A Novel MPPT Method for PV Arrays Based on Modified Bat Algorithm with Partial Shading Capability

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Summary

The power–voltage curve of photovoltaic arrays has one global peak and one or more local peak under partially shaded conditions. The conventional maximum power point tracking algorithms such as Perturb&Observe are converge to the first peak. Therefore they may not find global maximum power point. However; soft computing methods such as Bat Algorithm may find it. This paper proposes a dual algorithm search method that consist of modified Bat Algorithm and Perturb&Observe algorithm. The standard Bat Algorithm has been modified by adding a similar feature to tabu list of Tabu Search Algorithm. In search process, firstly, modified Bat Algorithm is used to determine the area of global peak, then Perturb&Observe is replaced to track the maximum power point in the area of global peak. If the power varies greatly and rapidly, the search process starts again. Standard Bat Algorithm, Perturb&Observe and the proposed method are simulated under standard test condition and partially shaded conditions. The simulations show that performans of the proposed method is superior to both the standard Bat Algorithm and Perturb&Observe.

Key words:

Bat algorithm, Perturb&Observe, Maximum power point tracking, Partial shading conditions.

1. Introduction

Since solar energy has high potential and is eco-friendliness, use of solar energy which is one of the renewable energy sources is increasing day by day. Photovoltaics (PV) is one of the methods of converting solar energy into electricity. PV cells are basic building blocks of PV systems. PV cells which are made of a semiconductor material directly convert sunlight into DC electricity at the atomic level. A PV module consists of PV cells which are connected electrically in series and/or parallel. Multiple PV modules can be wired together to form a PV array. PV modules output power depends on solar radiation and temperature. Because of the variation in the environmental condition, the power–voltage (P-V) curve of PV module exhibits a non-linear, time-varying maximum power point (MPP) problem. In order to continuously harvest maximum power from PV modules, the maximum power point tracking (MPPT) is employed in conjunction with the power converter.

To date, numerous conventional MPPT algorithms such as perturb and observe (P&O) [1], [2] incremental conductance (IC) [3] have been developed for PV systems. Besides, various soft computing methods such as fuzzy logic controller (FLC) [4], artificial neural network (ANN) [5], particle swarm optimization (PSO) [6] and bat algorithm [7] have been proposed for solar MPPT. The conventional MPPT methods have the advantages of simple structure, easy implementation, low equipment requirement and rapid convergence. However, they have the disadvantages of oscillation around the maximum power point (MPP). Also, they may not determine the global MPP under partially shaded condition (PSC). The soft computing methods are able to determine the global MPP under PSC despite the fact that they are generally harder, slower and more complex than conventional MPPT algorithms [8]. Although many microcontrollers has features to implementing MPPT methods, some methods may require expensive hardware such as DSP, advanced ADC and sensors [9], [10]. Due to the drawbacks of each MPPT method, superior MPPT method development works are still ongoing.

Ahmed and Salam [8] propose a MPPT method based Cuckoo Search (CS). They reported that CS outperforms both P&O and PSO with respect to tracking capability, transient behaviour and convergence. Shi et al. [6] propose a dual-algorithm search method consist of dormant PSO and IC. They reported that the excellent performance of the proposed model is verified by simulations and experiments. In this paper, the authors have made an attempt to develop a more efficient MPPT method based on bat algorithm (BA) to track global MPP even under partial shading conditions. The performance of the developed method has been demonstrate through simulations.

2. Material and Methods

2.1 Overview of Perturb and Observe Algorithm

P&O algorithm is one of the most used algorithm for MPPT. P&O focuses on the perturbation of the operating voltage of PV module by modifying the duty cycle of power converter to find the MPP. It modifies the duty cycle of power converter periodically, and then it compares the PV output power with that of the previous cycle of perturbation. When PV power and PV voltage increase at the same time and vice versa, the duty cycle of power converter will be decreased.

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When PV power increases and PV voltage decreases and vice versa, the duty cycle of power converter will be increased. This process is repeated continuously [11].
P&O has several drawbacks that reducing its tracking efficiency. P&O is not able to determine the actual MPP. It oscillates around the MPP continuously. It fails to determine the direction of tracking under rapidly solar irradiance change [12]. P&O has advantages as simplicity, ease of implementation and low cost.

