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Developing and Applying Chaotic Harris Hawks Optimization Technique for Extracting Parameters of Several Proton Exchange Membrane Fuel Cell Stacks

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ABSTRACT In this paper, an efficient optimization technique called Chaotic Harris Hawks optimization (CHHO) is proposed and applied for estimating the accurate operating parameters of proton exchange membrane fuel cell (PEMFC), which simulate and mimic its electrical performance. The conventional Harris Hawks optimization (HHO) is a recent optimization technique that is based on the hunting approach of Harris hawks. In this proposed optimization technique, ten chaotic functions are applied for tackling with the studied optimization problem. The CHHO is proposed to enhance the search capability of conventional HHO and avoid its trapping into local optima. The sum of squared errors (SSE) between the experimentally measured output voltage and the corresponding simulated ones is adopted as the objective function. The developed CHHO technique is tested on four various commercial PEMFC stacks to assess and validate its effectiveness compared with other well-known optimization techniques. A statistical study is performed to appreciate the stability and reliability of the proposed CHHO technique. However, the results show the effectiveness and superiority of proposed CHHO compared with the conventional HHO and other competitive metaheuristic optimization algorithms under the same study cases.

INDEX TERMS Proton exchange membrane fuel cell, parameter estimation, Harris Hawks optimization, sum of squared errors.

I. INTRODUCTION

With the continuous increase in the electric energy demand and the shortage in the reserves of fossil fuels, the need for a clean source of energy becomes necessary not only for small power applications but also in large industrial applications. Besides the most popular renewable energy sources (solar and wind), fuel cells are used in many applications and developed very fast to be a good competitor with these energy resources. In the past decades, fuel cells have attracted the attention of many researchers and manufacturers. Fuel cells directly convert the chemical energy obtained from the chemical reactions between hydrogen and oxygen or natural air in the presence of a catalyst into electrical energy [1]–[6]. Based on the electrolyte type, there are many types of fuel cells. Among these cells, the proton exchange membrane fuel cell (PEMFC) is the most common type [5]. PEMFC received high attention from researchers thanks to its high-power density under low temperature of operation and its fast response against electrodynamic processes [7], [8].

Due to the importance of PEMFC and its advances in industrial applications and reduction of cost, there is a need to build an accurate model for a good understanding of the dynamic processes and phenomenon occurred in the fuel cell without the need for complicated experiments to save effort and time [7]. In the last years, many papers tried to model the

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operation of PEMFC, and many models have been provided in literature [7], [8]. One of the essential characteristics of the fuel cell is its polarization curve, which explains the relation between the cell current and the output voltage (*I-V* curve) because the operating points and other auxiliary devices such as air conditioning and controllers mainly related to these curves.

The main difficulty that faces researchers when performing a mathematical model for studying the operation of a certain PEMFC and its polarization curves is a large number of unknown design parameters which have to be accurately determined. Usually, the information given in the datasheet of any PEMFC is not enough to determine the best values of these parameters. Therefore, if the accurate parameters are not determined, there is large deviations between the data received based on the model and that reported in the datasheet of the manufacturer [7]. Accordingly, the determination of unknown parameters of PEMFC can be addressed as an optimization problem and different algorithms can be utilized to find the optimum solution to this problem. Due to the high nonlinearity of polarization curves of PEMFC, the conventional optimization techniques will result in a poor matching with the measured data introduced by the manufacturer. To overcome the shortage of conventional optimization techniques, metaheuristics are recommended for such problems as they are derivative-free methods and their operation makes stochastic movements to find the global optimum solution. Over the past ten years, several metaheuristic optimization algorithms have been applied to address the problem of parameters' estimation of PEMFC. Particularly, Hybrid Genetic algorithm (HGA) has been proposed for modeling the parameters estimation in [9]. Particle swarm optimization (PSO) technique [10], simulated Annealing [11], [12], Artificial Immune System (AIS) [13], Hybrid Artificial bee colony (HABC) [14], Hybrid Adaptive Differential Evaluation (HADE) [15], Seeker Optimization Algorithm (SOA) [16], Artificial Bee Swarm Algorithm (ABSA) [17], the multi-verse optimizer (MVO) [1], the adaptive RNA genetic algorithm (ARNA-GA) [2], Eagle strategy based on JAYA algorithm and Nelder-Mead simplex method (JAYA-NM) [3], hybrid Teaching Learning Based Optimization–Differential Evolution algorithm (TLBODE) [4], shark smell optimizer (SSO) [5], Cuckoo search algorithm with explosion operator (CS-EO) [6], selective hybrid stochastic strategy [7], bird mating optimizer (BMO) [8], grasshopper optimizer (GHO) [9], Gray wolf optimizer (GWO) [10], have been utilized for solving the optimization problem of different PEMFC stacks depending on different number of unknown parameters.

