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Main Title:

Harmony Search–Assisted Perturb-and-Observe MPPT Algorithm for PV Systems

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Keywords

«Photovoltaic (PV) system», «maximum power point tracking (MPPT) », «harmony search (HS), perturb-and-observe (P&O) », «partial shading condition (PSC) »

Abstract

Nonuniform irradiation in photovoltaic (PV) systems can cause multiple power peaks, where traditional maximum power point tracking (MPPT) methods like perturb-and-observe (P&O) are only effective under uniform conditions. Accurate global MPPT is crucial under partial shading conditions (PSCs). This paper proposes a hybrid MPPT algorithm integrating harmony search (HS) with P&O. This approach reduces power loss during searches and avoids getting stuck at local maxima under PSCs, a common issue with standard P&O methods. A parameter-setting-free HS (PSF-HS) is introduced to enhance search efficiency, followed by variable-step-size P&O to fine-tune the GMPP location. Experiments on a 250 W PV system under various PSCs using a PV emulator demonstrate the algorithm's effectiveness.

I. Introduction

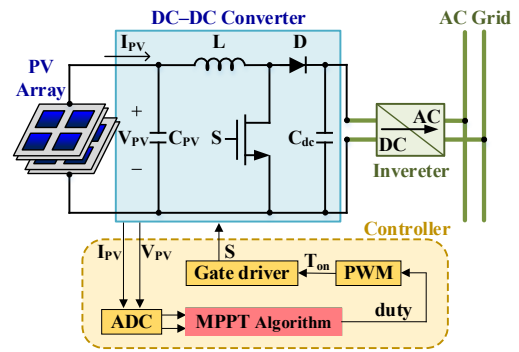


Fig. 1: Structure of typical PV system with MPPT algorithm.

Global warnings, the depletion of coal, and rising fossil fuel prices have increased attention to renewable energy. Solar energy, in particular, is favored for its abundance, renewability, and non-polluting nature. These benefits have spurred the rapid global adoption of photovoltaic (PV) systems, which are popular for their environmental cleanliness, low maintenance, and falling costs. Moreover, their integration into power grids reduces reliance on fossil fuels [1]. The typical structure PV system with maximum power point tracking (MPPT) algorithm is shown in Fig. 1. Generally, a PV system comprises a PV array, a DC-DC converter to regulate the DC-link voltage, a DC-AC inverter to interface with the AC grid, and a controller, which includes voltage and current information for the MPPT algorithm block to generate the maximum power point (MPP) of duty cycle.

Conventional MPPT techniques optimize PV system output by methods such as perturbation and observation (P&O), incremental conductance

(IC), constant voltage (CV), and advanced approaches like fuzzy logic and neural networks, each balancing complexity, efficiency, and adaptability to varying conditions [2]. In general, the P&O method is effective and preferred because of its simplicity and high tracking speed. However, P&O performs poorly in tracking global MPPs (GMPPs) under partial shading conditions (PSC) involving multiple local MPPs (LMPPs).

To overcome the limitations of traditional MPPT algorithms [3], metaheuristic algorithms have been developed to effectively tackle multivariable nonlinear problems. Metaheuristic algorithms are widely utilized in power systems to solve various optimization problems, including optimal power flow, economic and emission dispatches, reactive power dispatches, and distribution network optimization. They can effectively address complex constraints and multipurpose optimization problems. In recent years, various methods have been introduced, such as the grey wolf algorithm [4], Harris hawks optimization [5], the crow search algorithm [6], the bat algorithm [7], particle swarm optimization (PSO) [8], and normal harmony search (NHS) [9].

Among these nature-inspired algorithms, the harmony search (HS) method stands out for its simplicity and minimal parameter requirements. Despite this, it has not been extensively investigated in the context of MPPT algorithms.

In recent, hybrid MPPT was proposed to improve the problems of conventional MPPT. A literature review on hybrid MPPT algorithms shows that conventional methods, such as P&O (often adopted because of its ease of implementation), are assisted by various metaheuristic algorithms, such as PSO [10], adaptive butterfly PSO [11], enhanced leader PSO [12], the artificial bee colony [13], gray wolf optimization [14], and the flower pollination algorithm [15], [16]. Hybrid algorithms mainly aim to improve tracking accuracy and convergence time for GMPPs. In [10] and [11], the P&O method was initially used to find the nearest LMPP. Then, starting from the LMPP, the PSO method is adopted to identify the GMPP. However, this approach cannot effectively reduce the overall convergence time in cases with multiple LMPPs. In some past articles [12]-[16], two-stage approaches were developed by integrating metaheuristic algorithms in the first stage and then P&O in the second stage.