Algorithm 1: Perturb & Observe MPPT Algotrithm pseudo code

```
Initialize duty cycle, D=D(k-1)
Initialize voltage and current, V(k-1) and I(k-1)
Calculate initial power, P(k-1)
while (true)
   if ( time >= the sampling period)
      Measure voltage and current, V(k) and I(k)
      Calculate power, P(k)
      if (P(k) > P(k-1))
         if (V(k) > V(k-1))
            Increase module voltage (Decrease Duty)
         else
            Decrease module voltage (Increase Duty)
         end if
      else
         if (V(k) > V(k-1))
            Decrease module voltage (Increase Duty)
         else
            Increase module voltage (Decrease Duty)
         end if
      end if
      Update the previous voltage and power,
      V(k-1) = V(k) and P(k-1)=P(k)
   end if
end while
```

2.2 Overview of Bat Algorithm

Bat algorithm (BA) is a bio-inspired meta-heuristic optimization algorithm, firstly proposed by Xin-She Yang (2010) in [13]. BA was based on the echolocation features of micro-bats. Echolocation is the bio-sonar used to detect prey and avoid obstacles by bats. Micro-bats emit a loud sound pulse and listen for the echo that reflects from the objects. BA uses a frequency-tuning technique to increase the diversity of the solutions in the population. BA has a capability of automatically zooming into a region where promising solutions to reduce the convergence time [14]. BA, like Yang's previous algorithms, Cuckoo Search and Firefly, combines the advantages of existing algorithms [15]. Moreover, Harmony Search and PSO algorithms can be considered the special cases of BA. Therefore, it is no surprise that BA is efficient. [16]
The standard BA has many advantages as very quick convergence, simplicity and flexibility. BA guarantees to converge to the true global optimality. BA have been applied area of optimization, classifications, image processing, feature selection, scheduling, data mining [14].

Algorithm 2: BAT algorithm pseudo code [16]

```
Initialize the bat population xᵢ and vᵢ (i=1,2,…,n)
Define pulse frequency (fi) at xᵢ
Initialize loudness (Aᵢ) and pulse rates (rᵢ)
while ( t < Max number of iteration)
   Generate new solutions by adjusting frequency,
   and updating velocities and locations/solutions [equations (1), (2) and
(3)]
   if ( rand > rᵢ)
      Select a solution among the best solutions
      Generate a local solution around the selected best solution
   end if
   Generate a new solution by flying randomly
   if ( rand < Aᵢ & f(xᵢ) < f(x*))
      Accept the new solutions
      Increase rᵢ and reduce Aᵢ [equations (3) and (4)]
   end if
   Rank the bats and find the current best x*
end while
Postprocess result and visualization
```

Initially, bats position xi, rate of pulse ri, loudness Ai, pulse frequency fi, and velocity Vi are determined randomly. In the main loop the position x_i^t and the velocity V_i^t of the bats each time step t are updated as in (1) to (3).
Loudness A_i and rate of pulse r_i change during the iteration process. When a bat gets closer to prey its loudness decreases and the rate of pulses increases. In algorithm these changes are shown as in (4) and (5).

$$f_i = f_{min} + (f_{max} - f_{min}).\beta \quad (1)$$
$$v_i^t = v_i^{t-1} + (x_i^{t-1} - x_*).f_i \quad (2)$$
$$x_i^t = x_i^{t-1} + v_i^t \quad (3)$$
$$A_i^{t+1} = \alpha A_i^t \quad (4)$$
$$r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \quad (5)$$

where $\beta \in [0,1]$ is a random vector drawn from a uniform distribution, x_* is the current global best location among all bats, α and γ are constants.
For local search phase, once a solution is selected among the current best solutions, a new solution for each bat is generated locally using random walk.

$$x_{new} = x_{old} + \epsilon A^t \quad (6)$$
$$A^t = \langle A_i^t \rangle = \frac{1}{N}\sum_{i=1}^{N} A_i^t \quad (7)$$

where $\epsilon \in [-1,1]$ is random number, A^t is the average loudness of all the bats at this time step, and N is the number of bats.

