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RESEARCH ARTICLE

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Optimal control parameters for bat algorithm in maximum power point tracker of photovoltaic energy systems

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Summary

Partial shading conditions generate multiple peaks in the P-V curve of photovoltaic (PV) arrays. Smart MPPT optimization techniques should be used to capture the global peak (GP) and avoid being trapped in one of the local peaks (LPs). The tracking of the GP should be fast and reliable to enhance the stability and increase the generated efficiency of the PV systems. Bat algorithm (BA) is one of the fastest swarm optimization techniques. The BA control parameters (BA-CPs) have substantial effects on their performance. This paper introduced a nested BA strategy called BA-BA strategy to determine the optimal values of control parameters of BA for the lowest convergence time and failure convergence rate to be used in the online MPPT of PV systems. The inner BA loop used the BA as an MPPT of the PV system, meanwhile, the outer BA loop used the inner BA loop as a fitness function to determine the optimal BA-CPs for minimum convergence time and failure rate. Ten benchmark BA strategies, particle swarm optimization (PSO), and cuckoo search (CS) algorithm have been used to compare their results with the results obtained from the BA-BA strategy. The results of the BA-BA strategy reduced the convergence time of 250% of the time associated with the best benchmark BA strategy, 518%, and 395% as compared to the PSO, and CS algorithm, respectively. The simulation and experimental results obtained from the BA-BA strategy showed its superior for determining the optimal control parameters for BA in MPPT of PV systems or any other applications.

KEYWORDS

bat algorithm, MPPT, optimal control parameters, optimization, photovoltaic

List of Symbols and Abbreviations: d, duty ratio of boost converter; V_{DC}, DC-link voltage; V_{PV}, terminal voltage of PV array; I_{PV}, PV output current; L and C, inductor and capacitor of boost converter; j, counter to represent iteration of the BA; k, counter number to represent bat number; v, velocity of bats; P_j^k, output power of bat number k in iteration j; ω, inertia weight; ε, predefined tolerance; f, pulse frequency; f_{min} and f_{max}, minimum and maximum frequency; SS, swarm-size; n, number of peaks in the P-V curve; it, maximum iteration number; P_{best}, global best output PV power; F_{best}, global best value of outer BA loop; d_{best}, global best position; β, random value, $\beta \in [0,1]$; r_j^k, pulse emission rate of particle k at iteration j; A_j^k, pulse loudness of bat k at iteration j; $\hat{A}$, average pulse loudness; ϕ, constant used to enhance the searching stability of BA; γ, exponential constant to increase the pulse emission rate; α, reduction ratio of pulse loudness of bats; F, objective function value; dd, best bat fitness position; Fit, best bat fitness function value of outer BA loop; P_{it}, best bat fitness function power of inner BA loop; F_{best}, best objective function value of outer BA loop; $F_{max,j}$ and $F_{min,j}$, maximum and minimum objective function value at iteration j; N_T, predefined number of iterations to stop the execution of the code; Δd, difference in duty ratios between two peaks in P-d curve; V_{oc}, open circuit voltage; t_s, sampling time; N_{av}, number of times to execute the inner BA loop; t_c, convergence time; FR, failure rate; N_s, average number of iterations consumed to get the peak of the inner BA loop; N_{FR}, number of occurrences of premature convergence; M, weighting constant; o, i, suffix o and i is to represent outer and inner BA loops, respectively; d_{opt}, theoretical value of optimal duty ratio; GP, theoretical value of global peak.

1 | INTRODUCTION

The generated power from photovoltaic (PV) energy systems is a function in its terminal voltage. This relation is called the P-V curve which has only one peak when the irradiance is the same on all the modules of the PV array. Meanwhile, in the case of partial shading condition (PSC) this relation is having multiple peaks, the highest power one is called global peak (GP) and others are called local peaks (LPs). Many techniques have been used in the past as a maximum power point tracker (MPPT) under uniform irradiance which is called "traditional MPPT techniques" such as hill-climbing, perturb and observe, and incremental conductance.[1,2] These techniques work effectively in the case of uniform irradiance because only one peak exists in the P-V curve, but it may lose the tracking of the GP in the case of PSC. For this reason, smart techniques have been introduced in the literature to track the GP in case of uniform irradiance as well as the PSC. Two different factors are used to evaluate these techniques which are the convergence time, and the failure convergence rate. These smart techniques can be classified into three categories, brain-inspired, chaos, and metaheuristics. A brain-inspired category such as an artificial neural network (ANN),[3] fuzzy logic control (FLC),[4] etc. These techniques have a very short convergence time meanwhile they have a high failure convergence rate, high complex implementation, and should be modified if the size of the system is changed. Chaos search algorithms such as dual-carrier chaotic search.[5] Chaos search algorithms have a long convergence time and a high failure rate. The metaheuristic optimization category is subdivided into Bio-inspired algorithms (BI), Evolutionary algorithms (EA), Physics-based search algorithms, Mathematics-based search algorithms, Swarm intelligence (SI). Swarm intelligent techniques mimic the performance of animals, fish, insects in searching for their food to capture the GP of the PV systems. Swarm intelligent techniques such as (PSO)[6-8] ant colony optimization (ACO),[9] artificial bee colony (ABC),[10] bat algorithm (BA),[11] grey wolf optimization (GWO),[12] etc. Most of these techniques have been reviewed, discussed, and evaluated in References 13-15. The swarm intelligent techniques are characterized by long convergence time and low failure rate. The long convergence time acts as a barrier between these techniques and their use as an online MPPT of the PV systems and many similar applications. So, the main important issue in this regard is to reduce the convergence time of these techniques. The main reason for the long convergence time of these techniques is the unwise use of their control parameters. Determining the optimal control parameters of the swarm techniques can considerably reduce the convergence time which was the main motive of this study.

The BA has been introduced in 2010[16] as a modification of PSO. Despite of the superior performance of BA, it has been used as an MPPT of PV system in few papers.[11,17-22] All these studies did not show how they determine the BA-CPs or the swarm size. The first paper that used BA as an MPPT of a PV system is introduced in 2017.[17] This paper showed how to use the BA in MPPT and it showed a fast response and the importance of initialization of bats at optimal values. The BA technique has been used also as an MPPT of the PV system by controlling the duty ratio of boost converter taking into account the need for the reinitialization of bats in case of an acute change in the shading pattern of the PV system.[11,18-20] A new technique has been used with the BA called scanning bat strategy to scan the position of the GP and attracts all bats to work around this GP.[21] This technique reduced the convergence time and failure rate considerably. Lately, a hybrid technique used the BA with traditional MPPT to work together to effectively captures the GP and reduces the oscillations in the generated power generated.[22,23] In Reference 22, the advantage of the BA in fast capturing the GP is used in the initialization after that one of three traditional MPPT techniques is compared to smoothly track the GP. This paper[22] did not show the effect of BA-CPs on the convergence time and failure convergence rate. Moreover, it did not introduce the need for reinitialization when an acute change in the PSC occurred. Hitherto, there is no research introduced in the literature to determine the optimal value of control parameters and swarm size of BA or any other swarm optimization technique which will be handled in this paper to fill this research gap. All these MPPT BA techniques used a recommended BA control parameter without any tuning study or studying the effect of these parameters on the performance of BA which will be studied in this paper to fill this research gap. The performance of the BA technique is substantially affected by its control parameters and swarm size.

This paper introduces a new strategy to determine the optimal values of BA-CPs and swarm size for minimum convergence time and failure rate for MPPT of PV systems under all operating conditions. This strategy determines the optimal BA-CPs offline to be used in online MPPT of PV systems using BA. The idea introduced in this strategy is done by using two nested BA loops called the BA-BA strategy. The inner BA loop uses the PV energy system as a fitness function to determine the optimal duty ratio of boost converter at maximum power, convergence time, and the failure convergence rate. The outer loop optimizes the BA-CPs of the inner BA loop for minimum convergence time and a convergence failure rate of the inner loop. The BA used in the inner BA loop will be used for a different number of peaks to determine the optimal BA-CPs that can work with the PV system having any number of peaks. The main results obtained from this study are the optimal BA-CPs that can work as an MPPT of PV systems under all partial shading conditions.

The rest of the paper is designed to show the PV system model in Section 2, the new proposed BA-BA strategy is introduced in Section 3. Simulation results of the BA-BA strategy and its comparison with 10 benchmark BA strategies are introduced in Section 4. The experimental results are shown in Section 5. The conclusions and future work is introduced in Section 6.

