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Enhancing Photovoltaic System Performance with MPPT-PID Controller Using Particle Swarm and Tasmanian Devil Algorithms

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Abstract

In photovoltaic systems (PV), given the non-linear relationship between voltage and power, the implementation of a controlled power electronic converter is essential to achieve the desired voltage level. In this study, the boost converter is controlled by an MPPT-PID controller to obtain maximum power from the designed PV system. The PID (proportional-integral-derivative) controller parameters are determined by Particle Swarm Optimization (PSO) and Tasmanian Devil Optimization (TDO) algorithms. The objective function, Integrated Time Weighted Absolute Error (ITAE), is selected for the engineering problem. The system was applied to a series of tests within the MATLAB/Simulink environment, encompassing constant irradiance-fixed load, variable irradiance-fixed load, and constant irradiance-variable load conditions. A comparative analysis was subsequently performed. The performance of the scenarios was analyzed by peak value, overshoot ratio, rise time, and converter efficiency. The findings emphasize the important role of parameter optimization in enhancing energy efficiency and contribute to the current state of knowledge, leading to the development of more effective control strategies in solar energy systems.

Keywords: PV System, Incremental Conductance, Particle Swarm Optimization, Tasmanian Devil Optimization, Boost Converter.

1. Introduction

In the 21st century, population growth and technological advancements have led to an increased consumption of fossil fuels, thereby creating a growing demand for alternative energy sources. Global environmental agreements such as the Kyoto Protocol and the Paris Climate Agreement have been signed to increase the use of clean and sustainable energy sources [1, 2]. Solar energy, one of the renewable energy sources, has gained significant traction through the utilization of photovoltaic (PV) systems for the conversion of sunlight into electrical energy. The PV system was first discovered by Becquerel in 1893, who observed that the voltage between electrodes immersed in electrolyte is dependent on the light falling on the electrolyte [3]. The efficiency of PV systems is directly influenced by solar radiation and environmental conditions, such as wind, precipitation, and dust levels. These conditions complicate the process of Maximum Power Point (MPP) tracking, thereby hindering the system's ability to operate at its optimal efficiency. Consequently, Maximum Power Point Tracking (MPPT) algorithms assume a pivotal role in enhancing the efficiency of PV systems. This study investigates the Incremental

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Conductivity algorithm and metaheuristic algorithms, which are known for their ability to adapt to environmental changes and maintain the optimal performance of photovoltaic (PV) systems.

In literature, oscillation and observation (P&O) and incremental conduction (IC) classical MPPT algorithms are widely used [4]. The IC algorithm uses the differential variation of voltage and current values to determine the maximum power point of the PV panel. The performance of eight different forms of this algorithm is compared and the most suitable form is proposed [5]. The IC Algorithm has been evaluated in the literature under rapidly changing shading, variable temperature and variable environmental conditions [6-10]. The oscillation and observation algorithm has been widely used in literature due to its simple structure and easy applicability at low cost. However, due to the fact that this algorithm causes power fluctuations in the process of determining the maximum power point and is insufficient to respond to rapid changes, its use has decreased with the emergence of new algorithms [11]. In the literature, P&O and IC algorithms have been compared and analyzed in detail [12, 13]. There are also studies in which these two algorithms are used in a hybrid way. [14, 15].

Since the power generated from the sun depends on several factors such as solar temperature, solar irradiance, the number of photovoltaic (PV) panels connected in series and parallel, load resistance, and the angle of incidence of the sun, DC to DC converter equipment is needed to achieve a stable power level [16]. The use of conventional boost-buck converters is common. However, an effective control method is needed to overcome the disadvantages such as fluctuating output energy and high switching losses [17]. In this study, the voltage level of the PV panel increased with a boost converter.

