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In-Depth Comparison of PV Array Configurations and Boost Converter Topologies Using P&O and PSO Techniques

Fatma Talha*, Khalil Benmouiza, Mouhoub Birane

Laboratory of Materials, Energetic Systems, Renewable Energies and Energy Management, University of Laghouat, Laghouat 03000, Algeria

Corresponding Author Email: fatma.talha@lagh-univ.dz

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ABSTRACT

In the search for efficient renewable energy solutions, grid-connected photovoltaic (PV) systems have become a key technology. This paper delves into optimizing these systems through a thorough comparison of various PV array and boost converter topologies, employing advanced Maximum Power Point Tracking (MPPT) algorithms. Utilizing simulations, the research scrutinizes diverse configurations of PV arrays, including series and parallel, in conjunction with different boost converter designs. The focus is on enhancing power output in different irradiation conditions. Key performance metrics, such as efficiency, tracking precision, and system stability, are rigorously evaluated. The comparative analysis primarily hinges on two MPPT techniques: the Perturb and Observe (P&O) method and the Particle Swarm Optimization (PSO) algorithm. This investigation not only provides critical insights into the optimal selection of PV array and boost converter configurations for grid-connected systems but also underscores the superiority of intelligent algorithms like PSO in enhancing operational efficacy. Results demonstrate a remarkable 99% efficiency and energy output advantage of the parallel PV array configuration compared to the series configuration.

1. INTRODUCTION

Renewable energy sources are increasingly being utilized worldwide to meet the growing demand for energy and to address the environmental and health issues associated with conventional energy sources [1, 2]. One of the most promising forms of renewable energy is photovoltaic (PV) systems. These systems have two main applications: as autonomous electric power sources and as supplementary power sources integrated into the main grid [3]. Government interest in grid-connected PV systems has increased due to declining costs of PV modules, government support through subsidies and incentives, and the widespread adoption of solar PV systems in residential, commercial, and utility sectors. However, there are drawbacks to the grid-connected PV systems including, low efficiency and fluctuations in electricity generation caused by changes in solar radiation and temperature [4, 5]. To address these issues, researchers have explored various approaches to optimize the efficiency and reliability of PV systems, which are summarized below [6, 7].

Malathy and Ramaprabha [8] conducted an analysis and comparison of different PV array topologies to investigate the impact of architecture and array size on energy yield under shading conditions. Pachauri et al. [9] presented a comprehensive study on the diverse photovoltaic array architectures and metaheuristic algorithms to mitigate the impact of shading on overall system output. Dhople et al. [10] proposed a multiple-input boost converter topology that increases the power output of a PV module by individually tracking and optimizing the power output of each input. Murtaza et al. [11] proposed a bypass diode-based MPPT architecture for PV arrays and studied its performance under shading, comparing it to previous MPPT techniques. Roman et al. [12] proposed a micro-inverter maximum power point tracking (MPPT) architecture to maximize the power output of PV modules. This system uses individual micro-inverters for each module, which increases on the overall cost of the system but also decreases its overall performance.

The choice of PV system architecture depends on various factors, including location, load demand, budget, and resource availability [13]. The topology of PV systems is crucial in minimizing power losses and optimizing system performance. Most research in this field focuses on stand-alone systems [14], with little attention given to grid-connected systems. However, it is worth noting that the appropriate architecture for grid-connected systems can significantly reduce energy loss and improve system efficiency [9, 15, 16]. Therefore, this paper aims to determine the optimal architecture for grid-connected systems by exploring different arrangements of photovoltaic modules with associated energy converters.

In addressing the challenges posed by grid-connected PV systems, this study specifically aims to overcome the inefficiencies and performance fluctuations caused by variations in solar radiation and temperature. Despite advances in technology and growing interest, grid-connected PV systems often suffer from suboptimal power output and energy loss, particularly under non-uniform radiation conditions. Therefore, this paper seeks to define and analyze the optimal architecture for grid-connected PV systems to enhance their efficiency and reliability. The primary objectives of this research are: 1) to compare the effectiveness of series versus parallel configurations of solar panels and converters, and 2) to evaluate the performance of Perturb and Observe (P&O) [17] and Particle Swarm Optimization (PSO) [18] techniques in optimizing the output of these configurations. By utilizing Matlab/Simulink for simulation, the study will provide a detailed comparative analysis of the current, voltage, and power outputs of various PV system topologies under different environmental conditions. Ultimately, this research intends to offer significant insights into the design and selection of PV system architectures that maximize energy yield and minimize losses, thereby supporting the broader adoption of solar energy in grid-connected applications.