A review of the literature on PV applications revealed only one article discussing the use of the NHS method [9]. Initially, the NHS method

benefits from an expanded bandwidth, allowing for faster tracking of a closer GMPP. However, in the final stage, reducing the bandwidth may lengthen the time required to accurately identify the exact GMPP. Therefore, simply adjusting the bandwidth does not ensure improved tracking performance.

In this study, a hybrid algorithm (HS-assisted P&O) is created to address the shortcomings of the NHS method and compensate for the partial shading problem in the P&O method. Based on a metaheuristic algorithm, an affordable range of GMPPs can be narrowed down via the parameter-setting-free (PSF) HS method. Then, the GMPP can be identified accurately through fast-tracking using variable-step-size P&O.

II. Harmony search (HS) method

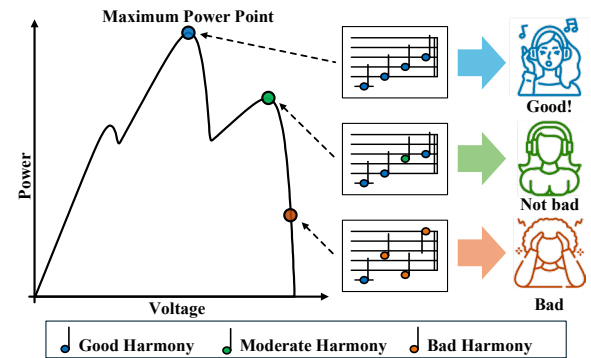


Fig. 2: Principle of HS method in MPPT control.

The HS method simulates creating new harmonies akin to jazz improvisation, with solution vectors termed as harmonies and their storage space as harmony memory (HM). An essential operator involves HM consideration, where a random HM value influences the creation of a new harmony. Decision variables, compared to pitches, are adjusted subtly through a "pitch adjustment" operator to introduce minor variations. Fig. 2 shows the principle of using the HS method for MPPT control.

Table I: Definition of hyperparameter in HS method

Hyperparameter	Definition
HM size (HMS)	Number of harmonies stored.
HM consideration rate (HMCR)	Possibility of executing HM consideration.
Pitch adjustment rate (PAR)	Possibility of executing HM consideration with pitch adjustment.
Number of segmentations (N_{seg})	Determines the bandwidth (bw) during pitch adjustment.

An HM is represented as follows.

$$\begin{array}{c} \begin{array}{cccc} x_1^1 & x_2^1 & \dots & x_n^1 \\ x_1^2 & x_2^2 & \dots & x_n^2 \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{HMS} & x_2^{HMS} & \dots & x_n^{HMS} \end{array} & \begin{array}{c} f(x^1) \\ f(x^2) \\ \vdots \\ f(x^{HMS}) \end{array} \end{array} \quad (1)$$

This means a number n of decision variables x up to the HMS are included in HM. $f(x)$ is the objective function for this study. The three major operators are listed in Table II.

Table II: Three major operators in HS method

Operator	Description and equation
Random generation	Generate a portion of the new harmony randomly within the range of the decision variables $x'_n = LB_n + r \times (UB_n - LB_n)$
HM consideration	A portion of the new harmony is copied randomly from the stored HM values $x'_n = x_n \in \{x_n^1, x_n^2, \dots, x_n^{HMS}\}$
Pitch adjustment	Apply fine-tuning to the copied values using the HM consideration operator. $x'_n = x'_n \pm r \cdot bw_n$

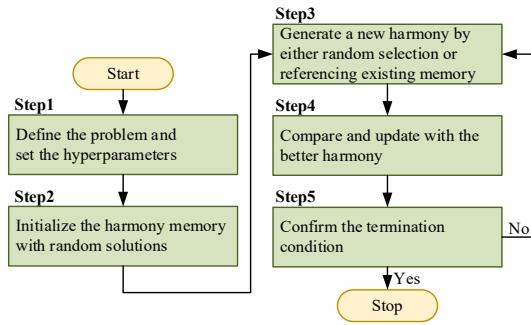


Fig. 3: Process of HS method.

