



Optimization of an MPPT-based Controller for PV System using PSO

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ABSTRACT

This paper presents a control method suitable for photovoltaic (PV) systems which ensure that power generated is maximized for various conditions. Due to partial shading conditions in PV, the power-voltage characteristics exhibit multiple local peaks; one such phenomenon is the global peak. These conditions make it very challenging for maximum power point tracking (MPPT) to locate the global maximum power point. Many tracking algorithms have been proposed for this purpose. In this paper, a modified particle swarm optimization (PSO)-based MPPT technique is proposed. Unlike the conventional PSO-based MPPT methods, the proposed method accelerates convergence of the PSO algorithm by consistently decreasing the weighting factor, the cognitive and social parameters thus reducing the steps of iterations and improved the tracking response time. The advantage of the proposed method is that it requires fewer search steps (converges to the desired solution in a reasonable time) compared to other methods. It requires only the idea of series cells; thus, it is system independent. The study is supported by numerical and experimental results.

Keywords: Photovoltaic, power control, control system, particle swarm optimization

INTRODUCTION

In the past decade, the photovoltaic (PV) system has gained wide popularity as a renewable-energy source due to the possibility of the depletion of conventional energy sources as well as the high cost of conventional energy sources and their negative effects on the environment. An essential feature of all PV systems is the efficacy of its maximum power point tracking (MPPT). This aspect has drawn immense attention from photovoltaic researchers and industry experts as the most economical means to enhance the photovoltaic system efficacy.

Several MPPT techniques have been proposed in [1-10]. These methods differ in their accuracy, speed or complexity. Hossain *et al* [4], Eltawil *et al* [5] and David *et al* [6] reviewed and discussed various techniques. For the partially-shaded condition where the shaded cell in a PV module causes a decrease in power, the conventional MPPT technique becomes invalid due to the PV characteristics becoming more complicated and also displaying multiple MPP. This effect of partial shading has been analyzed by many researchers [7- 8]. In [10], a global stage was employed to locate the regions of the local MPP, while a perturb-and-observe algorithm was employed at the local stage to find the global MPP. Adaptive P&O MPPT was proposed in [11].

Particle swarm optimization (PSO) has high potential for MPPT due to its simple structure, easy implementation and fast computation capability. Since PSO is based on search optimization in principle, it should be able to locate the MPP for any type of PV curve regardless of environmental variations. The direct control structure was adopted by some researchers where the positions of the PSO particles are used as the duty cycles. Excellent dynamic tracking speeds under severe partial-shading conditions were able to be handled using the method. Furthermore, the steady state oscillations were found to be exceptionally low. For instance, to track the global point in a constant bus voltage application, the conventional PSO was employed in [12]. An analytical expression of the objective functions based on PV current, irradiance and temperature was formulated in order to track the MPP.

The current-based PSO method was proposed by Miyatake *et al* [13], where the series inductor current of the boost converter is used as the reference signal to generate the PWM signals for the switching converter. A repulsive term in the velocity equation of the PSO was also introduced. Miyatake *et al* [13] proposed an adaptive perceptive PSO (APPSO)-based MPPT algorithm. Ishaque *et al* [14] presented an improved PSO-based MPPT algorithm for PV systems and discussed the advantages of using PSO in conjunction with the direct duty cycle control in detail. However, no system design guidelines and practical design considerations are provided in these papers. Miyatake *et al* [15] attempted to approach the global MPP using the PSO algorithm. The authors tried to realize centralized MPPT control of the modular (multi-module) PV system. The MPPT algorithms have good performance under various partial-shading conditions; however, these methods are only suitable for systems that consist of multiple converters. However, the use of one central high-power single-stage electronic converter is very common in the PV system due to the economic reasons and the relative simplicity of the overall system. It is not only valid for the centralized PV inverter system, but can also be applied to other topologies. Thus, this study uses the same topology with a modified PSO to track global MPPs quickly and consistently on the multi-peak characteristic curves of a PV module during partial shading.

For a particle swarm optimization problem, there is need for a better global search in starting phase to help the algorithm converge to an area quickly; there is need for a stronger local search to get high precision value. Thus, the contribution and the advantages of this paper is the use of modified particle swarm optimisation (PSO)-based MPPT technique for PV systems. Unlike the conventional PSO-based MPPT methods, the proposed method accelerates convergence of the PSO algorithm by consistently decreasing the weighting factor and the cognitive and social parameters thus reducing the steps of iterations and improved the tracking time response. It requires fewer search steps or iterations (converges to the desired solution in a reasonable time) compared to [16]. The method requires only the idea of series cells; thus, it is system independent. The study is supported by numerical simulation and experimental results.

DESIGN METHODOLOGY

Particle Swarm Optimization

The PSO algorithm was first developed by Kennedy and Eberhart in 1995. The technique was established through a simulation of the social behaviors of animals such as fish schooling and birds flocking when they are moving in the group to a food source. The main advantages of PSO compared to other optimization techniques are that its concept is simple and the algorithm requires a small amount of memory space at the time of computation.

PSO is a stochastic, population-based evolutionary algorithm search method, modelled after the behaviour of bird flocks [17]. The PSO algorithm maintains a swarm of individuals (called particles), where each particle represents a candidate solution. Particles follow a simple behaviour: they emulate the success of neighbouring particles and their own achieved success. The position of a particle is therefore influenced by the best particle (*pbest*) in a neighbourhood, as well as the best solution found by all the particles in the entire population (*gbest*). The particle position, x_i , is adjusted using:

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

where the velocity component, v_i , represents the step size.