Recently, the performance of different metaheuristic optimization techniques, namely, GWO, GA, Butterfly Optimization Algorithm (BOA), Harmony Search (HS), Krill-Herd Algorithm (KHA), Artificial Bee Colony (ABC) and Firefly Algorithm (FA), has been improved based on theory of chaotic [18], [19]. Replacing the random initial variables of optimization technique with the chaotic variables is the main principle operation of chaotic theory [18].

In this paper, novel CHHO techniques based on ten chaotic functions are proposed and applied for extracting the optimal values of the unknown parameters of different PEMFC stacks. However, the main contribution of this paper could be summarized in the following points:

- An accurate mathematical model is proposed for simulating the phenomenon occurred in the PEMFC stacks;
- Studying the impact of changing the operating conditions such as the cell temperature and the pressures of reactants (hydrogen and oxygen) at the inlet channels on the performance of fuel cells;
- Ten chaotic functions are applied to develop CHHO techniques and the best technique is determined based on a comprehensive comparison among them;
- Four different commercial PEMFC stacks are used to validate the proposed CHHO;
- The results obtained by the proposed CHHO are compared with those obtained by the conventional HHO and other recent optimization techniques dealing with the same PEMFC stacks.
- Parametric and non-parametric statistical analysis are performed to show the effectiveness of proposed CHHO compared with the conventional HHO [20] and other well-known optimization techniques.
- The obtained results prove the effectiveness and superiority of proposed CHHO in extracting the optimal parameters of PEMFC stacks.

The rest of this work is subdivided as follows. A simple mathematical formulation of PEMFC as well as the objective function are introduced in Section II. The proposed CHHO techniques and conventional HHO techniques are reported in Section III. The obtained results as well as the performance under various operating scenarios are presented and analyzed in Section IV. Finally, the conclusions are presented in Section V.

II. DESCRIBTION OF PEMFC MODEL

A. BASIC CONCEPT OF PEMFC

The construction of PEMFC includes two electrodes, namely, the anode and the cathode, as well as a proton-conducting membrane as the polymer electrolyte sandwiched between the two electrodes which can pass protons and prevent electrons [11]. Furthermore, a catalyst layers plugged between the electrolyte membrane and two electrodes to accelerate the chemical reaction. The schematic construction of PEMFC is shown in Fig. 1. The hydrogen gas is fed to anode electrode, once the hydrogen gas reaches the catalytic layer of anode electrode, it splits into electrons and protons. Then, the protons diffuse through the electrolyte membrane to the catalytic layer of cathode electrode while the electrons are passed through the external load. The oxygen/air gas is applied to cathode and when it reaches the catalytic layer of cathode electrode, it combines with the protons coming through the solid membrane and electrons transferred through the external load to produce water.

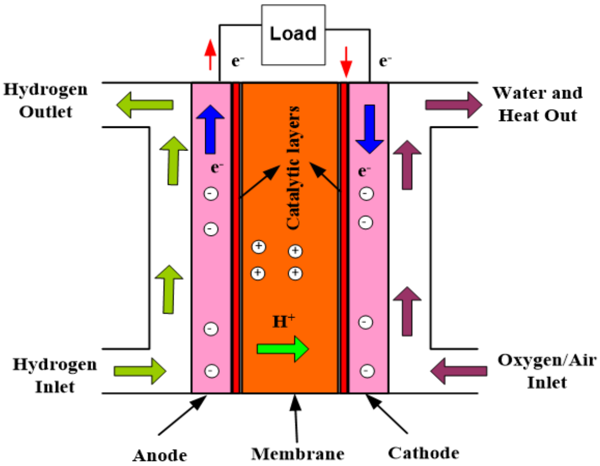

FIGURE 1. Schematic construction of fuel cell.

The electrochemical reactions that happens at electrodes sides of PEMFC given as [11]:

Anode side:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

Cathode side:

$$2H^+ + \frac{1}{2}O_2 \rightarrow H_2O \quad (2)$$

Total chemical reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Energy + Heat \quad (3)$$

The energy mentioned in (3) is the electrical energy produced due to the flow of electrons of hydrogen gas from the anode electrode to the cathode electrode through an external load.