The converter is controlled by MPPT and MPPT-PID controllers. The prevalence of PID controllers in industry and literature can be attributed to their ease of implementation and reliability [18]. The tuning of the controller’s parameters is achieved through the implementation of Ziegler-Nichols, Pole Placement, and Metaheuristic Optimization methods. Metaheuristic Optimization methods are algorithms based on computational methods that strictly mimic the biological evolutionary process [19]. Metaheuristic optimization methods such as Gray Wolf Optimization [20, 21], Particle Swarm Optimization [22, 23] and Tasmanian Devil Optimization [24, 25] are used to determine the parameters of classical controllers.

In this study, the performance of a boost converter controlled by an Incremental Conductance MPPT algorithm and a PID controller is comparatively analyzed under constant and variable input conditions. The coefficients of the PID controller are determined using PSO and TDO algorithms. The results obtained demonstrate that the implementation of metaheuristic algorithms within the MPPT-PID controller enhances the system’s performance. The remainder of the study is structured as follows: The photovoltaic system, boost converter, PID controller, incremental conductance algorithm, PSO algorithm and TDO algorithm are presented in Section II. The system model and simulation results performed in MATLAB/Simulink environment are presented in Section III. The evaluation of the results is presented in Section IV.

2. Materials and Method

In the optimization study, a conventional boost converter was preferred as the power electronic converter. The system model is given in figure 1. The controller parameters proposed as a result of the optimization method aim to stabilize the output voltage of the panel at 60 V despite constant and variable conditions.

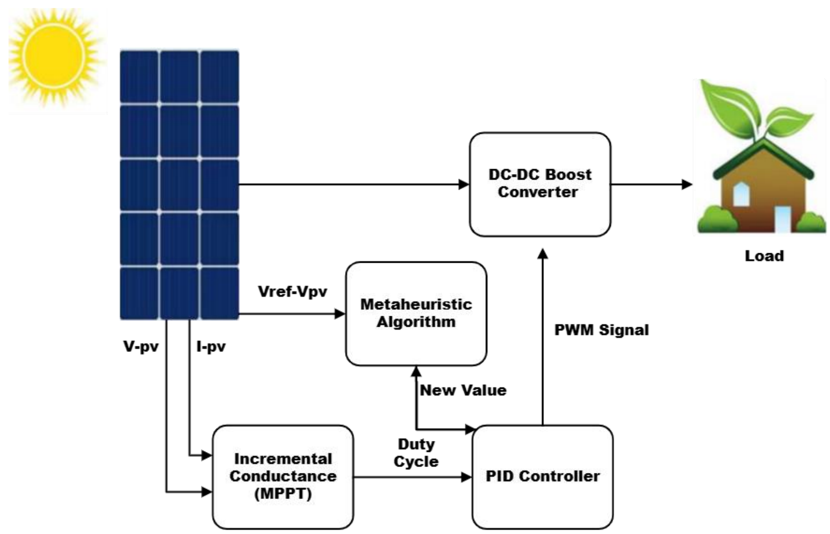

Figure 1. Photovoltaic system model

2.1. Photovoltaic Panel Model

Photovoltaic panels have various models depending on the number and position of diodes and resistors [26, 27]. In this study, a single diode model PV panel is taken as reference. The equivalent circuit for the model used is given in figure 2.

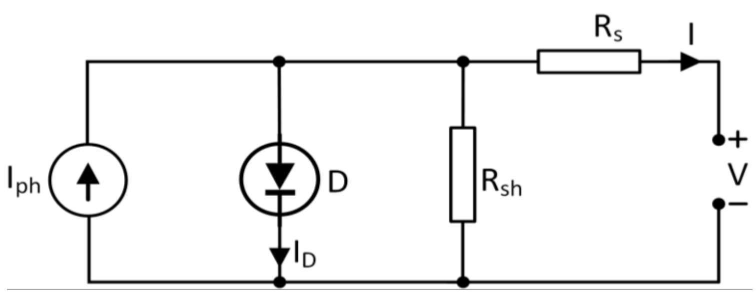

Figure 2. PV panel equivalent circuit model

The electrical parameters of a diode model can be determined from the linear distribution of solar radiation. When the node voltages method is applied to the circuit in figure 2, the expression of the current transferred is given in equation 1. Where q: electron charge (1.6x10-19C), K: Boltzman constant ($1.38x10^{-23}$), T: temperature in Kelvin units, n: diode factor [28]. Accordingly, in the equation, short circuit current V can be defined at V=0 and open circuit voltage V can be defined at I=0 [29]. The P-V and V-I characteristics of the panel are given in figures 3.