2 | PV SYSTEM MODELING

The generated power from the PV array is a function in its terminal voltage and for this reason, it should be connected to DC/DC converter to control its voltage to work at maximum power point (MPP). In this paper, the PV array will be connected to the boost converter as shown in Figure 1. The variation of power vs voltage is shown in Figure 2. The output of the boost converter is connected to the DC-link and the load when it is used to charge a battery or it can be connected to a PWM inverter to be synchronized with the electric utility. The relation between the input and output voltage of the boost converter is determined from (1). Based on the relation shown in (1), the relation between the generated power and the duty ratio of the boost converter can be determined as shown in Figure 3 which is called *P-d* characteristics. It is clear from Figures 2 and 3 that, the *P-V* and *P-d* relation are having only one peak in the case of

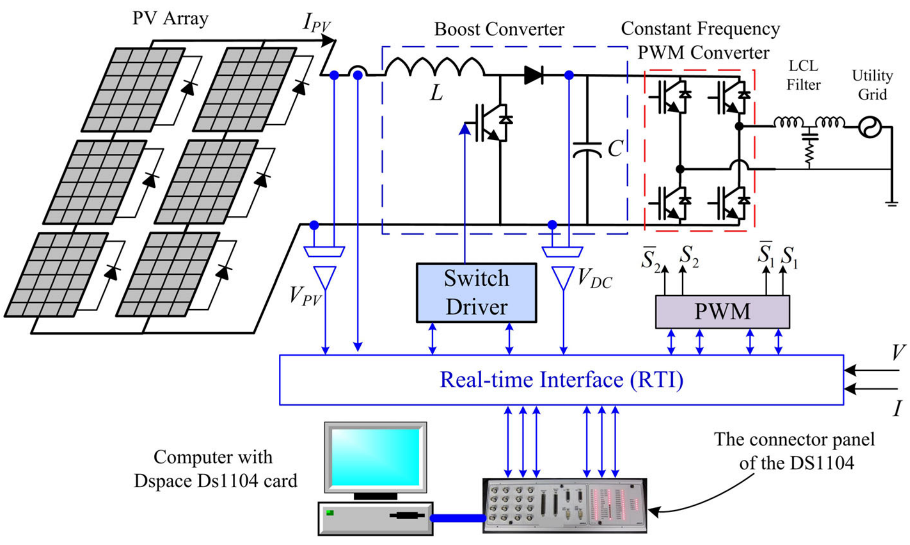


FIGURE 1 The PV energy system with a BA-based MPPT

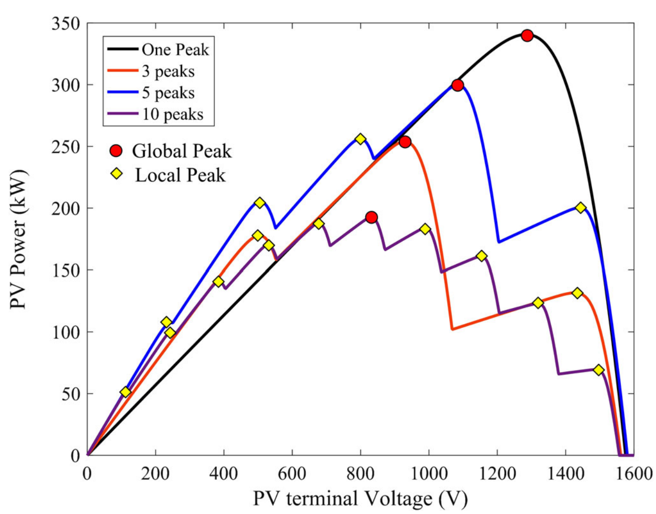


FIGURE 2 P-V characteristic of PV array under different shading conditions

uniformly distributed irradiance, meanwhile, they have multiple peaks in the case of PSCs. Controlling the duty ratio of the boost converter to work at the duty ratio associated with the GP will force the PV system to extract the maximum available power which is the target of this study.[24,25] The tracking of MPP of the PV system will be performed using the BA as will be discussed in the next sections.

$$V_{PV} = (1-d)V_{DC} \tag{1}$$

where V_{PV} is the terminal voltage of the PV array, V_{DC} is the DC-link voltage, and d is the duty ratio of the boost converter.

3 | THE BA-BA STRATEGY

Bat algorithm (BA) is one of the fastest convergence swarm optimization techniques where it mimics the bats' behavior in searching for their food. In nature, bats use the echolocation strategy by emitting several pulses with different amplitudes and frequencies and receive the echo of these pulses to extract some useful information. This information is enabling the bats to configure if the object is prey or not, the distance from the prey, and the size of the prey. Where the bat measures the distance between its position to the prey by the time elapsed from sending the pulse to receive the echo. The bat can also measure the size of the prey by measuring the intensity of the echo sounds or pulses. Moreover, bats can evaluate the moving speed and direction of the prey by tuning the frequency difference. In nature, the bats emit short-duration sound pulses around 10-100 times per second.[16] The searching behavior of the bats has inspired the researchers to imitate it in searching for the optimal solution for different life problems. The following sections explain the logic of using the BA as an MPPT of the PV systems.

3.1 | BA initializations

Initialization of bats (duty ratios of boost converter) should be done at the starting of the BA algorithm or when an acute change in the output power is detected which may be an indication for shading pattern changes that may replace the GP from its previous position. The need for the initialization of bats is to search in the whole searching area. The searching variable of the inner BA loop is the duty ratio of the boost converter which is in range ($0 < d < 1$). The code can detect the acute change in generated power using the following condition:

$$\left|\frac{P_j - P_{j-1}}{P_{j-1}}\right| > \varepsilon_1 \tag{2}$$

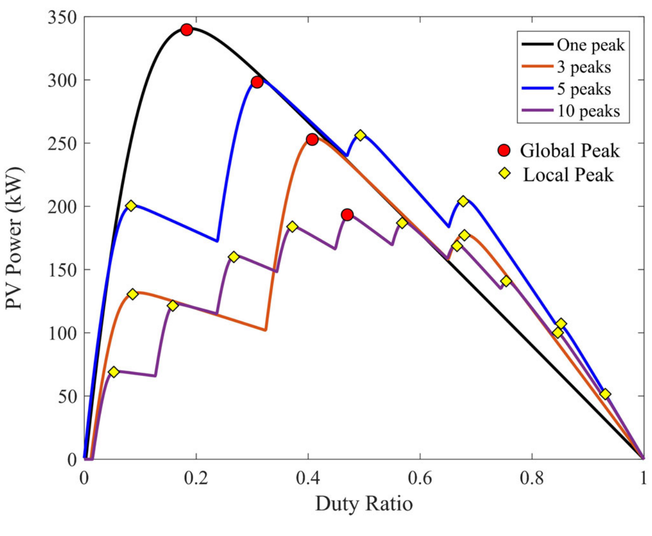


FIGURE 3 *P-d* ratio of PV array under different shading conditions with a boost converter

where P_j and $P_{j\text{-}1}$ are the generated power at iteration j and $j-1$, respectively. ε_1 is a predefined tolerance used to detect the acute change in generated power. The value of ε_1 is used equally to 5%.[21]

The normal practice is to randomly initialize the bats (duty ratios of boost converter) in the searching area between 0 and 1. Many studies showed that the random initializations of bats in MPPT of the PV systems may prolong the convergence time and increase the failure rate and for this reason, the bats are initialized based on dividing the searching distance 0 to 1 equally between the bats as shown in Equation (3).

$$d_0^k = k/(ss+1) \tag{3}$$

where d_0^k is the initial positions of bats (duty ratio) with order k in the swarm, SS is the swarm-size. As an example, if $SS = 4$, then the initial bats positions (duty ratios) are [0.2, 0.4, 0.6, 0.8].

The initial velocity ${v_0}^{1:SS}$ and initial frequency ${f_0}^{1:SS}$ of all bats are set to zero (where SS is the swarm size). The initial values of bats that can be determined from (3) will be used to start the boost converter where it will be sent to it one by one and the corresponding power ${P_0}^{1:SS}$ will be collected after waiting the sampling time to get the steady-state from the boost converter. The best value of maximum power is determined from as $P_{best} = \max({P_0}^{1:n})$ and the corresponding duty ratio, d_{best} will be determined.

3.2 | Global peak tracking using BA

The equations used to mimic the behaviors of bats are shown in Equations (4–6), where the impulse frequency is shown in (4) which will be used in (5) to determine the bats' velocities ${v_j}^{1:SS}$. The new positions of bat k, $({d_j}^k)$ can be obtained from Equation (6) by adding this velocity to the previous positions of bats.

$$f_j^k = f_{\min} + (f_{\max} - f_{\min})\beta \tag{4}$$

$${v_j}^k = \omega {v_{j-1}}^k + \left(d_{best} - d_{j-1}^k\right) f_j^k \tag{5}$$

$${d_j}^k = d_{j-1}^k + v_j^k \tag{6}$$

where the values of f_{min} and f_{max} is the minimum and maximum frequency range where their values are chosen in many studies between 0 and 2, respectively.[21] β is a random value, $\beta \in [0,1]$, as the case of PSO, the velocity of bats is multiplied by inertia weight value, ω which is used to enhance the searching stability of bats.[16]

After determining the new position from (6), a random walk around this position should be performed to get the new position of the bat. If the rate of pulse emission r_i that can be obtained from (7) is less than a random number, then the new position ${d_j}^k$ should be updated with the new position shown in (8).[11,21] The value of r_j is called the pulse transmission and can be determined from (7).

$${r_j}^k = r_0\left[1 - e^{(-\gamma j)}\right] \tag{7}$$

where, the value of γ is exponential constant and its value is about 0.9 in many kinds of research.[21,26]

$${d_j}^k = d_{best} + \varepsilon \phi \hat{A} \tag{8}$$

where, ε is a random number, $\varepsilon \in [-1,1]$,[11,21] and ϕ is used to enhance the stability or limitations to the number walk around the best solution, $\hat{A}$ is called the average loudness of bats and its value equal to the average of A in the current iteration. The value of the loudness (A_j) of the impulse should start from high-value A_0 and should be decreased by α, its previous value as shown in (9).