B. MATHEMATICAL MODEL OF PEMFC STACKS

The terminal voltage of each single fuel cell V_{cell} can be calculated using the following formula [12]–[14]:

$$V_{cell} = E_{O.C} - \Delta V_{act} - \Delta V_{ohm} - \Delta V_{con} \quad (4)$$

where, $E_{o.c}$ represents the open-circuit voltage of cell, ΔV_{act} is the activation overpotential per cell, ΔV_{ohm} is ohmic resistive voltage drop per cell due to the resistance of electrons conduction through the externally connected load and the resistance which the protons face through their motion in the electrolyte membrane as well ΔV_{con} is the concentration overpotential per cell. Amphlett et al. [13], have adopted a fuel cell's electrochemical model. When the number of cells N_{cells} of identical fuel cells are connected in series to get a high value of voltage, the total output voltage of stack calculated as:

$$V_{stack} = N_{cells}.V_{cell} \quad (5)$$

where, N_{cells} represents the number of cells connected in series, and V_{cell} is the output voltage of each single fuel cell, which calculated using (4).

$E_{o.c}$ is called reversible potential which given using (6) [15], [16].

$$E_{O.C} = 1.229 - 8.5 \times 10^{-4}\left(T_{fc} - 298.15\right) + 4.3085\times 10^{-5} T_{fc} \times \left[\ln\left(P_{H_2}\right) + \ln\left(\sqrt{P_{O_2}}\right)\right] \quad (6)$$

where, T_{fc} denotes the operating absolute temperature of cell in Kelvin; P_{H2} and P_{O2} are the partial pressures of hydrogen and oxygen at the input channels of the fuel cell stack (atm), respectively. when the inputs to the PEMFC stack are hydrogen and natural air during its operation, the partial pressure of oxygen P_{O2} can be calculated as follows [17], [18]:

$$P_{O_2} = P_c - RH_c P^{sat}_{H_2O} - \frac{0.79}{0.21} P_{O_2} \times \exp\left(\frac{0.291\left(I_{fc}/A\right)}{T_{fc}^{0.832}}\right) \quad (7)$$

where, P_c denotes the inlet channel pressure at the cathode electrode (atm), RH_c is the relative humidity in the cathode electrode, I_{fc} is the operating current of cell (A), A is the area of membrane surface (cm^2), $P^{sat}_{H_2O}$ is the water vapor pressure at saturation, which is defined as [21]:

$$\log_{10}\left(P^{sat}_{H_2O}\right) = 2.95 \times 10^{-2}\left(T_{fc} - 273.15\right) - 9.18 \times 10^{-5}\left(T_{fc} - 273.15\right)^2 + 1.44 \times 10^{-7}\left(T_{fc} - 273.15\right)^3 - 2.18 \quad (8)$$

When the inputs of fuel cell stack are hydrogen and pure oxygen, the partial pressure of oxygen. P_{O2} will be calculated as follows [21]:

$$P_{O_2} = RH_c P^{sat}_{H_2O} \times \left[\left(\exp\left(\frac{4.192\left(I_{fc}/A\right)}{T_{fc}^{1.334}}\right) \times \frac{RH_c P^{sat}_{H_2O}}{P_a}\right)^{-1} - 1\right] \quad (9)$$

In both previously mentioned conditions, the partial pressure of hydrogen P_{H2} is calculated as [17]:

$$P_{H_2} = 0.5 RH_a P^{sat}_{H_2O} \times \left[\left(\exp\left(\frac{1.635\left(I_{fc}/A\right)}{T_{fc}^{1.334}}\right) \times \frac{RH_a P^{sat}_{H_2O}}{P_a}\right)^{-1} - 1\right] \quad (10)$$

where, P_a represents the input channel pressure at the anode electrode (atm), RH_a denotes the relative humidity of water vapor in the side of the anode.

