

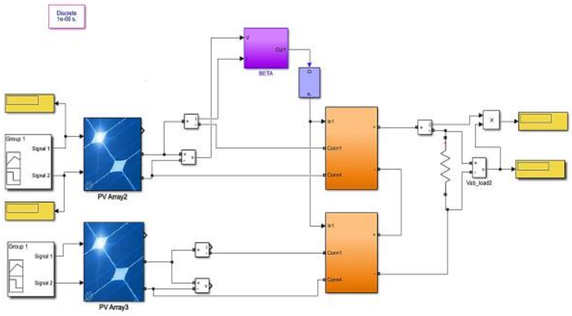

Fig. 10 – Simulink model of the PV system (converters are connected in series).

The comparison study focuses on two MPPT approaches: the P&O and Beta methods.

5.1. THE CONVERTERS ARE ARRANGED IN A SERIES CONNECTION

In the simulation, we used a converter series configuration consisting of two photovoltaic (PV) modules and two dc/dc converters interconnected in series, with each converter model being identical to the string converter model. The system was governed by an MPPT controller.

The comparison of the used MPPT methods is first conducted under STC conditions of 1 kW/m^2 and 25°C, as depicted in Fig. 11.

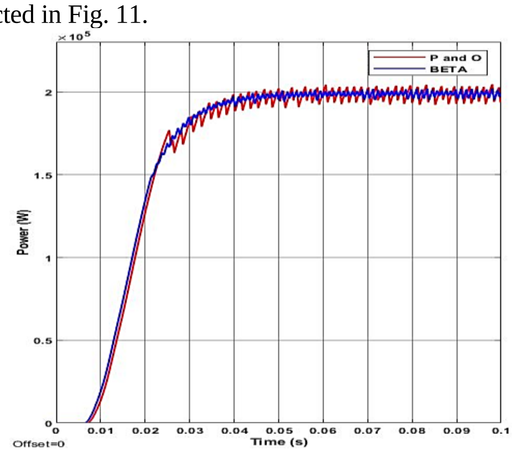

Fig. 11 – The output power of the photovoltaic system during STC condition (converters are connected in series).

In Fig. 11, the output power of the analyzed methods is presented at STC, with the converters connected in a series configuration. The Beta and P&O methods yielded power outputs of 201 kW and 199.3 kW, respectively, while achieving efficiency rates of 99.8 % and 99.1 %, respectively. The results show that the Beta method attained a higher level of efficiency than the P&O method. However, during transient states, noticeable oscillations may occur in the P&O method, leading to power loss and fluctuations near the MPP in the steady-state operating point.

The findings of the study indicate that the Beta MPPT method outperforms other methods in terms of MPP identification. It exhibits the quickest MPP tracking time, minimal oscillations during transients around the MPP, and the highest tracking accuracy, leading to the lowest power loss.

5.2. PARALLEL CONFIGURATION OF CONVERTERS

The two string converters in this simulation are identical and connected in parallel, as shown in Fig. 12.

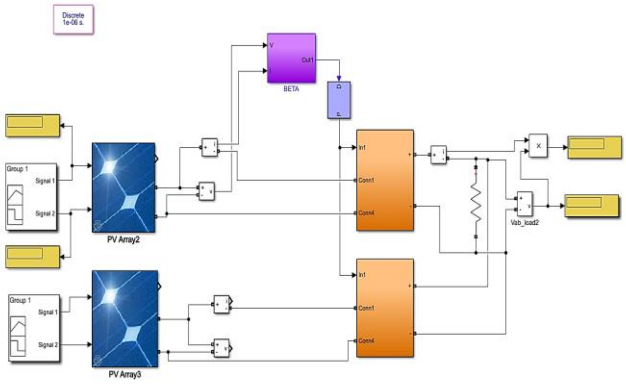

Fig. 12 – Simulink model of the PV system (converters are connected in parallel).

Simulation results for the output power is presented in Fig. 13. The comparison of the used MPPT methods is first conducted under STC conditions of 1 kW/ m^2 and 25°C.

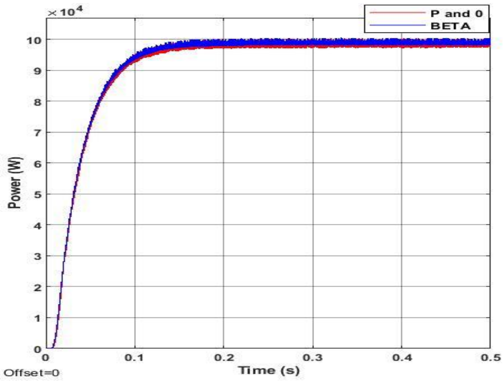

Fig. 13 – The output power of the photovoltaic system during STC condition (converters are connected in parallel).

Figure 13 shows the output power of the considered methods at STC with converters connected in parallel. The Beta and P&O algorithms resulted in power outputs of 100.2 kW and 99.6 kW, respectively, with corresponding efficiency rates of 99.5% and 98.9%. The tracking time to reach the MPP was 0.16 s for Beta and 0.22 s for P&O. It is worth noting that the Beta method exhibits faster convergence to the maximum power point.

5.3. VARIATION OF IRRADIATION

MPPT ensures that the PV operating voltage and current always remain at the MPPT on the PV curve. Currently, the PV panel is subjected to changing environmental conditions.

