Enhancing the output power of solar cell system using artificial intelligence algorithms

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ABSTRACT
The main objective of research in the field of solar cell systems is to obtain the maximum output power. In this respect, artificial intelligence (AI) is considered the current icon. Hence, in the present paper, perturbation & observation (P&O) and particle swarm optimization (PSO) algorithms were used to achieve the maximum power. Solar irradiance at three different regions of Egypt was measured using a new technique based on Arduino microcontroller. The obtained experimental results of the solar irradiance were inlaid to the MATLAB simulation program to study the performance of the proposed algorithms. Many improvements were carried out in P&O and PSO algorithms to harvest maximum power for long hours daily by a continuous modulation of the duty cycle. The output maximum power and the reaching time of both improved P&O and PSO are better than the traditional one and PV array, which indicates their efficiency in harvesting the maximum power and enhancing the performance of solar cell systems. The reinforcing of the PV system by P&O improved its efficiency by 98.733%, while PSO improved its efficiency by 99.968%.

Keywords:
Artificial intelligence
Maximum power point
P&O
PSO
PV system
Solar irradiance

1. INTRODUCTION
One of the main obstacles to the spread of solar cells systems is the loss of output solar energy, which results due to environmental changes. Accordingly, in order to overcome this problem, various artificial intelligence algorithms such as perturbation & observation (P&O), particle swarm optimization (PSO), artificial immune system (AIS), artificial bee colony (ABC), and artificial fish swarm algorithm (AFSA) play a pivotal role to get the maximum power point MPP [1]–[6]. In solar energy, artificial intelligence is extensively applied in predicting, controlling, and hence improving the performance of solar cell systems [7], [8]. Simplicity, flexibility, and high performance have made the PSO algorithm a nerve for many applications. Additionally, PSO has been considered as an effective tool to perform multi-objective functions. It also provides a valuable high-accuracy solution and fast convergence speed to optimization problems [6]–[9]. On the other hand, the P&O algorithm is one of the most common artificial intelligence (AI) techniques that provide better tracking under uniform solar conditions. It is classified as the simplest and easiest AI algorithm [10], [11]. A DC-DC converter is an effective tool for controlling the PV output voltage to get the desired value, even though the photovoltaic (PV) voltage changes with solar irradiance. The DC-DC converter continually adjusts the energy amount absorbed from the source and injected into the load,
which achieves the desired output voltage regulation, i.e., controlling the relative periods of energy absorption and injection [12], [13]. In 2017, Kermadi and Berkouk [14] studied the possibility of getting maximum power using different AI algorithms, fuzzy logic, artificial neural network, genetic algorithm, PSO, and proportional integral derivative under the same conditions. The authors conducted a comparison between the used algorithms to evaluate their efficiency and cost [14]. Priyadarshi et al. [15] used particle swarm optimization linked by the internet of things (PSO-IoT) to get maximum power point tracking. The authors showed that the PV system performance improved through using PSO-IoT technique. They also compared the efficiency of the proposed PSO-IoT algorithm with other algorithms, P&O, ant colony optimization, and artificial bee colony [15]. Qasim and Vladimir in studied the role of the changes in the pulse width modulation (PWM) of a DC/DC converter for wind and solar energy hybrid system. The authors used incremental conductance and P&O maximum power point tracking algorithms. The authors obtained a regulated AC output voltage to obtain a constant RMS voltage at different loads [16].

From the aforementioned above, P&O and PSO algorithms were used to get the maximum power point of a solar cell system. Improvements in P&O and PSO through the changing in duty cycle to control the pulse width were conducted to obtain a highly maximum power point. The used solar irradiance was measured using a new highly efficient technique based on Arduino microcontroller in three different solar profiles cities at Egypt; Cairo, Luxor, and El-Beheira as shown in Figure 1 [17]. The chosen of the three regions was intended to obtain different solar irradiance because they are characterized by different climatic conditions, which enhances the validity of the results of the maximum power that will be obtained from the P&O and PSO algorithms [17], [18].

Figure 1. The solar atlas of Egypt

2. PRACTICAL PROCEDURES AND METHODOLOGY

The built proposed system, which contains solar irradiance tracer, PV array, DC-DC converter, and maximum power point tracking system (MPPT), is shown in Figure 2. A commercial 1 Soltech ISTH-215P 213.15w linked by a DC-DC converter was used. The output PV voltage and current are sensed by the maximum power point tracking algorithm, P&O and PSO. The controller algorithms adjust the duty ratio producing PWM to the DC-DC converter.