$$A_j^k = \alpha A_{j-1}^k \quad (9)$$

3.3 | New proposed BA-BA strategy

The new proposed strategy is used to determine the optimal BA-CPs (ω, f_{min}, f_{max}, A_0, r_0, α, γ) and swarm size (SS) by the two nested BA loops algorithm called BA-BA strategy. This new proposed strategy will be used offline to determine the 8 BA-CPs. After determining these optimal parameters, they can be used to work with an online BA in tracking the MPP of the PV systems with superior performance. The inner BA loop gets the values of BA-CPs from the outer BA loop to be used to determine the maximum power and optimal duty ratio using the PV model. The convergence time will be determined to get this peak and the global best value will be examined if it is near to the theoretical GP or not. This process will be performed several times, N_{av} to get an average value of convergence time and an average value of failure rate as shown in (10) and (11), respectively. The convergence time and failure convergence rate will be used to determine the objective function as shown in (12). The resultant value of the objective function, F will be sent back to the outer BA loop as a fitness value, where the BA-CPs are used as a bat position for the outer BA loop. So, the inner loop is used as a fitness function for the outer BA loop. Figure 4 shows the main block diagram of the input and output to the parts of the BA-BA strategy. The detailed flowcharts of outer and inner BA loops are shown in Figures 5 and 6, respectively.

$$t_c = N_s * SS_i * t_s \quad (10)$$

where N_s is the average iterations consumed to get the final solution of the inner BA loop. The average value of N_s can be obtained from dividing the total number of iterations of the inner BA loops and dividing this number by the total number of averaging cycles N_{av}.

$$FR = (N_{FR}/N_{av}) * 100 \quad (11)$$

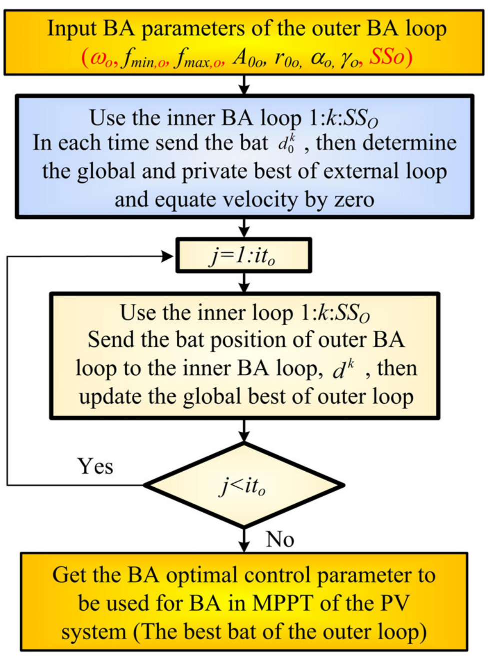
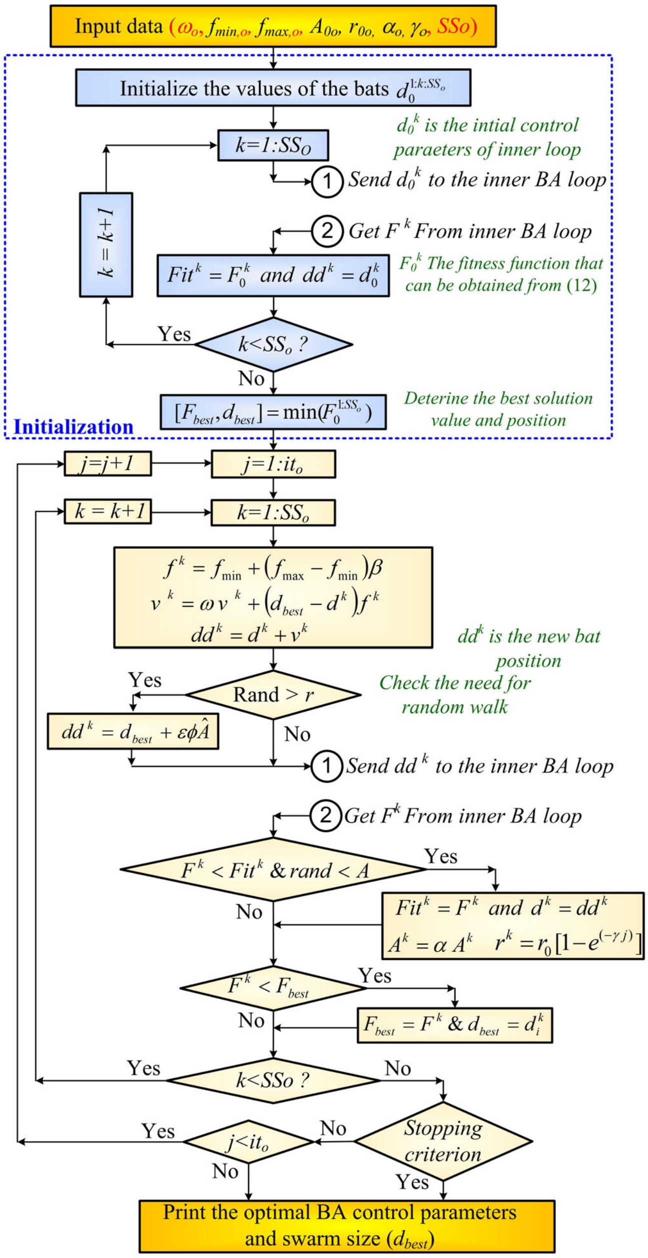


FIGURE 4 The Flowchart showing the brief logic of BA-BA strategy

FIGURE 5 The outer loop of BA-BA strategy



where N_{FR} is the number of occurrences of failure in all attempts of the inner BA loop.

$$F = M{*}FR + t_c \tag{12}$$

where M is a weighting constant used to give the failure rate some sort of importance, where higher the value of M reduces the value of the failure rate and vice versa. In case it is required to get a zero failure rate, this value should be a high value ($M = 1000$) to give more weight to the failure rate.

3.4 | BA-BA steps

The steps showing the logic of the BA-BA strategy in determining the optimal BA-CPs when it is used as an MPPT of the PV systems are shown in the following points and are shown in detail in Figures 5 and 6 for the outer and inner BA

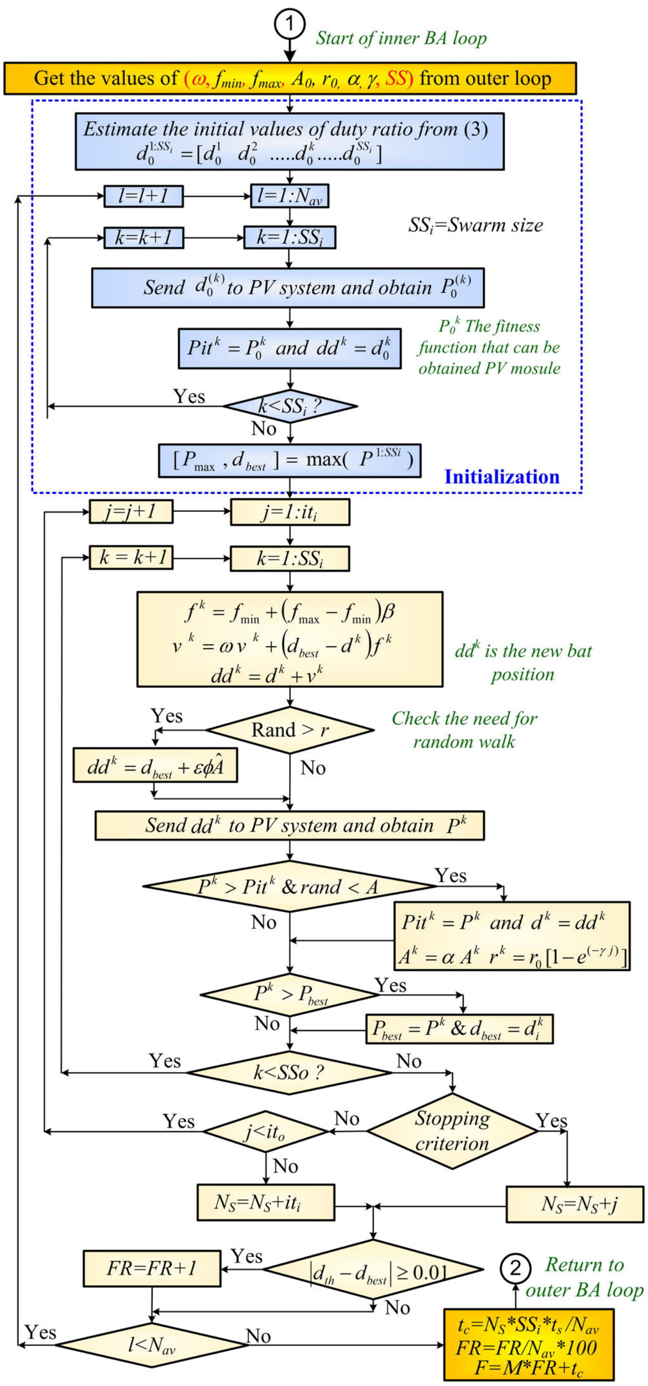


FIGURE 6 The inner loop of BA-BA strategy

loops, respectively, where the suffix "o" is used to represent the outer BA loop, and the suffix "*i*" is to represent the inner BA loop of the BA-BA strategy.

The steps of the outer loop of the BA-BA strategy are shown in the following points:

Step out 1: Set the values of BA-CPs of the outer BA loop ($\omega_o, f_{min,o}, f_{max,o}, A_{0o}, r_{0o}, \alpha_o, \gamma_o, SS_o$).

