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(Original article)

Monitoring and enhancing the performance of PV systems using IoT and artificial intelligence algorithms

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ABSTRACT

Monitoring and enhancing the performance of PV systems is a critical criterion for PV power plants. Hence, in the present paper, a smart prototype of the IoT technique and AI algorithms (here PSO) were used to achieve monitoring and enhancing performance of PV systems. A smart IoT technique based on embedded system through Node MCU ESP8266 has been constructed to monitor the solar power irradiance of solar cell systems. The measured results were displayed by ubidots through the HTTP protocol. Meanwhile, enhancing the performance of PV system is carried out using the PSO algorithm. The measured solar power irradiance was inlaid to the MATLAB simulation program as hardware in the loop to estimate the current, voltage, and output power in order to study the performance of the proposed PSO algorithm. Many improvements were carried out on the conventional PSO algorithm by a continuous modulation of the duty cycle to harvest maximum power output for long hours daily. The accuracy and rapidity of obtaining monitoring results using the proposed IoT system and the achieved power output using the improved PSO made them a strong candidate for enhancing the performance of PV systems.

Keywords: PV systems, Maximum power output, IoT, AI algorithms.

1. Introduction

Enriching the industrial revolution without harming the environment, especially with the increasing climate changes, requires increased reliance on clean sources of electrical energy. PV systems are one of the sustainable and green energy sources, the demand for which is increasing day by day [1-3]. PV systems face many challenges starting from the materials of manufacturing the cells themselves passing by the rapid monitoring of the environmental conditions surrounding the installed PV systems, such as solar irradiance drop, temperature, and humidity reaching to the losses in the output power. Monitoring these variables and receiving their results quickly and accurately accelerates taking appropriate procedures to repair any defect in solar systems during operation [4-6]. Internet of Things IoT is one of the highest efficient modern tools that proposed to monitor the PV systems [7-11]. IoT works effectively to connect physical gadgets quickly and easily to the cloud, which in turn works on exchanging the data freely that is facilitating getting the results and interacting with the gadgets via the Internet. The Internet of Things has enhanced the development of solar systems modeling and control, and the effectiveness of data prediction and acquisition [7-13]. Artificial intelligence algorithms such as P&O, PSO, AIS, ABC, and AFSA are one of the effective tools that play a pivotal role to overcome the occurred losses of the output power [14-19]. 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 [19-21]. In [21], N. Priyadarshi et al. 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, perturb & observe, ant colony optimization, and artificial bee colony. In [10], A. Mellit et al. discussed in a review article the challenges, recommendations, and future directions of both artificial intelligence and internet of things. In their conclusion, the authors mentioned the feasibility of their review in assisting researchers and industrial bodies in studying and applying artificial intelligence and Internet of Things techniques in several areas, one of them being PV systems.

Hence, an IoT monitoring system based on an embedded system through Node MCU ESP8266 was carried out experimentally to measure the solar power irradiance (W/m^2). The measurements were carried out on 1st-3rd of September 2023. The measured solar power irradiance was loaded on the MATLAB simulation to study the output power enhancement using PSO artificial intelligence algorithm. Many improvements in PSO through changing the duty cycle to control the pulse width modulation were conducted to obtain a high maximum power output (W).

2. Methodology of the proposed system

Embedded system of smart monitoring IoT system and PSO artificial intelligence algorithm were designed and constructed, as shown in Figure 1. The built embedded system consisted of a LDR starter, relay, solar irradiance & temperature tracer, Node MCU ESP8266-ESP12E, PV array, DC-DC converter, and maximum power point tracking algorithms MPPT (PSO). The carried-out procedures of the built IoT-PSO system are detailed as follows.