$$I = I_{ph} - I_D = I_{ph} - I_0.\left(e^{\frac{q.V}{n.K.T}} - 1\right) \quad (1)$$

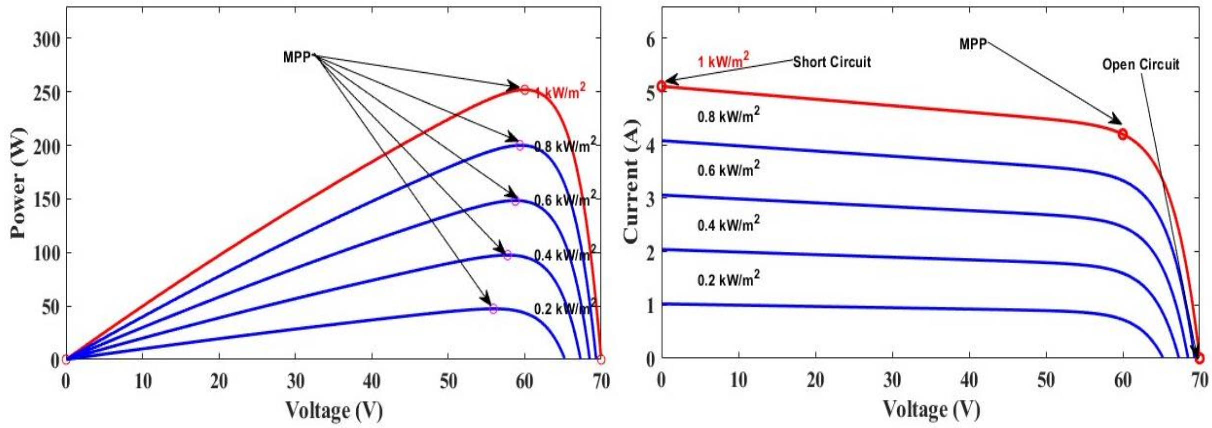

Figure 3. Photovoltaic panel characteristic data

2.2. Incremental Conductance (MPPT) Algorithm

PV systems convert solar energy into electrical energy depending on environmental factors such as solar irradiance and ambient temperature. In these systems, Maximum Power Point Tracking (MPPT) algorithms are used to achieve maximum efficiency. Considering the high cost of photovoltaic systems, it is of great importance that energy production is always maximized. However, under varying environmental conditions, not every MPPT algorithm can provide the desired performance.

The Incremental Conductance (IC) MPPT algorithm examined in this study is used to analyze the power-voltage (P-V) characteristics of photovoltaic panels to determine the optimum operating point and to ensure that they operate at the maximum power point.

The IC algorithm works based on the instantaneous conductivity change (dI/dV) on the power-voltage curve. The maximum power point occurs at the point where this derivative value satisfies a certain condition. The algorithm tries to determine the point where dP/dV = 0 by measuring the instantaneous voltage and current values of the panels.

If dP/dV > 0, the operating point is located to the left of the maximum power point, and if dP/dV < 0, it is located to the right. Based on this information, the operating point of the panel is continuously updated and kept at the maximum power point. The flow diagram of the algorithm model is given in figure 4.

