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MPPT-BASED CONTROL ALGORITHM FOR PV SYSTEM USING ITERATION-PSO UNDER IRREGULAR SHADOW CONDITIONS

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Abstract
The conventional maximum power point tracking (MPPT) techniques can hardly track the global maximum power point (GMPP) because the power-voltage characteristics of photovoltaic (PV) exhibit multiple local peaks in irregular shadow, and therefore easily fall into the local maximum power point. These conditions make it very challenging, and to tackle this deficiency, an efficient Iteration Particle Swarm Optimization (IPSO) has been developed to improve the quality of solution and convergence speed of the traditional PSO, so that it can effectively track the GMPP under irregular shadow conditions. This proposed technique has such advantages as simple structure, fast response and strong robustness, and convenient implementation. It is applied to MPPT control of PV system in irregular shadow to solve the problem of multi-peak optimization in partial shadow. In order to verify the rationality of the proposed algorithm, however, recently the dynamic MPPT performance under varying irradiance conditions has been given utmost attention to the PV society. As the European standard EN 50530 which defines the recommended varying irradiance profiles, was released lately, the corresponding researchers have been required to improve the dynamic MPPT performance. This paper tried to evaluate the dynamic MPPT performance using EN 50530 standard. The simulation results show that iterative-PSO method can fast track the global MPP, increase tracking speed and higher dynamic MPPT efficiency under EN 50530 than the conventional PSO.

Keywords: Photovoltaic, iteration-PSO, MPPT, Controller, Irregular shadow, EN 50530

1. Introduction

In the past decade, the photovoltaic (PV) system has gained wide popularity as a renewable-energy source due to 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 technique has drawn immense attention from photovoltaic researchers and industry experts as the most economical means to enhance the photovoltaic system efficiency. MPPT is primarily an operating point co-coordinating the PV module and the DC-DC converter. However, MPPT is not simple and easy to track because of the non-linear I–V characteristics of the PV curve and the effect of partial shading causing the inconsistent in irradiance and temperature. Therefore, tracking the accurate maximum power point (MPP) has been always an intricate issue. The tracking eventually becomes sophisticated when all the PV modules do not experience constant irradiance.

Several MPPT techniques have been proposed (Petreus *et al*., 2010; Ishaque *et al*., 2011; and Abdulkadir *et al*., 2012). These methods differ in their accuracy, speed or complexity. (Hossain *et al.* 2013; Eltawil *et al, 2013;* and David *et al*, 2014) 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 (La Manna *et al*., 2014 and Ishaque *et al*., 2011). (Zegaoui *et al*, 2011) proposed a two-stage technique to track the global MPP. In the first stage, the operating point of the PV system moves from the vicinity of the global MPP by estimating the equivalent load line. Then, in the second stage, the incremental conductance method is employed which converges the MPP. However, this method fails to track the global MPP if the global MPP lies on the left of the load line. In (Miyatake *et al*., 2011), 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. A sequential extremum seeking control (ESC)-based MPPT technique was proposed in (Luo *et al*., 2009) based on approximate modelling and analysis of the characteristics of PV modules under variable partial-shading conditions. However, this method exhibits steady-state error and is system-dependent. (Zang *et al.* 2012) proposed a PV system which adapts the parallel configuration at a particular cell level so that an individual cell in the PV module can achieve its MPP under partial-shading conditions. The input voltage of this configuration is very low, which may increase the difficulty of designing an appropriate power converter. Moreover, the proposed configuration is only suitable for low power applications.

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 for the PSO algorithm, 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 utilized in (Venugopalan *et al*., 2013). An analytical expression of the objective functions based on PV current, irradiance and temperature was formulated as in (Miyatake *et al*., 2011) and the conventional PSO was then utilized to track the MPP.

The current-based PSO method was proposed by (Miyatake *et al.* 2011), where the series inductor current of the boost converter is used as the reference signal to generate the pulse width modulation signals for the switching converter. A repulsive term in the velocity equation of the PSO was also introduced (Phimmasone *et al*., 2009). (Miyatake *et al.* 2011) proposed an adaptive perceptive PSO (APPSO)-based MPPT algorithm. Ishaque *et al.* 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.* 2011) attempted to approach the global MPP using the PSO algorithm. In these investigations, the authors tried to realize centralized MPPT control of the modular (multi-module) PV system (Coelho et al, 2010). These MPPT algorithms have good performance under various partial-shading conditions; however, these methods are only suitable for systems that consist of multiple converters.