Figure 2. The block diagram of the proposed system
2.1. Solar irradiance tracer

A new technique based on the Arduino microcontroller was implemented to measure solar irradiance as shown in Figure 3. The solar irradiance in three different regions in Egypt which are Cairo, Luxor, and El-Beheira was measured. The chosen of the three regions is based on their sunshine and weather. Luxor is an Upper Egypt city distinguished by a high solar irradiance, El-Beheira coastal city has low irradiance, and Cairo is categorized as a fair weather. The solar power radiation has been obtained through converting the measured solar irradiance (lux) to solar power radiation W/m² as in the following relation [19]:

\[ 1 \text{ kW/m}^2 = 683 \text{ klux}, \text{i.e. 1 lux} = \frac{1}{683} \text{ W/m}^2 \]

![Figure 3. Solar irradiance tracer control system](image)

2.2. PV array model

A PV panel with the characteristics listed in Table 1 was used as a power source for the system. Three series PV modules in one string have been connected to build the used MATLAB/Simulink PV array model. Two inputs, solar irradiance in W/m² and cell temperature in °C are fed into the PV array as shown in Figure 4 because they are the main influences on the electrical behavior of solar cells.

![Figure 4. PV array model of the present study](image)

<table>
<thead>
<tr>
<th>Array data</th>
<th>Module data (1Soltech 1STH-215-P)</th>
<th>Maximum Power (W)</th>
<th>213.15</th>
<th>Voltage at maximum power point Vmp (V)</th>
<th>29</th>
<th>Cells per module (Ncell)</th>
<th>60</th>
<th>Current at maximum power point Imp (A)</th>
<th>7.35</th>
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<td>Parallel strings</td>
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<td>Series-connected modules per string</td>
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<td>Table 1. The used PV panels characteristics</td>
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</table>

2.3. DC-DC converter

In order to track the maximum power point generated from the PV, a duty cycle is controlled, which in turn controls the DC-DC converter. The MATLAB/Simulink simulated DC-DC converter topology diagram is shown in Figure 5. PV array source, Boost converter, and load connection are conducted. Boost inductor, load resistor, capacitor, diode, and MOSFET as a switch are the fundamentals constituents of the DC-DC boost converter.
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2.4. MPPT algorithms

The P&O and PSO algorithms were used as an MPPT controller to supply the DC-DC converter by PWM. The conventional P&O and PSO were used and many improved were conducted to enhance the output power of the PV system. The details of the conventional and improved P&O and PSO are discussed in below.

2.4.1. Conventional P&O

Voltage pulses perturbation, increasing and decreasing, around its initial value is the basis of the P&O MPPT controller. The perturbation is the main factor affecting the duty cycle of PWM, which controls the DC-DC converter output [19]–[22]. The MPP is reached using P&O through achievement the condition:

\[
\Delta P_{pv} \Delta V_{pv} = 0
\] (1)

The Simulink block diagram model of the conventional P&O MPPT controller algorithm is shown in Figure 6.
\[ v_i(n + 1) = w v_i(n) + c_1 r_1 (p_{best,i} - x_i(n)) + c_2 r_2 (g_{best} - x_i(n)) \] (2)

\[ x_i(n + 1) = x_i(n) + v_i(n + 1), i = 1, 2, 3, ... \] (3)

Where, \( v_i, x_i, n, w, r_1, r_2, c_1, c_2 \) are the velocity of particle \( i \), the position of particle \( i \); \( n \) the iteration number, \( w \) is the inertia weight, \( r_1 \) & \( r_2 \) random variables uniformly distributed within \([0,1]\), and \( c_1 \) & \( c_2 \) the cognitive and social coefficients, respectively. The best position that found by the \( i^{th} \) particle stored in \( p_{best,i} \), while that for all the particles stored in \( g_{best} \).

Tracking the MPP and adjusting the duty cycle of the DC-DC converter to get the maximum power is the main goal of the PSO algorithm. The PSO algorithm is centered on the particle iteration, duty cycle ranges, and the weights. The PSO algorithm calculates the required duty cycle for the initial particle for supplying the DC-DC converter to obtain the output volts, current, and power. This procedure will be repeated for all particles until the maximum value of the generated power is reached. In conventional PSO, the duty cycle remains fixed for all conditions even if the shading condition changed because the particles not reinitialize. The Simulink block diagram of the conventional PSO MPPT controller algorithm is shown in Figure 7.