The velocity is calculated by:

$$v_i^{t+1} = \omega v_i^t + c_1 r_1 \cdot (pbest, i - x_i^t) + c_2 r_2 \cdot (gbest - x_i^t) \quad (2)$$

$$i = 1, 2, \dots, N$$

where x_i denotes the particle position for i ; the velocity of the particle at i is represented by v_i ; the number of iterations is denoted by t ; the inertia weight is represented by ω ; r_1 and r_2 are uniformly distributed random variables within [0, 1]; and the cognitive and social coefficients are denoted by c_1, c_2 , respectively [18]. The best position for the storage of the i th particle that has been found so far is denoted by the variable *pbest, i* and the best position for the storage of all the particles is represented by *gbest*. Figure 1 depicts the movement of the particle in the optimization process.

Weaknesses of Conventional PSO-Based MPPT Technique

The conventional PSO technique is fast and accurate when searching for the output characteristic curves of PV module arrays with single peak values. However, when some modules are shaded, the weights in conventional PSO must be readjusted appropriately based on various multi-peak curve characteristics. If this is not performed, the excessively high or low weights result in tracking failure. Thus, conventional PSO-based MPPT must be modified when some of the modules in a PV module array are shaded.

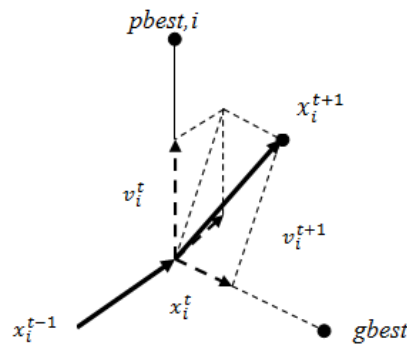


Fig. 1 Movement of particles in the optimization process [18]

Merits of PSO-Based MPPT Technique

Evolutionary algorithm techniques offer a better approach to tracking the global MPP in PV system power optimization. It is considered to be very effective in handling the MPPT problem because of its ability to deal with nonlinear objective functions. PSO is one of the evolutionary algorithm techniques that have high potential because of its easy implementation, fast computation capability and, above all, it's simple structure [19]. Based on these enormous merits, many researchers have employed PSO to track the global MPP in the case of partial-shading conditions [20]. In [21], the researchers tried to modify the conventional PSO searching scheme or equations by adding some extra coefficients: in some cases, it became complex and thereby increased the computational burden of the algorithm. In the proposed system, the main advantages are that the expressions of the weighting factor and the cognitive and social parameters are variable; it has high sensitivity for a relatively small area of partial shadow; and it has very good robustness against changes in series resistance.

Modified Particle Swarm Optimization

In the proposed method, the parameter selection is very important in demonstrating the application of PSO in tracking the MPP; thus, the position of the particle is designated as the duty cycle of the power converter, while the fitness value evaluation function was chosen as the extracted power P_{PV} for the entire PV system.

For the initialization step of the PSO, the particles could be either established in the random range or placed in the stationary position. In this case, it makes more sense to initialize the particles around a definite point if there are data available regarding the position of the global MPP in the search range. Thus, the searching spaces of the particles that cover (d_{min}, d_{max}) are initialised on a definite point, where d_{min} and d_{max} are the duty cycle minimum and maximum values of the DC-DC converter used, respectively.

The main purpose of this proposed method is to extract the optimal power P_{PV} of the PV system; therefore, the objective function can be formulated as follows [21];

$$P(d_i^t) > P(d_i^{t-1}) \quad (3)$$

where P is the PV power, d is the duty cycle, i is number of particle, t is the number of iteration. As illustrated in Figure 2, the fitness value which is designated as the generated power is then evaluated. The pulse width modulation acts according to the particle position i that denotes the duty cycle state; then the PV voltage V_{PV} and current I_{PV} can be measured to calculate the fitness value P_{PV} of particle i , which can then be used. However, to obtain the right sampling time, it should be noted that the power converter's settling time has to be less than the evaluation time interspaces between subsequent particles.

In this study, in order to update the individual and global best values, consistent decreases of the weighting factor and cognitive and social parameters reducing the steps of iterations were adopted for the PSO equations. The means that greater step sizes are used to increase the particle search velocity during the initial search because the distance to the global optimum is relatively large initially. However, even though it is not always that there is need to increase the particle search velocity at the initial search, but it also depends on the choice of another important factor which the initial generation solution to be considered. This prevents an excessively small step size from making local optimum traps unavoidable, and the weighting factor, ω , decreases gradually as the number of iterations increases because the particles are now approaching the MPP; the decrease in ω causes the steps in the particle movements to reduce, enabling the particles to track the MPP more accurately.

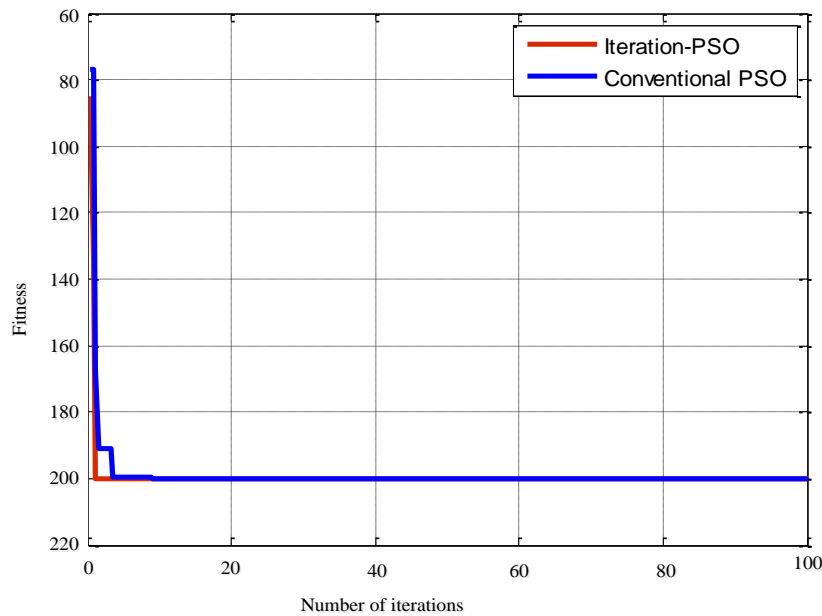


Fig. 2 Convergence Characteristics of PSO and modified PSO based Optimization.