This paper is organized as follows: Section II provides a description of the PV module and converter, along with their mathematical models. Section III describes the use of PSO and P&O for tracking purposes. The simulation results are then explained in Section IV. Finally, Section VI presents the conclusions of this paper.

2. METHODOLOGY

The methodology involves connecting solar panels and converters in series and parallel to create various architectures of a grid-connected PV system. Furthermore, the performance of the conventional P&O algorithm and the optimization PSO algorithm are compared in each architecture to ensure the extraction of the maximum possible amount of energy, even when shading is present. Figure 1 depicts a detailed diagram of the methodology used, illustrating the connecting mechanisms.

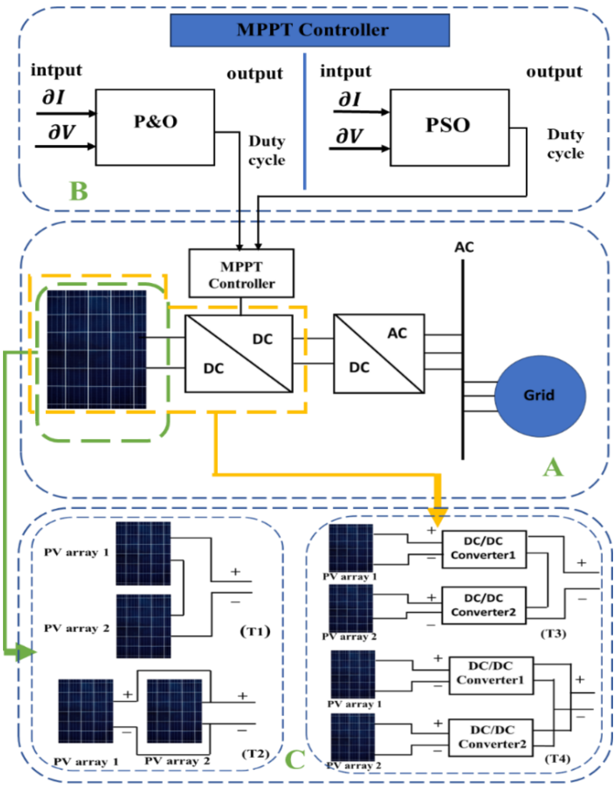

Figure 1. Diagram of methodology

3. DESCRIPTION OF GRID-CONNECTED PV SYSTEM (A)

3.1 PV system

In solar systems, the photovoltaic module consists of a group of solar cells that are connected in series and parallel. These PV cells are made up of p-n junction semiconductors that directly convert the light energy into electricity. To accurately model the behavior of PV cells, electrical equivalent circuits are constructed. These circuits are based on a light-generated current source connected in parallel to a p-n junction diode.

The double diode model offers improved accuracy and clear characteristics in different weather conditions. Figure 2 presents a double-diode model of a solar cell. It consists of a single current source and two diodes, with two resistances connected, one in series and the other in parallel [19, 20].

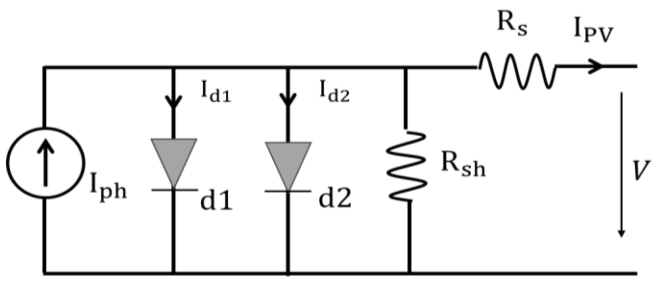

Figure 2. Double-diode model of a solar cell

Thus, the output current of the PV module is presented in Eq. (1).