![Simulink block diagram of the conventional PSO MPPT controller algorithm](image)

Figure 7. The block diagram of PSO MPPT controller and the subsystem of PSO algorithm.
2.4.3. Improved P&O

The improved P&O based on tune the variable value of the perturbation is shown in Figure 8(a). The tune of the output voltage was conducting by the changing in the duty cycle D through the factor $\Delta D$. The fluctuation of the output value around MPP was controlled and minimized using reducing the step size. Step size makes a large change in the duty cycle if the operating point is far from MPP and reduces the change when the operating point is close to MPP.

2.4.4. Improved PSO

Enhancement was carried out on the PSO algorithm by controlling the adjustment of the duty cycle and then obtaining a higher power than the traditional algorithm. In the conventional PSO, the three parameters $w, c_1, $ and $c_2$ are constant. In the present article, the improved PSO achieved through variation $w, c_1,$ and $c_2$ to accelerate the convergence. Hence, in (2) must be rewrite as (4).

$$v_i(n + 1) = w(n)v_i(n) + c_1(n)r_1(n) + c_2(n)r_2(n)(p_{best,i} - x_i(n))$$

(4)

The $w(n)v_i(n)$ term is used to maintain the continuity of particle movement in the same direction as its original movement, leading to an increase in the efficiency of controlling the convergence of PSO. On the other hand, the appropriate selection of the inertia weight works to fade $v_i(n)$ during the implementation of the algorithm, leading to an acceleration of convergence.

The flowchart of the proposed PSO algorithm is shown in Figure 8(b). With any shadow, the steps of the operating principle return to the beginning to implement the new conditions. As a result, a modification in the duty cycle will be carried out. The employed proposed PSO parameters are listed in Table 2.

![Flowchart](image)

Figure 8. The improved flowchart (a) P&O and (b) PSO

Table 2. PSO simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$w$</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$r_1$</th>
<th>$r_2$</th>
<th>Number of particles</th>
<th>Maximum iterations</th>
<th>$V_{max}$</th>
<th>$V_{min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.4</td>
<td>0.8</td>
<td>1.2</td>
<td>0.25</td>
<td>0.25</td>
<td>3</td>
<td>10</td>
<td>0.4</td>
<td>0.95</td>
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</table>
3. RESULTS AND DISCUSSION

3.1. Solar power radiation

Solar radiation measurements were conducted in the summer (June) and the built solar irradiance tracer system began detecting solar radiation from the sunrise (6 AM) to sunset (7 PM) as shown in Figure 9. Initially, all results of the measured solar power in the three selected regions throughout the day follow the standard behavior of the solar spectrum variation with time as shown in Figure 9. In other words, the solar power behavior shows an increase up to its maximum value at 11 am followed by a gradual decrease through the rest of the day. Luxor results showed slightly higher values than Cairo and both of them are higher than El-Beheira.

This was attributed to the clearness of the sky and the low humidity and mist in the Luxor and Cairo areas compared to the El-Beheira. On the other hand, the lower values of Cairo than Luxor are due to the dustiness of the surrounding factories and their relative raising of humidity compared to Luxor. MATLAB was fed by the measured solar power irradiance, Figure 9, to study the output power of PV and the role of P&O and PSO algorithms in improving the solar system’s performance and obtaining the maximum power.

![Figure 9. Measured solar power radiation in the three regions, Luxor, Cairo, and El-Beheira](image)

3.2. MPPT algorithms

The simulation was conducted over a period of 14 seconds, each 1 second equivalent to an hour of the measured spectrum. The obtained simulation results of current, voltage, and maximum generated power waveforms of the studied PV array, the conventional P&O, conventional PSO, improved P&O, and improved PSO algorithm under different solar irradiance conditions are shown in Figures 10-13. First, it was found that both the current and voltage are dramatically influenced by irradiance changes for the PV, P&O, and PSO as shown in Figures 10(a)-10(b), 11(a)-11(b), 12(a)-12(b), and 13(a)-13(b) respectively. On the other hand, the output voltage of the improved P&O is the highest as shown in Figures 11(b), 12(b), and 13(b) due to the permanent control in the duty allowing tracking of the maximum power. Consequently, the output power of the system based on the improved P&O outperforms that of conventional P&O and PV [Figure 10(c)] array for each value of solar irradiance as shown in Figures 11(c), 12(c), and 13(c). The broadening of the output power full width at maximum height FWMH strongly reflected the effective role of the AI algorithm in the improvement of the system performance. This broadening means that P&O accelerates the reaching of the MPP for each value of solar irradiance and also the length of the harvest period of the highest power of the system. As shown in Figures 10-13 the FWMH of the improved P&O is wider than both the conventional P&O and PV array. The improved P&O has a bandwidth of 9.45, 10.04, and 9.24 hours for Luxor, Cairo, and El-Beheira respectively, while the conventional has 9.36, 9.42, and 9.09 hours, and PV array has 8.39, 8.51, and 7.54 hours. Hence, the system reinforced by the improved P&O is an efficient than both conventional P&O and PV array.

