Maximum photovoltaic array power point tracking algorithm based on modified particle swarm optimization under non-uniform irradiance

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Abstract. Under fast-changing non-uniform solar irradiance level the multiple local maximum power points are observed but only one global maximum power point exists which lead to a dynamic optimization problem. This paper presents a maximum photovoltaic array power point tracking algorithm based on the modified particle swarm optimization. The modification of particle swarm optimization employs re-randomization and the particles around a maximum power point initialization. The simulation results show that the proposed algorithm provides stability and fast maximum power point tracking of a photovoltaic array, as compared to a classical Perturb and Observe or particle swarm optimization algorithms under fast-changing non-uniform solar irradiance level.

1. Introduction
Solar energy is the most inexhaustible and environment friendly among all the clean and renewable energy resources. The main advantages of photovoltaics include its applicability in most regions of the world, both in industrial and household applications. The power generated by photovoltaic (PV) array dependents on temperature, solar irradiation level and shading. The power-voltage (P-V) characteristic of partially shaded PV array have several peaks and conventional maximum power point tracking (MPPT) algorithm, such as Perturb and Observe (P&O), fails to track the global maximum power point (GMPP) under fast-changing non-uniform solar irradiance level [1]. There are many optimization algorithms implemented in MPPT controller [2–4]. Among those, in [3] particle swarm optimization (PSO) to track the GMPP is presented. A pure PSO algorithm can work as MPPT and set a direct duty cycle [4]. A velocity equation provides the convergence of the particles to the GMPP. The PSO algorithm exhibits considerable potential, due to easy implementation, fast computation capability, and its ability to determine the GMPP irrespective of fast-changing non-uniform irradiation level of a PV system. One of the drawbacks of the PSO algorithm is that during slow changing in the solar irradiance level, the alteration of the control signal needs to be small in order to track the GMPP properly. The initialization of the swarm in PSO is a crucial issue affecting performance. This forms the motivation to initialize the particles around the maximum power point based on constant voltage method approximation and interpolation polynomial in the Lagrange form.

Compared to the conventional PSO algorithm the proposed MPPT algorithm provides closeness of new operating points to the MPP and requires less iteration. The comparison simulation study of the proposed algorithm and classical Perturb and Observe or particle swarm optimization algorithms under fast-changing non-uniform solar irradiation level is elaborated. The simulation results show that the
proposed algorithm provides stability and fast maximum power point tracking, as compared to a classical Perturb and Observe or particle swarm optimization algorithms under fast-changing non-uniform solar irradiation level.

2. Model of the photovoltaic module

The Shockley's simple "one diode" model describes the operating of a PV module [5].

The corresponding current-voltage (I-V) characteristic expression is written as:

\[ I = I_{ph} - I_d \exp\left(q(V+IR_s)/NcsgkT_e\right) - \frac{V+IR_s}{R_{sh}} \]

where \( I \) – current supplied by the module (A), \( V \) – voltage at the terminals of the module (V), \( I_{ph} \) – photocurrent (A), \( I_d \) – inverse saturation current (A), \( R_s \) – series resistance (ohm), \( R_{sh} \) – shunt resistance (ohm), \( q \) – charge of the electron, \( k = 1.381 \times 10^{-23} \) – Boltzmann's constant (J/K), \( g \) – diode quality factor (normally between 1 and 2), \( N_c \) – number of cells in series, \( T_e \) – effective temperature of the cells (Kelvin).

A model of the 250-W photovoltaic array fulfilled in the Octave environment under non-uniform solar irradiance level. This Octave model implements a PV array built of three series connected PV modules with the bypass diodes neutralizing negative current under a partial shading condition.

3. MPPT algorithms under fast-changing non-uniform solar irradiation level

PSO is a stochastic optimization algorithm based on a quasi-random search of the solution space. The key advantages between the PSO and other global optimization algorithms are the easy implementation and fast convergence. Therefore, PSO has received growing implementation in MPPT PV systems. PSO describes the optimization process by the position and velocity vectors.

