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Modified variable neighborhood search algorithm for maximum power point tracking in PV systems under partial shading conditions

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ABSTRACT

Photovoltaic (PV) systems are being increasingly popular for power generation from solar radiation as the usage of renewable energy grows. To improve the efficiency, the system should operate at its the maximum power point. Hence, several algorithms have been developed for this purpose. Continuous tracking for the maximum power point often leads to heavy energy loss. Furthermore, partial shading can dramatically lower the performance of the system. A modified variable neighborhood search algorithm is proposed resulting zero oscillations around the operating point. A set of variables are used to improve the system's configurability in various atmospheric and geographical conditions. Simulation result proves the operation of the proposed algorithm, its accuracy, and its fast response time.

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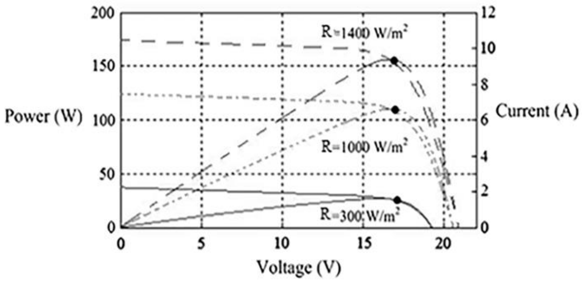
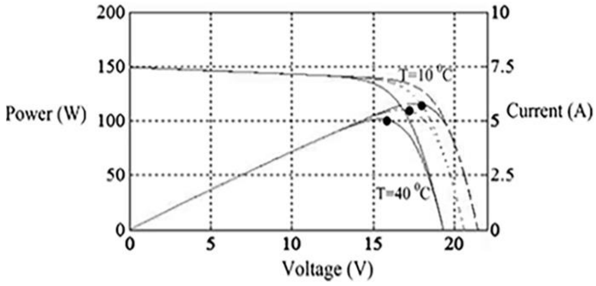
1. INTRODUCTION

In the global energy landscape, solar energy is increasingly becoming a significant power source, as the cost of photovoltaic (PV) systems continue to plummet and concerns about greenhouse gas emissions widespread. PV systems are technologically simple to install, extremely safe, cheap to maintain, and, most importantly, environmentally friendly. Considering their long-term economic potential, large PV power plants are being deployed all over the world. Additionally, as proven by the popularity of building integrated PV (BIPV) programs in several nations [1], [2] underutilized space, such as roof tops of residences, industrial, and skyscrapers, can be efficiently employed to capture the energy of the sun. Despite these benefits, PV power systems in general have yet to achieve grid parity due to their relatively high initial investment and installation costs. Despite ongoing attempts to enhance the efficiency of PV cells, fabrication and assembly processes, inverter technology, and other aspects of the system, the possibility of increasing the system's throughput by boosting the maximum power point tracking (MPPT) capabilities should not be ignored. The PV characteristics curve indicates a non-linear, time-varying maximum power point (MPP) problem due to continual fluctuation in the ambient conditions, particularly temperature (T) and sun radiation (R). Figure 1(a) illustrates a typical poly-crystalline silicon cell current-voltage (I-V) and power-voltage (P-V) relationships showing that the MPP per each curve is distinct with solar iirandiance variations while Figure 1(b) shows the MPP with temperature variations.



(a)



(b)

Figure 1. Maximum power point: (a) with solar irradiance variations and (b) with temperature variations [2]

In addition to partial shading, uniform shading may occur during the operation of PV systems. Under uniform shading, all solar cells receive the same quantity of solar irradiation for the same degree of shadowing. Consequently, the reductionof sunlight is uniform across all cells. As a consequence, short circuit current, I_{SC}, which is proportional to received irradiation, had a clear link with percentage shading. Figure 2 illustrates the P-V characteristics of a solar panel experimental setup with uniform shade at various degrees of shading. Though the uniform shading condition is less likely to occur in large-scale PV systems, the proposed system is still able to accurately locate the MPPT.