Therefore, the conventional maximum power point tracking (MPPT) techniques can hardly track the global maximum power point (GMPP) because the power-voltage characteristics of photovoltaic (PV) exhibit multiple local peaks in irregular shadow, and therefore easily fall into the local maximum power point. These conditions make it very challenging, and to tackle this deficiency, an efficient Iteration Particle Swarm Optimization (IPSO) has been developed to improve the quality of solution and convergence speed of the traditional PSO (Phimmasone *et al*., 2009, Liu and Liu, 2011), so that it can effectively track the GMPP under irregular shadow conditions. This proposed technique has such advantages as simple structure, fast response and strong robustness, and convenient implementation. It is applied to MPPT control of PV system in irregular shadow to solve the problem of multi-peak optimization in partial shadow. In order to verity the rationality of the proposed algorithm, however, recently the dynamic MPPT performance under varying irradiance conditions has been given utmost attention to the PV society. As the European standard EN 50530 which defines the recommended varying irradiance profiles, was released lately, the corresponding researchers have been required to improve the dynamic MPPT performance. This paper also tries to evaluate the dynamic MPPT performance using EN 50530 standard. The simulation results show that iterative-PSO method can fast track the global MPP, increase tracking speed and higher dynamic MPPT efficiency under EN 50530 than the conventional PSO.

2. Materials and Methods

2.1 Particle Swam Optimization

PSO is a stochastic, population-based evolutionary algorithm search method, modelled after the behavior of bird flocks (Miyatake *et al*., 2007). The PSO algorithm maintains a swarm of individuals (called particles), where each particle represents a candidate solution. Particles follow a simple behavior: they emulate the success of neighboring particles and their own achieved success. The position of a particle is therefore influenced by the best particle (*pbest*) in a neighborhood, as well as the best solution found by all the particles in the entire population (*gbest*). The particle position, x_i, is adjusted using:

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

where the velocity component, v_i , represents the step size.
The velocity is calculated by:

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

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 (Venugopalan *et al*., 2013, Chen et al, 2010). 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.

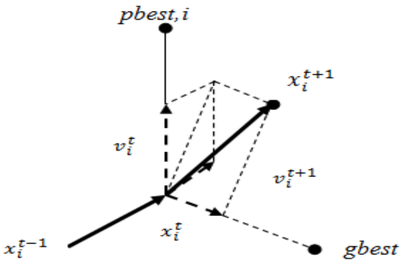

Figure 1: Movement of particles in the optimization process

2.2 Iterative Particle Swarm Optimization

A new PSO technique is introduced in this paper to mitigate the effect of oscillations in maximum power point tracking power systems. The standard PSO is modified by adding a new directory called Iterative Best (I_{best}) to enhance the computational time and the quality of the solution. I_{best} is known to be the best value of the fitness function that will be achieved by any agent (particle) in the iteration. A new PSO strategy time varying acceleration coefficient is also introduced. Equation (7) shows the modified form of (3) and is referred to as the Repetitive Particle Swarm Optimization (RPSO) here.

$$v_i^{t+1} = \omega v_i^t + c_1 r_1.(pbest, i - x_i^t) + c_2 r_2.(gbest - x_i^t) + c_3 r_3.(I_{best}^t - x_i^t)$$

$$i = 1,2,\dots,N \tag{3}$$

where c_3 represents the weight of the stochastic acceleration terms that is pulling each agent towards the iteration best. I_{best}^t refers to the best value of the fitness function that has been obtained by any agent in the t^{th} iteration during optimization process. The cognitive and social learning factors c_1 and c_2 in the classical PSO algorithm are usually pre-specified to fixed values of 2.0 basically (Chatteijee et al, 2013, Fu and Tong 2010). This may lead to premature convergence and may allow the particles to wander around the search space due to relatively high values of coefficients. The cognitive and social learning factors c_1 and c_2 are updated as in equations (4) and (5) Furthermore, the dynamic acceleration constant parameter c_3 is introduced and presented in equation (6).

$$c_1(t) = c_{1,i} + \frac{c_{1f} - c_{1i}}{t} \times t \tag{4}$$

$$c_2(t) = c_{2,i} + \frac{c_{2f} - c_{2i}}{t} \times t \tag{5}$$

$$c_3(t) = c_1(1 - e^{-c_2(t)}) \tag{6}$$

where t is number of iterations. Therefore, the new velocity update of the proposed algorithm can be updated as follows:

$$v_i^{t+1} = \omega v_i^t + \left(c_{1,i} + \frac{c_{1f} - c_{1i}}{t} \times t\right) r_1.(pbest, i - x_i^t) + \left(c_{2,i} + \frac{c_{2f} - c_{2i}}{t} \times t\right) r_2.\Big(gbest - x_i^t + \left(c_3(t) = c_1(1 - e^{-c_2(t)})\right) r_3.(I_{best}^t - x_i^t)\Big) \tag{7}$$