III. Proposed hybrid MPPT algorithm

The method suggested in this paper has two stages. In the first step, PSF-HS is implemented to find the nearest GMPP, followed by the second stage to retrieve the exact GMPP using P&O with variable step size.

A. Applied variable-step-size P&O method

Fixed-step-size P&O is used in most studies on P&O-based hybrid MPPT algorithms combined with metaheuristic approaches [10], [12]-[16]. Variable-step-size versions have been proposed in a few studies. In [11], the step size was changed according to the power-voltage (P-V) relationship, such as $\Delta P/\Delta V$. An adaptive-step-size version was proposed in [8] based on the $\Delta P/P_{k-1}$ relationship. These methods can improve

the performance of conventional fixed-step-size P&O, which may deteriorate the average MPPT efficiency with oscillation after the MPP is reached. The main reason for adopting a variable step size is the mitigation of the oscillation problem as the MPP is approached. However, oscillation may be worsened by a rather enlarged step size due to the sensing noise when the step size is too small. Predefined values were set for the minimum and maximum step sizes in [8] and the voltage and current threshold values in [11], but this approach can reduce the reliability of the system and increase the dependence of performance on the predefined values.

A variable-step-size SS is used in this study ($SS_k = 0.9 \times SS_{k-1}$) to avoid the noise problem and simplify the methods in [8] and [11]. As the applied P&O method is only used in the second stage to finalize the GMPP, the value of 90% is reasonable for tracking speed and accuracy based on experimental validation in Section IV.

B. Applied PSF-HS method

PV systems typically consist of various types of panels and generate power at different scales. Additionally, the challenge of MPPT is compounded by the fact that the shape of the P-V curve—the objective function—continuously shifts due to changing weather conditions during operation. As a result, the PSF-HS method [17] proves more effective in solving MPPT issues than other harmony search approaches. In the PSF-HS method, the parameters HMCR and PAR are automatically determined by the method itself, rather than being user-defined. Initially, the PSF-HS method follows the same procedure as the traditional HS method until the harmony memory (HM) is established. Afterward, a “rehearsal” phase occurs, during which HMCR and PAR are set to 0.5, and the harmony is regenerated to match the size of the HM.

Table III: Comparison of parameters among HS methods

Parameter	HS	NHS	PSF-HS
HMS	D/U	D/U	D/U
Max iteration	D/U	D/U	D/U
bw	D/U	Automatic	D/U
$bw_{min} \quad bw_{max}$	N/U	D/U	N/U
HMCR	D/U	D/U	Automatic
PAR	D/U	Automatic	Automatic
$PAR_{min} \quad PAR_{max}$	N/U	D/U	N/U

In Table III, ‘D/U’ means a parameter value defined by the user. The relatively higher number of D/U means high complexity. ‘Automatic’ means that the value is automatically determined by a specific equation used in the algorithm. ‘N/U’ means that the parameter is not used in the algorithm.

C. Implementation of proposed algorithm

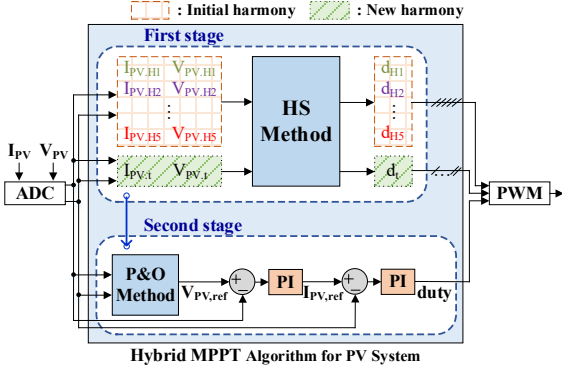


Fig. 4: Block diagram of proposed hybrid MPPT algorithm.