The voltage drop resulting from the activation process ΔV_{act} around the anode and cathode electrodes can be mathematically calculated according to the following expression [13], [15]:

$$\Delta V_{act} = -\left[\xi_1 + \xi_2 T_{fc} + \xi_3 T_{fc} \ln\left(C_{O_2}\right) + \xi_4 T_{fc} \ln\left(I_{fc}\right)\right] \quad (11)$$

where, ξ_1, ξ_2, ξ_3, ξ_4 are semi-empirical coefficients; C_{O2} represents the oxygen concentration at the cathode in (mol.cm^{-3}), which can be expressed as below [13], [17]:

$$C_{O_2} = \frac{P_{O_2}}{5.08 \times 10^6 \times \exp^{-\left(498/T_{fc}\right)}} \tag{12}$$

The ohmic resistive voltage drop loss ΔV_{ohm} that occurs in the fuel cell is determined as follows:

$$\Delta V_{ohm} = I_{fc} \left(R_M + R_C\right) \tag{13}$$

where, R_M denotes the resistance of membrane surface in ohm (Ω), R_C denotes the equivalent resistance of the connection which the protons face during passing through the membrane. The membrane resistance can be expressed as follows:

$$R_M = \frac{\rho_M . l}{A} \tag{14}$$

where, ρ_M denotes the specific membrane resistance for the flow of electron (Ωcm), l is the membrane thickness (cm). the empirical formula for ρ_M can be expressed as follows [15]:

$$\rho_M = \frac{181.6\left[1+0.03\left(\frac{I_{fc}}{A}\right)+0.062\left(\frac{T_{fc}}{303}\right)^2\left(\frac{I_{fc}}{A}\right)^{2.5}\right]}{\left[\lambda-0.634-3\left(\frac{I_{fc}}{A}\right)\right]\times\exp\left[4.18\left(\frac{T_{fc}-303}{T_{fc}}\right)\right]} \tag{15}$$

where, λ is an adjustable empirical parameter that related to the steps of membrane preparation and needs to be estimated. The concentration voltage drop is the last type of voltage losses occurs in the fuel cell due to concentration and the mass transfer, which can be calculated as follows [12]:

$$\Delta V_{con} = -b \ln\left(1 - \frac{J}{J_{\max}}\right) \tag{16}$$

where, b is a parametric coefficient (V); J and J_{max} are the current density and the maximum current density (A/cm^2), respectively.

Based on the previous mentioned equations, the mathematical model of PEM fuel cell can be demonstrated. It clearly noticed that there are seven parameters for the PEMFC are not mentioned in the manufacturer's datasheet. Thus, in order to provide an accurate modelling of PEMFCs under simulation and control, precise estimation of these parameters is very important. Especially, the model of PEMFC has seven unknown parameters such as $\zeta_1, \zeta_2, \zeta_3, \zeta_4, \lambda, R_C$, and b. These seven parameters are optimized to have the best values within their minimum and maximum bounds using the proposed CHHO optimization technique.

C. OBJECTIVE FUNCTION

From the mentioned previous equations, it is clearly noticed that the fundamental operation of PEMFC basically depends on seven unknown variable parameters. To match well between the model outputs and the experimentally measured data of PEMFC, this paper aims to solve this optimization problem by developing CHHO technique. However, the sum of squared errors (SSE) between the experimentally measured voltage of PEMFC and the calculated stack output voltage is defined as the objective function (OF) [4]–[6], [9], [10].

$$OF = MinSSE(x) = Min\left(\sum_{i=1}^{N}\left[v_{meas}(i) - v_{cal}(i)\right]^2\right) \tag{17}$$

where, X is a vector of unknown parameters, N represents the number of measured data, i denotes an iteration counter, v_{meas} defines the experimentally measured voltage of PEMFC and v_{cal} represents the estimated PEMFC voltage, according to the following inequality operating constraints:

$$\begin{aligned} \xi_{i,\min} &\le \xi_i \le \xi_{i,\max},\ i = 1:4 \\ R_{C\min} &\le R_C \le R_{C\max} \\ \lambda_{\min} &\le \lambda \le \lambda_{\max} \\ b_{\min} &\le b \le b_{\max} \end{aligned} \tag{18}$$

where, $\zeta_{i,min}$ and $\zeta_{i,max}$ are the lower and upper limits of empirical coefficients,R_{Cmin} and R_{Cmax} express the lower and upper values of cell connections resistance, λ_{min}, and λ_{max} are the lower and upper ranges of water content, as well as, b_{min} and b_{max} are the minimum and maximum limits of parametric coefficient.

III. OPTIMIZATION TECHNIQUES

In this section, the conventional HHO and proposed CHHO techniques based on ten chaotic functions are explained.