Figure 2 depicts the convergence behaviors for the IPSO algorithm fitness over the original PSO, it can be seen that the fitness value of IPSO offers better result as compared to the original PSO. Not only that, IPSO also convergence faster with attractive result (3rd iteration) compared to the PSO algorithm that required nearly 10th iteration before it converged. Even though the difference between IPSO and PSO appears too minor as shown in Figure 2, but it has a significant impact to the performance of MPPT in PV systems. The eigen-values obtained by both optimization algorithms.

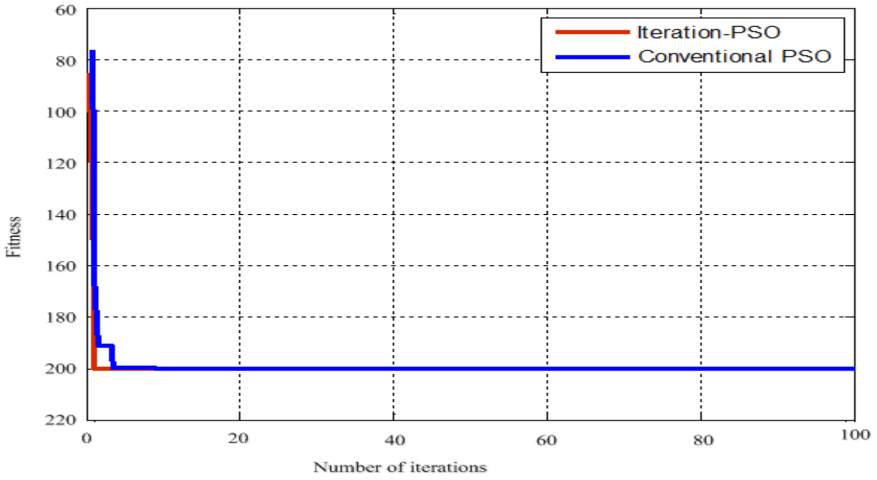

Figure 2: Convergence Characteristics of PSO and iteration-PSO based Optimization

2.3 Proposed iterative-PSO based MPPT control algorithm

Basically, PSO algorithms are utilized to solve the optimization problem 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, thus, the iterative-PSO-based MPPT is utilized in this study and the procedure are as follows;

i. The Iteration-PSO parameters including number of particles (duty cycle) which cover the search space [d_{min}, d_{max}] with equal distance where d_{min} and d_{max} are the minimum and maximum values of the duty cycle of the dc-dc converter respectively, the weighting factors, c_1, c_2, and c_3 and the maximum number of iteration are initialized.

ii. Initialize the Iteration-PSO-based MPPT technique is to extract the optimal power P_{PV} of the photovoltaic system; therefore, the fitness value which is designated as the generated power is evaluated. The PWM 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 utilized.

iii. Initialize *Pbest* and *Gbest* and obtain the fitness of each particle in the search space.

iv. Record and update the velocity of each particle according to equation (3).

v. Record and update the position of each particle according to equation. (2).

vi. End the program if the displacements between *gbest* and all the *pbests* become lower the 1%; and transfer the best particle, $d_{optimum}$ to the dc-dc converter otherwise repeat steps iii to v.

Figure 3 shows the flow diagram of the proposed iteration-PSO based MPPT algorithm. The steps followed for the iteration-PSO algorithm is mostly similar to that of the original PSO; the slight difference comes from updating the new velocity for ascertaining the new position.

Two convergence criteria are employed in this study. The proposed IPSO-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 reinitialized.