$$I = I_{ph} - I_{d1}\left(e^{\left(\frac{q.(V+I\,.\,R_S)}{n_1.k.T_C}\right)} - 1\right) - I_{d2}\left(e^{\left(\frac{q.(V+I\,.\,R_S)}{n_2.k.T_C}\right)} - 1\right) - \frac{(V+I\,.\,R_S)}{R_{sh}} \quad (1)$$

where, *V, I* is voltage and current of PV cell. R_s, R_{sh} is series and shunt resistances respectively, (Ω). T_c is PV cell temperature in Kelvin, (K). k is Boltzmann's constant, (1,38×10e-23J/K). q is charge of Electron, (e=1.6×10-19C). n is number of cells in series. I_{ph} is light-generated current.

3.2 DC/DC boost converter

The boost converter depicted in Figure 3 converts the input voltage into a higher constant voltage output [21].

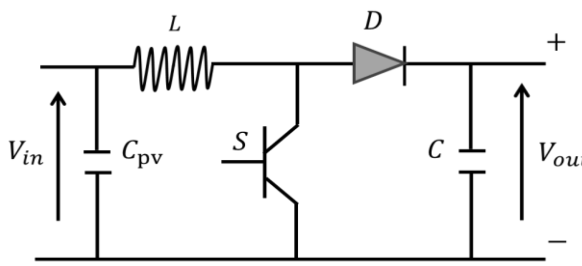

Figure 3. DC/DC boost converter

The duty cycle is expressed by Eq. (2) as follows:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-\alpha} \quad (2)$$

where, V_{in} is input voltage(V). V_{out} is output voltage(V). α is duty cycle.

4. MAXIMUM POWER POINT TRACKING ALGORITHM (B)

4.1 P&O algorithm

The Perturb and Observe (P&O) algorithm is a popular choice for many photovoltaic (PV) systems because of its simplicity and cost-effectiveness [22]. This algorithm works by periodically perturbing the operating voltage or current and comparing the PV output power with the previous output power value. When a decrease in power output is detected due to further perturbation, the P&O algorithm determines that it has passed the Maximum Power Point (MPP). It then takes a step backward in the opposite direction. If the power output increases, the P&O algorithm continues to perturb in the same direction. This iterative process continues until the exact MPP is determined [23]. The procedural steps [24] of the P&O MPPT technique are visually outlined in Figure 4.

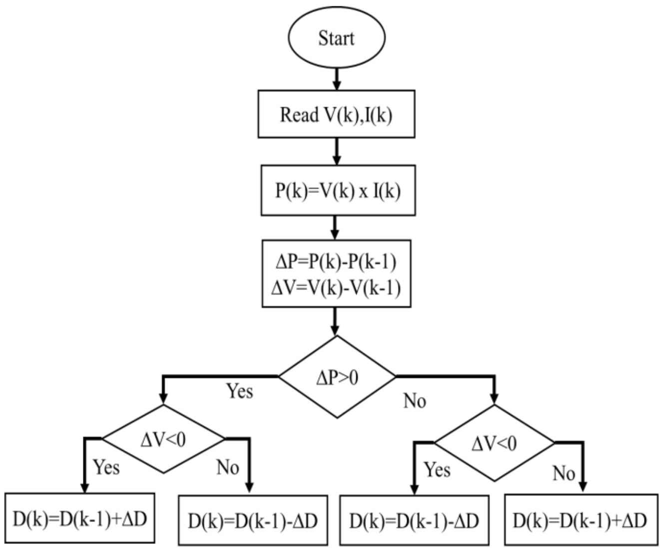

Figure 4. Flowchart of P&O algorithm

4.2 Particle Swarm Optimization (PSO)

PSO is a metaheuristic algorithm that proven to be effective in solving optimization problems. It was first proposed by Kennedy and Eberhart and is inspired by the social behavior of animals such as birds and fish. The algorithm is known for its simplicity of implementation and rapid convergence.

The primary concept of PSO is to use a swarm of particles that move within the search space to find the global best solution to the optimization problem. Additionally, each particle seeks its own local best solution. Initially, each particle is assigned a random position and zero velocity.