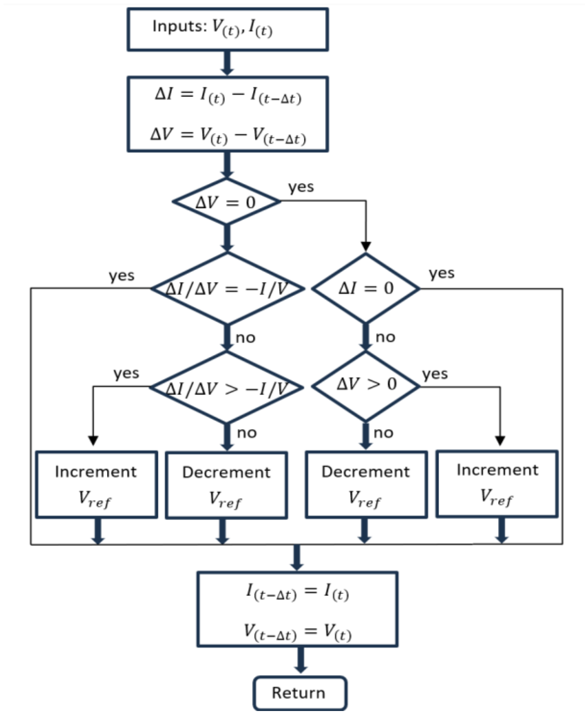

Figure 4. Flow chart of the IC MPPT algorithm

2.3. DC-DC Boost Converter

A boost DC-DC switching mode converter is a power electronic device that converts a low irregular input voltage to a highly regular output voltage. It is widely preferred in renewable energy systems, electric vehicles and power electronics applications. The converter includes an inductor (L), a power electronic switch (S), a diode (D), a filter capacitor (C) and a load resistor (R). The circuit topology is shown in figure 5. The parameters of the system are given in table 1.

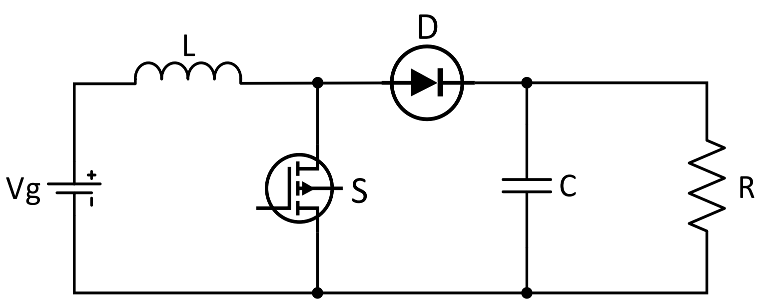

Figure 5. DC-DC Boost converter

The operating principle of the converter is based on energy storage and transfer capacity of the inductance. When the switch is closed, energy is stored in the inductance. When the switch is open, the energy stored by the inductance is transferred to the output through the diode and the output voltage is higher than the input voltage. The minimum capacitor and inductor values of the converter are calculated using equations 2 and 3 respectively [30]. f_s is the switching frequency and D is the duty cycle. Equation 4 shows the duty cycle of the converter.

$$C_{min} = \frac{I_{çıkış_{max}} . D}{f_s . \Delta V_{çıkış}} \tag{2}$$

$$L_{min} = \frac{V_{giriş}(V_{çıkış} - V_{giriş})}{\Delta I_L f_s V_{çıkış}} \tag{3}$$

$$V_0 = \frac{V_i}{1-D} \tag{4}$$

Table 1. System Parameters

Converter Parameters	
Switching Frequency	10 khZ
Output Voltage	120 V
Input Capacitor	100 μF
Filter Capacitor	87.5 μF
Inductance	0.00476 H
Load	60 Ω
Photovoltaic Panel Parameters	
Power	252 W
Maximum Point Voltage	60 V
Maximum Point Ampere	4.2 A

2.4. PID Controller

PID controller is a type of controller that combines the advantages of proportional, integral and differential control in a single system. The P coefficient is proportional to the error and adjusts the system's response speed, which affects the settling time and overshoot. The I coefficient sums past errors and helps eliminate steady-state errors, improving long-term accuracy. The D coefficient is the prediction of future errors and regulates the steady-state oscillation values [31]. The general structure of the PID controller is given in figure 6. The mathematical expression and transfer function of the PID controller are given in equation 5 and equation 6 respectively. Where K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, $u(t)$ is the control signal and e(t) is the time-dependent error function.