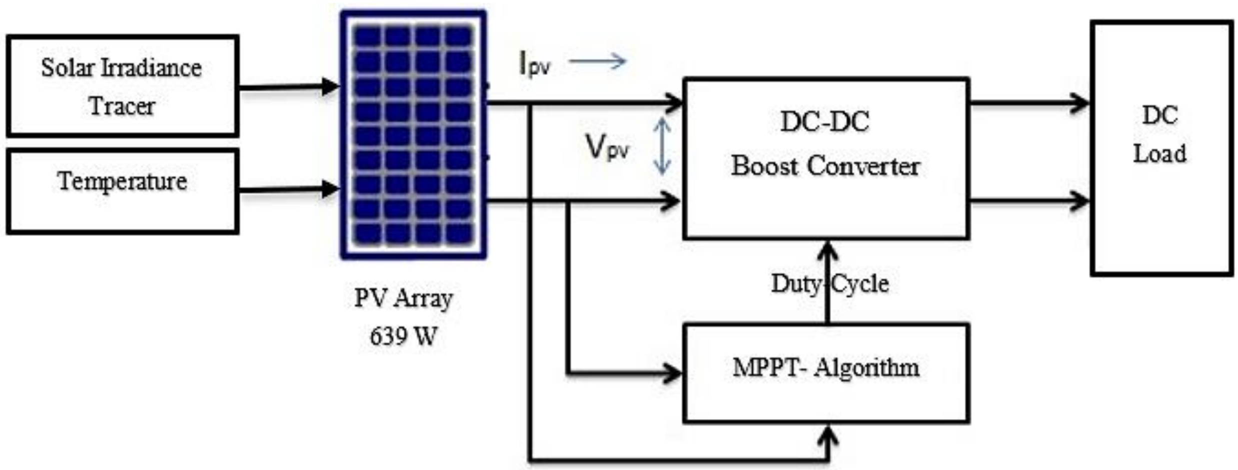


Figure 1. The block diagram of the built IoT-PSO system.

2.1. IoT system

The main description of the block diagram of the smart IoT system, the feeding system circuit diagrams, and the flow chart are shown in Figure 2.

An embedded system of Light Dependent Resistor LDR as a radiation sensor linked with Node MCU ESP8266 module was built as shown in block diagram (Figure 2a) and circuit diagram (Figures 2b). The monitoring system was fed through a PV to save energy and protect from outages. The 12-volt feeding system consists of a solar panel, charger controller, and solar battery as shown in Figure 2b:b1. As shown in Figure 2b:b2, the LDR was connected to Node MCU ESP8266 analog pins A0 to act as the input for the system. The Node MCU ESP8266 module integrates with router through TCP/IP protocol stacks giving the microcontroller access to the WiFi network. The Node MCU ESP8266 was programed to sense the solar irradiance (lux) and convert it to the solar power irradiance (W/m^2) based on the following equation [22]

$$solar\ power\ irradiance = \left(\frac{lux}{683}\right) \times 345.396656 \qquad (W/m^2) \tag{1}$$