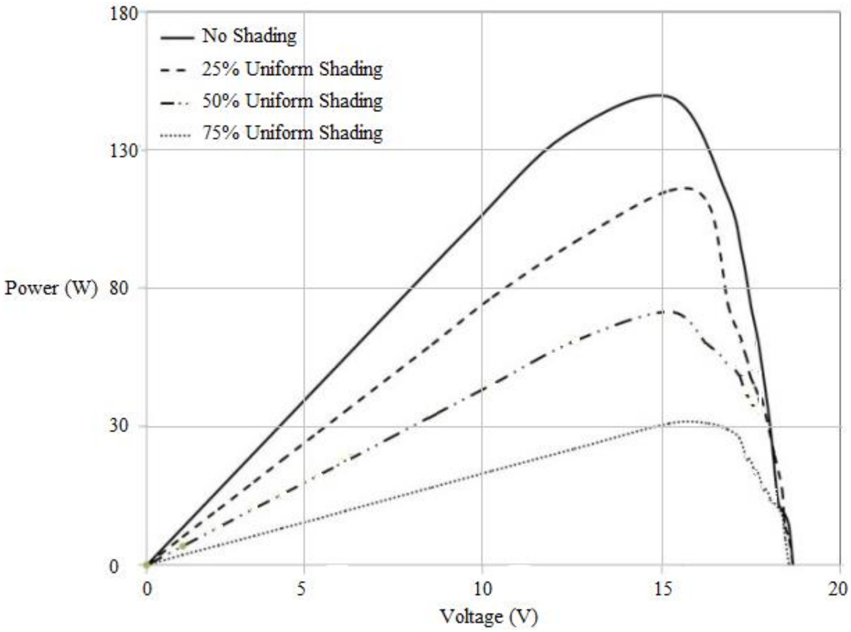


Figure 2. P-V characteristic curve under uniform shading

The MPPT is used along with the power converter (DC-DC converter and/or inverter) to ensure that the maximum power from PV arrays is consistently delivered. Many MPPT algorithms have been developed to date; they are divided into two categories: 1) traditional computing approaches and 2) soft computing methods. Numerous strategies in both categories have been reviewed in [3], [4]. Perturb and observe (P&O) [5]-[7] is a widely used algorithm used for tracking the MPP due to its simplified operation and implementation. If the generated power of the PV module is continuously increasing while the operating voltage is changed in given direction, the operating point has shifted closer to the MPP, as a result, the operating voltage must be increasedmore. On the contrary, if there is a decrease in the power drawn from the PV array, it can be concluded that the operating point has shifted far from the MPP, and the operating voltage perturbation direction must be reversed. The major drawback in the P&O technique is that the operating point oscillates about the MPP during steady state, resulting in the loss of some available energy. Multiple P&O algorithm improvements have been recommended to minimize the amount of oscillations around the MPP in steady state, but they limit the system's reactions to fluctuating atmospheric circumstances and impair its efficiency on cloudy days or under partial shading conditions [8].

Hill climbing (HC) [9] is also a common algorithm used in which the output current of the PV array is compared against a reference current measured by a microcontroller that compares the PV output power before and after a duty cycle change in the DC/DC converter control signal. The PV output current is regulated by the proportional-integral (PI) controller to match the reference current. Incremental conductance [10] is another extensively used approach for conventional MPPT. Other simpler approaches include fractional short circuit current [11], fractional open circuit voltage [12], ripple correlation control [9], sliding control [13], and the mathematical-graphical approach [8].