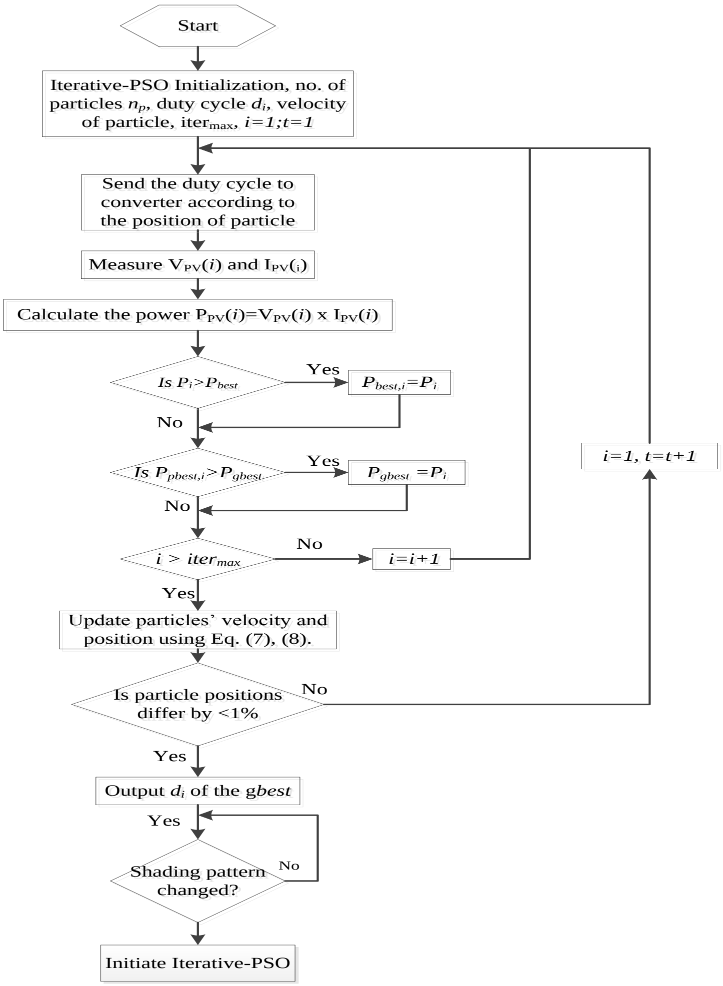

Figure 3: Flowchart of the proposed iteration-PSO-Based MPPT algorithm.

Considering the change in irradiance and shading pattern to be detected here, the following constraint is utilized. In the proposed technique, the particles will be reinitialized whenever the following condition is satisfied as in Equation (8):

$$\frac{P_{pv,new}-P_{pv,old}}{P_{pv,old}} \geq \Delta P(\%) \tag{8}$$

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 normalized 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 4 depicts the comprehensive flowchart of the proposed system.