The MPPT controller based on P&O algorithm adjusts the voltage by a small amount and measures power. It is referred to as a hill climbing algorithm, because it depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point.

Perturb and Observe MPPT algorithm is the most common due to simplicity and easy implementation. But controllers based on Perturb and Observe MPPT algorithm for PV systems have slow response times to changing reference commands, take considerable time to settle down from oscillating around the target reference state, and must often be designed by hand.

If solar irradiance continuously increases then the misjudgement phenomenon of Perturb and Observe MPPT algorithm occurs. In such cases Perturb and Observe MPPT algorithm moves operating point in direction which opposes the global maximum point.

For the proposed MPPT algorithm, the control signal – PV voltage have been coded into position of particle \( X \).

The modified PSO process at \( j \)-th iteration is represent by the following characteristics: \( p_{X,i} \): the personal best (pbest) position of particle \( X \); \( x_{X,i} \): the position of particle \( X \); \( v_{X,i} \): the velocity of particle \( X \); \( e_j \): the evaporation rate; \( g \): Global Best position of swarm; \( w \): inertia; \( c_2 \): cognitive weight; \( c_3 \): social weight; \( E \): the base value of the evaporation rate.

We the calculated \( w \), \( c_2 \), \( c_3 \) based on the constricted PSO formula [6] and their values are 0.73, 1.5 and 1.5, respectively. We evaluated the fitness function of the modified PSO at \( j \)-th iteration as follows:

\[ f(x_{X,i}) = P_j = V_jI_j, \]

where \( I_j \) – current supplied by the PV array at \( j \)-th iteration (A), \( V_j \) – voltage of the PV array at \( j \)-th iteration (V), \( P_j \) denotes the power of the PV array at \( j \)-th iteration.

The proposed algorithm includes procedure \( L \) based on constant voltage method approximation and interpolation polynomial in the Lagrange form. This procedure \( L \) estimates \( x \) – voltage at MPP based on following equation:
\[ L(x_i, y_i = 0.3) = \prod_{i=1}^{N} (x_i - x_{ij}) \prod_{i=1}^{L} (y_i - y_{ij}) + \cdots + \prod_{i=1}^{N} (x_i - x_{ij}) \prod_{i=1}^{L} (y_i - y_{ij}), \]  

(3)

where \( x_0 \) represents the voltage \( V_0 = 0 \) of the short circuit current, \( x_i \) represents the open circuit voltage which provided by the PV array data sheet, \( x_i \) is voltage and the corresponding value \( y_i \) represent the duty cycle \((i = 0, 3, y_i = 1, y_i = 0)\).

The task of PV array MPPT after a quick change of the global maximum power point represents the dynamic optimization problem. Because of that proposed MPPT algorithm elaborates growth of the evaporation rate and re-randomization during fitness function updating in order to locate the global maximum.

We expressed the proposed modified PSO MPPT algorithm as follows:

Step 0. We initialize the particle's positions \( x_{1,0} \) and \( x_{2,0} \) as present and previous (stored at the end of the preceding cycle) voltage values, respectively, \( j=0 \).

Step 1. For \( \forall X \in \{1.4. S / 3\} \) do We initialize the particle's positions at fixed, equidistant points, which positioned around the MPPT: \( x_{kj} = x - v_{kj}, x_{k+1,j} = x, x_{k+2,j} = x + v_{k+2,j} \) where \( x \) is the voltage at MPP which estimated based on procedure (3) \( L(x_{k-i,j}, y_{k-i}, i = 1, 2) \). Therefore, initial values of the particle's positions \( x_{kj} \) set close to the MPP. If \( j > 0 \) then \( S = 2 * S, r = 0 \) go to step 3 End If. End For.

Step 2. For \( \forall X \in \{1, S\} \) do Initialize the particle's best known position if \( f(x_{kj}, y_k) > f(p_{k-1,j}) \) then Do: \( p_{kj} = x_{kj}, \max(f(p_{kj}, y_k)) \) Then Do \( g = x_{kj}, \) End If. End For.