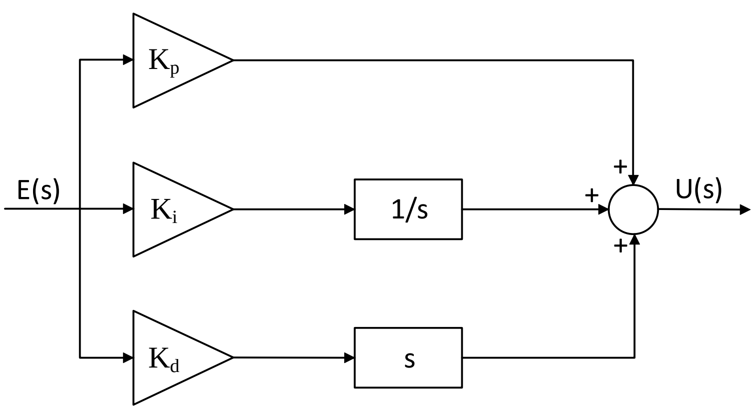

Figure 6. PID controller diagram

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{5}$$

$$G_{PID} = K_p + \frac{K_i}{s} + K_d s \tag{6}$$

2.5. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a nature-inspired meta-heuristic optimization algorithm developed from the collective movements of swarms of birds or fish. The basic idea of the algorithm is that many solution agents (particles) try to find the best possible solution to a problem in n-dimensional space representing different parameters of each problem [32,33].

Each particle moves using information about its best past position (personal best solution) and the best position reached by the whole swarm (global best solution). Particles positions are updated using inertia, cognitive and social components. Inertia refers to the particle's tendency to continue the previous direction of movement, while the cognitive component allows the particle to learn from its own experience and the social component allows it to learn from other particles that have discovered the best solution [34]. The velocities of the particles are given in equation 7. The algorithm ensures that the particles act by considering both their own best solution and the swarm's best solution [35].

$$v_i^{(t+1)} = w v_i^{(t)} + c_1 r_1 (p_i - x_i) + c_2 r_2 (g - x_i) \tag{7}$$

Here $v_i^{(t)}$ is the velocity of particle (i) at iteration (t) and the inertia coefficient. Where c_1 and c_2 are the cognitive and social coefficients, p_i is the particle's own best position, g is the best position in the swarm and x_i is the current position of the particle. The new position of the particle is calculated by adding the velocity to its previous position as given in equation 8.

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \tag{8}$$

Here $x_i^{(t+1)}$ represents the position of particle (i) at iteration (t+1) and $v_i^{(t+1)}$ represents the new velocity value.

2.6. Tasmanian Devil Optimization (TDO)

Tasmanian Devil Optimization (TDO) algorithm is a metaheuristic optimization method that imitates the movement and feeding behavior of the Tasmanian devil (Sarcophilus harrisii) in nature [36]. The algorithm aims to find the optimum points in the solution space by balancing exploration and exploitation. The initial population of the algorithm is mathematically expressed by equation 9 [37].

$$X_i = X_{min} + rand\ x\ (X_{max} - X_{min}) \tag{9}$$

Where X_i is the starting position of the individual, X_{min} and X_{max} represent the lower and upper bounds of the search space. The rand value given in the equation is a randomly generated number in the range [0,1]. The motion model used by TDO to reach the optimum solution is as given in equation 10 [38].

$$X_i^{t+1} = X_i^t + a\ x\ (X_{best}^t - X_i^t) + \beta\ x\ rand \tag{10}$$

Where X_i^t is the position of the (i) individual at the (t) iteration and X_{best}^t is the best solution obtained so far. The rand value given in the equation is a randomly generated number in the range [0,1] and a and β are the adaptive control parameters. The first stage of TDO is exploration using the carrion eating strategy. Here, the position of an individual is updated with a random reference point. The position of the next generation individual is given in equation 11 [39].