Step out 2: Initialize the values of the bats of the outer BA loop $d_0^{1:k:SS_o}$ that contain the BA-CPs of the inner BA loop, Equation (13) shows the bat k of this swarm.

$$d_0^k = \left\{ \left(\omega_0^k\right)_i, \left(f_{\min,0}{}^k\right)_i, \left(f_{\max,0}{}^k\right)_i, \left(A_{0,0}{}^k\right)_i, \left(r_{0,0}{}^k\right)_i, \left(\alpha_{0,0}{}^k\right)_i, \left(\gamma_{0,0}{}^k\right)_i, \left(SS_0^k\right)_i \right\} \tag{13}$$

Step out 3: Send the values of d_0^k as shown in (13) to the inner BA loop and get the objective function, F_0^k as defined in (12) for all bats of the swarm.

Step out 4: Determine the value of the minimum fitness function and its corresponding bat such as Set $F_{\min} = \min\left(F_0^{1:SS_o}\right)$, $(d_{best})_o = d_0^k$, and equate the best bat fitness function $Fit^k = F_0^k\, and\, dd^k = d_0^k$.

Step out 5: Use Equation (4) to update the frequency, f^k determine the new velocity from (5) where $v^k = \omega\, v^k + (d_{best} - d^k)f^k$, and determine the new bat positions from (6) such as $dd^k = d^k + v^k$.

Step out 6: If $rand > r$, then $dd^k = d_{best} + \varepsilon\varphi A$, otherwise go to step out 7 without modifying dd^k.

Step out 7: Send the values of the new particle position dd^k to the inner BA loop and get the value of the fitness function, F^k as shown in (12).

Step out 8: Check if $F^k < Fit^k$ & $rand < A$, then, $Fit^k = F^k$ *and* $d^k = dd^k$ and determine the value of r_j^k and A_j^k from Equations (7) and (9), respectively.

Step out 9: Check if $F^k < F_{best}$, then $F_{best} = F^k$ and $d_{best} = d^k$.

Step out 10: Check if all bats are evaluated, go to step out 11 otherwise go to "step out 5."

Step out 11: Check the stooping criteria of the outer BA loop, if it is valid print the values of best BA-CPs and swarm size, d_{best}, otherwise, go to "step out 5."

The following steps is showing the inner BA loop:

Step in 1: Receive the values of inner BA-CPs from the outer BA loop (these values represents one bat positions of the outer BA loop) $(\omega, f_{min}, f_{max}, A_0, r_0, \alpha, \gamma, SS)$.

Step in 2: Set $N_{av} = 1000$ and $N_s = 0$ and $N_{FR} = 0$.

Step in 3: Initialize the positions of the bats of the inner BA loop $d_0^{1:SS_i} = \left[d_0^1\ d_0^2\ .....d_0^k.....d_0^{SS_i}\right]$ from Equation (3) and send these values one by one to the model of the PV system and collect the corresponding generated power, P^k for all bats of the swarm.

Step in 4: Determine the value of maximum fitness function and its corresponding bat such as: Set $P_{\max} = \max\left(P^{1:SS_i}\right)$, $d_{best} = d_0^k$, and equate the best bat fitness function $Pit^k = P^k\, and\, dd^k = d_0^k$.

Step in 5: Use Equation (4) to update the frequency, determine the new velocity from (5) where $v^k = \omega\, v^k + (d_{best} - d^k)f^k$, and determine the new bat positions from (6) such as $dd^k = d^k + v^k$.

Step in 6: If $rand > r$, then$dd^k = d_{best} + \varepsilon\varphi A$, otherwise go to "step out 7" without modifying dd^k.

Step in 7: Check if the bat position is in the normal operating range by (if $dd_k < d_{min}$, then $dd_k = d_{min}$ and if $dd_k > d_{max}$, then $dd_k = d_{max}$), where $d_{min} = 0.02$ and $d_{max} = 0.98$.

Step in 8: Send the values of new particle position dd^k to the PV system model and get the corresponding power value, P^k.

Step in 9: Check if $P^k > Pit^k$ & $rand < A$, then, $Pit^k = P^k$ *and* $d^k = dd^k$ and determine the value of r_j^k and A_j^k from Equations (7) and (9), respectively.

Step in 10: Check if $P^k > P_{best}$, then $P_{best} = P^k$ and $d_{best} = d^k$.

Step in 11: Check if all bats are evaluated, go to step in 12 otherwise go to "step in 5."

Step in 12: If the stopping criterion is validated set $N_s = N_s + j$, then go to step in 13, otherwise, go to step in 14.

Step in 13: If $j \geq it_i$, then $N_s = N_s + it_i$, then go to step in 15, otherwise go to step in 14.

Step in 14: If the stopping criterion is not validated and $j \leq it_i$, then $j = j + 1$, then go to step in 5.

Step in 15: Check if the solution is not GP by using the condition (if $|P_{best} - GP| > \varepsilon_1$), then $N_{FR} = N_{FR} + 1$, where, ε_1 is a predefined tolerance, $\varepsilon_1 = 0.001$ in the simulation.

Step in 16: If the average number of simulation times is less than N_{av}, go to step in 3 otherwise, go to step in 17.

Step in 17: Calculate the FR, t_c, and objective function from (6), $FR = N_{FR}/N_{av}*100$, $t_c = N_s*SS_i*t_s/N_{av}$, $F = M*FR + t_c$.

Step in 18: End of the inner BA loop and go to the outer one.

3.5 | Execution termination criteria

The code should have a termination criterion to stop the execution of the code when it goes to a steady-state. The BA-BA strategy has two nested BA loops each one should have one or more termination criteria. Many termination criteria have been used to stop the execution of swarm optimization techniques which have been discussed in Reference 27. The normal execution termination criterion used in most of the swarm optimization techniques is the end of iteration number, where the execution of the code will be terminated when the number of iterations reached the predefined maximum number of iterations. There are two termination criteria have been used in this paper to terminate the iterations before it reaches the end of iteration number which are introduced in the following.

3.5.1 | Fitness convergence

This termination criterion ensures that all the fitness function values during a single iteration are concentrated at the final solution. This means that all the bats are concentrated around the final solution. This can be implemented in the code by terminating the code when the absolute difference between the highest and the lowest values of the objective function is lower than predefined tolerance as shown in the following condition:

$$\left|F_{\max,j} - F_{\min,j}\right| \le \varepsilon_2 \tag{14}$$

where $F_{max,j}$ and $F_{min,j}$ are the maximum and minimum value of objective function during the iteration, j, and ε_2 is a predefined tolerance which has been used in this paper equal to 10^{-6}.

The steady-state can be checked also by ensuring the best fitness function did not change for a certain number of iterations. The implementation of this criterion is shown in the following condition:

$$\text{For}\, j > N_T, \textit{if}\; F_{best,j} = F_{best,j-N_T}\ \text{stop the execution of the code} \tag{15}$$

where N_T is a predefined number of iterations used to terminate the code if the fitness function did not change, $F_{best,\,j}$ is the objective function value at j iteration, and $F_{best,j-N_T}$ is the objective function value at $j\text{-}N_T$ iteration.

These fitness convergence criteria shown in (14) and (15) have been used in parallel to stop the outer BA loop. The observations of the results proved the superiority of using these termination criteria.

3.5.2 | Swarm position convergence

This criterion is performing the termination when it ensures that the swarm positions are concentrated at their final steady-state. This criterion can be implemented by ensuring the difference between the highest and lowest bats' positions of the swarm is lower than predefined tolerance. This criterion is ideal to be used in the inner loop because in MPPT of the PV system it is required to see the swarm position values are concentrated at very near to each other to judge the state of convergence. This criterion can be implemented easily as shown in the following condition:

$$\max\left(d_j^{1:k:SS_i}\right) - \min\left(d_j^{1:k:SS_i}\right) \le \varepsilon_3 \tag{16}$$

where $d_j^{1:k:SS_i}$ are the swarm positions of all bats at iteration j, and ε_3 is a predefined tolerance which has been used in this paper equal to 10^{-6}.

3.6 | Failure rate determination

The failure rate is measuring the number of trials of premature convergence or failure occurrence (convergence at one of the LPs) with respect to the total number of trials. It is essential to determine the predefined tolerance between the theoretical optimal duty ratio, GP and the actual duty ratio to judge the actual best duty ratio is GP or LP. The position of the anticipated peaks in the *P-d* curve can be obtained from (17).[6] In the case of the 10 peaks (n = 10) which is the maximum possible number of peaks in this paper, and $V_{OC} = V_{DC}$, and $k_v = 0.8$, the difference between every two sequential peaks is 0.08. In the case of two peaks the difference between two peaks, Δd is 0.4 and this value is reduced with an increasing number of peaks. Table 1 shows the approximate difference between any two peaks for a different number of peaks in the *P-d* curves.

$$d^{(k)} \approx 1 - \frac{(n-k+1)^{*} k_V}{n} * \frac{V_{OC}}{V_{DC}} \tag{17}$$

where n is the total number of peaks, k peak order (k = 1, 2, …., n), the constant k_V has a value between 0.76 and 0.82[6] and taken equal to 0.8 in this paper, V_{DC} is the DC-link voltage, V_{oc} is the open-circuit voltage.