The positions and velocities of the particles are then updated based on the local best solution and the global best solution found so far. The calculation of the velocity and position of each particle is done according to equations [24, 25]. The procedural steps of the PSO MPPT technique are illustrated in Figure 5.

$$\overrightarrow{V_i^{t+1}}=w\overrightarrow{v_i^t}+c_1r_1(\overrightarrow{P_i^t}-\overrightarrow{X_i^t})+c_2r_2(\overrightarrow{G^t}-\overrightarrow{X_i^t}) \quad (3)$$

$$\overrightarrow{X_i^{t+1}}=\overrightarrow{X_i^t}+\overrightarrow{V_i^{t+1}} \quad (4)$$

where, w Inertia weight. c_1 and c_2 are the acceleration coefficients. r_1 and r_2 are two random sequences generated from the interval [0, 1].

4.3 Comparison between P&O and PSO MPPT algorithms

Perturb and Observe (P&O) is a straightforward MPPT method where the voltage is incrementally adjusted, observing power changes to decide the direction of adjustment. While easy to implement, it tends to oscillate around the Maximum Power Point (MPP) in variable conditions, potentially reducing efficiency. However, PSO simulates social behaviors of swarms to optimize the MPP finding process, adapting based on collective experience. It excels in complex conditions like partial shading, achieving faster and more stable convergence at the cost of increased computational complexity and implementation effort. Table 1 give a brief comparison between the two algorithms.

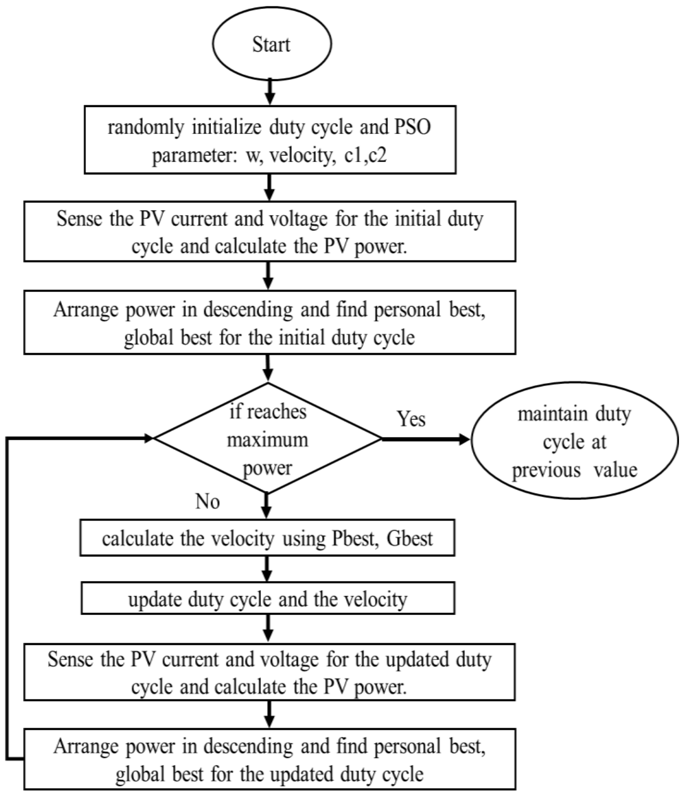

Figure 5. Flowchart of PSO algorithm

Table 1. Comparison between P&O and PSO MPPT algorithms

Feature	P&O	PSO
Complexity	Low	High
Implementation cost	Lower	Higher
Efficiency	Moderate (can oscillate)	High (less prone to oscillation)
Speed of convergence	Moderate	Fast
Robustness to variability	Lower (sensitive to changes)	Higher (better at handling changes)
Optimal for weather changes	Stable environmental conditions	Rapidly changing or varied conditions

5. TOPOLOGIES

In order to enhance the performance of the grid-connected PV system and achieve an optimal architecture, different arrangements of photovoltaic modules with associated energy converters are utilized. These arrangements are illustrated in Figure 1.

Topology1(T1): Two PV arrays connected in series with one boost converter.

Topology2(T2): Two PV arrays connected in parallel with one boost converter.

Topology3(T3): One PV array connected in parallel with one boost converter, following the same architecture.

Topology4(T4): One PV array connected in parallel with one boost converter, also following the same architecture.