To assess the reliability and effectiveness of the studied MPPT methods in tracking the MPP under varying weather conditions, the PV panel's operating voltage and current must be kept at the MPP on the photovoltaic curve. The system was tested by maintaining the cell temperature at a constant value of 25 °C while the irradiance level was varied. The PV system was subjected to solar irradiance of 1 kW/m^2 from t = 0 to 0.7 s, followed by a decrease to 250 W/m^2 between 1.2 s and 1.5 s, then an increase back to 1000 W/ m^2 between 2 s and 2.3 s, and another decrease to 250 W/ m^2 between 2.3 s and 2.65 s. Finally, it was stepped up to 1000 W/ m^2 between 2.65 s and 3 s, as shown in Fig. 14.

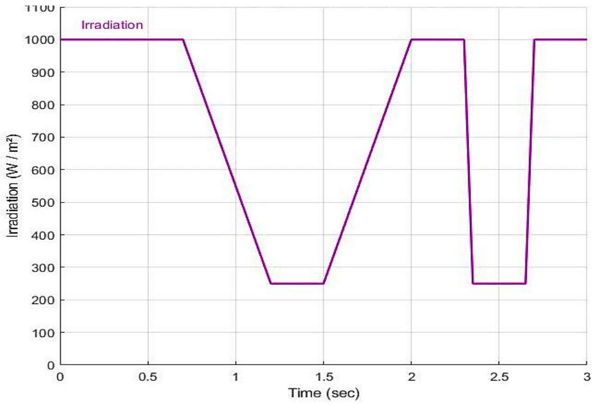

Fig. 14 – Changes in irradiation.

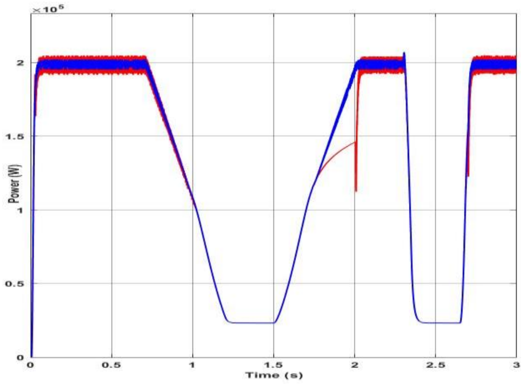

Fig. 15 – The output power of the photovoltaic system during a sudden change in irradiation (converters are connected in series).

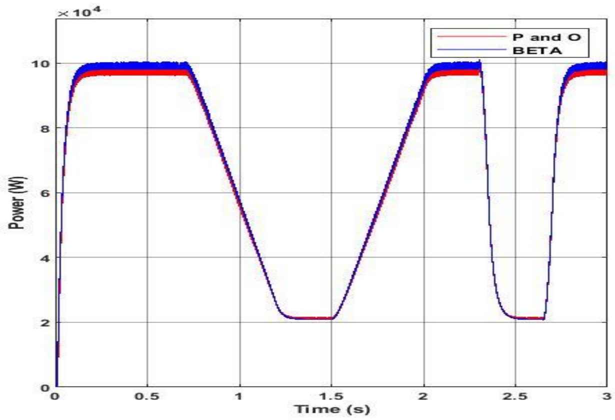

Fig. 16 –The output power of the photovoltaic system during a sudden change in irradiation (converters are connected in parallel).

Figures 15 and 16 depict the performance of the Beta and P&O MPPT methods under changing irradiance levels from 1000 to 250 W/m^2. Both methods successfully track the MPP in real time, with the Beta method showing faster convergence and no overshoot. However, the P&O method exhibits significant fluctuations near the MPP and a significant overshoot.

The Beta algorithm outperforms the P&O algorithm in terms of stability and power extraction, even under rapid changes in irradiance. The steady-state power loss due to MPP is relatively low, and power oscillations around MPP are minimal, with a faster convergence rate than the P&O algorithm. The parallel configuration of boost converters is better than the series configuration in tracking irradiance variations, as it responds quickly to changes in irradiance.

6. **CONCLUSIONS**

In this study, we have developed and analyzed a high-power transfer converter for photovoltaic (PV) systems, demonstrating its adaptability in both series and parallel configurations. The key contribution of this work is integrating an MPPT control system, which significantly enhances the output power of a PV module. Through MATLAB simulations, we have validated the effectiveness of this system in different operational topologies, confirming that the performance aligns well with theoretical expectations. A critical finding of our research is the superiority of the Beta MPPT method over traditional P& O methods. This superiority is evident in its ability to track the MPP with minimal oscillations and high speed, particularly under sudden irradiation changes. The Beta MPPT method demonstrates a remarkable balance in computing load, accuracy, steady-state variations, and dynamic response, effectively overcoming the limitations commonly associated with earlier MPPT systems. Furthermore, our comparative analysis under scenarios with and without shading highlights the robustness of the Beta MPPT approach in diverse environmental conditions. This underscores its potential applicability in real-world PV systems, where varying levels of shading and irradiation are common.

Overall, this research contributes to the field of renewable energy by providing a more efficient and reliable approach to power conversion in PV systems. The Beta MPPT method, with its improved performance characteristics, presents a significant advancement in solar energy technology, promising enhanced energy harvesting and system reliability.

Our proposed method significantly enhances power extraction from partially shaded PV systems, yet it's crucial to recognize its limitations, particularly in implementing the conventional beta method. The choice of the scaling factor, N, critically affects performance in both steady-state and transient conditions. This factor's performance is highly dependent on environmental conditions. While optimization through parameter sweeping is proposed, it's effective only under specific conditions, limiting its universal applicability. Additionally, even with optimization, steady-state oscillations persist, highlighting the need for further refinement. These limitations indicate the necessity of continued enhancement, particularly in adapting the beta method to diverse environmental scenarios. Future research should focus on improving the method's adaptability through algorithmic development or integration with other optimization techniques.

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