2.3 Proposed MPPT Method

We propose a dual MPPT algorithm model with modified BA and P&O for solar MPPT. Firstly, modified BA is executed for five iteration and then global MPP area is determined. P&O is executed and the actual MPP is tracked in global MPP area. During the process of P&O, BA is reactivated if the ratio of power change exceed predetermined parameter (8). But P&O remains active if the power changes little and slowly.

$$\frac{|P_{(k)}-P_{(k-1)}|}{P_{(k-1)}} > \Delta \mathrm{P} \qquad (8)$$

where $P_{(k)}$ is instant power of PV array, $P_{(k-1)}$ is power of PV array received in previous period, ΔP is parameter of power change [6].

Algorithm 3: The proposed method pseudo code

```
Initially the bat population xi and vi (i=1,2,…,n)
Define pulse frequency (fi) at xi
while (true)
    Initialize loudness (Ai) and pulse rates (ri)
    Clear tabu list
    while ( t < Max number of modified BA iteration)
        do
            Generate new solutions by adjusting frequency,
            and updating velocities and locations/solutions
            [equations (1), (2) and (3)]
            if ( rand > ri )
                Select a solution among the best solutions
                Generate a local solution around the selected best solution
            end if
            Generate a new solution by flying randomly
        while (Is the new solution on the tabu list?)
        if ( rand < Ai & f(xi) > f(x*))
            Accept the new solutions
            Increase ri and reduce Ai [equations (3) and (4)]
        end if
        Rank the bats and find the current best x*
        Add all solutions except the best solution to the tabu list
    end while
    do
        Run P&O algorithm (Algorithm 1)
    while (Power change < Limited power change parameter)
end while
```

In the standard BA, the bats can have the same/almost same solution because the solutions of the bats are determined randomly. That the bats have the same/ almost same solution creates a waste of time. To overcome this problem, a similar feature to the tabu list of the Tabu Search algorithm [17] has been added to the standard BA. In the modified BA, all solutions except the best solution are added to the tabu list. During the update, it is ensured that the bats have solutions that is not on the tabu list. If a bat cannot produce an unbanned solution, it will get the best solution available. The tabu list is cleared every time the modified BA is activated. This modification reduces time loss and increases convergence to the global MPP.

2.4 Simulation

To use BA as MPPT algorithm, the values of parameters have to be selected appropriately. The most important parameter is the number of bats. A large number of bats can improve the optimization capability to find global MPP, but it will spend more time. In this paper, the number of bats is selected as 5. Other parameters are selected as follows: $A_i^0 = 0.9$ (initial loudness of each bat), $\alpha = 0.9$ (loudness update constant), $r_i^0 = 0.98$ (pulse rate upper limit), $\gamma = 0.85$ (pulse rate update constant), $f_{min} = 0$, $f_{max} = 1/4$. Initially, pulse frequency constant (β), pulse frequency (f_i) and velocity (V_i) are determined randomly. But initial positions of bats are selected as uniformly distributed (as 0.15, 0.3, 0.45, 0.6, 0.75) to increase the possibility of convergence to global MPP.

Because the task of the P&O algorithm in the proposed method is to track minor changes in MGN, its perturbation step is selected very small, as 0.001. Parameter of power change (ΔP) is selected as 0.15. The sampling periods of BA and P&O are 20ms and 1ms respectively.

A modified buck-boost converter which was presented by Alnejaili and Drid [18] is used to implement MPPT control (Figure 1). PV array which is consist of three PV modules connected in series was used to simulate partially shaded conditions. Kyocera KC200GT solar panels are used as PV modules. KC200GT has the following specifications: P_{MAX}=200W, V_{MPP}=26.3V, I_{MPP}=7.61A, V_{OC}=32.9V, I_{SC}=8.21A.