Furthermore, to maintain the particle acceleration in the same direction in which it was originally moving, the first term $\omega(t) V_i(t)$ in Equation (2) is employed so that the converging demeanor of the PSO is controlled. For a PSO problem, there is need for a better global search in starting phase to help the algorithm converge to an area quickly and then the need for a stronger local search to get high precision value [22]. Suitable selection of ω provides a balance between global exploration and local exploitation which eliminates the need of V_{max} and also reduces the total number of iterations [23]. Therefore, it is paramount to keep ω as a variable value and not constant. In this paper, the inertia weight ω is set to a larger value and slowly reduce it for better exploration (changes from range $\omega_{max} = (1.0)$ to $\omega_{min} = (0.1)$) according to iterations and the velocity constants c_{1max} and c_{1min} are set to 1.2 and 1 while c_{2max} and c_{2min} are set to 1.6 and 1 respectively. r_1 and r_2 are random numbers between (0, 1) as in Equation (4):

$$\omega(t) = \omega_{max} - \beta t \quad \text{where } \beta = \frac{1}{t_{max}}(\omega_{max} - \omega_{min}) \quad (4)$$

The minimum and maximum bounds of ω are denoted by ω_{min} and ω_{max} . While the maximum allowed number of iterations is denoted by t_{max} . Likewise, the social and cognitive terms can be remodelled. Also, the search ability of PSO can be affected by the values of c_1 and c_2 which changes the particle direction. Selecting c_1 greater than c_2 sampling with respect to the bearing of $pbest$ would be biased, while selecting c_1 less than c_2 in the reverse case sampling in respect to the bearing of $gbest$ will be much preferred [24]. For these reasons, these two terms are defined as continuously increasing and continuously decreasing functions, as in Equations (5) and (6) respectively:

$$c_1(t) = c_{1,max} - x_1 t \quad \text{Where } x_1 = \frac{1}{t_{max}}(c_{1,max} - c_{1,min}) \quad (5)$$

$$c_2(t) = c_{2,max} - x_2 t \quad \text{Where } x_2 = \frac{1}{t_{max}}(c_{2,max} - c_{2,min}) \quad (6)$$

Two convergence criteria are employed in this study. The proposed MPSO-based MPPT method will terminate and yield the $gbest$ solution if the maximum number of iterations is attained or if all the particles' velocities become smaller than a certain threshold. Basically, PSO algorithms are utilized to solve the optimization difficulty, so that the optimum result is time invariant. However, in this case, the fitness value (which is the global MPP) sometimes varies or depends on environmental factors as well as loading states. To search for the new global MPP again in these cases, the particles must be reinitialised. Considering the change in irradiance and shading pattern to be detected here, the following constraint is employed. The particles will be reinitialised whenever the following condition is satisfied as in Equation (7):

$$\frac{|P_{pv,new} - P_{pv,old}|}{P_{pv,old}} \geq \Delta P(\%) \quad (7)$$

where $P_{pv,new}$ is the new PV power, $P_{pv,old}$ is the PV power at the global MPP of the last operating point and $\Delta P(\%)$ is the normalised power tolerance. Its value is set to 10% or selected as 0.1. Thus, if the normalized power mismatch is larger than 0.1, the samples will be dispersed on the PV curve; otherwise they remain on the MPP. Figure 3 depicts the comprehensive flowchart of the proposed system.