Based on the results shown in Table 1, the difference between any two neighbor peaks is less than 0.04 in case of any number of peaks less than or equal to 20 peaks. So, the difference between the best duty ratio from the convergence of inner BA loop and theoretical duty ratio at GP, d_{opt} is greater than or equal to 0.04 it should be counted as failure occurrence. For safe results, this value is set as 0.01 and the condition for the convergence occurrence is shown in (18). This logic is shown in the steps of the inner BA loop steps and the flowchart of the inner loop of the BA-BA strategy shown in Figure 6.

$$\text{If} \left| d_{opt} - d_{best} \right| \geq 0.01, \text{the} FR = FR + 1, \tag{18}$$

4 | SIMULATION RESULTS

The main objective of the simulation section is to prove that, the MPPT of the PV system is tracking the GP much faster and reliable when their parameters are extracted from the BA-BA strategy compared to any benchmark strategies that use different values of the BA-CPs and at the end of the simulation the optimal BA-CPs should be determined. To show that, the BA-BA strategy should be performed first to extract the BA CPs, then the second simulation study is introduced to use these parameters and the parameters of different benchmark BA strategies to show the superiority of the BA-CPs obtained from the BA-BA strategy compared to others. For this reason, the first simulation study is the extraction of the optimal BA-CPs suitable for each number of peaks in the *P-d* curves of the PV system. The second simulation study is performing a comparison between the results obtained from using the BA-BA strategy to the results obtained from 10 benchmark BA strategies when they are used as an MPPT of the PV system. The PV system used in this simulation is consists of 10 series connected PV market available modules (Sunperfect CRM185S156P-54[28]) with 185 W rated power, 32.2 V open-circuit voltage, and 7.89 A short circuit current for each module. The boost converter parameters are L = 0.5 mH and C = 200 μF. Single-phase H-bridge pulse width modulation (PWM) converter is used to transfer the power from DC-link to the electric utility.

4.1 | Extracting the optimal BA-CPs using BA-BA strategy

The logic introduced in the BA-BA strategy steps and flowcharts shown in Figures 4–6 is implemented in co-simulation between the Matlab and Simulink programs. The outer BA loop is implemented in Matlab and it calls the inner BA loop in Matlab too as a separate function which is counted as a fitness function for the outer BA loop to determine the objective function value shown in (12). The inner BA loop is sending the duty ratio to the PV energy system model in Simulink to determine the corresponding generated power from this system. The value of power should be extracted at the end of the sampling period (0.05 second) to be sure the PV system went to a steady-state condition.

The number of peaks in the *P-d* characteristics of PV systems is depending on the shading conditions and for this reason, the BA-BA strategy will be used separately for each number of peaks. The insolation on the PV system is selected to get the required number of peaks. It has been taken into consideration to have a different position of the GP in each case to prevent biasing the results on a single shape of the *P-d* curves and for this reason, the insolation values are selected randomly in each trial of tracking the GP in the inner BA loop.

TABLE 1 The difference between any two peaks for a different number of peaks in the *P-d* curves

Peaks (n)	2	4	6	8	10	12	14	16	18	20
Δd	0.4	0.2	0.133	0.1	0.08	0.0667	0.0571	0.05	0.0444	0.04

The values used in the simulation are, $N_{av} = 1000$ trials, the sampling time, t_s is selected to be 0.05 second, the lower and upper limits of duty ratios are 0.02 and 0.98, respectively. The BA-BA strategy shown above has been applied for 10 different numbers of peaks separately. After using the BA-BA strategy for each case, the optimal BA-CPs along with a different number of peaks are shown in Table 2. It is clear from this table that; the minimum swarm size is 4 which is associated with one peak case (C_1) and the maximum number of swarm size is 9 which is associated with 10 peaks case (C_{10}). The convergence time is starting from 0.57 second for C_1 and the highest value of convergence time is 0.9179 second for the C_{10} case which means that the optimal parameters obtained from the BA-BA strategy reduced the convergence time for all possible cases of peaks. It is clear from Table 2 that the convergence time is less than 1 second which proves the superior convergence performance where the convergence time associated with the benchmark strategies is up to 70 seconds as shown in the following section. The relations between the optimal swarm-size (number of bats or duty ratios in each iteration) and the convergence time along with the number of peaks in the *P-d* characteristics are shown in Figure 7. It is clear from this figure that the optimal swarm-size is varied between 4 and 10 when the number of peaks varied between 1 and 10 with an almost direct proportional relationship. The relation between the convergence time along with the number of peaks in the *P-d* characteristics is linearly proportional with the number of peaks in the low number of peaks and it takes an almost constant value of peaks greater than 6 peaks. Moreover, the convergence time for all number of peaks is lower than 1 second. This substantial improvement of the BA in terms of convergence time and failure rate enables BA to work very fast in tracking the GP of the PV system in an online application which is the main objective of this study.

TABLE 2 The simulation of the system is performed with a different number of peaks using the BA-BA strategy

BA-BA Cases	No of peaks	f_{min}	f_{max}	ω_ι	A_0	r_0	α	γ	SS_i	t_c(s)
C_1	1	0	7.6069	−0.0073	1.2541	0.227	0.9705	1.1833	4	0.57
C_2	2	0	7.1724	−0.388	3.8462	0.0813	0.9631	1.7496	5	0.725
C_3	3	0	5.4871	0.7257	2.3630	0.0326	1.5364	1.6915	6	0.8205
C_4	4	0	5.0107	0.8300	6.5934	−0.0057	0.9589	1.6147	6	0.879
C_5	5	0	0.5771	1.3985	3.4254	−0.0536	1.0737	1.5735	6	0.909
C_6	6	0	0.6754	2.2602	1.8121	0.0001	1.2767	2.3936	6	0.915
C_7	7	0	0.7152	0.9120	2.5142	−0.0361	1.1358	1.5833	7	0.917
C_8	8	0	6.2587	3.9443	1.4428	−0.0024	0.9326	1.6526	8	0.9172
C_9	9	0	6.5735	0.1726	7.3028	−0.0762	1.1572	1.4548	8	0.9172
C_{10}	10	0	8.1932	4.8205	5.2156	−0.0411	1.5885	2.1967	9	0.9179

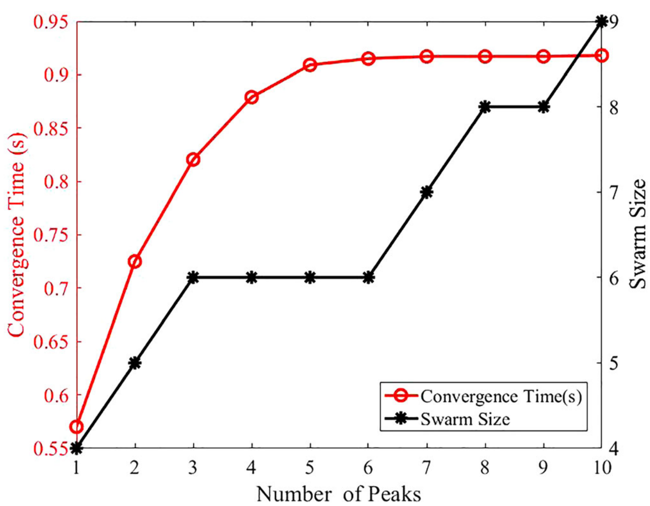


FIGURE 7 The relations between the optimal number of swarm-size and convergence time against the number of peaks in the P-V curves

4.2 | Comparison between BA-BA strategy to the benchmark BA strategies

Ten benchmark BA strategies (B_1-B_{10}) are introduced for the purpose of comparison with the BA-BA strategy. The control parameters of these benchmark strategies are shown in Table 3. The results obtained from using these benchmark functions in all cases of peaks compared to the results obtained from the BA-BA strategy are shown in Table 4. For a fair comparison between these techniques, the swarm size used for these strategies is chosen equal to 6, where 6 is the most swarm-size number shown with the BA-BA strategy as shown in Table 2. The swarm-sizes used with the BA-BA strategy are obtained from Table 2. The results obtained from Table 4 show the best benchmark strategy is B_3[26] with 6.034 seconds average convergence time, meanwhile, the worst benchmark strategy is B_9[31] with 69 seconds average convergence time. It is also clear from Table 4 that, the convergence time obtained from the BA-BA strategy is less than 1 second which is substantially lower than the ones obtained from all benchmark strategies (B_1-B_{10}). The average convergence time obtained from using the BA-BA strategy is 0.849 second which is substantially lower than the average convergence time associated with all the benchmark BA strategies as shown in Table 4.