There are also several soft computing (SC) approaches offered to track the MPP. Artificial neural network (ANN) [14], fuzzy logic controller (FLC) [15], genetic algorithm (GA) [16], differential evolution [17], particle swarm optimization [18], and ant colony optimization [19] among others. Despite their versatility, SC algorithms are usually more complicated and require longer times to converge compared to traditional approaches. For instance, in order to provide correct results, ANN needs a specific and extensive training time to produce outputs. ANN also necessitates the use of a costly microprocessor due to its heavy processing demands. FLC, on the other hand, has a fast convergence rate, but its performance is dependent on the programmers' knowledge of a certain PV modules as well as the installation environment. Other algorithms, such as GA and ant colony optimization (ACO), are implemented, but mostly as an optimization for the standard MPPT. Such methods are referred to as hybrid MPPT.

In this paper, the large neighborhood search algorithm is used for MPP tracking. The algorithm proves to be an efficient solution for the problem. Section 2 discusses the large neighborhood search algorithm and its limitations. The design methodology and implementationis presented in section 3. Simulation results are discussed in section 4 and section 5 provides the conclusion.

2. THE PROPOSED ALGORITHM

The large neighborhood search (LNS) algorithm was first introduced in [20]. In LNS, an initial solution is refined over time by deleting and restoring it alternatively. The LNS heuristic is part of the very large scale neighborhood search (VLNS) algorithm family [21]-[25]. All VLNS methods are built on the principle that scanning a broad neighborhood yields high-quality local optima, and hence a VLNS algorithm may produce superior overall results. However, since exploring a vast region takes time, several filtering techniques are utilized to narrow down the results. The neighborhood in LNS algorithms is usually limited to a subset of the solutions that can be searched effectively. The neighborhood in LNS is defined implicitly by methods (typically heuristics) for destroying and repairing an incumbent solution. The basic principle of the large neighborhood search algorithm is to continuously change the neighborhood during the search while adhering to the following rules:

1) A local maximum with respect to one neighborhood structure is not necessarily locally maximal with respect to another neighborhood structure.
2) A global maximum is locally optimal relative to all neighboring structures.

In the proposed solution, the P-V characteristic curve is divided into several neighborhoods. Such division can be relative to the PV's output voltage. Hence, an increment of 1V per neighbor can be used. Therefore, for a typical PV panel, as described in Figure 1, the number of neighbors can be around 20. The number of neighbors can be increased to improve the accuracy by reducing the voltage step per neighbor. Figure 3 presents the pseudo code for the variable large neighborhood search algorithm.

As seen by the algorithm in Figure 3, the number of neighbors is a configurable parameter by the user. By having this option, the response time and the accuracy can be configurable and can be varied depending on the application. It should be noted that the evaluation function (f) also depends on the application. In this study, the evaluation function (f) is basically measuring the power delivered by the PV panel at neighborhood (N_k).

The major drawback in this algorithm is that it has to be infinitely running searching for a global maximum to make sure to capture the MPP. Whenever the search is done, the algorithm has to reset (k) to 1 to rescan the graph searching for any new global maximum. This means that the operating point oscillates during steady state, resulting in the loss of some available energy. Furthermore, the algorithm fails under partial shading conditions since the algorithm should sweep the whole graph to find the global maximum every time partial shading occurs. Such limitations make the variable large neighborhood search unfeasible to be used in MPP tracking. The proposed solution solves these issues by introducing a set of configurable variables and a modified neighborhood range whenever there is a need to track the global MPP.

input: starting solution: S_0
input: neighborhood operators: $\{N_k\}$;k=1,...k_{max}
input: evaluation function: f
current ⇐ S_0
k⇐ 1
while k ≤ k_{max}**do**
S⇐ the best neighbor in N_k (current)
  if f(S) > f(current) **then**
      current ⇐ S
      k⇐1
  else
      k⇐k+1
  end if
end while

Figure 3: Variable large neighborhood search pseudo code

3. METHOD

The proposed solution combines the quality features of LNS algorithm with a set of configurable elements that could highly impact the overall performance of the system including the reference voltage the searching threshold voltage, and the change in output power. The reference voltage ($Vref$), corresponds to the PV array voltage, at the MPP, under specific atmospheric operating conditions. Hence, $Vref$ is a variable that can be altered based on geographical location or environmental conditions.