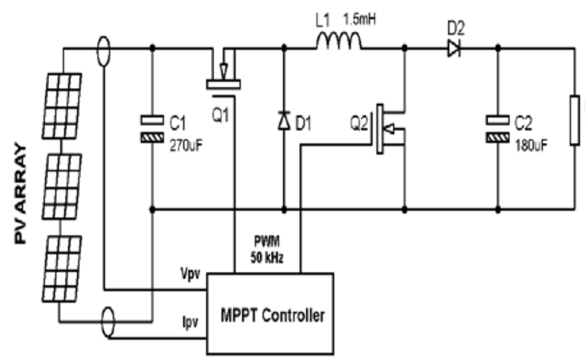

Fig. 1. Simulation model of PV system

Simulations were implemented in Matlab/Simulink when PV modules under PSC1, PSC2 and standard test condition (STC). The proposed method was also tested under slight change of irradiation conditions. In this condition, all of the PV modules have the same temperature (constant 25°C) and irradiation. The irradiation was increased from 800W/m2 to 1200W/m2 by 100W/m2 steps. An irradiation of 1000W/m² and a cell temperature of 25°C are called STC. Non-uniform irradiations of 800W/m2-200W/m2-200W/m2 and a cell temperature of 15°C are called PSC1. Non-uniform irradiations of 400W/m2-800W/m2-1100W/m2 and a cell temperature of 20°C are called PSC2. P-V curve has a peak under STC while it has many peaks under PSCs. The MPP is 600W under STC. The global MPP is 156W while the local MPP is 130W under PSC1. The global MPP is 345W while the local MPPs are 279W and 211W under PSC1. The P-V curves of PV array are shown in Figure 2-3.

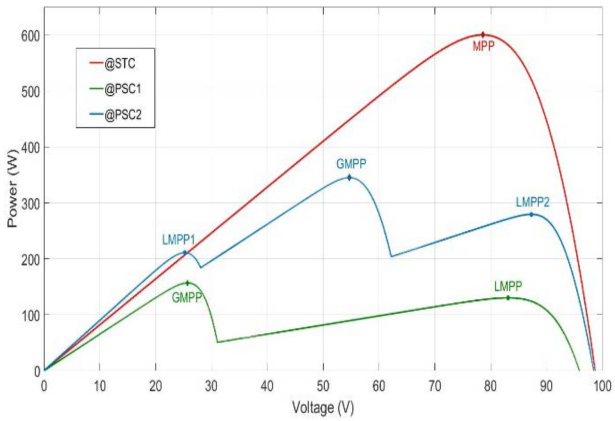

Fig. 2. P-V curves under different simulation conditions

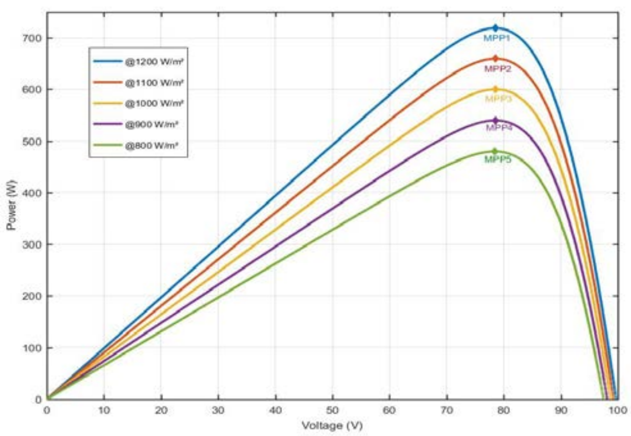

Fig. 3. P-V curves under different irradiations

3. Result and Discussion

The simulation results of proposed method are shown in Figure 4-5. In the first simulation, three different conditions (PSC1, PSC2 and STC) are tested at 0.6 second intervals. BA is activated immediately at start in simulation. The solutions of five bats are updated five times. All of iterations last 0.5 second.