$$x_{ij}^{newS1} = \begin{cases} x_{ij} + r\ x\ (c_j - x_{ij}), F_{C_i} < F_i \\ x_{ij} + r\ x\ (x_{ij} - c_j) \end{cases} ; X_i = \begin{matrix} x_{ij}^{newS1}, F_{C_i}^{newS1} < F_i \\ X_i \end{matrix} \tag{11}$$

Where x_{ij} is the (j) variable of the (i) individual and c_j is the variable value of the randomly selected individual. F_i is the fitness value of the current individual, $F_{C_i}^{newS1}$ is the fitness value of the new individual and r is a randomly generated number in the range [0,1].

3. Results

In this study, the control of the photovoltaic panel system is realized with the MPPT-PID controller and evaluated in three different simulation experiments. The system model performed in MATLAB/Simulink is given in figure 7.

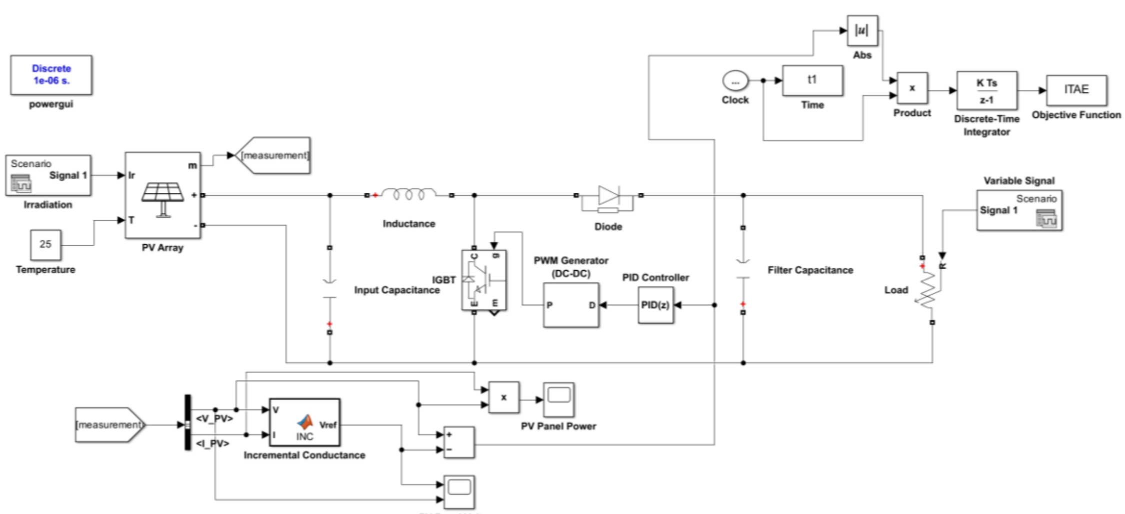

Figure 7. PV system model in MATLAB/Simulink

3.1. Constant Irradiance and Load Operation

The experiment was performed under 60 Ω load with 1000 w/m^2 irradiance. PID parameters were optimized with PSO and TDO algorithms and only MPPT control was performed by removing the PID controller. The photovoltaic panel output voltage of experiment 1 is presented in figure 8. The system parameters and results of experiment 1 are given in table 2.