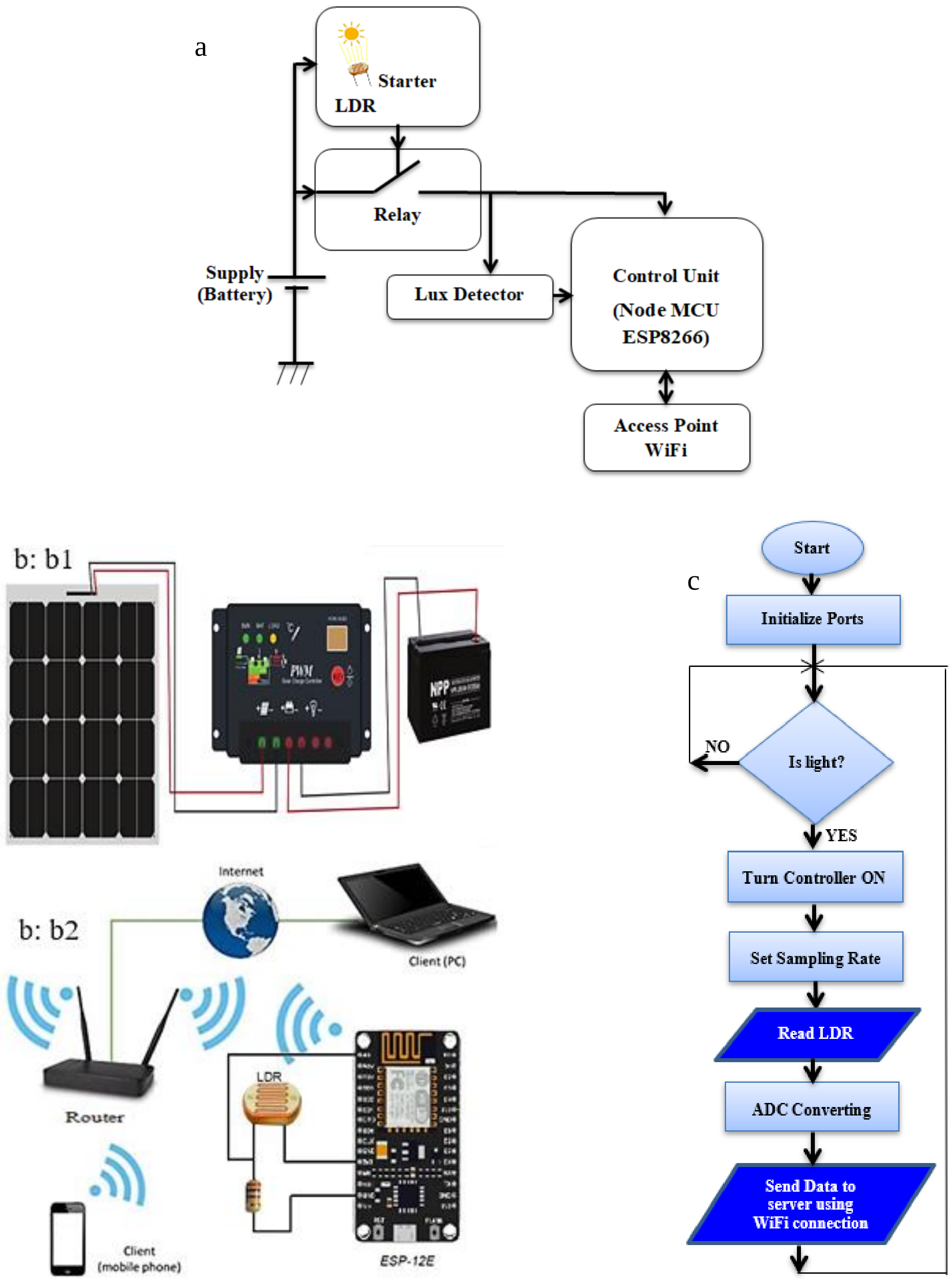


Figure 2. The proposed IoT system a) block diagram, b) circuit diagram (b1: the feeding system and b2: measuring and monitoring system), and c) flow chart.

Finally, an account was created on ubidots via the HTTP protocol for facilitating the rapid receiving and live displaying of the results. The library of HTTP ubidots ESP8266 was installed on Arduino IDE. The obtained Token ID from ubidots is fed into the code to support the results display authority.

The implemented IoT prototype, which consists of a PV module, charger controller, PV-battery, LM7805CT regulator, smart operating system, Node MCU ESP8266, and radiation sensor, is shown in Figure 3. The smart operating system consists of LDR linked with 5V relay driven by BC547BP transistor. The smart operating system automatically controls of the feeding power of the monitoring system depending on solar LDR starter through the relay. The PV-battery output is connected to the regulator, which in turn is connected to the smart operating system and the Node MCU ESP8266. The radiation sensor feeds from the Node MCU, while the router feeds directly from the PV system to avoid the loss of transferred data due to electricity outages.

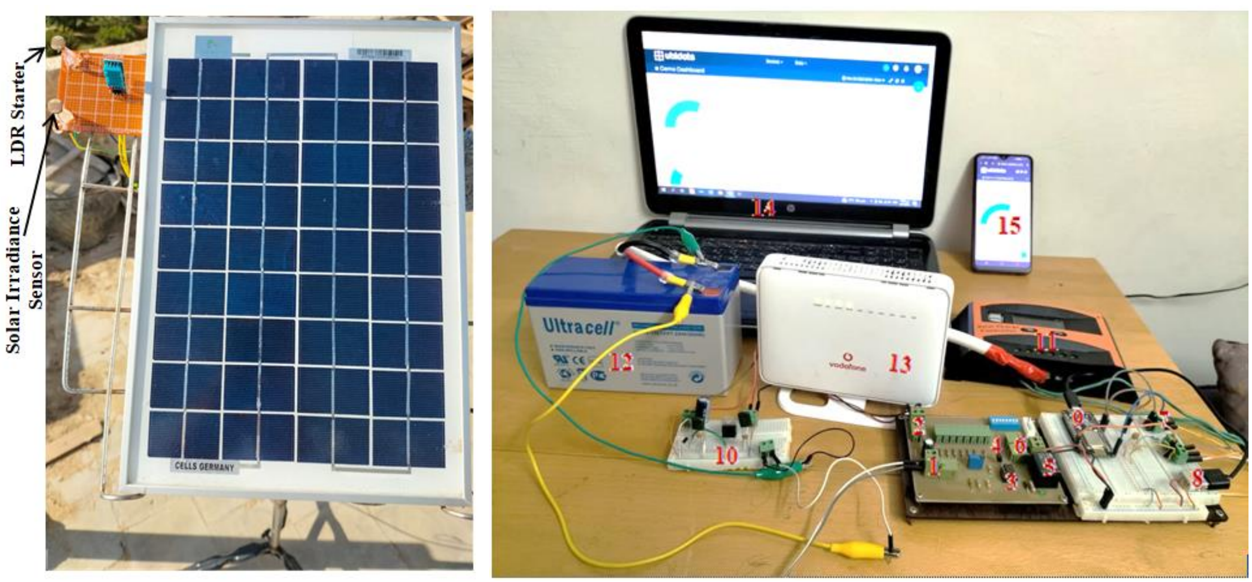


Figure 3. The implemented IoT prototype a) The installed PV panel, LDR starter, and solar irradiance sensor and b) The practical control system, 1) LDR starter jumper, 2) 5V from regulator, 3) Operational amplifier, 4) Transistor BC547BP, 5) 5V Relay, 6) 5V to Node MCU, 7) 2 jumpers from solar radiation sensor to 3.3V of Node MCU and analog pins A0, 8)Usb cable, 9) Node MCU ESP8266, 10) Regulator LM7805CT and diode 1N4007, 11) Solar charger controller (12V, 10A), 12) Rechargeable PV battery (12V, 7.2A), 13) Router, 14) Laptop, 15) Mobile phone.