The pseudocode of the proposed hybrid MPPT algorithm is as follows.

```

Proposed MPPT Algorithm
begin HS_stage
  for each index in Harmony Memory (HM)
    Generate duty cycle ( $d_{index}$ ) and calculate power for
    initializing the HM
  end for
  for each iteration until the early stop condition is satisfied or
  reached the limit
    if the HMC operator is not performed by probability  $HMCR$ 
    then
      Generate a new duty cycle ( $d_{new}$ ) with a random value
    else
      Generate new  $d_{new}$  with a value stored in the HM
       $d_{new} \leftarrow d_{new} \pm r \times bw$  ( $r$  is a random real number
      between 0 and 1)
    end if
    if new harmony's power is higher than worst harmony's
    power then
      Replace the worst harmony in HM with a new harmony
    end if
    if rehearsal phase is over then
      Count the number of harmonies that created by the
      HMC&PA operator in  $HM(N_{HMC\&PA})$ 
       $HMCR \leftarrow N_{HMC\&PA}/HMS$ 
    end if
  end for
end HS_stage
begin P&O_stage
  Start P&O from the best harmony ( $d_{best}$ ) found in the HS stage
  Calculate power ( $P_{old}$ ) with sensed voltage ( $V_{old}$ ) and current value
   $d \leftarrow d_{best} + initial\_step\_size$ 
  Check the voltage ( $V_{new}$ ) and power ( $P_{new}$ ) again after moving.
  for each iteration until the step size becomes smaller than the limit
    if the power has increased compared to before moving then
      if the voltage has increased compared to before moving then
         $d \leftarrow d_{best} - initial\_step\_size \times 0.8^{iteration}$ 
      else
         $d \leftarrow d_{best} + initial\_step\_size \times 0.8^{iteration}$ 
      end if
    else