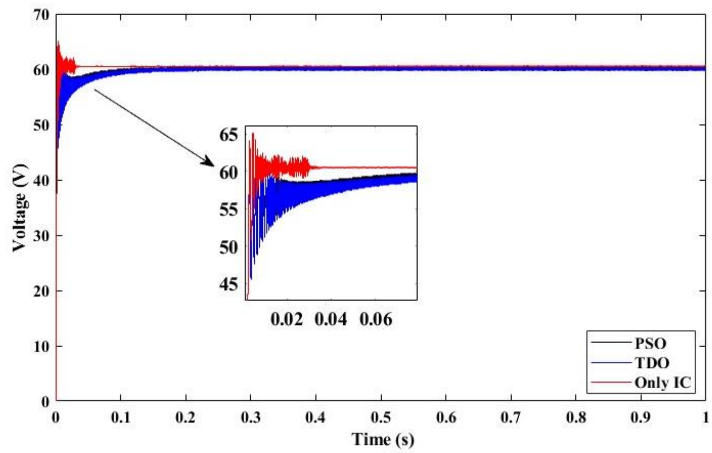

Figure 8. PV panel output voltage

Table 2. System Parameters

Parameter /Algorithm	PSO	Only IC	**TDO**
Kp	81.4724	-	81.4724
Ki	45.2896	-	13.8013
Kd	2.5397	-	3.2436
Peak Value (V)	61.47	65.0388	**61.23**
Overshoot (%)	2.725	7.4521	**1.8141**
Rise Time (ms)	**2.5**	2.6	2.6
Converter Efficiency (%)	96.8	96.5	**97**

In this study, the photovoltaic panel system is operated under constant irradiance and constant load conditions using PSO, Only IC and TDO algorithms and the graph of the panel output voltage is obtained. According to the experimental results, a higher overshoot is observed in the tests without using the PID controller. When the MPPT-PID controller is used, it is observed that the overshoot value decreases the most in the TDO algorithm, while the PSO algorithm improves the rise time. The highest converter efficiency among the three algorithms was obtained with the TDO algorithm. Therefore, the next experiments were performed using only the TDO algorithm.

3.2. Variable Irradiance and Constant Load Operation

In the second experiment, the performance of the system was performed with the TDO algorithm under variable solar irradiance (800-1000-600-400 W/m²) and constant load conditions. In this condition, the power and voltage graphs are presented in two separate graphs, a and b, in figure 9.

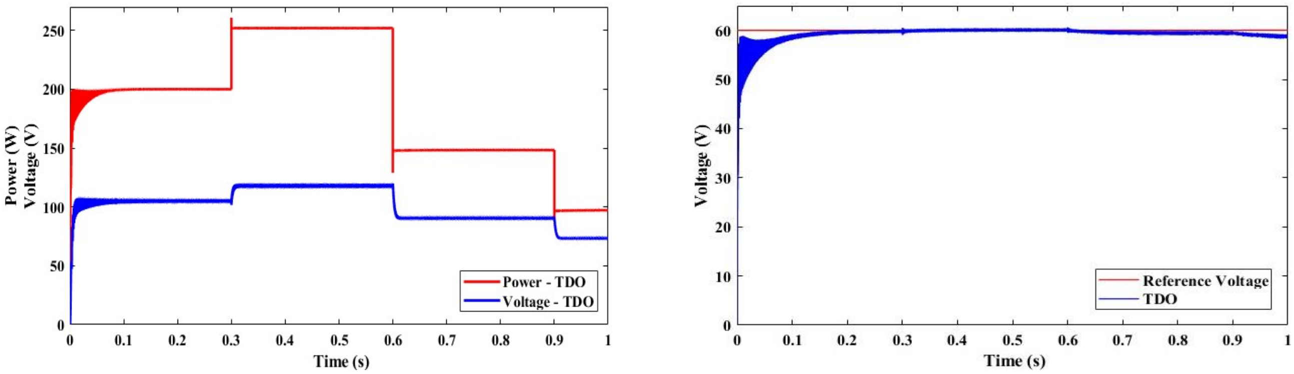

Figure 9. PV panel output power (a) and voltage (b)

3.3. Constant Irradiance and Variable Load Operation

In the third experiment, the performance of the system under constant solar radiation (1000 W/m²) and variable load (60-48-60-72) **Ω** conditions was analyzed. The power and voltage graphs obtained in this experiment are shown in two separate graphs, a and b, in figure 10. In addition, the convergence curve of the objective function of experiment 3 is presented in figure 11. This curve shows that the algorithm converges to the optimal operating point and demonstrates its effectiveness in application.