6. RESULTS AND DISCUSSION

To evaluate the efficiency of solar panels and converters using PSO based on MPPT in both series and parallel topologies, and compare them with the conventional P&O method, MATLAB simulations were conducted on a grid-connected PV system that experienced non-uniform irradiation. The Simulink model is illustrated in Figure 6.

A sunPowerSPR-305E-WHT-D PV module is used to construct the PV array, which consists of 330 modules connected in series-parallel. This array functions as a power supply, delivering 100kW. The characteristics of the PV module can be found in Table 2. Additionally, a boost converter with an output voltage of 500V is utilized.

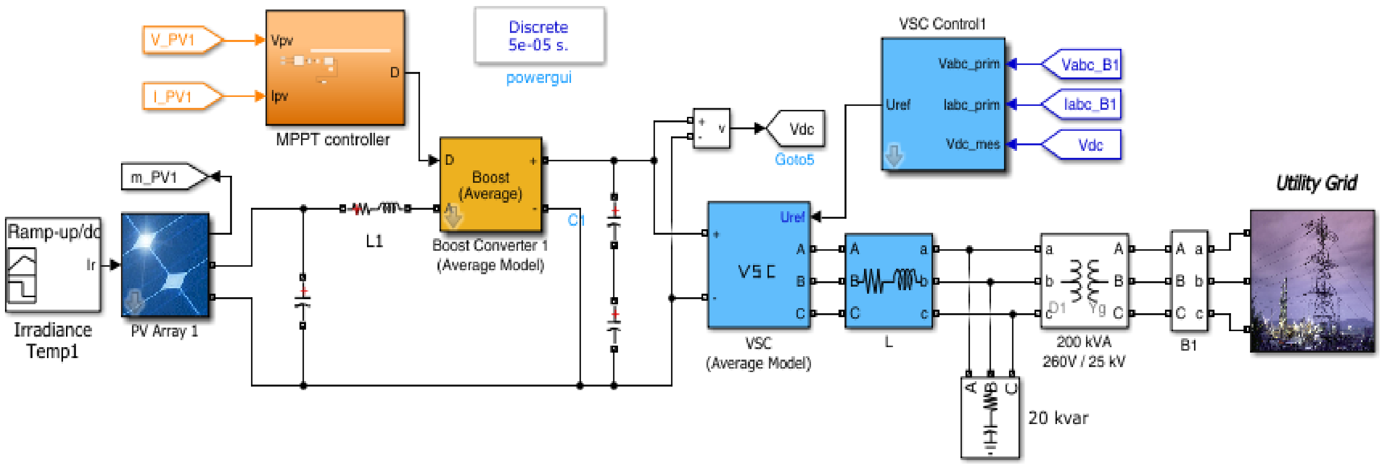

Figure 6. Simulink model for grid connected PV

Table 2. Solar module specifications

SunPowerSPR-305E-WHT-D	
Normal power (W)	305.226
Open circuit voltage (V)	64.2
Short circuit current (A)	5.96
Vmpp (V)	54.7
Impp (A)	5.58
Number of series cells	96
Series resistor (Rs)	0.037998
Parallel resistor (Rp)	993.51

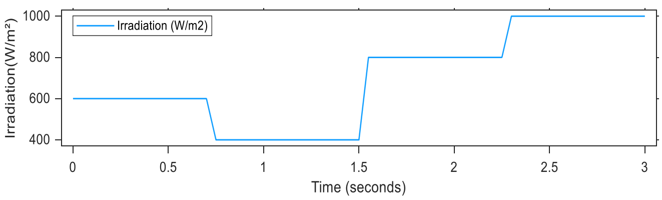

Figure 7. Different levels of irradiance

The presented architectures are compared based on the operation of PV arrays under non-uniform irradiation and constant temperature (25°C), as depicted in Figure 7. The irradiance levels range from 400W/m^2 to a maximum of 1000W/m^2. The simulation results, shown in Figures 8-13, were obtained over a simulation time of 3 seconds.

The performance of the parallel and series architectures, using P&O MPPT in the first case and PSO in the second case, is assessed through these results. The simulation clearly demonstrates the superior performance of the parallel architectures over the series architectures.