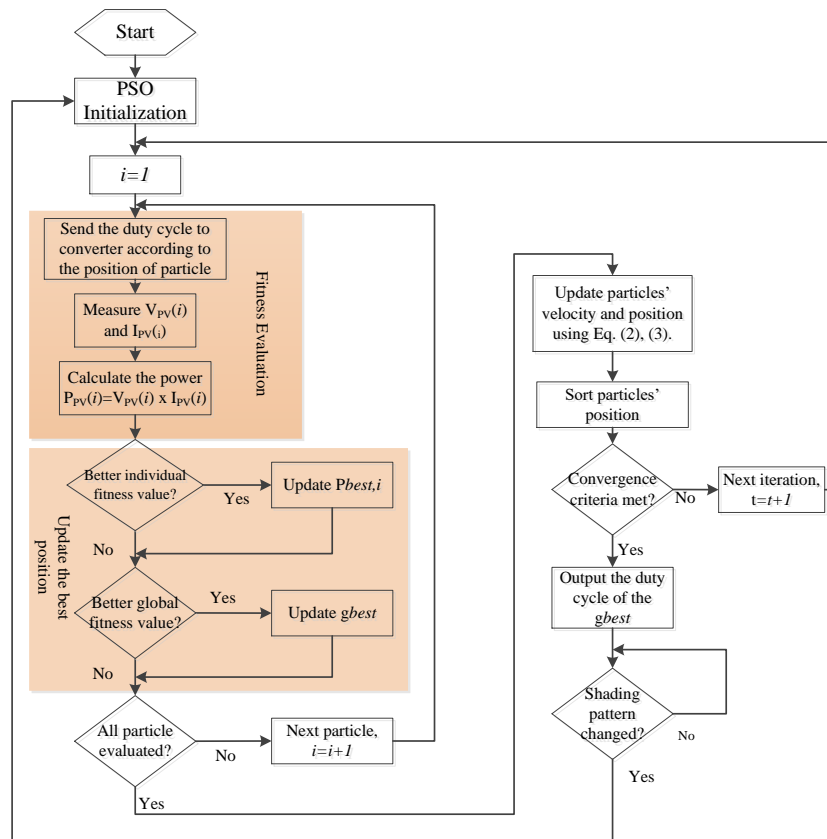


Fig. 3 Flowchart of the proposed Modified PSO-Based MPPT algorithm

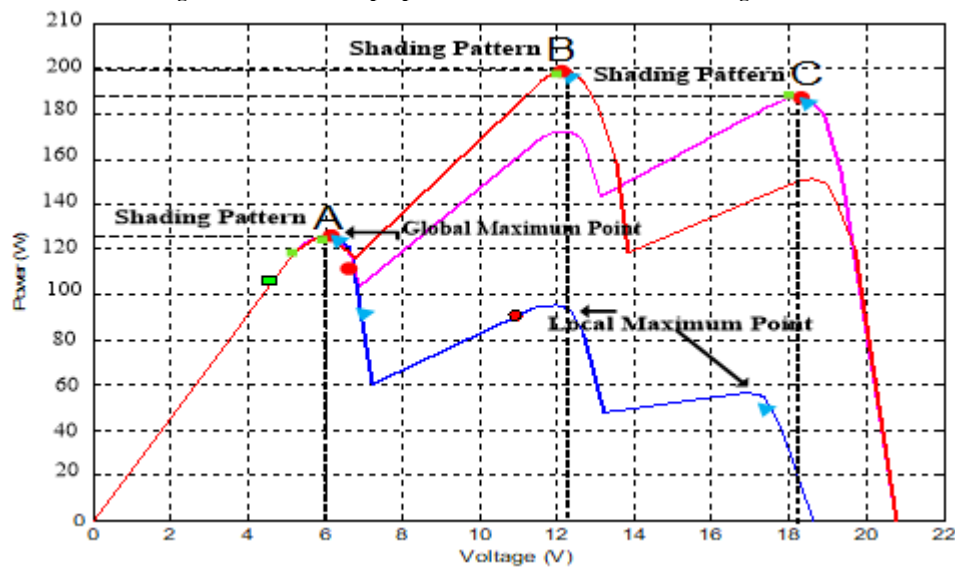


Fig. 4 Shows the P-V characteristic of the PV shading condition

The phenomenon of Partial-Shading Conditions

A PV module comprises many PV cells, either connected in series to produce a higher voltage or connected in parallel to increase current. Many PV cells are therefore connected either in series or in parallel to form a PV system. The PV curve of the PV cell would exhibit multiple MPPs under partial-shading conditions because of the bypass diodes as reported in [25]. In the partial-shading pattern, the shaded portion of the cells acts as a load rather than as a generator and creates the hot spot; hence, the bypass diodes of these shaded cells will conduct in order to avert this undesirable situation [26]. Multiple peaks in the PV curve would be obtained since the shaded modules are bypassed. The PV curves that result when this system is under different shading conditions are shown in Figure 3. As can be seen in the figure, the global MPP could occur either below or above the voltage range (i.e. either on the left or right of the PV curve) depending on the type of shading pattern. For this reason, the conventional MPPT algorithms will be very difficult to apply directly.

Tracking the Global Maximum Power Point

As shown in Figure 3, in the first pattern, there are two local MPPs, and the global MPP occurs at the leftmost one on the PV curve. In the second pattern, there are two local maximum points, and the global MPP does not occur at the rightmost or leftmost of the PV curve but occurs in-between. In the third pattern, there are two local maximum points, and the global MPP occurs at the rightmost one on the PV curve (i.e. close to the open-circuited voltage on the PV curve).

In order to begin the optimisation process, the search spaces of the particles that cover $[d_{\min} d_{\max}]$ are initialised on the definite point, where d_{\min} and d_{\max} are the duty cycle minimum and maximum values (as shown in Figure 4, where the triangular, circular and square points represent *duty cycle 1*, *duty cycle 2* and *duty cycle 3*) to be transmitted to the DC-DC converter respectively. The duty cycles are computed using Equation (2) which serves as the $p_{best, i}$ in the first iteration. As described earlier, consistently decreasing weighting factors with reduced iteration steps was adopted for the PSO equation. The advantage of this is that greater step sizes are used to increase the particle search velocity during the initial search because the distance to the global optimum is relatively large. Even though it is not always that there is need to increase the particle search velocity at the initial search, but it also depends on the choice of another important factor which the initial generation solution to be considered This prevents an excessively small step size from making local optimum traps unavoidable. Thus, the particle tracking will be faster because they are approaching the global MPP. The decrease in the weighting factor causes the steps in the particle movements to reduce, enabling the particles to track the global MPP more accurately (i.e. points A, B and C).

RESULTS AND DISCUSSION

To demonstrate the effectiveness of the proposed MPSO-based MPPT technique, simulations and experiments are performed. The simulation model parameters of the PV module are shown in Table 1. The simulation is performed using MATLAB, Simulink model. According to the design principle, the specified parameters of the complete MPSO-based MPPT algorithm is shown in Table 2. The PV module characteristic curves are simulated by arbitrarily setting the irradiation of the series-connected PV cells under the effect of uniform and partial-shading conditions. The PV module temperature is taken to be constant at 25 °C during the simulation. Unshaded PV modules are considered entirely radiated at 1000 W/m². Irradiation on the shaded PV modules is considered constant and changes from 0 to 1000 W/m². The MPSO-based MPPT algorithms are tested and verified for different shading patterns and the simulation results are presented with a comparison.

Tracking under Uniform Irradiance

In the case of uniform irradiance, under normal operating conditions, there is only one MPP, which occurs at 200 W. Figures 5 and 6 show the power, voltage and current waveforms in comparison to incremental conductance and conventional PSO. As can be seen from the voltage plot, V_{pv} closely tracks the voltage at maximum power V_{mpp} . The proposed method has higher accuracy and better response time in comparison with the other two algorithms. This is because the method consistently adjusts the weighting factor, cognitive and social learning factor which enabled it to track true MPPs at a 99.99% success rate under any irradiance conditions. It has been demonstrated that the proposed method for tracking MPP is highly robust to variations in solar irradiation, temperature and high tracking efficiency. During the first cycle or iteration, the three particles follow the initial values; then, the reference values are calculated based on Equations (1) and (2) for the remaining cycles or iterations before reaching the MPP. This further demonstrates the efficacy of the proposed method.