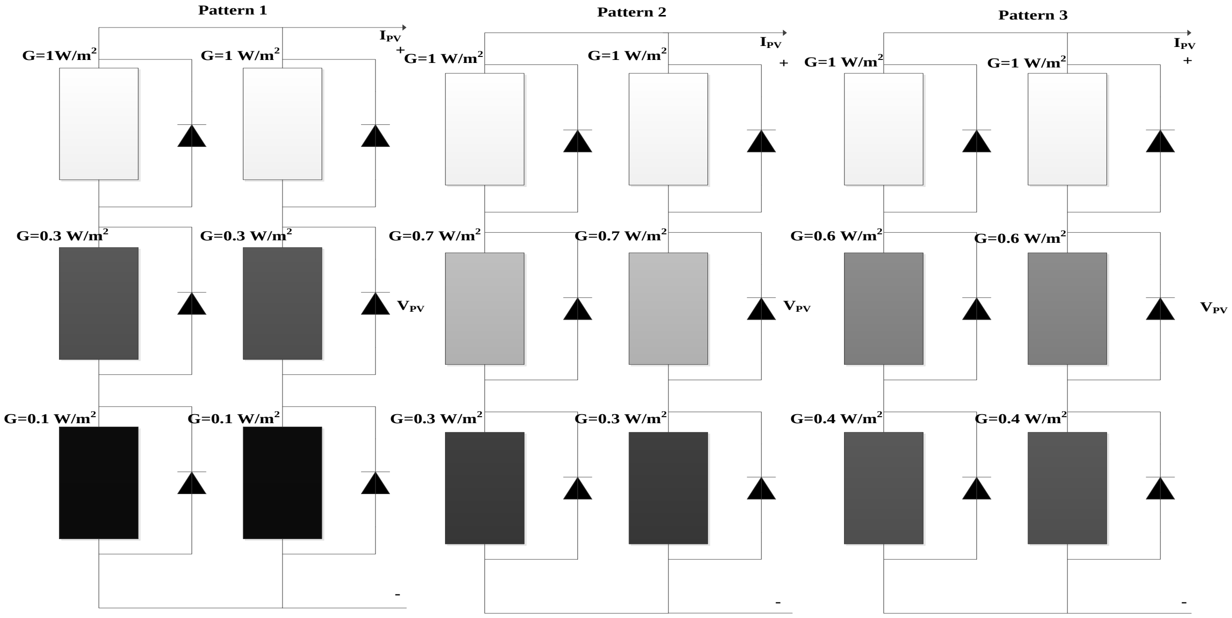

Figure 4: Layout of PV configurations under study with PSC

2.4 Phenomenon of Irregular Shadow 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 (Ishaque *et al.*, 2011; Bastidas-Rodriguez et al, 2014, and Abdulkadir *et al*., 2012). The PV module characteristics under irregular-shadow conditions are connected at the module terminal with bypass diodes were described in Ishaque *et al*. (2011). In the irregular-shadow pattern, the shaded portion of the cells acts as a load rather than as a generator and creates the hot shot; hence, the bypass diodes of these shadowed cells will conduct in order to avert this undesirable situation (Ganjefar *et al*., 2014, Eltawil and Zhao 2013). Multiple peaks in the PV curve would be obtained since the shadowed modules are bypassed. The PV curves that result when this system is under different shadow conditions are shown in Figure 5.

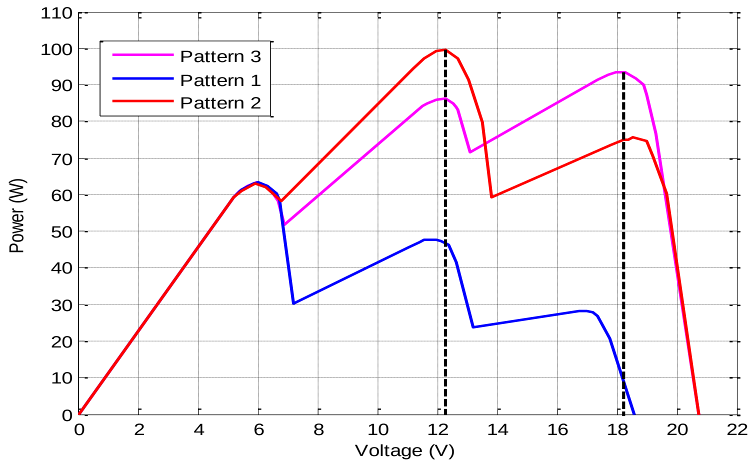

Figure 5: P-V characteristic curves of PV system under different shading conditions

Generally speaking, the column of cell that is shelter from the same shadow is classified as a pattern, as shown in pattern1, pattern2 and pattern3 of Figure 5. 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 shadow pattern. For this reason, the conventional MPPT algorithms will be very difficult to apply directly.

3. Simulation of Results and Discussion

The selection of proper values for algorithm control parameters plays a significant role in solution's quality. In order to obtain the best performance, fitness of the objective was implemented to evaluate the convergence speed of the algorithm in finding the best solution. It should be noted that the convergence test is performed using the size of population. It is evidently observed from Figure 2 that the maximum number of iterations needed for IPSO and conventional PSO are 3 and 10 respectively. The effect of the initial and final values of cognitive and social components acceleration factors on solution performance are studied by varying their values. Figure 6 show the MPP searching mechanism by iteration-PSO method under partial shading.

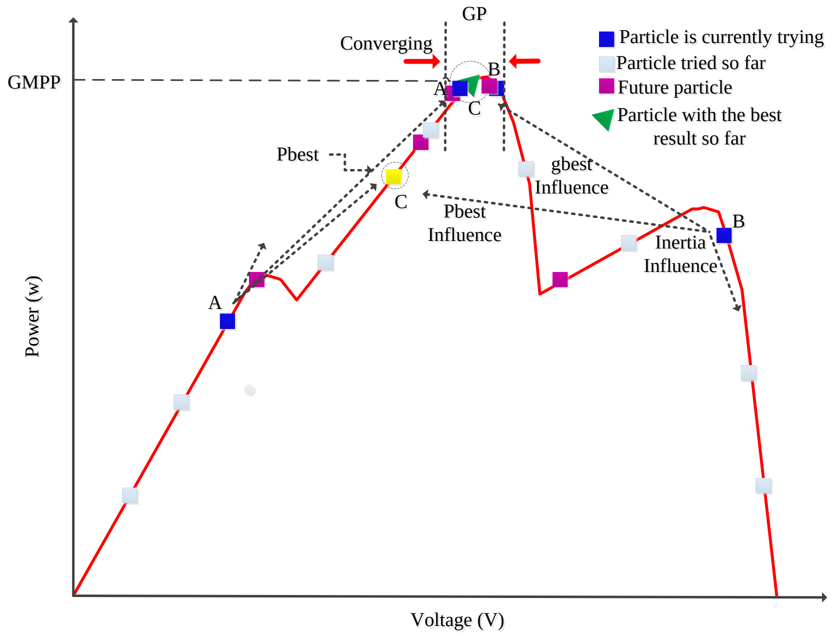

Figure 6 The MPP searching mechanism by iteration-PSO method under partial shading.