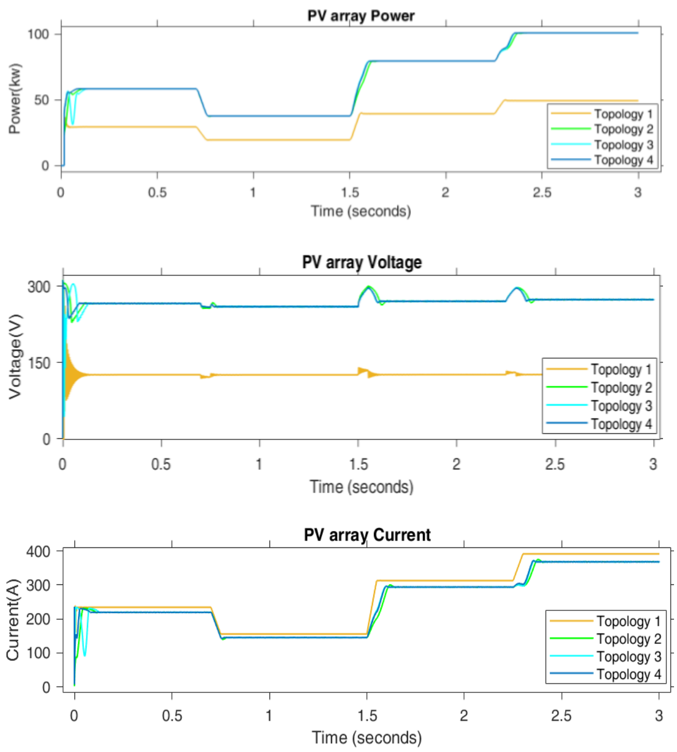

Figure 8. Simulation results of the output PV for P&O algorithm

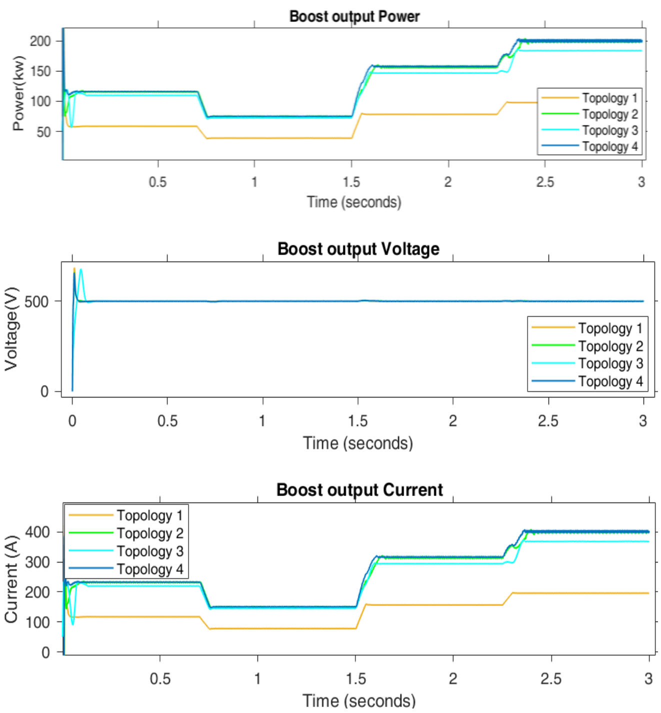

Figure 9. Simulation results of output boost for P&O algorithm

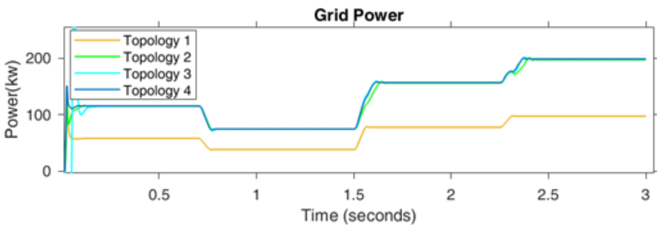

Figure 10. Simulation results of the grid power for P&O algorithm

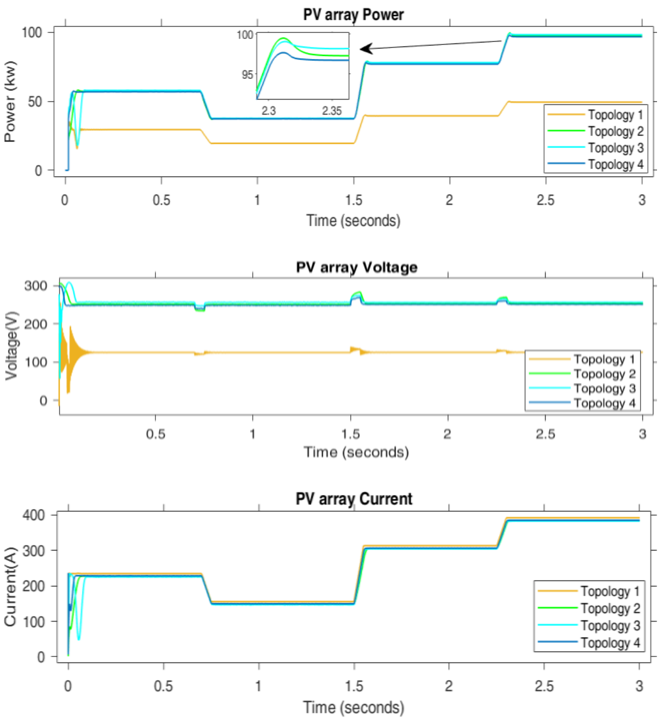

Figure 11. Simulation results of the output PV for PSO algorithm

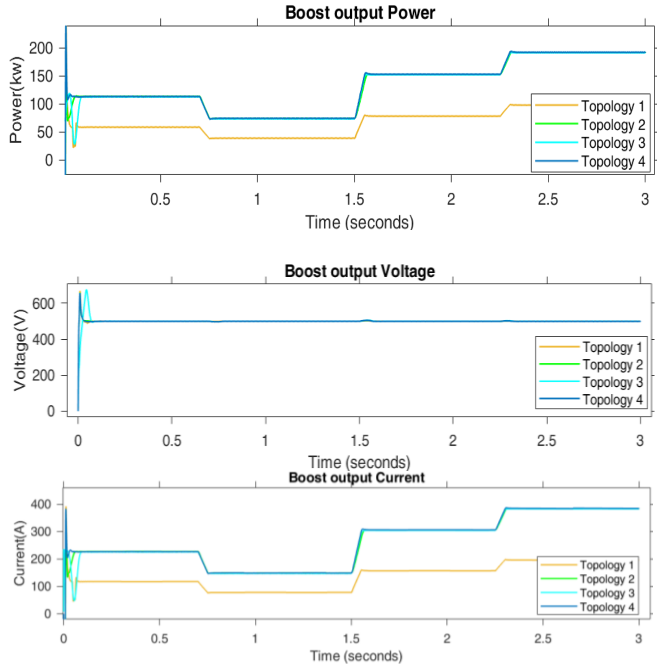

Figure 12. Simulation results of the output boost for PSO algorithm

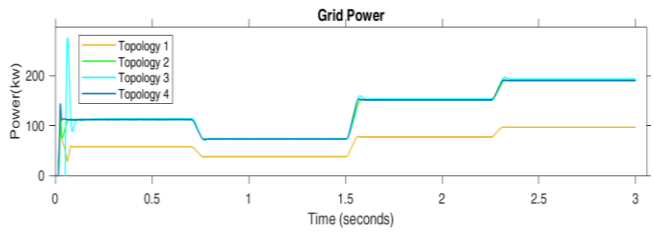

Figure 13. Simulation results of the grid power for PSO algorithm

Firstly, topologies with P&O. It can be seen that topologies 2, 3, and 4 give a constant power value equal to 100 kilowatts with an output voltage of 300 volts, in contrast to topology 1, which gives a greater current value and half the amount of power and voltage. This is a result of the serial connection of photovoltaic arrays, which increases the current but not the voltage. Moreover, it can be seen that the P&O of the MPP trace of topology 4 has a shorter rise time and higher accuracy than that of 2 and 3, as shown in Figure 6.

From Figure 7, which shows the DC/DC output curves, we can see that both topologies 2 and 4 provide maximum power and output current compared to 3 because the boost converters connected in series do not provide maximum DC power.