TABLE 3 The performance evaluation of BA with benchmark strategies and tuned strategy

Parameters Strategy	Frequency f_{min}	f_{max}	ω	A_0	r_0	α	γ	SS
B_1[29]	0	100	1	1	0.001	0.9	0.9	6
B_2[17]	0	100	0.4	1	0.001	0.9	0.6	6
B_3[26]	0	1	0.5	0.85	0.85	0.75	0.6	6
B_4[30]	0	0.25	1	0.9	0.98	0.9	0.85	6
B_5[18]	0	1	1	0.7	0.5	0.9	0.9	6
B_6[22]	0	0.2	1	1	0.5	0.7	0.7	6
B_7[19]	0.3	0.5	1	0.5	0.67	0.5	0.5	6
B_8[11]	0	100	0.5	1	0.001	0.9	0.9	6
B_9[31]	0	1	1	0.5	0.01	0.6	0.05	6
B_{10}[31]	0	5	1	0.95	0.9	0.8	0.7	6

TABLE 4 The convergence time from all benchmark strategies compared to the results from BA-BA strategy for all number of peaks under study

Strategy	Peaks 1	2	3	4	5	6	7	8	9	10	Average t_c
B_1[29]	60.00	10.46	7.840	28.25	5.980	2.680	65.08	45.56	30.58	31.38	28.78
B_2[17]	53.52	11.45	8.050	25.88	6.060	2.795	61.94	43.93	29.44	28.68	27.17
B_3[26]	3.96	4.373	4.130	3.840	4.130	3.955	9.17	6.660	9.58	10.54	6.034
B_4[30]	39.94	25.34	22.38	25.78	22.90	22.12	29.33	20.28	20.61	25.02	25.37
B_5[18]	52.28	26.55	11.17	52.21	17.98	6.035	88.76	41.23	39.82	29.97	36.60
B_6[32]	60.00	83.18	27.31	62.19	49.68	10.52	38.54	26.15	33.29	28.46	41.93
B_7[33]	59.51	118.7	49.03	88.80	77.39	42.12	112.0	47.42	59.62	38.31	69.29
B_8[11]	41.99	10.38	7.370	25.64	6.300	2.47	58.49	43.56	28.56	29.61	25.43
B_9[31]	59.51	119.0	46.09	82.31	72.42	36.15	120.0	46.17	59.20	34.21	67.50
B_{10}[31]	59.41	112.6	46.65	86.66	77.03	35.26	101.2	46.16	59.08	34.61	65.86
PSO[34]	3.63	4.26	4.86	4.92	5.12	5.34	5.49	6.19	6.23	6.43	5.25
CS[35]	3.05	3.14	3.54	3.81	4.13	4.22	4.65	4.96	5.18	5.32	4.20
BA-BA	0.57	0.725	0.8205	0.879	0.909	0.915	0.917	0.917	0.917	0.918	0.849

4.3 | Comparison between the results from the BA-BA strategy, PSO and CS algorithm

To validate the superiority of BA when it used the control parameters obtained from the BA-BA strategy it should be compared with other benchmark swarm optimization techniques. Particle swarm optimization (PSO)[34-39] and cuckoo search (CS)[40] algorithms are used as an MPPT of PV systems and their results for a different number of peaks in the P-V curve of PV system have been compared with the results obtained from the BA when used the control parameters obtained from BA-BA strategy. The parameters used in this study for different swarm optimization techniques are shown in Table 5. The results obtained from using the PSO and CS algorithm when they are used for a different number of peaks are shown in Table 4 to easily compare their results with the state of the art BA and the values from the BA-BA strategy. It is clear from Table 4 that the best average BA strategy is B_3[26] with a convergence time equal to 6.034 seconds, meanwhile, the average PSO and CS convergence time are 5.25 and 4.2, respectively. The average convergence time associated with the BA with control parameters obtained from the BA-BA strategy is 0.849 second. So, the reduction of average convergence time from the B_3[26] compared to the BA-BA strategy is (6.034 − 0.849)/0.849 * 100 = 610%. Similarly, the reduction of average convergence time of using the BA-BA strategy compared to the PSO and CS algorithm are 518% and 395%, respectively. The time variation of the power and duty ratio of the BA from the BA-BA, PSO, CS for one peak, 5 peaks, and 10 peaks are shown in Figure 8. It is clear from Figure 8 that the BA using the control parameter from BA-BA strategy (C10) captured the GP much faster than the PSO and CS for all number of peaks in the *P-d* Curve which proves the superiority of BA-BA strategy when used to determine the control parameters of BA when used as an MPPT of PV systems. Moreover, it is worth to be noted here that the BA and CS captured the GP for all number of peaks, meanwhile, the captured the GP only with one peak, 5 peaks, and lost the

TABLE 5 The control parameters of the optimization techniques used in this study

Technique	Parameters
PSO[34]	$\omega = 0.42$, $c_l = 1.55$, $c_g = 1.55$, $SS = 6$
CS[35]	$p_a = 0.05$, $\beta = 1.5$, $\alpha = 0.1$, $SS = 6$

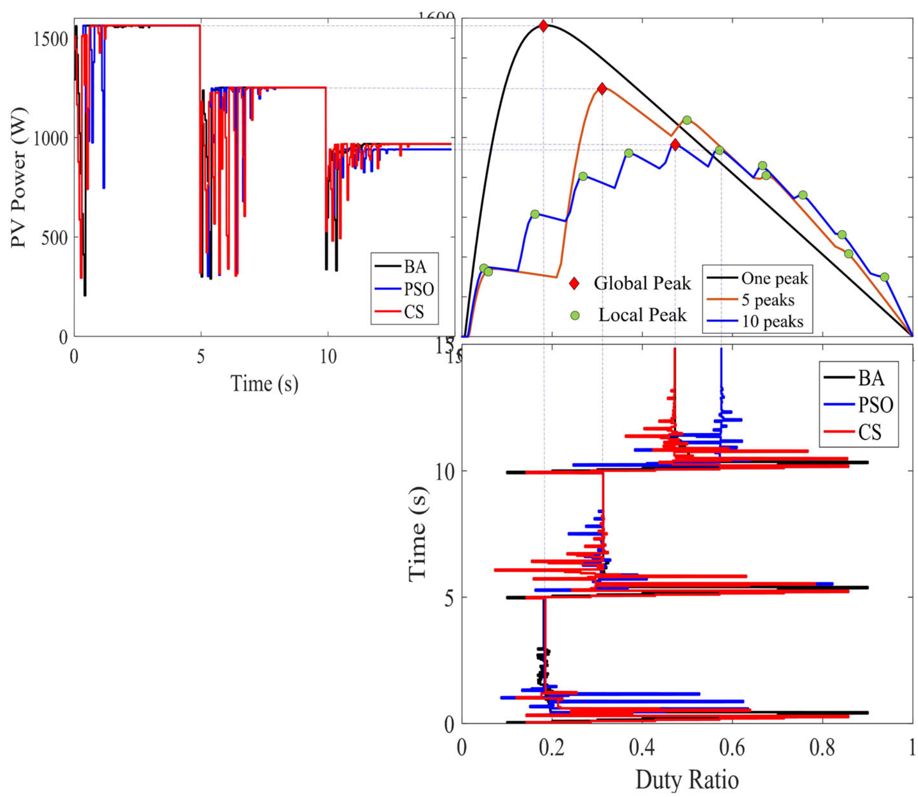


FIGURE 8 The performance of BA from C10, PSO, CS for different number of peaks

GP when the number of peaks is 10. For this reason, the number of searching agents used with the PSO should be increased by 6 when the number of peaks is more than 5 peaks (Table 6).

4.4 | Single BA-CPs for different number of peaks

The real-world application of the MPPT of the PV system does not have a single value of the number of peaks but it may change with the dynamic variation of shading conditions. For this reason, it is required to have a single value of BA-CPs that can well perform with all operating conditions and all number of peaks. For this reason, the variations of convergence time for each BA-BA strategy C_1-C_{10} with a different number of peaks are determined as shown in Table 7. It is clear from this table that all these techniques are work will with the number of peaks that are optimized for but its performance is getting worse when it is used with other numbers of peaks. The highest average convergence time is corresponding to the use of the BA-BA strategy of one peak (C_1) to be used for all peaks with 7.742 seconds. So, this strategy is not recommended to be used for a real PV system with a different number of peaks. Meanwhile, the lowest average convergence time is corresponding to the use of the BA-BA strategy of 9 peaks (C_9) to be used for all peaks with 2.952 seconds. So, C_9 is the best strategy to be used in a real PV system with an unknown number of peaks. The convergence time from C_9 is the best among the different strategies shown in Table 2 (C_1-C_{10}) but it is not the optimal one. For this reason, it is recommended to have only one optimal BA-CPs that work well with all peaks to recommend everybody to use whatever the number of peaks in the *P-d* curves. A new proposed study is introduced to have a random number of peaks from 1 to 10 with the BA-BA strategy to determine the optimal BA-CPs that produce the lowest failure rate and shortest convergence time for all these cases. This strategy is called C-ALL and its values of optimal BA-CPs that work with all number of peaks from 1 to 10 are shown in Table 7. The convergence time of the optimal control parameters is shown in Table 8. It is clear from this table that when using the overall optimal control parameters obtained from C-ALL with any number of peaks the convergence time never increased than 1.3 seconds and the

TABLE 6 The convergence time in seconds when used the BA-BA strategies C1-C10 for all number of peaks under study

BA-BA Strategy \ Peaks	1	2	3	4	5	6	7	8	9	10	Average
C_1	0.570	2.490	14.35	2.583	4.15	4.803	15.24	9.603	6.273	7.363	7.742
C_2	3.353	0.725	9.450	1.933	2.408	4.589	13.03	7.692	6.896	5.600	5.567
C_3	8.378	1.935	0.820	2.705	2.280	1.215	10.63	19.82	4.800	5.240	5.782
C_4	6.214	1.170	1.125	0.879	1.380	2.215	11.99	17.99	4.920	5.885	5.376
C_5	5.558	1.430	1.440	1.715	0.909	1.865	12.54	16.89	3.535	4.835	5.072
C_6	5.450	1.945	1.763	2.375	1.943	0.915	10.72	15.19	3.580	4.325	4.820
C_7	3.285	2.007	2.228	1.243	10.05	1.546	0.915	2.444	8.738	2.392	3.485
C_8	1.035	5.660	1.710	10.34	8.715	8.553	2.970	0.917	1.260	15.27	5.643
C_9	0.998	2.020	1.313	2.473	1.688	2.313	1.425	1.105	0.917	15.27	2.952
C_{10}	0.585	1.335	3.105	1.305	1.545	9.503	13.82	16.78	10.33	0.918	5.922
Average	3.542	2.072	3.730	2.755	4.507	3.752	9.326	10.84	5.125	6.710	5.236