2.2. Artificial intelligence simulation

To improve the efficiency of solar cell systems by controlling the output of solar cell systems through artificial intelligence algorithms (PSO), a solar cell system of PV-array linked to DC-DC boost converter was built on MATLAB, as shown in Figure 4. The PV array and DC-DC boost converter characteristics are listed in Table 1. The built system was fed with the measured results of solar power irradiance that were measured using the aforementioned Internet of Things technique. The output PV voltage and current are sensed by the maximum power point tracking algorithm (PSO). The controller algorithm PSO adjust the duty ratio generating PWM to the DC-DC boost converter.

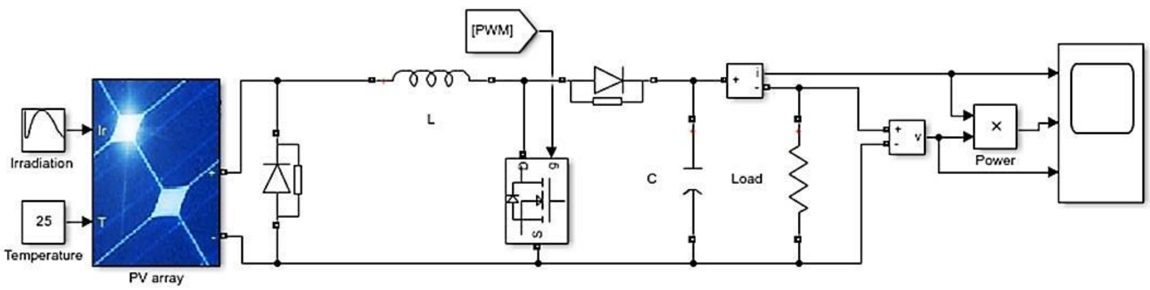


Figure 4. The PV source linked with DC-DC boost converter.

Table 1. The PV array and DC-DC converter characteristics.

PV-array		DC-DC converter	
Parallel strings	1	Inductor	10mH
Series-connected modules per string	3	Capacitor	500µF
Module	1Soltech 1STH-215-P	Switching frequency	50kHz
Maximum Power (W)/ module	213.15		

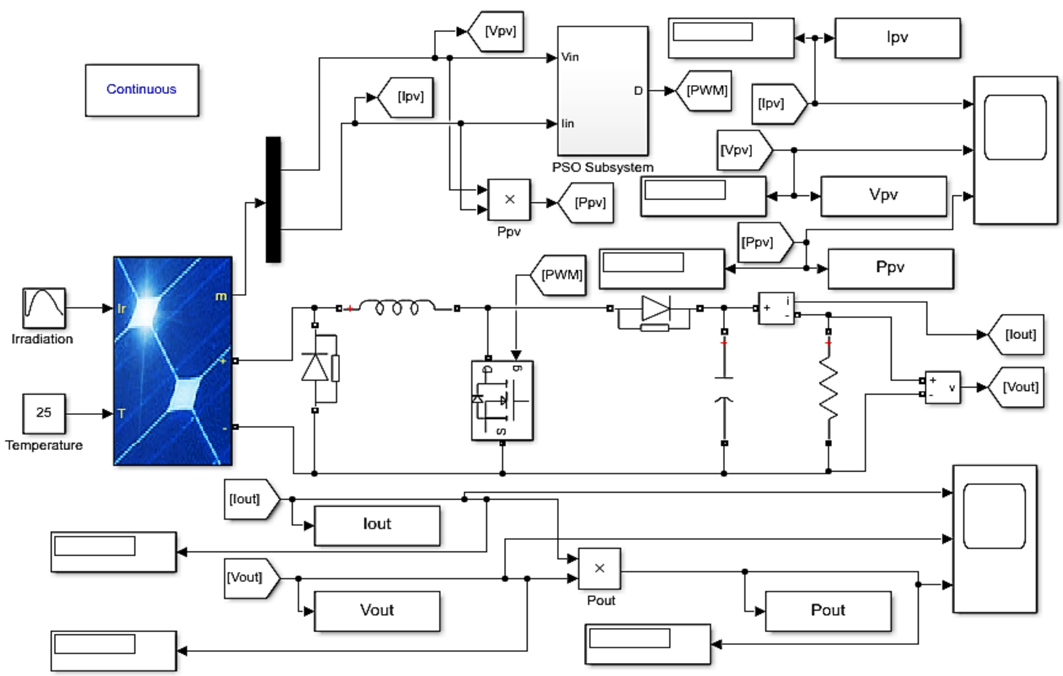
PSO algorithm technology is based on using a number of agents or particles in a specific region, as each agent or particle follows the best conditions that it has reached among those that were specified for it. Hence, each particle reaches the optimal solution or comes very close to it. The position and velocity of the particles in the conventional PSO algorithm are defined according to relation 2. [19-21]