The searching threshold voltage (STV) is the effective range during which the algorithm operates. The STV is a configurable variable that can be defined as in (1).

$$STV = V_{max} - V_{min} = 0.9V_{oc} - 0.1V_{oc} \tag{1}$$

Where, V_{oc} = is the open-circuit voltage of a PV panel.

When the maximum and minimum bounds are exceeded, the (1) will automatically halt the LNS algorithm's operation. This scenario might occur during partial shading or at night. Once the PV voltage is beyond the searching threshold voltage bounds, an incremental delay subroutine is called to resolve the issue. The pseudo code for the incremental delay is shown in Figure 4.

Using the LNS algorithm, and prior to the occurrence of partial shading, the system will track and retrieve the MPP and record the relevant maximum power value (P_{max_last}), the K neighborhood operator at which the MPP occurs (K_{max_last}), and the voltage at the MPP (V_{max_last}). The algorithm then keeps checking if the output voltage is within the threshold limits and if the difference between (P_{max_last}) and the instant PV output power (P_{pv}) is larger than ΔP, the algorithm will research for the global maximum power point (GMPP) using an update function. In (2) shows how to calculate the absolute value of ΔP.

$$|\Delta P| = P_{max\_last} - P_{pv} \tag{2}$$

Delay counter in seconds: counter =1
Maximum delay in seconds: $counter_{max}$=86400 \\seconds in 24 hours
while 0.1Voc ≥ Vpv ||0.9Voc ≤ Vpv**do**
    while counter ≤ $counter_{max}$**do**
      sleep (counter)
      counter*=2
    end while
  counter =1
end while

Figure 4. Incremental delay pseudo code

ΔP is a configurable variable that is determined by the PV system's maximum output power as well as the surrounding environment. In the proposed system, it is assumed that when the sun radiation (R) varies by 30 W/m^2, the PV system's output power varies by around 5 W (P = 5 W). In other words, if the difference between P_{max_last} and P_{pv} is higher than 5 W, then (R) has changed, meaning that a new MPP point might be available. Figure 5 presents the proposed algorithm runtime flowchart.

After the algorithm has identified the occurrence of partial shading, the update function will first check the right side of the current MPP. The function will record the voltage and power at K_{max_last+1} and calculate the slope with respect to K_{max_last}. This is done by forcing an increase in the output voltage of the solar panels and observing the output power. With all calculations relative to V_{max_last} and P_{max_last} occurring at K_{max_last}, if the slope is positive, the existence of a new MPP at the right-hand side can be concluded. The function will reuse the LNS algorithm to find the global maximum. However, the neighborhood operators will be $\{K_{max\_last}, K_{max}\}$. This will improve the searching process speed as the number of neighbors is dramatically reduced. If the slope is negative, the function will explore the left side of the P-V characteristic curve and record the voltage and power at K_{max_last-1} and calculate the slope with respect to K_{max_last}. Similarly, If the slope is positive, the existence of a new MPP at the left hand side of the curve can be possible. The function will reuse the LNS algorithm to find the global maximum. However, the neighborhood operators will be $\{1, K_{max\_last}\}$. If both slopes are negative, then the current MPP is still the global maximum with a possibility of a change in the operating conditions. Therefore, the function returns to checking the voltage and power levels boundaries. Since the P-V characteristic curve is a hill shaped graph, the proposed algorithm will always be able to track the MPP in a fast manner. The reduced LNS neighborhood operators will also boost the overall response time of the system.