Table -1 Simulation Parameters of ICO-SPC 100W PV [26]

Parameter	Value
Maximum Power (P_{\max})	100 W
Voltage at P_{\max} (V_{\max})	17.3
Current at P_{\max} (I_{\max})	5.79
Open Circuit Voltage (V_{oc})	20.76
Short Circuit Current (I_{sc})	6.87

Table -2 Simulation Parameter Setting of the MPSO-based MPPT

Parameter	Value	Parameter	Value
Number of particles	3	ω_{\min}	0.1
Minimum duty cycle	0.02	$C_{1, \min}$	1
Maximum duty cycle	0.98	$C_{1, \max}$	1.2
Sampling time	0.1s	$C_{2, \min}$	1
Maximum iteration	3	$C_{2, \max}$	1.6
ω_{\max}	1.0		

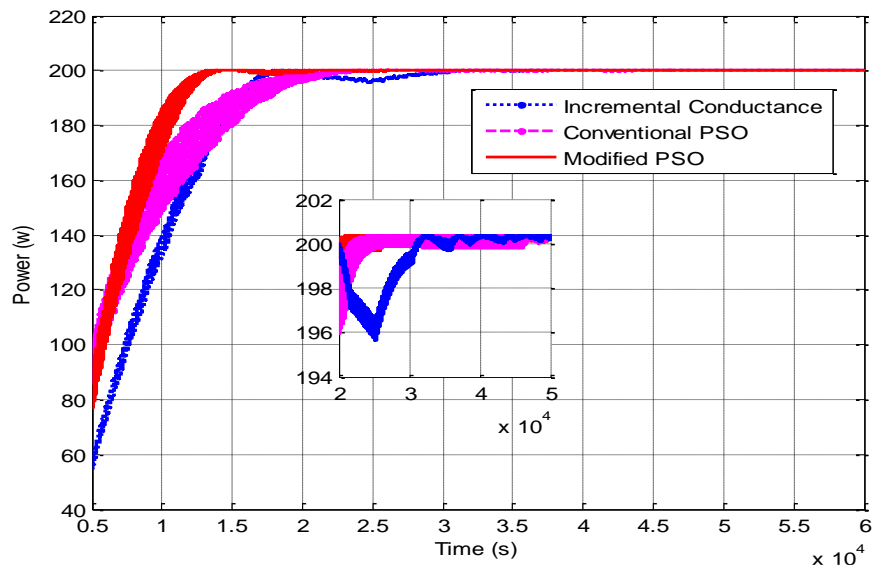


Fig. 5 Power comparisons for dynamic response time for the proposed and other methods

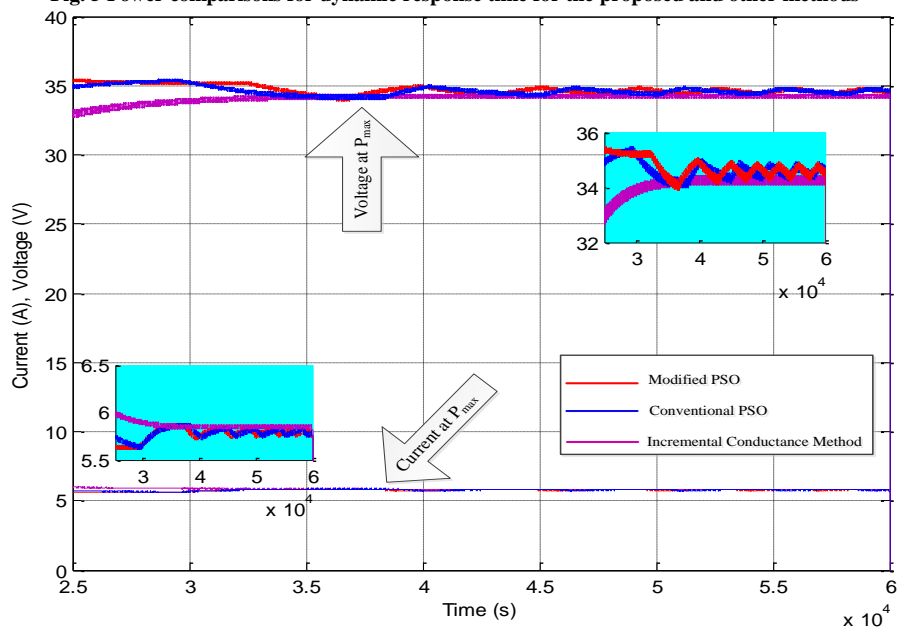


Fig. 6 Voltage and current comparison for dynamic response tracking time for the proposed and other methods

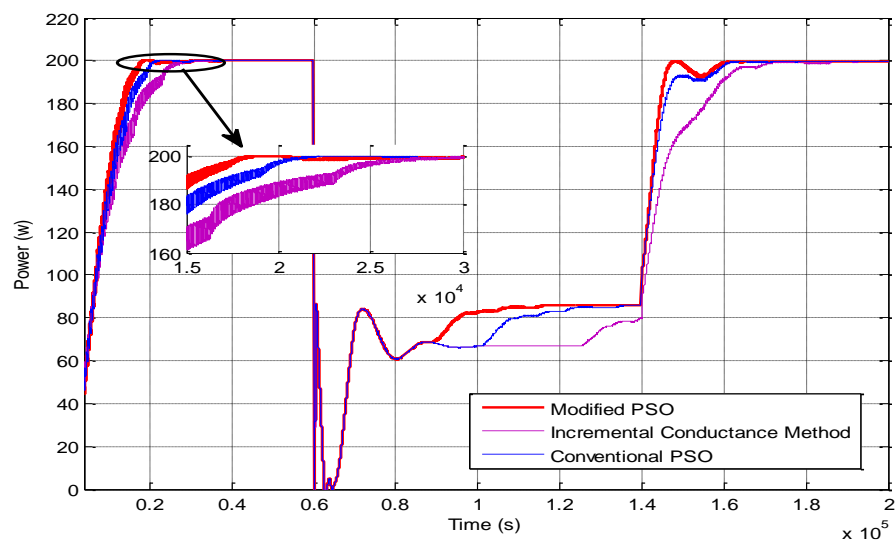


Fig. 7 Power comparisons for dynamic response time for the proposed and other methods under large change in irradiance.