To demonstrate the effectiveness of the proposed IPSO-based MPPT technique, simulations is performed appropriately. The simulation model parameters of the PV module are shown in Table 1.

TABLE 1: Simulation Parameters of ICO-SPC 100 w Photovoltaic

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

In this paper, the simulations are implemented using the MATLAB Simulink model. According to the design principle, the specification parameters of the complete IPSO-based MPPT algorithm are shown in Table 2.

TABLE 2: Simulation Parameter Setting of the IPSO-Based MPPT

Parameter	Value
Number of particles	3
Minimum duty cycle	0.02
Maximum duty cycle	0.98
Sampling time	0.1s
Maximum iteration	20
ω_{max}	1.0
ω_{min}	0.1
$C_{1, min}$	1
$C_{1,max}$	1.2
$C_{2,min}$	1
$C_{2,max}$	1.6

As can be seen from Figure 8, tracking time of conventional PSO algorithm is about 0.8 s, and there is relatively large fluctuation near MPP.

For the rapidly irregular shadow, Figure 7 and Figure 8 has shown the experimental results for the tracking power of the proposed technique and the conventional PSO respectively under rapidly irregular shadow conditions. 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.

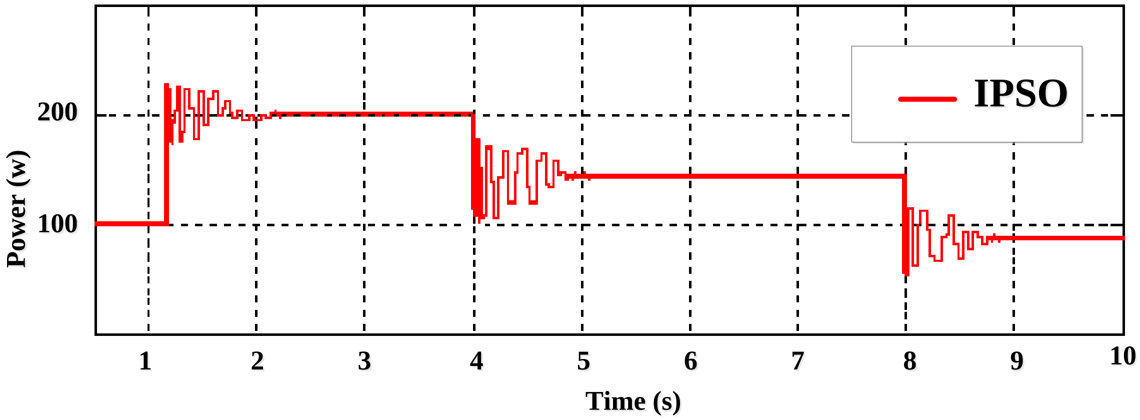

Figure 7: Simulated power tracked using iteration-PSO algorithm for variation in irradiation condition

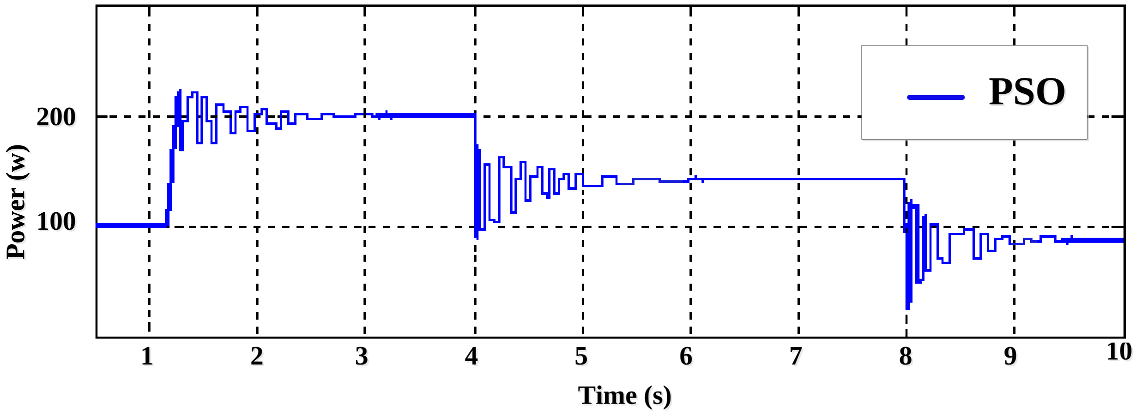

Figure 8: Simulated power tracked using conventional PSO algorithm for variation in irradiation condition