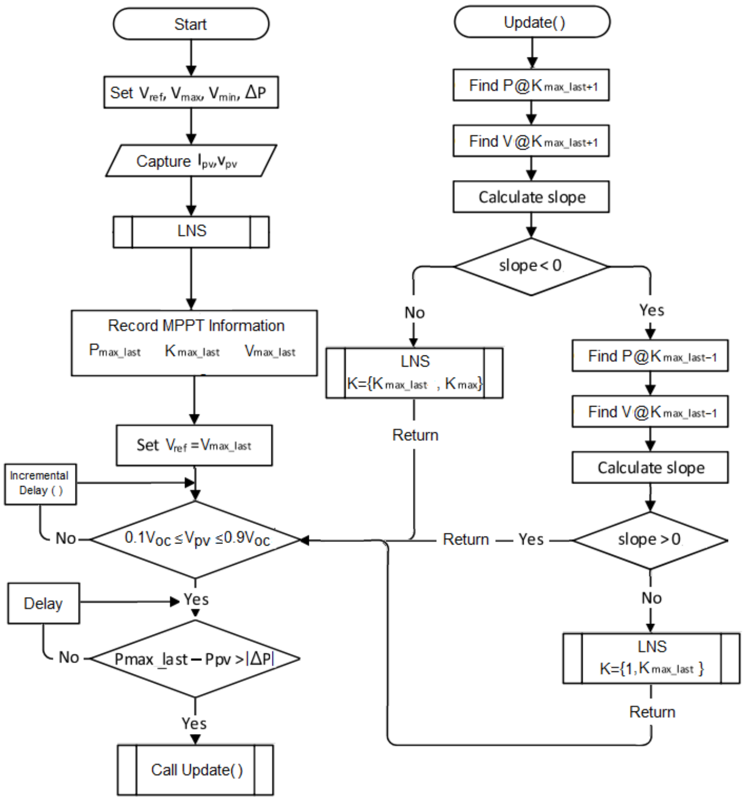


Figure 5. Proposed algorithm flowchart

4. RESULTS AND DISCUSSION

This paper used Matlab and Simulink for simulations. The modeled PV panels has V_{oc} = 21.1 V and I_{sc} = 3.8 A. To simulate real-time problems, the PV panel's maximum output power is limited to 60 W under normal standard operating conditions. To test and simulate the proposed algorithm, three PV panels connected in series are used, and the sun radiation (R) is varied with respect to time to simulate the partial shading condition. In the simulations, Δp was set at 5 W. This corresponds to a variation of 30 W/m^2 in the sun radiation (R). Therefore, if the power's change exceeds the setting value, it is said that the R is start to change. The P-V characteristic curve, during non-uniform sun radiation, is illustrated in Figure 6. Upon the occurrence of partial shading (at t = 1 s), the radiation of the three PV panels is 1000 W/m^2, 700 W/m^2 and 300 W/m^2 respectively. Such partial shading condition will create several peaks in the P-V curve. Under such conditions, the MPPT occurs at about (89.3 W).