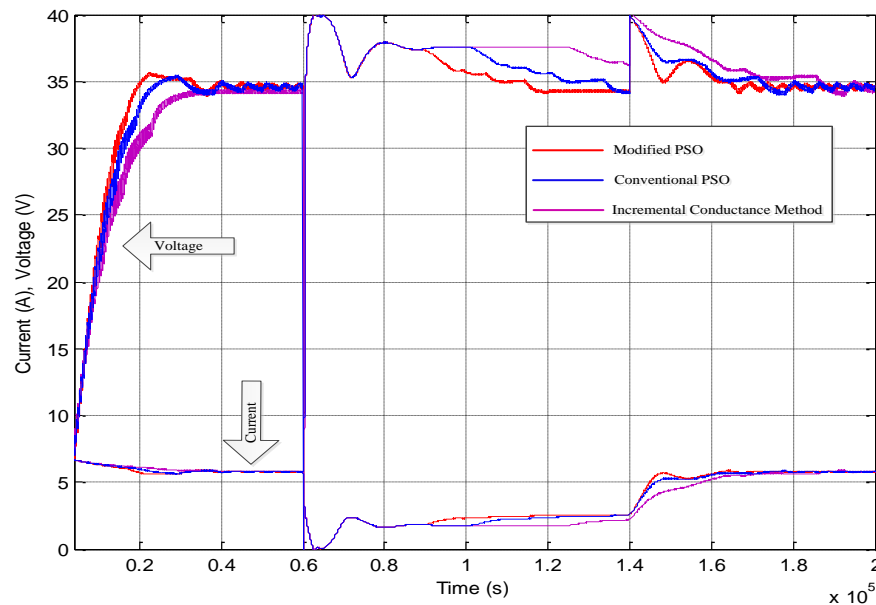


Fig. 8 Voltage and current waveforms comparison of the proposed and other methods for change in irradiance condition

Tracking under Non-Uniform Irradiance

Figures 7 and 8 show the power, voltage and current waveforms of the proposed method in comparison to incremental conductance and conventional PSO by a relatively large step change in the irradiance level (50% and 100%) up and down. As can see from the figure, the proposed method can find the global MPP in non-uniform-irradiance conditions and had a better response performance in dynamic tracking compared to the conventional PSO and incremental conductance method. Initially, when the controller is activated, it takes a few cycles or iterations for the proposed method to track the first global MPP. It takes less than 0.1 s for the proposed method to track back the global MPP faster than the other methods having no oscillation at the MPP with step change in irradiance compared to the other methods. This is because of the modification of the weighting factor and cognitive and social parameters. It enhances above all PV tracking accuracy and efficiency (a significant energy gain).

Test of the MPPT technique, a DC-DC boost converter, a programmable DC power supply emulated as solar photovoltaic is used as a result of the experimental constraint of educational laboratory equipments. The characteristics generated by the Matlab simulation model of the PV (ICO-SPC-100 watts) are then used to program the programmable DC power supply via interfacing software, providing the foundation for the experimental work. The DC power supply is able to emulate solar arrays with its Application Area Programming (AAP) feature which permits the loading, editing and storing of hundreds of current and voltage values.

The PV system had been tested for rapidly irregular shadow condition. This condition would change the characteristics of photovoltaic array, thereby altering the global maximum point (GMP) of P-V curve. The results are shown in figure 9 is the output power of the PV emulating system of the proposed techniques. Figure 10 shows the conventional PSO has a slow tracking response time because the conventional PSO failed to reach MPP faster. Figure 11 shows the incremental conductance with larger oscillation in the output power. For the rapidly changing irradiance, figure 12 has shown the experimental results for the tracking power of the proposed technique. The experiment was conducted under the same conditions as described in the simulation. It can be seen that the experimental results match very closely to the simulations. For each condition, the MPP is attained in relatively short time and exhibits almost zero oscillation in steady state. Hence the correctness of the proposed technique is validated.

Tracking Efficiency of the MPPT Algorithm

The accuracy of the tracker in tracking the MPPT and the efficiency of the technique also helps in determining the method to be used by the user. Some techniques provide accurate results, whereas some are not able to track the MPPT efficiently, thus decreasing the efficiency of the tracker. The efficiency can be calculated by the following formula [27]:

$$\eta_{MPPT} = \frac{P_{pv}}{P_{MPPT}} \times 100\% \quad (8)$$

The accuracy of the tracker to make the P_{pv} closer to P_{MPPT} determines the efficiency of the system. The closer the P_{pv} is to P_{MPPT} , the more accurate is the technique. It is particularly difficult to estimate the exact accuracy of a technique without implementation of the same.