$$v_i(n+1) = wv_i(n) + c_1 r_1 \left(p_{best,i} - x_i(n)\right) + c_2 r_2 \left(g_{best} - x_i(n)\right) \quad (2)$$

$$x_i(n+1) = x_i(n) + v_i(n+1), \qquad i = 1, 2, 3, \ldots. \quad (3)$$

Here, v_i & x_i, n, w, r_1 & r_2, and c_1& c_2, are the velocity & the position of the i^th particles, the iteration number, is the inertia weight, r_1 & r_2 random variables uniformly distributed within [0,1], and c_1 & c_2 the cognitive and social coefїcient, respectively. The optimal postion of the i^th particles stored in $p_{best,i}$, while that for all the particles stored in g_{best}.

One of the main ways to track the maximum power point through adjusting the DC-DC duty cycle is the PSO algorithm. The particle iteration, duty cycle ranges, and weights are the basic variables on which the idea of the PSO algorithm is based, where the required duty cycle of the initial particle is calculated to supply the DC-DC converter and then obtain the output voltage, current, and power. This process repeats for all particles up to reaching the maximum value of the generated power, which is in contrast to what is presented by the conventional PSO, where the duty cycle remains constant even with the change in solar irradiance, which is a major shortcoming that must be overcome to improve the output of solar systems. The Simulink block diagram of the PSO MPPT controller algorithm is shown in Figure 5.



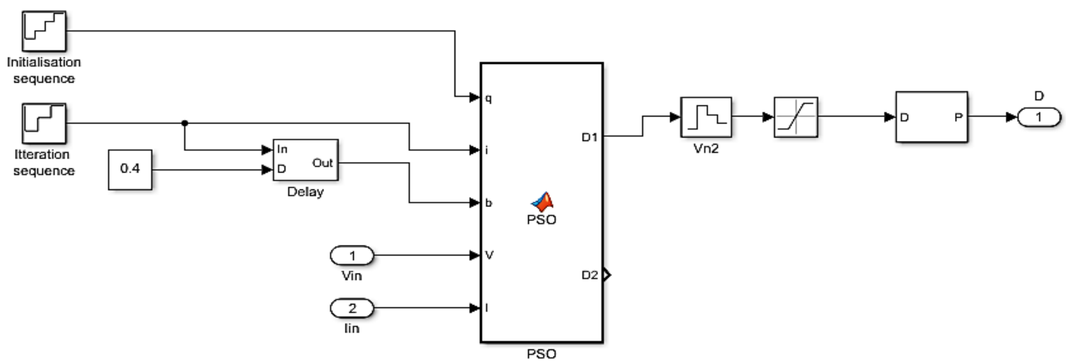


Figure 5. The block diagram of the proposed PSO MPPT controller and the subsystem of PSO algorithm.

Interesting modifications were conducted on the PSO algorithm through controlling the duty cycle adjustment and therefore, obtaining a higher output power than this of the traditional algorithm. In the conventional PSO, the three parameters $w, c_1,$ and c_2 are constant, while here, the improved PSO achieved through variation $w, c_1,$ and c_2 to accelerate the convergence. Therefore, equation 3 must be modify to be

$$v_i(n+1) = w(n)v_i(n) + c_1(n)r_1\left(p_{best,i} - x_i(n)\right) + c_2(n)r_2\left(g_{best} - x_i(n)\right) \quad (4)$$

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 suitable 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 improved PSO algorithm and carried out improving in its parameters is shown in Figure 6 and listed in Table 2. With any change in solar power irradiance, the steps of the operating principle return to the beginning to implement the new conditions. As a result, perfective modifications in the duty cycle will be carried out.