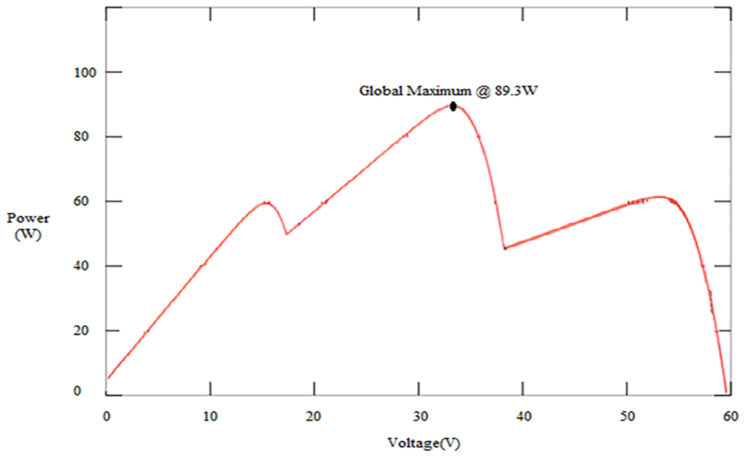
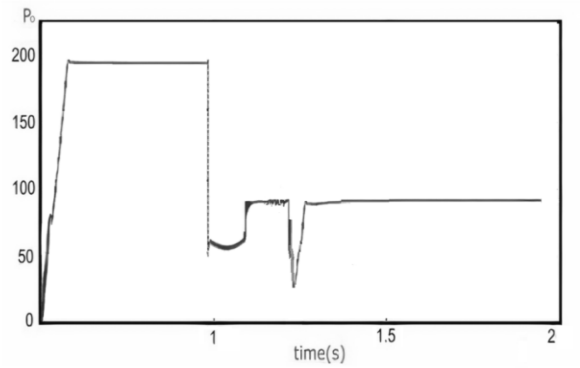
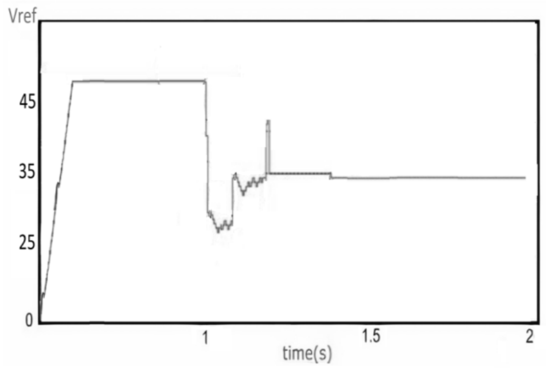


Figure 6. P-V characteristic curve during partial shading

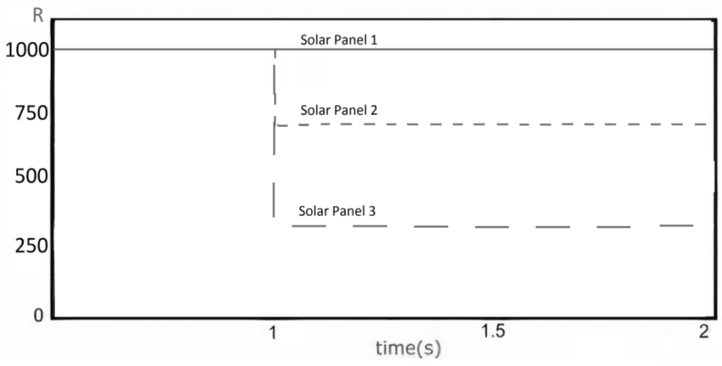
Prior to the partial shading condition, the system used the modified LNS to obtain the global MPP. The system is able to successfully converge in less than 0.2 seconds. One partial shading occurs (at t = 1 s), the systems calls the update function in which the slope is calculated to the left and right sides of the MPP. Once a decision is made, the system converge at the new maximum operating point. The proposed system's response is shown in Figure 7. Figure 7(a) shows the output power of the system while Figure 7(b) shows the reference voltage used within the algorithm. The panels solar irradiance is shown in Figure 7(c).



(a)



(b)



(c)

Figure 7. Response of the proposed system after the occurrence of partial shading: (a) System's output power, (b) System's reference voltage, and (c) Irradiance of solar panels

Despite having only three solar panels in the simulation environment, the proposed algorithm is capable of operating in systems with several panels. Further simulations including many panels were done and proved the intended operation of the proposed system. However, it should be notes that increasing the number of peaks in the system due to different levels of shading will result an increase in the response time of the system.

5. CONCLUSION

A maximum power point tracking algorithm with no oscillations at steady state is proposed. Using a modified large neighborhood search algorithm, the system is able to identify partial shading occurrence and relocate the MPP efficiently. The enhanced behavior of the proposed system resulted from slope calculations from the P-V characteristic curve and the minimization of search elements in the LNS algorithm. Furthermore, user controlled variables and parameters is introduced to control the algorithm operation. The proposed system is able to track the MPP reliably with minimal power loss, hence, overcoming the drawbacks of conventional algorithms.

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