Modified BA is replaced by P&O at t=0.5s under PSC1. Also, the best solution which is determined within five iterations as 156W is transferred to P&O algorithm. P&O tracks the actual MPP in area of the global MPP until the power changes greatly and rapidly. At=0.6s, the environmental conditions rapidly changes to PSC2. Therefore, the search process is restarted. The best solution is determined as 345W under PSC2. At=1.2s, the environmental conditions rapidly changes to STC. The best solution is determined as 600W under STC. All of the global maximum power points are determined successfully. Due to the very small perturbation step of P&O, the oscillation around MPP is extremely small. For example, the oscillation is 2W under STC.

In the second simulation (Figure 5), the irradiation is increased step-by-step with 0.1 second intervals. Because the power changes are relatively small, P&O tracks MPP's. The MPP's are found as 480W, 540W, 600W, 660W and 718W respectively. After change of irradiation, the new MPP's are found within 0.02s.

Simulation results show that the proposed MPPT method could find the global MPP and maintain the operating point at the global MPP. MPPT efficiency of the proposed method is calculated as 99.85%.

Figure 6 shows the simulation results of P&O. P&O converges to the local MGN of 129W under PSC1 although the global MPP is 156W. P&O converges to a local MGN of 277W under PSC2 although the global MPP is 345W. P&O converges to the MPP of 600W under STC. Due to convergence to a local MPP instead of the global MPP, the power loss is occurred. MPPT efficiencies of P&O algorithm under PSC1, PSC2 and STC are calculated as 82.37%, 80.26% and 99.03% respectively. Increased perturbation step (0.01) to faster convergence increases the oscillation around the MPP. The oscillations around of the MPP are occurred 4W under PSC1, 12W under PSC2, and 20W under STC.

Figure 7 shows simulation results of the standard BA under PSC2. The standard BA converges to 332W with 5 iterations under PSC2 although the global MPP is 345W. MPPT efficiency of the standard BA is calculated as 96.23%.

When the standard BA is used as single MPPT algorithm, it needs more time to converge to the global MPP. The standard BA converges to the global MPP with 8 iterations. In case of power change, the search process is necessary to restart. Repeating the search process at every power change increases power loss. Moreover, repeated unsuccessful solutions increase time loss and power loss. The standard BA has a disadvantage of not being able to track the MPP fast when MPP changes slightly or slowly