On the contrary, the MPP can be quickly tracked if using Iteration PSO technique, its tracking time is only 0.35 s, which accelerates by 60% compared to the former. These curves show that PSO based algorithm is capable of reaching the GMPP with lesser time for convergence. Further the conventional PSO based algorithm produces oscillations in PV output power for a longer duration when compared to the iteration PSO algorithm.

Also, to further verify the rationality of the proposed technique, the performance of the proposed iteration PSO MPPT techniques is tested under dynamic environmental conditions as in Figure 9, Figure 10 and Figure 11 respectively. This dynamic condition was adopted using the European Efficiency Test EN 50530, which is a newly standard for evaluating the dynamic performance of PV system. As can be seen in Figure 11, iteration PSO method adequately tracks the ideal MPP power for the whole dynamic profile (ramps sequence). However, a consistent deviation between the dotted line (ideal MPP power) and solid line (actual PV power) is clearly visible.

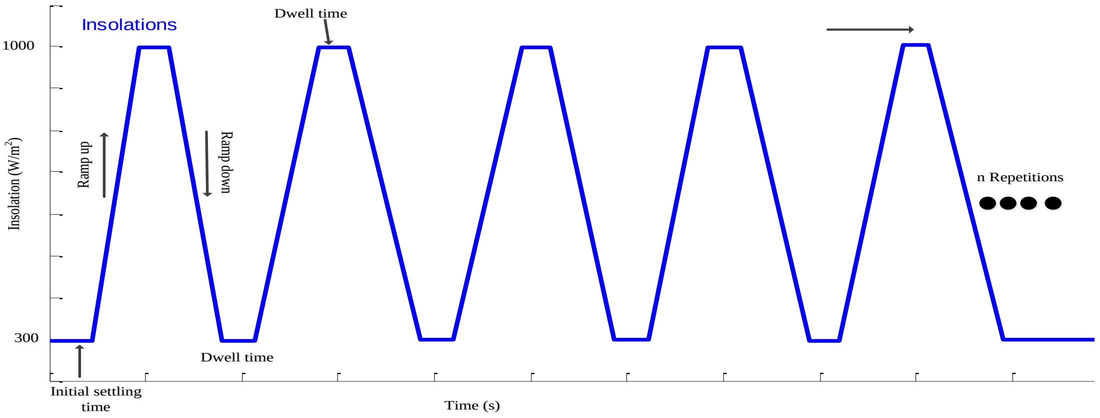

Figure 9: Ramp test sequence (low-medium insolation) for the characterization of the MPPT efficiency under changing insolation conditions