TABLE 7 The optimal BA-CPs that work for all number of peaks

Parameters Strategy	Frequency f_{min}	Frequency f_{max}	ω	A_0	r_0	α	γ	SS
C-ALL	0	6.2818	1.611	6.3522	0	1.061	1.4268	11

TABLE 8 The results of using the recommended BA-CPs generated from over all BA-BA strategy shown in Table 5

Peaks	1	2	3	4	5	6	7	8	9	10	Average
C- ALL	1.4758	0.7425	1.2283	1.1275	1.0725	1.4117	0.8983	1.49	0.9442	0.7792	1.117

average convergence time is 1.117 seconds for all number of peaks. These stunning results prove the superiority of the optimal control parameters obtained from the BA-BA algorithm. So, it is recommended for all users of BA in MPPT of PV systems to use the BA-CPs as shown in Table 7 values for optimal performance for all number of peaks. These values are very helpful for the researchers, experts, and designers working in this field to use these values without wasting their time in tedious parameter tuning studies that for sure will not produce the optimal results as the one obtained from the BA-BA strategy for every single peak. The same study can be performed for all applications that need very fast convergence when it is used for online applications. These results encourage the researchers to use the same logic to obtain the optimal control parameters of all swarm optimization techniques for different applications which can open a new gate for many helpful studies in many real-world applications. Figure 9 shows the performance of the overall optimal BA-CPs strategy compared to the strategy obtained for 5 peaks and 10 peaks, C_5 and C_{10}, respectively. The simulation time is 8 seconds, the first 4 seconds is having 5 peaks and the next 4 seconds is having 10 peaks. It is clear from Figure 9, the initialization of the C_5 strategy is having the fastest convergence (about 0.5 second), then the C-ALL optimal BA-CPs (about 1.2 seconds), meanwhile C_{10} is having a longer convergence time (about 4 seconds). The second initialization occurred at $t = 4$ seconds, the number of peaks is 10 peaks, the fastest convergence time is associated with C_{10} (0.6 second), the second one is the C-ALL optimal BA-CPs (0.7 second) and the last one is C_5 (4 seconds). So, it is clear from the results shown in Figure 9 that the BA-BA strategy is fastest when the right strategy is used with its known number of peaks, meanwhile, in real life, the number of peaks is not known and always varied with the shading condition and for this reason, it is better to use the C-ALL optimal BA-CPs strategy shown in Table 7.

5 | EXPERIMENTAL WORK

The experimental work is introduced in this paper to check the performance of MPPT of PV systems by BA when BA-CPs are extracted from the BA-BA strategy and the benchmark BA strategies. For this reason, a testbed system is built to perform the MPPT of the PV system using different BA-CPs obtained from simulation to prove the superiority of the BA-BA strategy compared to the BA benchmark strategies introduced in Table 3.

The proposed experimental setup is shown in Figure 10. The system consists of the following units:

- 10 module shown above in the simulation section
- Boost converter with $L = 0.5$ mH and $C = 200\,\mu$F, with 10 kHz switching frequency and the MOSFET used is STB18NF30[41] with 330 V drain to source voltage, and 18 A current continuous drain. The switch driver used with this switch is MC34152PG.[42]
- 470 μF DC-link capacitor
- 2 kW single-phase inverter

Current Sensors Part number: LTS 25-NP.

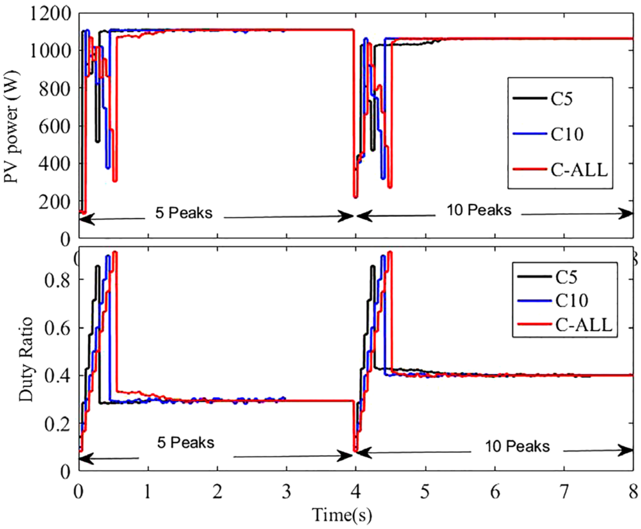


FIGURE 9 The performance of C5, C10, and C-ALL strategies for 5 and 10 peaks operating conditions

FIGURE 10 The picture of the experimental setup

- Voltage sensor, Part number: LV 25-P.
- dSPACE (DS1104 hardware card) and the connector panel of the DS1104.

The results obtained from the simulation results of the BA-BA strategy for the different number of peaks (C_1-C_9 and C-ALL) are used for comparison with the benchmark BA strategies (B_1-B_{10}) in the experimental study which are shown in Table 3. The code of BA MPPT of the PV system is implemented in Matlab, as introduced above. The code generates the duty ratios of the boost converter and sends it to the boost converter through the d-Space and the real real-time interface (RTI) hardware cards. After waiting for the sampling period (0.05 second) the corresponding power will be collected and feedback to the code through the RTI and dSpace. The new values will pass again from the code to the PV system to capture the GP.

Different values of BA-CPs will be fed to the Matlab code to examine the performance of BA MPPT of the PV system. The first study is done using one of the best benchmark BA strategies B_3[26] for one peak and 5 peaks shading conditions as shown in Figure 11. The same operating conditions are used with C_5 and C_1 strategies as sown in Figures 12 and 13, respectively. It is clear from Figure 11 that the B_3[26] benchmark BA strategy took about 5 seconds to capture the GP which means that it spent a long time to capture the GP in 5 peaks and 1 peak operating conditions. Figure 12 shows the operation of 5 peaks operating conditions for the first 10 seconds then from 10 to 20 seconds is showing the uniform distributed irradiance (1 peak) condition with C_5 strategy with BA-CPs shown in Table 2. It is clear from the first period ($t < 10$ seconds) of this figure that, the BA captured the GP less than 1 second when the C_5 strategy is used because this strategy is obtained for the 5 peaks condition. Meanwhile when the number of peaks becomes 1 peak in (10 seconds $< t <$ 20 seconds) it spent about 5 seconds to get the GP. These results show that each strategy is superior just for the number of peaks it built for. The same operating conditions are shown in Figures 11 and 12 is shown in Figure 13 when using the C_1 strategy. It is clear from Figure 13 that when using the C_1 strategy with the 5 peaks condition it spent almost 5 seconds to capture the GP, but once the number of peaks became 1 peak it reinitializes the bats