Step 3. While a convergence criterion is not met do: For \( \forall j \in \{1, T\} \) do: For \( \forall X \in \{1, S\} \) do: Pick random numbers: \( r_1, r_2 \sim U(0, 1) \), update the particle's velocity: \( v_{kj+1} = w v_{kj} + c_1 r_1 (p_{kj} - x_{kj}) + c_2 r_2 (g - x_{kj}) \).

If \( X_{min} \leq x_{kj+1} \leq X_{max} \) then \( x_{kj+1} = x_{kj} + v_{kj+1} \) else \( x_{kj+1} = U(X_{min}, X_{max}) + x_{kj} \) End If.

If \( f(x_{kj}) > f(p_{kj-1}) \) then Do: \( p_{kj} = x_{kj} \) else \( p_{kj} = p_{kj-1} \) End If.

If \( f(x_{kj}) > \max(f(p_{kj-1,j}, \max_{1 \leq k < j} (f(x_{kj}))) \) Then Do \( g = x_{kj} \) End If.

If \( F_j > 0 \) or \( \sum_{i=1}^{S} f(x_{i,j}) < 0.75 \sum_{i=1}^{S} f(x_{i,j-k}) \) then \( F_{j+1} = F_j + 1 \) End If.

In the case of a relatively rapid decline in the average power for all particles (when the power in the \( j \)-th iteration is lower than 75% of the power in one of the past 7 iterations), the rate of evaporation grows exponentially.

If \( f(x_{kj}) > e_j p_{kj-1} \) then \( r_{i,0} = 0, e_j = E^{1+F_j}, p_{kj} = e_j p_{kj-1}, r = r + 1 \) End If.

If \( r \geq 3 \) then \( x_{1,0} = p_{kj}, x_{2,0} = g, S = S / 2, \) go to step 1 End If. End For. End For.

The advantages of the proposed algorithm include a faster convergence obtained by procedure (3) than for pure PSO MPPT algorithm and a greater probability of finding the GMPP under partial shading condition than for a classical Perturb and Observe MPPT algorithm.

4. Result

To illustrate the benefits of the proposed MPPT algorithm based on the modified particle swarm optimization, the numerical examples from the previous section III are revisited. All the simulations of the 250-W PV array under fast-changing non-uniform solar irradiance level are carried out based on Octave model. According to statistic studies the solar plant power loss can vary from 10% to 70% due to partial shading [7-8].

Figure 1 shows the solar irradiance during the simulation time. In this simulation study we adopted three solar shading scenarios:

1) From time=0 s to 1 s graph presents fast change in solar irradiance from partial shading to sunshine;
2) From time=1.1 s to 2 s graph presents smooth and steady decline in solar irradiation;
3) From time=2.1 s to 3 s solar irradiance changes smoothly which simulates slow shade.

The swarm size of pure PSO and the proposed algorithm are 10 and 3 respectively. The base value of evaporation rate of pure PSO and the proposed algorithm is 0.9.
In the case of first scenario the objective function has three local maxima (Figure 2). The classical Perturb and Observe MPPT algorithm is trapped in the zone of the local maximum area (Figure 2 shows three operating points, marked as asterisk, provided by Perturb and Observe MPPT algorithm). The pure PSO algorithm in such a case, just activates the initialization procedure for particles (Figure 2 shows three operating points, marked as square, provided by pure PSO algorithm). The proposed MPPT algorithm in such a case, after taking the sudden cumulative power drop of the PV array into account, activates the re-randomization procedure for half consecutive particles which provides quick convergence to a global maximum (Figure 2 shows three operating points marked as circle provided by proposed MPPT algorithm).