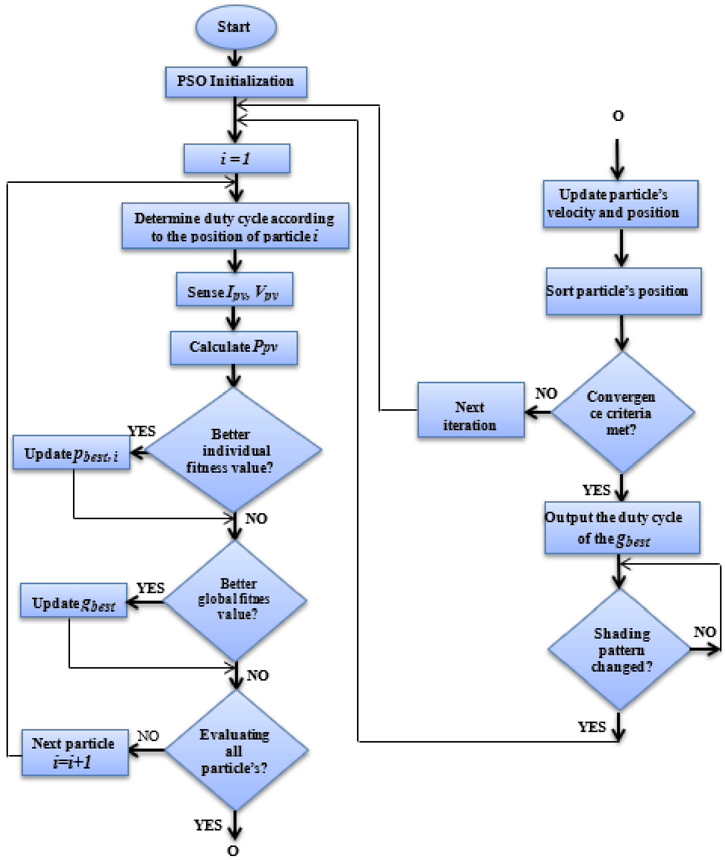


Figure 6. The flowchart of the improved PSO algorithm.

Table 2. PSO simulation parameters.

Parameters	Value	Parameters	Value
w	0.4	Number of particles	3
$c1$	0.8	Maximum iterations	10
$c2$	1.2	Var_{min}	0.4
$r1$	0.25	Var_{max}	0.95
$r2$	0.25		

3. Results and Discussion

The obtained solar power irradiance results, which were measured in Aswan and Alexandria cities were received using IoT system based on Node MCU ESP8266 through the common HTTP protocol. Figure 7a and b shows the results of the live profile of the measured solar power irradiance that was transmitted using the proposed IoT system at Aswan and Alexandria, respectively.