```

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    if the voltage has increased compared to before moving then
       $d \leftarrow d_{best} + initial\_step\_size \times 0.8^{iteration}$ 
    else
       $d \leftarrow d_{best} - initial\_step\_size \times 0.8^{iteration}$ 
    end if
  end if
   $P_{old} \leftarrow P_{new}, V_{old} \leftarrow V_{new}$ 
  Calculate power ( $P_{new}$ ) with sensed voltage ( $V_{new}$ ) and current
  value
end for
end P&O_stage

```

As shown in Fig. 4, the two-stage approach involves implementing PSF-HS in the first stage to find the nearest GMPP and variable-step-size P&O in the second stage to reach the exact GMPP rapidly. This proposed block diagram replaces the conventional PV system controller in Fig. 1. A flowchart of the proposed hybrid MPPT algorithm is presented in Fig. 5, which is based on Fig. 3 and the pseudocode.

In the HS algorithm for optimizing solar panel output, the objective function represents the solar panel's output, while the decision variable is the duty cycle. In other words, the optimization algorithm in the MPPT problem aims to identify the duty cycle that allows the PV system to generate maximum power. In the first stage, the initial duty cycles (d_{H1} - d_{H5}) are applied to the boost converter through the PWM block. The corresponding current and voltage outcomes in the PV system are collected through the ADC block and stored in HM. The results are calculated with their respective powers and are stored or replaced by comparing them with the power of new harmony. The process of creating a new harmony and updating HM is repeated, approaching the GMPP. In the second stage, HS-assisted P&O works with a smaller range to explore than if P&O were used alone, so a small initial step size of 0.02 is feasible. As this is a variable-step-size scheme, the step size is reduced by 20% per duty cycle update, and the algorithm is set to terminate when the step size becomes smaller than the minimum value of 0.0002.

IV. Experimental results

A 250 W experimental setup was built and tested to evaluate the performance of the proposed hybrid MPPT algorithm in tracking the global maximum power point (GMPP). The setup, as illustrated in Fig. 6, includes a GaN-based DC-DC boost converter operating at a switching frequency of 100 kHz. The hybrid MPPT algorithm is implemented using a TMS320F280049 microcontroller from Texas Instruments. Rather than using a physical photovoltaic (PV) array, a PV array simulator

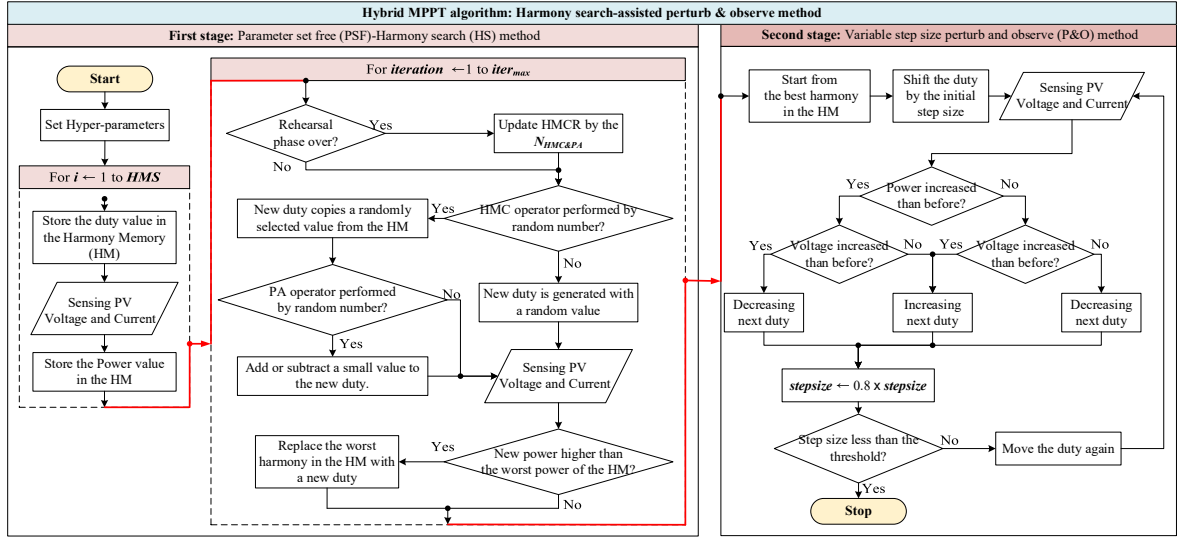


Fig. 5: Flowchart for proposed hybrid MPPT algorithm.

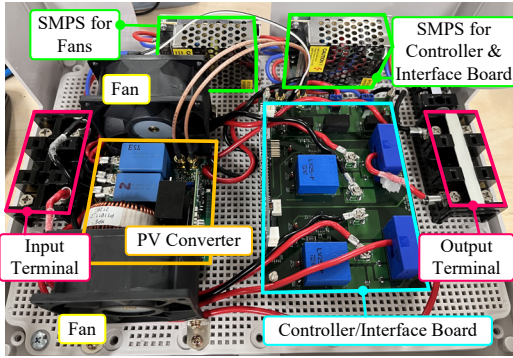


Fig. 6: Experimental setup of PV system.

(IT6012C-500-80 from iTEC) was used. Additionally, the SAS1000 solar array simulation software was utilized to simulate different PSCs. The experiment tested the algorithm's performance under three conditions: a scenario without partial shading (non-PSC) and two scenarios with partial shading (PSC-1 and PSC-2). In the non-PSC scenario, only one MPP was present. PSC-1 had one LMPP and one GMPP, while PSC-2 had four LMPPs and one GMPP. The performance of various algorithms, including P&O, HS, NHS, PSF-HS, PSO, and the proposed hybrid algorithm (PSF-HS+P&O), was compared in terms of time and accuracy over ten consecutive tests. The average values of time and accuracy are tabulated in Table IV under three different PSCs. A basic form of P&O was used and it can be noted that it is only applicable for non-PSC since it failed to find MPP under PSC-1 and PCS-2. Two kinds of hyperparameter sets (HMCR, PAR) are used, namely, (0.95, 0.7) and (0.8, 0.5), respectively, to show parameter sensitivity for HS.

Table IV: Average values of time & accuracy under non-PSC, PSC-1, -2