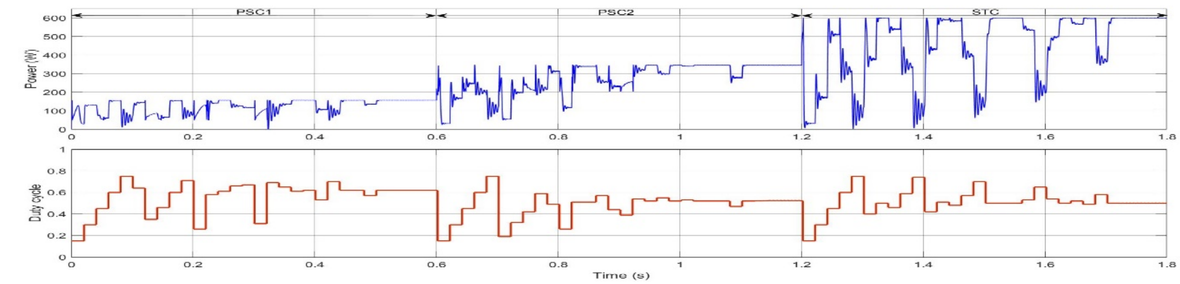

Fig. 4. Simulation curves of proposed method under STC and PSCs

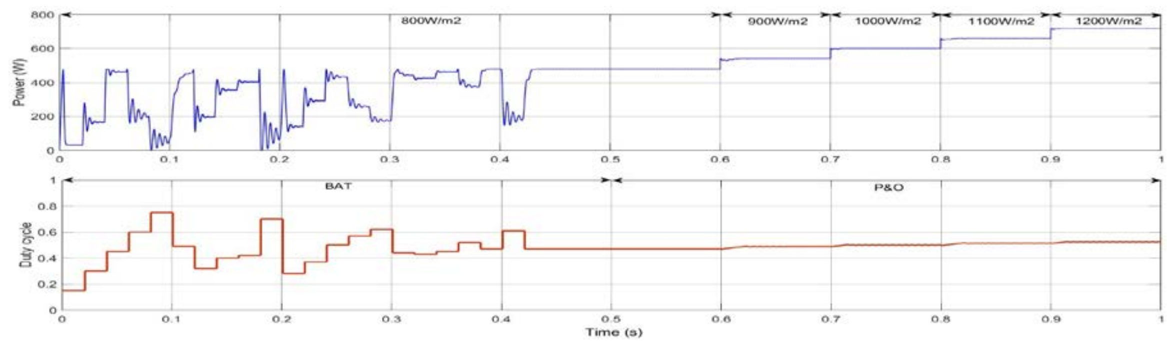

Fig. 5. Simulation curves of proposed method under slight change of irradiation

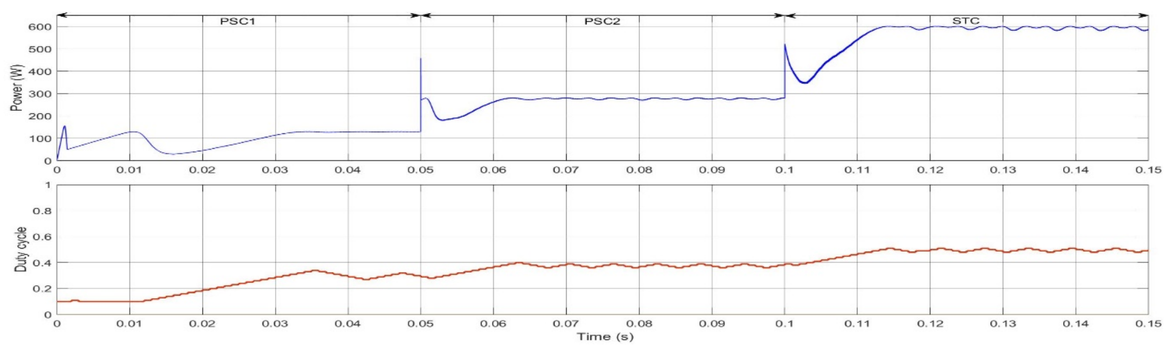

Fig. 6. Simulation curves of P&O

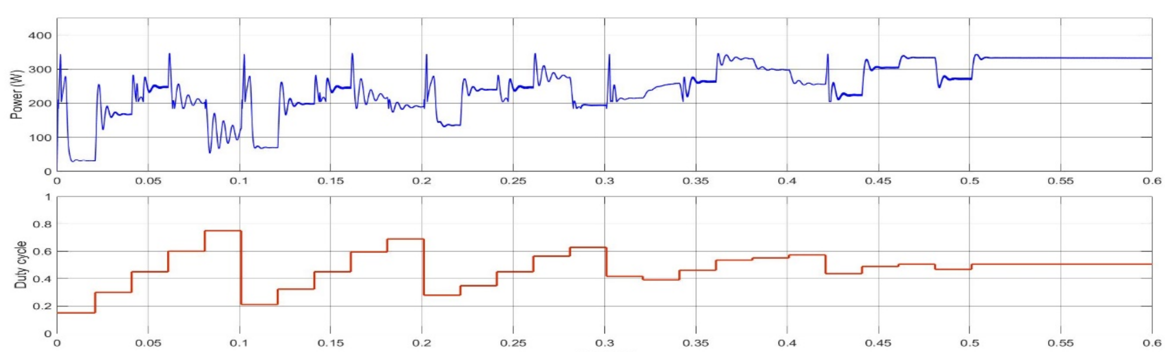

Fig. 7.Simulation curves of BA

4. Conclusion

In this paper, a dual algorithm MPPT method with modified BA and P&O is proposed. The standard BA has been modified by adding tabu list to avoid repeating of unsuccessful solutions. Also, P&O has been added to the search method for fast tracking in case MPP changes slightly or slowly. Because the sampling period of modified BA is longer than P&O's, the proposed MPPT method is faster than BA. Whereas P&O algorithm may not converge to the global MPP, the proposed MPPT method is able to. Consequently, performance of the proposed MPPT method is superior to both the standard BA and P&O.

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