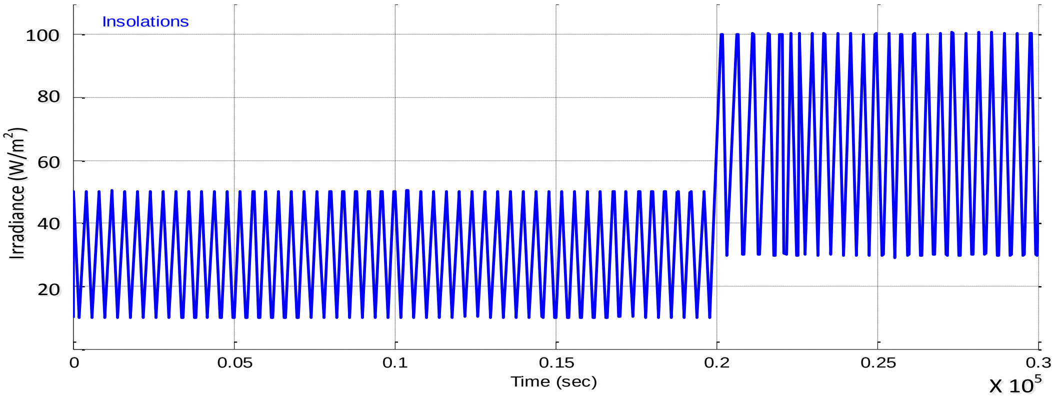

Figure 10: The complete dynamic test profile

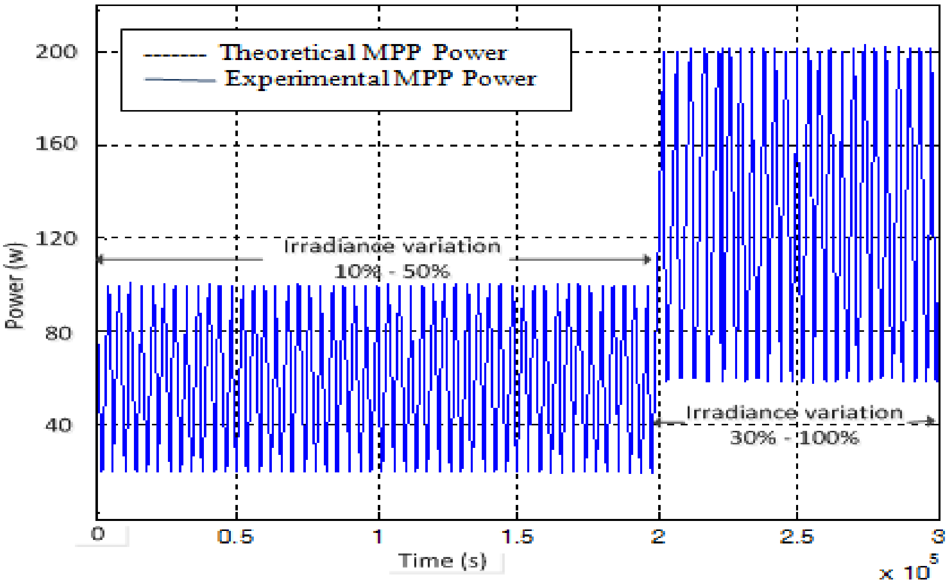

Figure 11: Performance of iteration-PSO method under dynamic test conditions

3.1 Experimental results

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 equipment. Figure 12 show the experimental set-up of the iteration-PSO method. 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.

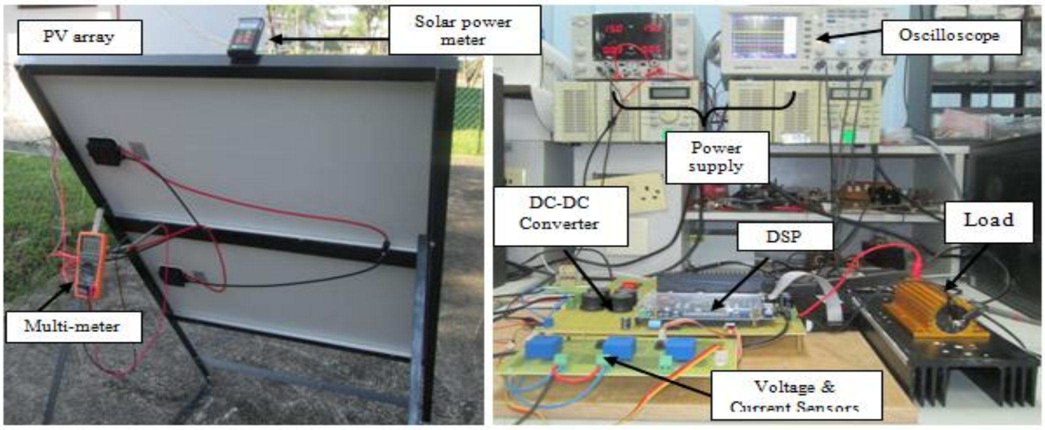

Figure 12: Experimental set-up of iteration-PSO method

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 result as shown in Figure 7 is the output power of the PV emulating system of the proposed techniques. Figure 8 shows the conventional PSO has a slow tracking response time and larger oscillation in the output power because the conventional PSO failed to reach MPP faster.

4. Conclusion

In this paper, an iteration-PSO based MPPT method for tracking MPP was presented. The proposed algorithm was studied, and the advantages of this strategy over conventional PSO-based method were highlighted. The performance of the proposed system was validated using MATLAB simulation and an experimentation system comprising a digital signal controller, a boost converter, and a programmable DC power supply emulated as PV simulator. Fast and accurate performance under different conditions, including irregular shadow condition, was proven as the main advantage of the proposed algorithm. The performance of the proposed iteration PSO MPPT techniques is tested under dynamic environmental conditions using the European Efficiency Test EN 50530. The simulation and experimental results indicate that the converter can track the MPP of the PV system. The obtained results also confirmed that the response time of the proposed method is faster compared to the other methods, and the structure of the algorithm is simple. From these results, it is concluded that the control scheme can be utilized for reliable and high quality PV systems.

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