Non-PSC/PSC-1/PSC-2 191.61/127.73/84.89 [W]	Time [s]			Accuracy [%]		
P&O	3.25	N/A	N/A	99.9	N/A	N/A
HS (0.95/0.7)	6.21	6.74	7.37	99.8	99.8	99.9
HS (0.8/0.5)	7.38	6.97	7.91	99.8	99.8	99.8
NHS (0.8/-)	10.92	9.28	10.35	99.5	99.8	99.8
PSF-HS (-/-)	6.25	6.10	6.84	99.8	99.8	99.8
PSO (0.4.1.2.1.6)	6.71	6.76	6.92	99.8	99.9	99.8
Proposed algorithm	3.58	3.25	3.78	99.9	99.9	99.9

According to the NHS parameter setting [9], the HMCR is set to 0.8 in this test. The PSO parameters are set $w=0.4$, $c_1=1.2$, $c_2=1.6$ with reference to [18].

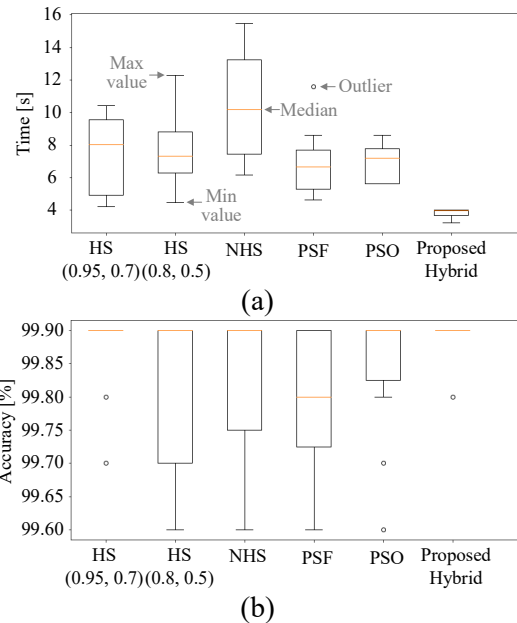


Fig. 7: Boxplots of HS, NHS, PSF-HS, PSO, and proposed hybrid algorithm under PSC-2: (a) time, (b) accuracy.

The parameters during the comparative experiment are defined in Table III. The proposed hybrid algorithm is much more beneficial in terms of the number of hyperparameters than conventional HS and NHS methods. In this paper, the results of PSC-2 will be highlighted using boxplots as summarized in Fig. 7.

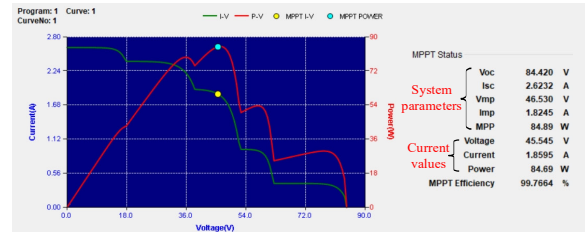
It can be noted that the parameter setting for conventional HS, HS (0.8, 0.5) performs better in the median time than HS (0.95, 0.7). Also, the box of HS (0.95, 0.7) is wider than HS (0.8, 0.5), indicating that there is more variability in the time it takes to reach the GMPP. The wider box that the performance is less consistent. However, HS (0.95, 0.7) shows better accuracy than HS (0.8, 0.5), which means its results are more closely clustered around 100%. This result is caused by the difference in HMCR. A lower HMCR increases the probability of using random generation, thus shortening the tracking time needed to reach the nearest GMPP. A higher HMCR enhances the accuracy of tracking the exact GMPP because HM consideration is executed instead of random generation.

NHS has the highest median time and widest box among the compared methods under PSC-2. As for accuracy, NHS was slightly better with a narrower box than HS (0.8, 0.5). However, the long whiskers indicate that NHS can occasionally result in much lower accuracy, leading to inconsistent performance. The NHS method, with its slower processing times and higher variability in accuracy, is less efficient and less reliable compared to the other methods examined.

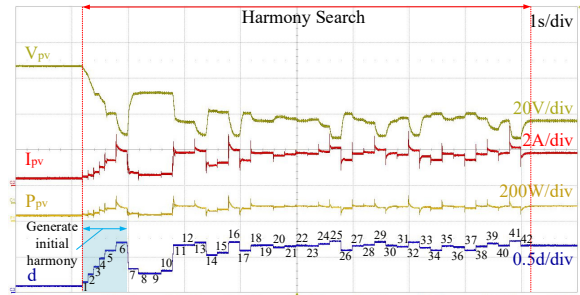
PSF-HS has a lower median time than NHS and HS methods. The box is smaller than the NHS and HS methods, indicating less variability and consistent performance. However, there is one outlier, the method's accuracy can drop significantly, although this occurs infrequently. The median accuracy for PSF-HS is the lowest of the other methods and the box is wider than NHS. The whiskers of the box plot for PSF extend to a lower accuracy value, which indicates that the method can sometimes perform slightly below its median accuracy. PSF-HS performs with moderate consistency and occasional minor drops in accuracy.

PSO is similar to PSF-HS in terms of median time, and it is better than NHS and the HS methods. The box of PSO is comparable to that of PSF-HS, showing moderate variability, which is less than NHS and the HS methods. PSO achieves a high median accuracy, it has a relatively small box area. PSO has an outlier, where accuracy

drops to around 99.60%. This suggests that in some rare cases, the method's performance can significantly decline, making it less reliable in maintaining consistently high accuracy. PSO offers a balance between speed and accuracy, with moderately fast processing times and generally high accuracy. However, it has greater variability in accuracy, as evidenced by the presence of an outlier. The proposed method has the lowest median time, making it the fastest on average compared to all other methods.