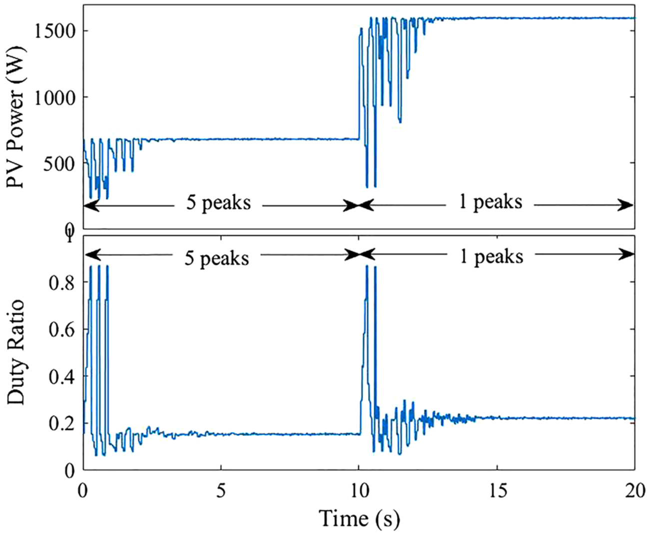


FIGURE 11 The experimental results of using B_3 for 5 peaks and 1 peak

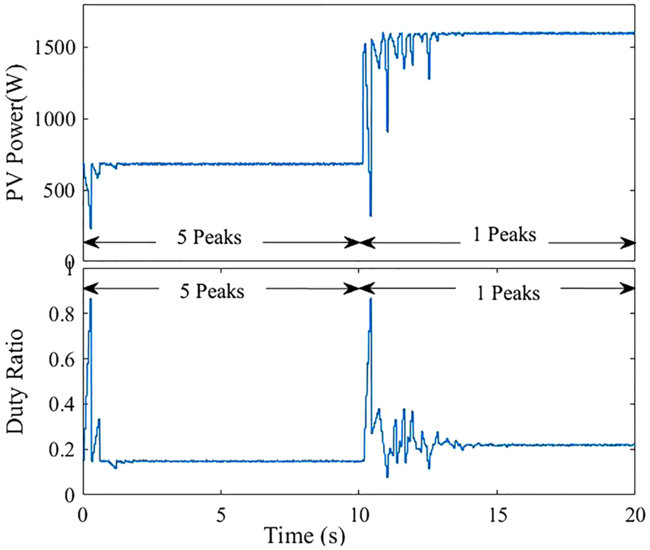


FIGURE 12 The experimental results of using C_5 for 5 peaks and 1 peak

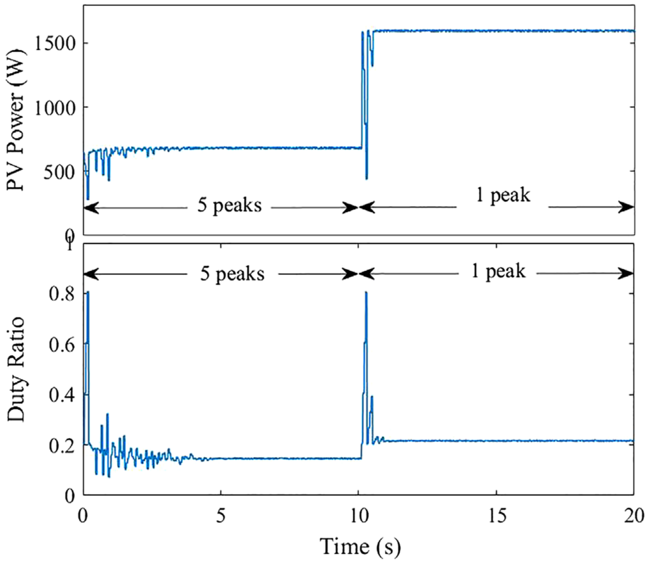


FIGURE 13 The experimental results of using C_1 for 5 peaks and 1 peak

due to acute change in power based on the condition shown in Equation (2) and it captured the GP in less than 1 second because C_1 is the optimal strategy that can work with 1 peak condition.

From the above discussions and the results shown in Figures 12 and 13, it is recommended to use the right BA-BA strategy for the number of peaks condition. In the real world this is not a practical solution because the number of peaks changes with the operating conditions and for this reason, the C-ALL strategy is introduced as shown in the simulation section. Similar operating conditions are shown in Figures 11–13 is used with the BA-CPs introduced in Table 7 for the C-ALL strategy as shown in Figure 13. It is clear from this figure that the convergence time in case of 5 peaks ($t < 10$ seconds) and in one peak condition (10 seconds $< t <$ 20 seconds) that the convergence time is about 1 second in both cases which prove the superiority of C-ALL strategy to have superior performance in different types of shading conditions (Figure 14). To enhance the same idea, the C-ALL strategy is compared to the best benchmark strategy B_3

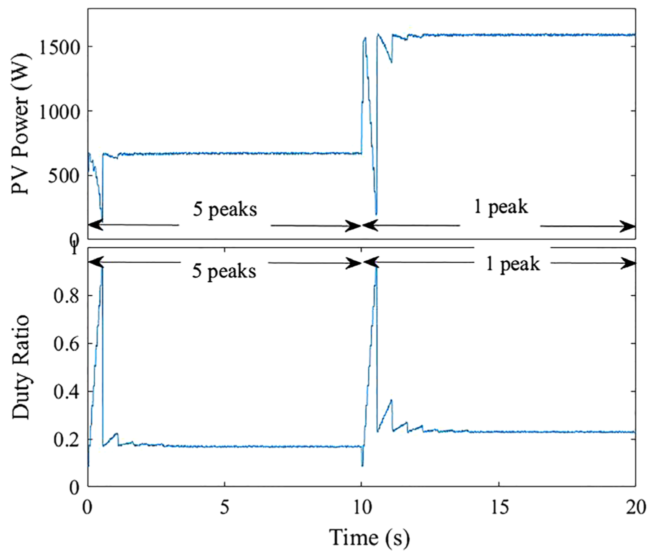


FIGURE 14 The experimental results of using C-ALL for 5 peaks and 1 peak

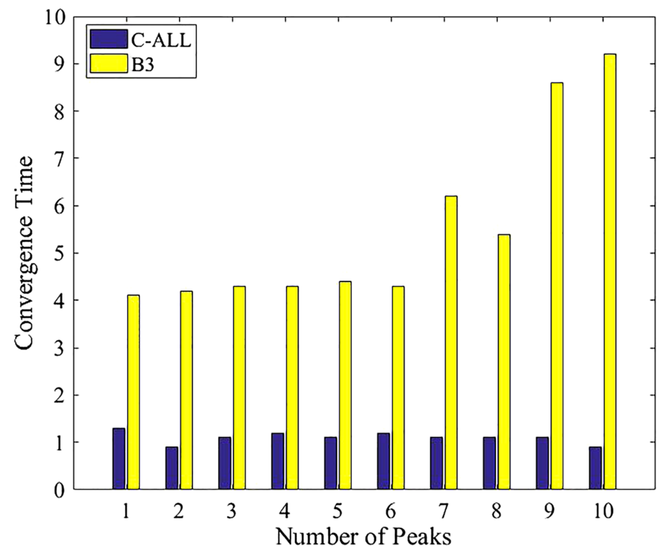


FIGURE 15 The convergence time along with the number of peaks for C-ALL and B_3 strategies

TABLE 9 The convergence time from experimental results for C-ALL from BA-BA strategy compared to the best benchmark strategies B_3[26]

Strategy \ Peaks	1	2	3	4	5	6	7	8	9	10	Average
C-ALL	1.3	0.9	1.1	1.2	1.1	1.2	1.1	1.1	1.1	0.9	1.047
B_3 [28]	4.1	4.2	4.3	4.3	4.4	4.3	6.2	5.4	8.6	9.2	6.034

for all number of peaks from 1 to 10 peaks as shown in Figure 15 and Table 9. It is clear from Figure 15 and Table 9 that, the convergence time is varied from 4 to 9 seconds when B_3 is used, but when C-ALL is used the convergence time is about 1 second, which shows the superior of C-ALL when it is used for all number of peaks.

The comparison between the convergence time associated with BA (C-ALL) and the PSO and the CS algorithm is shown in Figure 16. It is clear from this figure that the convergence times associated with BA (C-ALL) are better than the one associated with the PSO and CS algorithms which prove the superiority of the BA when it gets its parameters from BA-BA strategy proposed in this paper compared to the other swarm optimization techniques.

6 | CONCLUSIONS AND RECOMMENDATIONS

Swarm optimization techniques have been used as an MPPT of the PV system to track the maximum power in case of partial shading. The main drawbacks of these techniques are the long convergence time and the high failure rate. The main reason for these drawbacks is the unwise use of the control parameters of these swarm techniques. Bat algorithm (BA) is one of the fastest swarm techniques and it has been used here in this paper as an MPPT of the PV system. The values of BA control parameters have been collected from 10 benchmark BA strategies to examine the performance of the PV system under different shading conditions. The convergence time is varied between 70 and 3.5 seconds for different benchmark strategies and different shading conditions. These wide variations of convergence time show the importance of BA control parameters and it was the motive of this paper to search for optimal ones. For this reason, the new proposed strategy called BA-BA strategy is introduced to determine the optimal BA control parameters at different shading conditions. This new strategy contains to nested BA loop the inner loop is performing the MPPT function of the PV system for maximum power tracking, meanwhile, the outer BA loop is used to get the optimal control parameters of the inner BA loop for minimum convergence time and failure rate. The first study introduced a special strategy for each number of peaks from 1 to 10 peaks. The convergence time is lower than 1 second which reduced the convergence time 250% lower than the best benchmark strategy. In the real world, the number of peaks is not known and it varies based on the shading condition and for this reason, another strategy is introduced to get optimal BA control parameters that can work with all number of peaks called C-All. In this strategy BA-BA strategy is performed with a random number of peaks in the inner BA loop and the results obtained from the C-ALL strategy is examined in simulation and experimental work and it shows a great improvement of convergence time for all number of peaks and it is recommended for all users of BA in the MPPT of PV systems applications. This reduction in the convergence time will open a new opportunity to use BA or any other swarm optimization technique as an MPPT for the PV system in case of fast shading condition changes. The results obtained from the BA-BA strategy are compared to the PSO and CS algorithm and a substantial reduction in convergence time from BA-BA strategy compared to the PS and CS proved the superiority of the BA-BA algorithm when used as an MPPT of the PV systems.

This new proposed BA-BA strategy encourages the other researchers to introduce similar studies for other swarm optimization techniques when used as an MPPT of PV systems to improve their performance in this application.

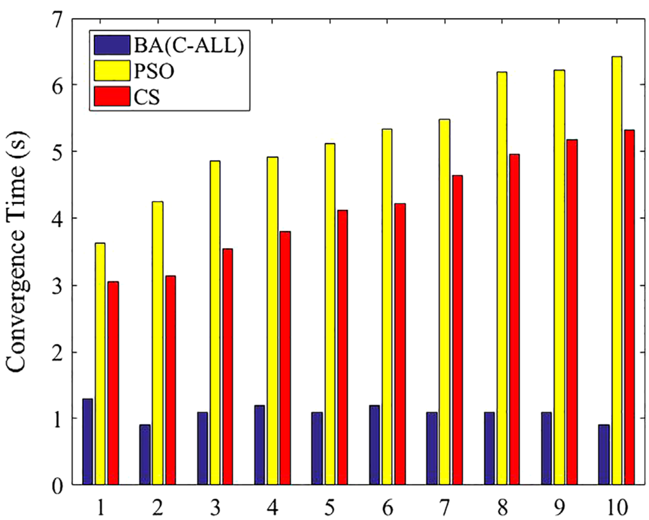


FIGURE 16 The experimental results of convergence time for BA, PSO, and CS along with number of peaks

Moreover, the superior results obtained from this strategy encourage new research to get similar optimal control parameters for different swarm optimization techniques for different applications.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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