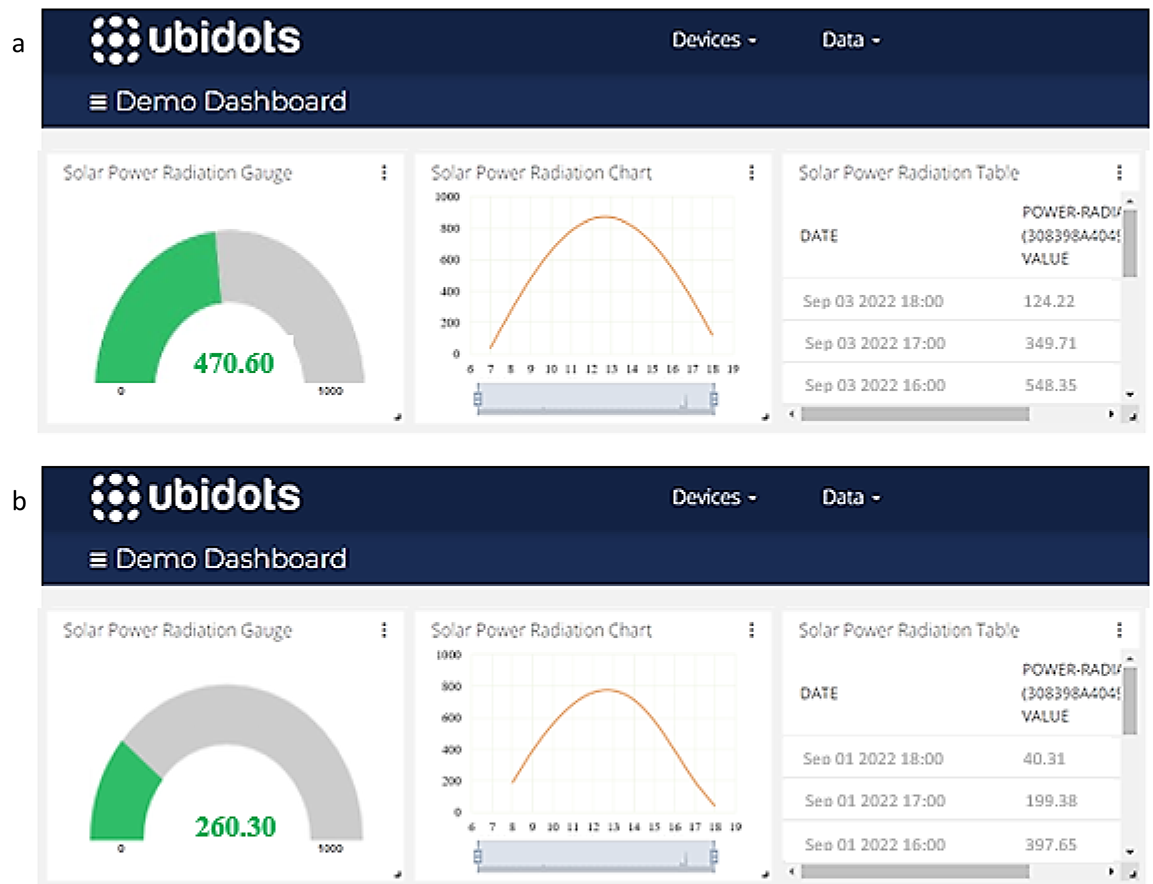


Figure 7. The ubidots live visualization of the measured solar power irradiance using the proposed IoT system in a) Aswan and b) Alexandria cities.

The results of the measured solar power irradiance in Aswan city (As an example) were used to investigate the role of PSO algorithm in improving the performance of the solar system and obtaining the maximum power output. The simulation was conducted over a period of 14 seconds, each 1 second equivalent to an hour of the measured spectrum. Initially, the output current, voltage, and power from the PV and DC-DC converter without PSO (without MPPT) were obtained to check the occurred improved by using PSO-MPPT algorithm.

The results of the measured solar power irradiance of Aswan (as an example) were used to study the role of PSO algorithm in improving the performance of the solar system and obtaining the maximum power output. The simulation was conducted over a period of 14 seconds, each 1 second equivalent to an hour of the measured spectrum. Figure 8 shows the responses of current, voltage, and the maximum generated power of the conventional and improved PSO algorithm.