![Figure 10. Comparing the simulation results of PV array for the three studied regions in (a) output current, (b) output voltage, and (c) output power](image)
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The comparison of FWMH of the improved P&O for the three studied regions showed that the bandwidth of Cairo is wider than that of Luxor, which was attributed to the long of the solar day period (the period between sunrise and sunset) for Cairo compared to Luxor. The sunrise in Cairo begins early and ends late compared to Luxor. Although the solar day of El-Beheira is longer than that of Cairo and Luxor its bandwidth is the least, which is attributed to the density of the mist in it that reduces the actual solar day for it, in addition to its high humidity compared to Cairo and Luxor. As a result of the inability of the conventional PSO algorithm to reinitialize the particles when a sudden shade occurs, the system always has a constant duty cycle for all values of solar irradiance conditions. But in the same regard, the multi-duty cycle of improved PSO during the system operation produces higher maximum generated power at each value of solar irradiance conditions as shown in Figures 11(c), 12(c), and 13(c). The FWMH of improved PSO is 10.24, 10.45, and 9.48 hours for Luxor, Cairo, and El-Beheria respectively, while of the conventional PSO are 9.54, 10.06, and 9.21 hours and for PV array 8.39, 8.51, and 7.54 hours. The wide broadening of FWMH of improved PSO compared to the conventional and PV array reflect the effectiveness of the designed improved PSO control.

\[
\text{Efficiency} \% = \frac{\text{MPPT algorithm extracted power}}{\text{PV maximum power}} \times 100
\]

Figure 11. Comparing the obtained simulation results using conventional P&O, conventional PSO, improved P&O, and improved PSO for Luxor city in (a) output current, (b) output voltage, and (c) output power

Figure 12. Comparing the obtained simulation results using conventional P&O, conventional PSO, improved P&O, and improved PSO for Cairo city in (a) output current, (b) output voltage, and (c) output power

Figure 13. Comparing the obtained simulation results using conventional P&O, conventional PSO, improved P&O, and improved PSO for El-Beheira city in (a) output current, (b) output voltage, and (c) output power
As a comparison between the conventional P&O, conventional PSO, improved P&O and improved PSO, the FWMH of them are plotted in Figure 14(a). Both P&O and PSO achieve the maximum power for each solar irradiance value in a shorter time than PV array and cover a long time period at maximum power. On the other hand, PSO reaches in a slightly shorter time than the P&O. So, P&O and PSO are efficient in reaching the maximum power immediately and the PSO is slightly better than the P&O. Finally, the efficiency of the used conventional P&O and PSO and the implemented improved P&O and PSO was calculated using in (5) [15] and is displayed in Figure 14(b). As can be seen from Figure 14(b), the MPPT based on the improved P&O and PSO algorithms has much higher efficiency compared to the conventional.

![Figure 14. Comparison between the conventional and improved of P&O and PSO (a) FWMH and (b) efficiency](image)

4. CONCLUSION

The series of conducted studies in this paper to enhance the performance of solar cell systems using new improved P&O and PSO algorithms showed the extent of its efficiency in reaching the maximum power point MPP faster. Irradiance of three different regions, Luxor, Cairo, and El-Beheira, was experimentally measured using highly efficient technique to be used as a radiation source. Improved P&O and PSO have a faster-reaching speed to MPP and cover a longer period of time than conventional P&O and PSO and PV array. The bandwidth values confirmed the ability of both improved P&O and PSO systems to achieve maximum power faster and for a longer period of time. The improved P&O and PSO harvest maximum power for period 9.24, 9.45, and 10.04 hours and 9.48, 10.24, and 10.45 hours for El-Beheria, Luxor, and Cairo respectively compared to 7.54, 8.39, and 8.51 hours for the PV array. The comparison between improved P&O and PSO showed that PSO was achieved the maximum power slightly faster and for a longer period than P&O. The efficiency of the output power of the PV system was improved by 98.733% and 99.968% by using P&O and PSO algorithms, respectively. Hence, both P&O and PSO algorithms enriched the solar systems’ ability to harvest maximum power faster and for a longer period.

REFERENCES


**BIOGRAPHIES OF AUTHORS**

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