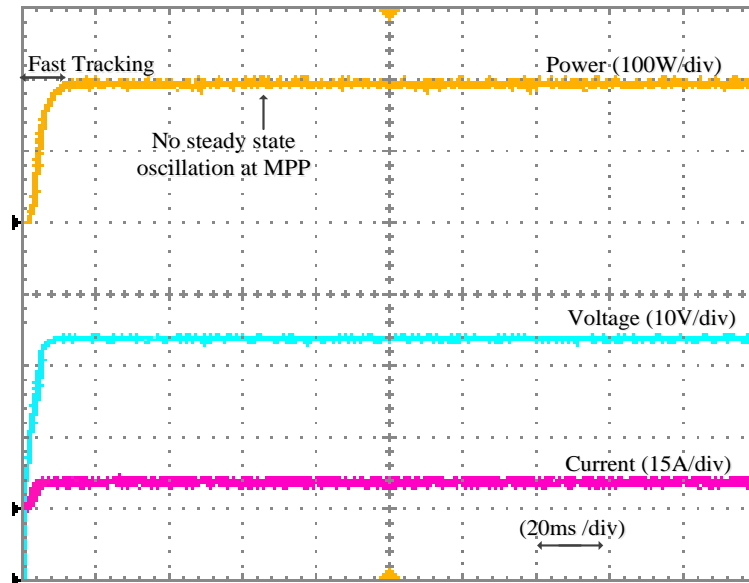


Fig. 9 The tracking power response time for the proposed modified PSO

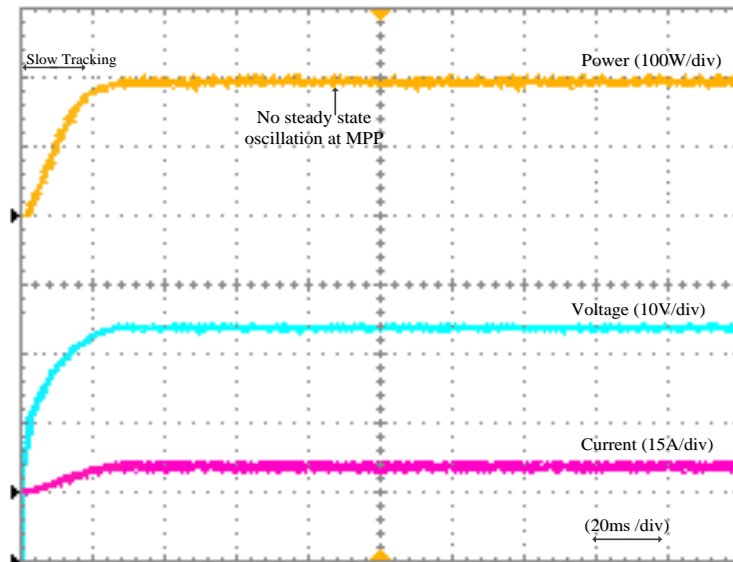


Fig. 10 The tracking power response time for conventional PSO

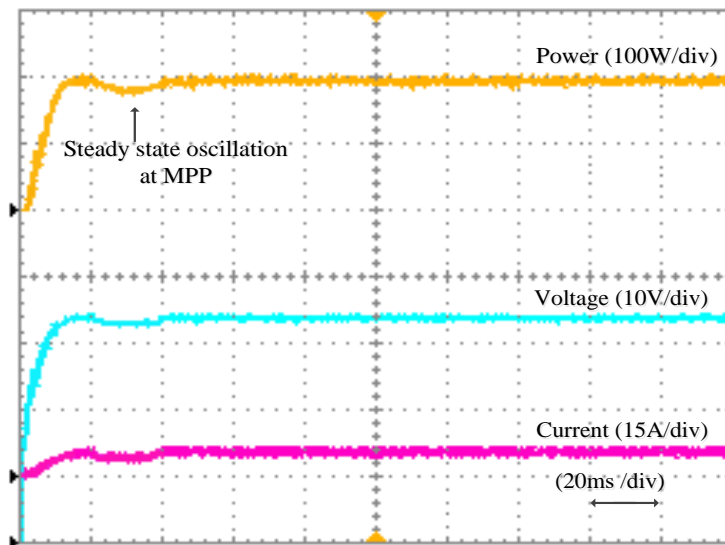


Fig. 11 The tracking power response time for incremental conductance

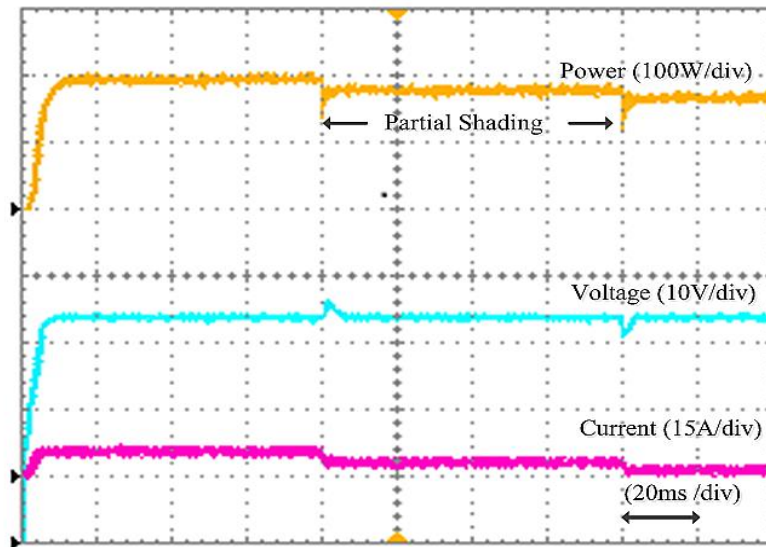


Fig. 12 Tracking power, voltage and current of the proposed method for step change in input.

Performance Evaluation and Comparison

It is very difficult to analyze, through simulations, the amount of energy obtainable from a PV system while taking into account the effect of partial shading. The challenge lies in simulating the rapidly changing shading as well as its shape in such a way that the simulation vividly reflects the actual behaviour of a PV system. Hence, the most reliable means to evaluate the effectiveness of the proposed method is by having real-time measurements of generating power for some hours. Then the performance of the proposed algorithm is compared with other established MPPT schemes for the same conditions, namely, i) the incremental conductance algorithm (INC), and ii) the MPPT based on the conventional PSO search method. A similar study was carried out in [27]. Figure 8 shows the experimental set-up of the proposed method.

Taking into account the actual sun power, the same clear day was chosen for conducting the experiment. The weather data for the day was taken between 8:00 am to 6:00 pm. In addition, the experiments were carried out in the month of March as the weather is clear and more stable in Skudai Malaysia during this period. Figure 14 shows the irradiance and temperature profile. Figure 15 shows the experimental power waveforms of the proposed methods under partial conditions. It should be noted that there was a difference in the power extracted by three different MPPT algorithms. This was mainly due to the nature of the MPPT algorithm capability. The incremental conductance and conventional PSO methods showed lower generated power compared with that of the proposed method under partial-shading conditions; hence, the power generated was comparatively higher than other tracking methods.