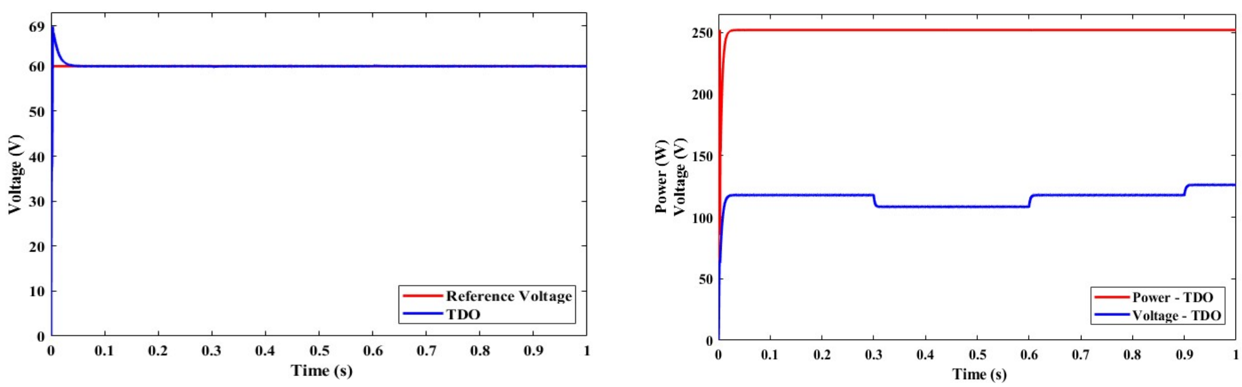

Figure 10. PV panel output power (a) and voltage (b)

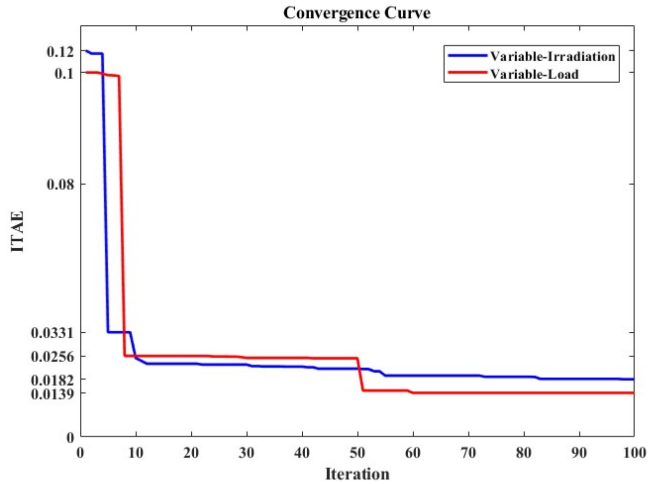

Figure 11. Objective function convergence curve

4. Conclusions

In this study, according to the comparison between the three algorithms, the TDO algorithm performed the best for the photovoltaic panel system. The use of the PID controller reduced the overshoot value by about 5% in the system with only the MPPT algorithm. The PSO algorithm presented a better rise time than the TDO algorithm with a result of 2.5 ms. As an interesting finding, it is noteworthy that both PSO and TDO algorithms find the same Kp (81.4724) value in the search space. Based on the obtained PID parameters, the highest converter efficiency (97%) was observed with the TDO algorithm. In other experiments with reference to the TDO algorithm, a stable output voltage was achieved under varying conditions. Under varying load conditions, even though the inductor parameter was calculated according to the minimum value, a constant voltage level (60V) was maintained under under and overload conditions, but a small overshoot was observed. A new controller design is needed to minimize this overshoot.

The No Free Lunch Theorem (NFL) states that no algorithm can give the best results for all problems. That is, an algorithm may be successful for a certain problem, but not for another problem. Therefore, the application of TDO, an up-to-date algorithm, to real-time photovoltaic system engineering problems will make significant contributions to the literature and increase the accuracy of the algorithm in this problem. In addition, increasing panel efficiency in solar energy systems and improving the converters and controllers between the panel and the load is an important focus for the future world, and it is predicted that the developments in this field will contribute to sustainable energy systems.

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