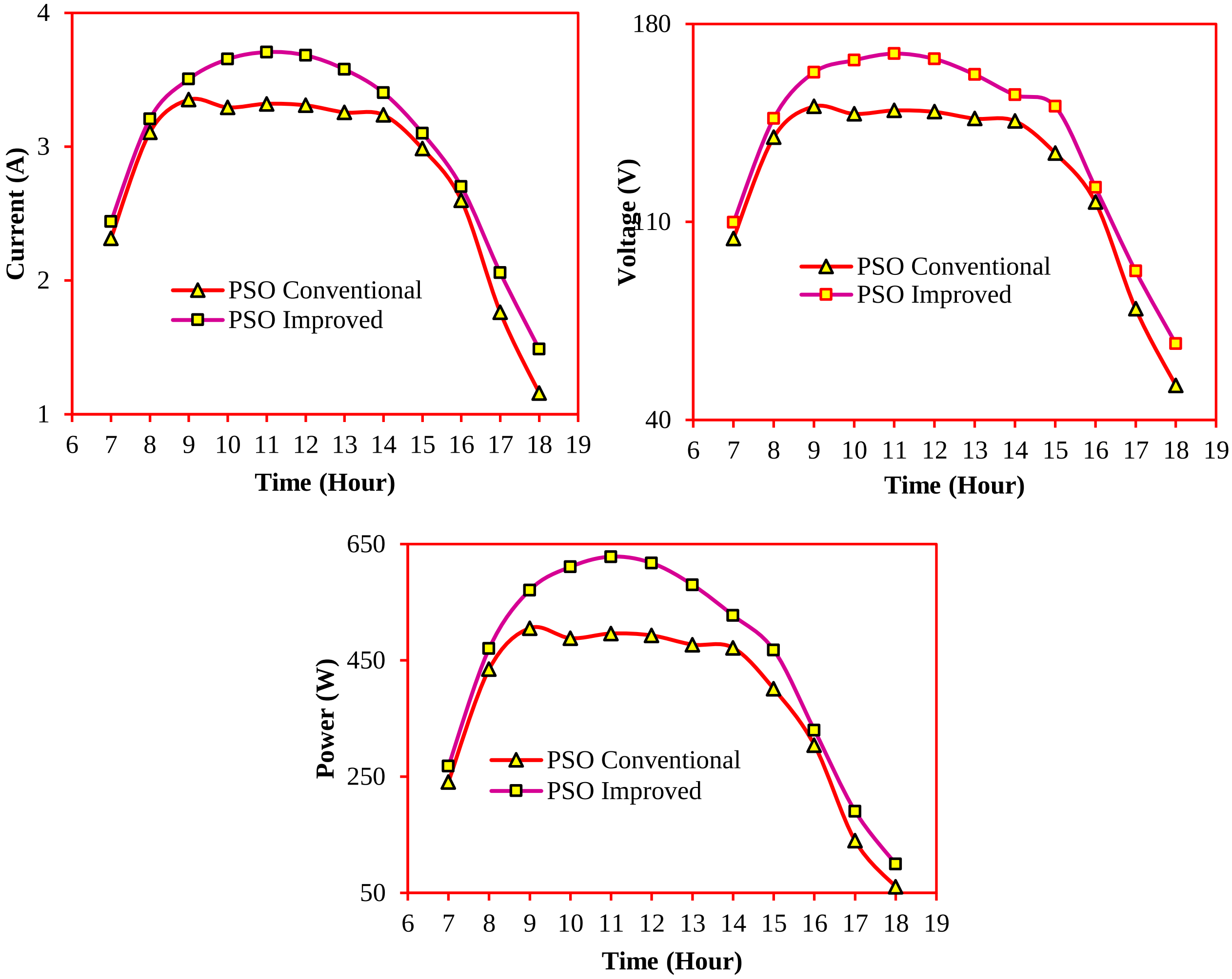


Figure 8. The output current, voltage, and maximum power of the conventional and improved PSO.

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 power irradiance conditions. The FWMH of improved PSO is 10.24 hours; while of the conventional PSO is 9.54 hours. The wide broadening of FWMH of improved PSO compared to the conventional reflect the effectiveness of the designed improved PSO control.

Finally, as a comparison between the conventional and improved PSO, FWMH of both of them output powers are plotted in Figure 9. It was observed that the improved PSO has a wide FWMH than the conventional, which reflect ability of improved PSO in harvesting more power than conventional.

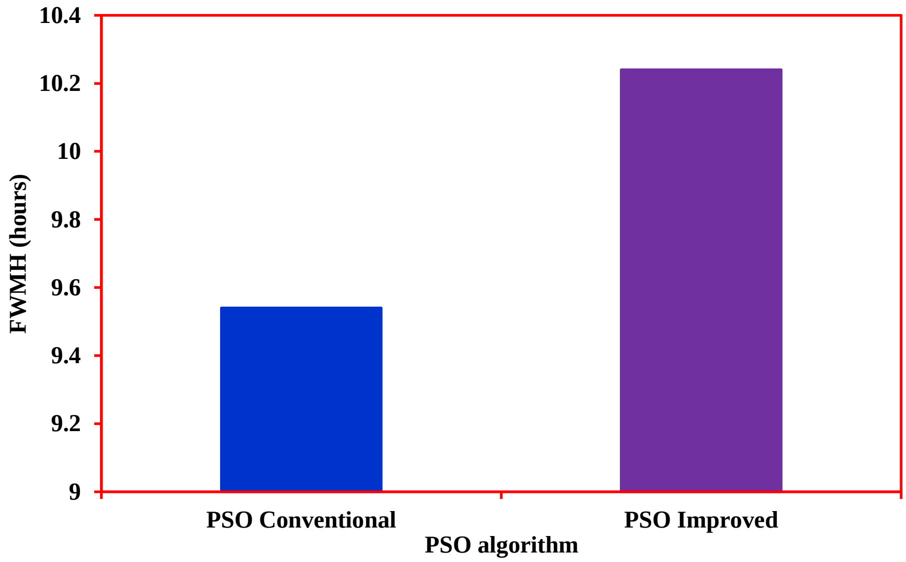


Figure 9. The power FWMH of the conventional and improved PSO.

4. Conclusion

A developed IoT system based on an embedded system using Node MCU ESP8266 in order to monitor solar cell systems and the rapid of receiving the results of solar power irradiance and improved PSO artificial intelligence algorithm were used to enhance the output power of solar cell systems. The proposed system succeeded in displaying a live profile of the solar power irradiance of the installed solar cell system. Improved PSO have a faster-reaching speed to MPP and cover a longer period of time than conventional one. The bandwidth values confirmed the ability of both improved PSO systems to achieve maximum power output faster and for a longer period of time. The improved PSO harvest maximum power output for period 10.24 hours compared to 9.54 hours for the conventional one. Hence, the considered IoT system is a strong candidate for use in the continuous monitoring of solar cell systems aiming to quickly intervene to solve any problems encountering operation, which is reflected positively on improving the solar cell system's performance. On the other hand, the PSO artificial intelligence algorithm enriched the solar cell systems' ability to harvest maximum power output faster and for a longer period.

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- **Conflict of Interest**

The authors declare that there is no conflict of interest related to the article.

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