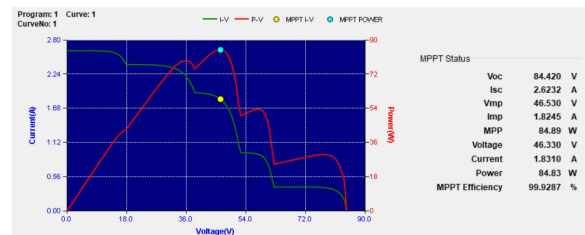


(a)

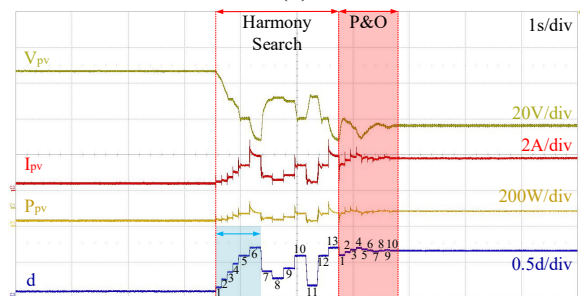


(b)

Fig. 8: Experimental results of PSF-HS under PSC-2: (a) I-V and P-V curves in SAS1000, (b) measured waveforms.



(a)



(b)

Fig. 9: Experimental results of the proposed hybrid algorithm under PSC-2: (a) I-V and P-V curves in SAS1000, (b) measured waveforms.

The box of the proposed method is the smallest, indicating the least variability.

This means it is not only faster but also more consistent in its performance. Also, the proposed method achieves an exceptionally high median accuracy, close to 99.9%. This demonstrates that it consistently delivers precise results across various trials.

The box of the proposed method is nonexistent, indicating that the accuracy is extremely consistent.

The results are tightly clustered around the median, showing minimal variability in performance. The proposed method excels in both speed and accuracy, offering the fastest processing times and the most consistent accuracy among the methods evaluated. It has the most accurate performance in finding the GMPP among the HS methods only except for similar accuracy with HS (0.95, 0.7) under PSC-2, as seen in Table IV.

Among the comparative experimental results, the outcomes of HS (0.95, 0.7) are selected since it could be regarded as optimized tracking performance using the conventional HS method compared to the case of HS (0.8, 0.5).

The I–V and P–V curves (captured by SAS1000) and measured experimental waveforms (voltage, current, and power of the PV system with duty cycles) are presented in Figs. 8–9. Further, the PSC-2 is only included in this Section to highlight the most severe case study of partial shading.

The shading pattern, PV array parameters, generated power, and tracking accuracy (efficiency) are confirmed in Figs. 8(a)–9(a). The GMPP is successfully located regardless of the applied method.

As indicated in Fig. 8(b), at the duty cycle, once the initial harmony is generated, the consecutive iterations follow. In Fig. 9(b), *max iter* = 13 is identified in the first stage and P&O is implemented in the second stage. Under PSC-2, the accuracies of 99.77% (HS (0.95, 0.7)) is improved to 99.93% (proposed algorithm) and the tracking times are significantly reduced from 7.8 s (HS (0.95, 0.7)) to 3.2 s (proposed algorithm).

V. Conclusion

This paper introduces a hybrid MPPT algorithm that integrates harmony search (HS) with the P&O algorithm to address partial shading in photovoltaic (PV) systems. The key contributions of the research are as follows: (a) Given the limited application of HS in PV systems,

conceptual illustrations are provided to explain its working principles; (b) This study is the first to propose a hybrid MPPT algorithm that combines HS with P&O; (c) The algorithm incorporates the PSF scheme, reducing the parameter-setting complexity compared to conventional HS and NHS methods; (d) A robust, variable-step-size P&O algorithm is integrated into the hybrid model to enhance tracking efficiency; and (e) A detailed flowchart and pseudocode are included for practical implementation. Extensive experimental testing demonstrates that the proposed hybrid MPPT algorithm achieves the fastest convergence time compared to P&O, HS, NHS, PSF-HS, and PSO. Specifically, the proposed algorithm improves tracking accuracy to an average of 99.89% under non-PSC condition, 99.88% under PSC-1, and 99.89% under PSC-2. Additionally, the proposed algorithm reduces average tracking time by 2.63s, 3.49s, and 3.59s compared to the conventional HS method under non-PSC, PSC-1, and PSC-2 respectively.

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