The second scenario, which occurred at 1.2 sec, simulates a cloud that covers PV array at an appropriate speed to trigger the re-randomization mechanism of the proposed MPPT algorithm. This does not happen at a uniform irradiance change that occurs over all cells of PV array (Figure 3 shows three operating points marked as circle provided by proposed MPPT algorithm). Figure 3 shows that the re-randomization mechanism is not necessary because the proposed MPPT algorithm copes precisely with solar irradiation changes. The usage of re-randomization in second scenario would decrease the speed of convergence to the global maximum. The pure PSO algorithm in such a case, just activates the initialization procedure for particles (Figure 3 shows three operating points, marked as square, provided by pure PSO algorithm). In the second scenario the solar irradiance continuously increases, which occurred from 1.5 sec to 1.7 sec, and Figure 3 shows the misjudgment phenomenon of Perturb and Observe MPPT algorithm. In such situation P&O MPPT algorithm moves operating
point in direction which opposes the global maximum point (Figure 3 shows three operating points marked as asterisk provided by proposed MPPT algorithm).

![Graph](image1)

**Figure 3.** The numerical results of the MPPT algorithms in the second scenario.

The third scenario, which occurred at 2.1 sec, simulates a shadow cast by an obstacle, covering cells of PV array non-uniformly. Subsequently, the objective function has three local maxima (Figure 4). Even a slower rate of irradiance, compared to the second scenario, the proposed MPPT algorithm triggers the re-randomization (Figure 4). As a result, the proposed MPPT algorithm quickly converges to a global maximum (Figure 4 shows three operating points marked as circle provided by proposed MPPT algorithm). The classical Perturb and Observe MPPT algorithm is ineffective to finding of the global maximum in such conditions. Figure 4 shows the misjudgement phenomenon for the Perturb and Observe algorithm when solar irradiance continuously increases. (Figure 4 shows three operating points, marked as square, provided by Perturb and Observe MPPT algorithm) The pure PSO algorithm in such a case, just activates the initialization procedure for particles (Figure 4 shows three operating points, marked as square, provided by pure PSO algorithm).

![Graph](image2)

**Figure 4.** The numerical results of the MPPT algorithms in the second scenario.

Table 1 summarizes the simulation results of the proposed algorithm, a classical Perturb and Observe and particle swarm optimization algorithms under fast-changing non-uniform solar irradiance level accordingly three solar irradiance scenarios.

**Table 1.** The average power of PV array provided by pure PSO, P&O MPPT algorithm and the proposed MPPT algorithm for the first and third.

| Ir of PV1 (W/m²) | Ir of PV2 (W/m²) | Ir of PV3 (W/m²) | P&O (W) | PSO (W) | Proposed algorithm (W) | Maximum power of PV array (W) |
|------------------|------------------|------------------|---------|---------|------------------------|-----------------------------|
| 1000             | 700              | 500              | 70      | 135     | 210                    | 215                         |
| 1000             | 900              | 800              | 72      | 82      | 135                    | 138                         |
It is clear that the PV array power provided by the proposed MPPT algorithm is above 99.5 % under all solar irradiance scenarios. The simulation results show that the proposed algorithm provides stability and quick convergence to a global maximum, as compared to a classical Perturb and Observe or particle swarm optimization algorithms under fast-changing non-uniform solar irradiation level.

This paper proposes a maximum power point tracking algorithm of a photovoltaic array based on the modified particle swarm optimization. The modification of particle swarm optimization employs re-randomization and the particles around the maximum power point initialization. This efficient initialization of particles provides avoiding both unnecessary and redundant searching and a situation in which the area of swarm search doesn’t include global maximum. As a result, this significantly reduces the time that wasted by searching GMPP in the wrong area. Thus, substantially enhancing the system’s tracking speed, while also reducing the steady-state oscillation (practically to zero) once the GMPP is located. This is a huge improvement upon the conventional PSO method which provides the new operating point too far from the MPP and requires many iterations to reach GMPP. To illustrate the benefits of the proposed MPPT algorithm based on the modified particle swarm optimization, the numerical simulation is carried out. The simulation results show that the proposed algorithm provides stability, faster response rate and fast maximum power point tracking, as compared to a classical Perturb and Observe or particle swarm optimization algorithms under fast-changing non-uniform solar irradiation level. The utilization of the proposed MPPT algorithm can help to overcome some of the technical barriers that still limit the PV array power provided by the MPPT. It can be also used as a starting point or a support tool to promote and design efficient solar energy projects faster.

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