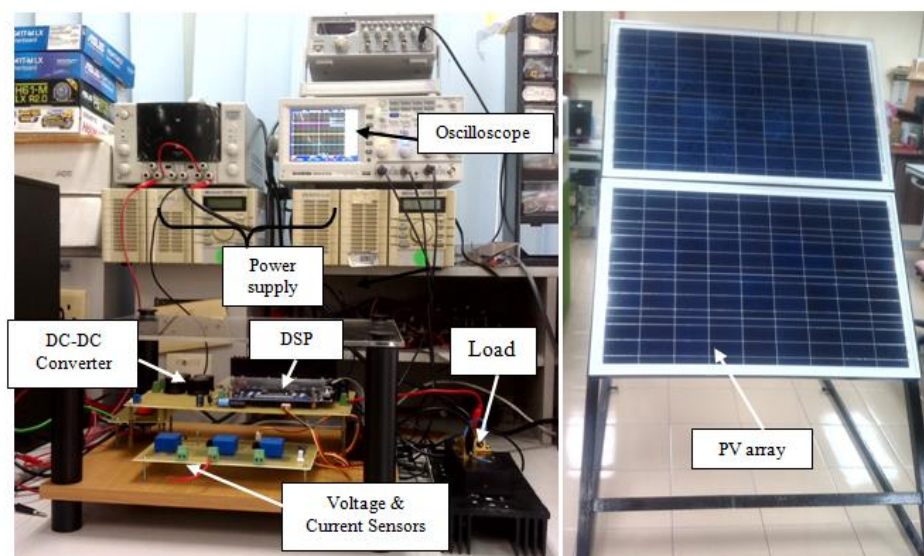


Fig. 13 Experimental setup of the proposed PV system

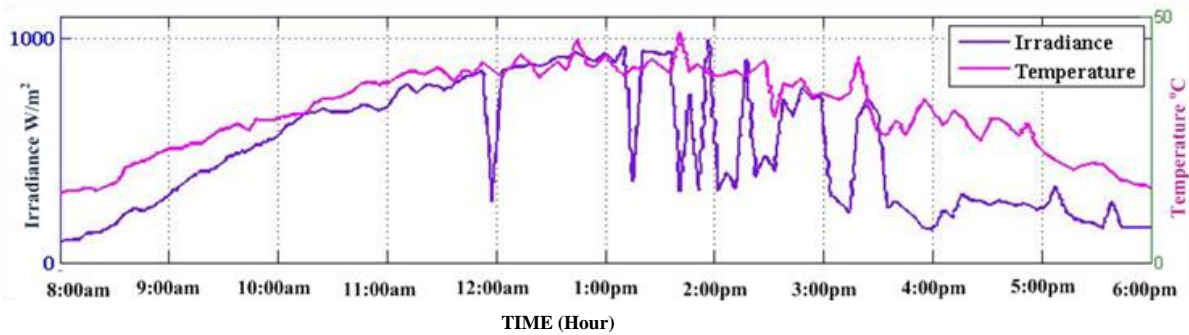


Fig. 14 Irradiance and temperature profile

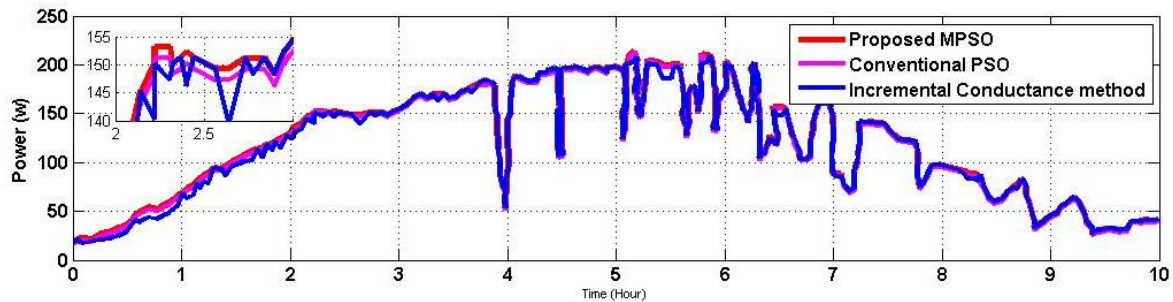


Fig. 15 Power comparisons for partial shading condition of the proposed and other methods

The INC and PSO tracking methods showed unwanted oscillations in their power. These oscillations were mainly due to: i) fluctuations of the operating point, ii) the algorithms' shortcomings with respect to systems in which solar insolation is not uniformly distributed, and iii) the algorithms' inability to identify the global optimum point when the power curve exhibits multiple local MPPs. In view of these reasons, the two power tracking algorithms were unable to track the true MPP when the PV array was under slowly shading conditions. This discussion clearly demonstrates that the power extracting feature of the proposed controller—both in ideal conditions as well as in partial shading—provides a feasible alternative solution to real-time PV systems.

CONCLUSION

In this paper, a modified PSO-based MPPT method for tracking MPP was presented. The proposed method accelerates convergence of the PSO algorithm by consistently decreasing the weighting factor and the cognitive and social parameters thus reducing the steps of iterations and improved the tracking time response. The advantage of the proposed method is that it requires fewer search steps (converges to the desired solution in a reasonable time) compared to other methods. The method requires only the idea of series cells; thus, it is system independent. It has been demonstrated that the proposed method for tracking MPP is highly robust to variations in solar irradiation and high tracking efficiency. The proposed method has been verified by numerical simulations and experimentally tested under shading conditions. The results show good performance in terms of speed of convergence and also guaranteed convergence to global MPP with faster time response compared to the other methods.

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