Additionally, all four topologies maintain a constant output voltage of 500V in order to deliver maximum power. Furthermore, topologies 3 and 4 demonstrate the highest grid output power. Figure 11 illustrates the discrepancy in response time and the presence of some oscillations caused by the P&O algorithm.

Secondly, topologies with PSO. The results are confirmed through Figure 12 when using the PSO MPPT for the four topologies that topologies 2, 3, and 4 give a power value higher than 1. It can also be noted that the power value and output voltage PV of topology 3 has increased when using the PSO algorithm compared to case 1 when using P&O. Moreover, we note that PSO provides tracking efficiency and High accuracy and low oscillations compared to P&O. On the boost converter side, topologies 2, 3, and 4 also give maximum power and current at a fixed output voltage of 500 for all topologies. The grid output power topologies 2, 3, and 4 provide the maximum power with 4 advancing than topologies 3 and 2.

In light of the findings from this study, practitioners looking to implement grid-connected PV systems should consider adopting topologies 2, 3, and especially 4, which have demonstrated superior performance in terms of power output and efficiency when coupled with the PSO MPPT algorithm. It is recommended that the serial connections of photovoltaic arrays, which tend to increase current but not voltage, be optimized to balance the system's voltage and power requirements effectively. Furthermore, the deployment of PSO should be prioritized over P&O, as PSO consistently shows higher tracking efficiency with minimal oscillations, enhancing overall system reliability. When configuring the associated boost converters, ensuring they operate at a consistent output voltage of 500V, as observed in the top-performing topologies, will be crucial for maximizing DC power delivery and efficiency. Finally, practitioners should regularly monitor and adjust the configurations to maintain optimal performance, even under varying irradiation conditions.

In comparing the performance of parallel versus series configurations in our PV array setups, the parallel configurations (particularly topology 2 and 4) have shown a distinct advantage using both P&O and PSO algorithms. Specifically, parallel configurations demonstrated an increase in power output efficiency by approximately 100% compared to series configurations. This enhancement is attributable to the better voltage handling and reduced losses in parallel setups. These quantified improvements underscore the substantial benefits of opting for parallel configurations and utilizing advanced algorithms like PSO for optimizing the performance of grid-connected PV systems.

While this simulation study provides valuable insights into PV array configurations, its applicability may be limited by assumptions on parameters and scale, which do not always reflect real-world complexities. Validating these results with real-world data, conducting sensitivity analyses, and implementing pilot tests are crucial to ensuring the reliability and practical relevance of our findings. These steps will bridge the gap between simulated predictions and actual system performance

7. CONCLUSIONS

This paper has conducted an in-depth comparison between series and parallel topologies of PV arrays and boost converters within grid-connected systems. Utilizing the Particle Swarm Optimization (PSO) algorithm and contrasting it with the conventional Perturb and Observe (P&O) method, this study aimed to maximize the power extraction from photovoltaic panels under conditions of sudden irradiation changes. The results clearly indicate that parallel architectures, when compared with series configurations, deliver superior performance in terms of efficiency and energy output. Additionally, the implementation of dual boost converters, as opposed to a single converter setup, has significantly enhanced the power output.

Further analysis revealed that advanced MPPT algorithms like PSO not only provide better performance but also contribute to high efficiency, minimal oscillation, and more precise tracking compared to traditional methods. These findings underscore the importance of selecting appropriate system architectures and advanced control strategies to optimize the functionality and efficiency of grid-connected PV systems.

However, this study is not without its limitations. The scope of environmental conditions tested was limited, potentially affecting the generalizability of the results to other geographical areas or climatic conditions. Additionally, the economic analysis of the system configurations was beyond the scope of this research, leaving questions about cost-effectiveness and scalability unanswered.

Future research should therefore expand on the range of environmental conditions to test the robustness of different PV system configurations. Moreover, a comprehensive cost-benefit analysis could be undertaken to evaluate the economic viability of various system architectures and control strategies. Exploring other advanced MPPT techniques could also offer further insights into enhancing the performance of grid-connected PV systems. Through continuous improvement and exploration of these systems, we can better understand and mitigate the challenges associated with integrating solar power into the energy grid, ensuring the sustainability and feasibility of solar energy systems in diverse settings.

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