A. HHO

This subsection introduces the mathematical formulation of HHO based on the hunting approach of Harris hawks [20]. As any population-based optimization technique, HHO has been formulated using exploration and exploitation phases.

1) EXPLORATION PHASE

Harris hawks use two strategies to detect the prey which is usually a rabbit. The first strategy assumes that the hawks allocate close to the family members and the prey. In the second strategy, the hawks place on random trees. These two strategies can be modeled mathematically using (19):

$$X(t+1) = \begin{cases} X_{rand}(t) - r_1\left|X_{rand}(t) - 2r_2X(t)\right| & q \ge 0.5 \\ \left(X_{rab}(t) - X_m(t)\right) - r_3\left(LB + r_4\left(UB - LB\right)\right) & q < 0.5 \end{cases} \tag{19}$$

where, $X(t)$ and $X(t+1)$ are the hawk's positions at the current iteration t and the next iteration $t+1$, respectively. $X_{rab}(t)$ is the rabbit position, $X_{rand}(t)$ is a random hawks position, r_1, r_2, r_3, and r_4 are randomly generated number between [0,1], LB and UB are the lower and upper limits of control variables, q is a random number between [0,1], which used to switch between the two exploration strategies, and $X_m(t)$ is the average position of hawks which calculated as:

$$X_m(t) = \frac{1}{n}\sum_{i=1}^{n} X_i(t) \tag{20}$$

where, $X_i(t)$ is the position of each hawk i within the total number of hawks n.

2) TRANSITION FROM EXPLORATION TO EXPLOITATION

The change from the exploration to exploitation in the HHO can be modeled based on the rabbit escaping energy as follows:

$$E = 2 \times E_0 \left(1 - \frac{t}{T}\right) \tag{21}$$

where, E is the rabbit escaping energy during the chasing period which is represented in the HHO by the maximum iteration numbers T and E_0 is the initial energy of the rabbit which is generated randomly between [−1,1]. Hence, if $E \geq 1$, this means the rabbit has enough energy to escape, so the hawks should continue exploring the rabbit location, and if $E < 1$, this means the rabbit is weak, hence the hawks should exploit close to the rabbit location.

3) EXPLOITATION PHASE

The exploitation process of HHO has been modeled based on the escaping energy of rabbit E and its chance for escaping r. The chance of escaping could be successful when $r < 0.5$, and unsuccessful when $r \geq 0.5$. On the other hand, the hawks will make a hard or soft besiege based on the escaping energy of rabbit E, hence when $|E| \geq 0.5$, the hawks will do a soft besiege, and when $|E| < 0.5$, the hawks will perform a hard besiege. According to the previous conditions, there are four chasings besiege in the exploitation phase of HHO.

a: SOFT BESIEGE

The soft besiege occurs when $r \geq 0.5$ and $|E| \geq 0.5$, where the rabbit tries to escape using random jumps, but the hawks surround it softly. This process can be expressed as:

$$X(t+1) = \Delta X(t) - E\left|J \times X_{rab}(t) - X(t)\right| \tag{22}$$

$$J = 2(1 - r_5) \tag{23}$$

$$\Delta X(t) = X_{rab}(t) - X(t) \tag{24}$$

where, $\Delta X(t)$ indicates the distance between the rabbit location and the hawks' position, J is the random jump of the rabbit during the escaping, r_5 is a random number between [0,1].

b: HARD BESIEGE

The hard besiege happens when $r \geq 0.5$ and $|E| < 0.5$, where the rabbit is so tired, and the hawks hardly surround the prey. This move can be modeled as:

$$X(t+1) = X_{rab}(t) - E\left|\Delta X(t)\right| \tag{25}$$

c: SOFT BESIEGE WITH PROGRESSIVE RABID DIVES

This is an intelligence besiege happens when $r < 0.5$ and $|E| \geq 0.5$, where the rabbit able to escape and the hawks softly surround it. To model this besiege, a Levy flight (LF) concept is used as follows:

$$Y = X_{rab}(t) - E\left|J \times X_{rab}(t) - X(t)\right| \tag{26}$$

where, Y is the soft besiege positions. The hawks dive based on the LF as:

$$Z = Y + S \times LF(D) \tag{27}$$

where, D is the dimension of problem, S is a vector of random values with size $1 \times D$. The LF is calculated as:

$$LF(x) = 0.01 \times \frac{\mu \times \sigma}{|\nu|^{\frac{1}{\beta}}} \tag{28}$$

$$\sigma = \left(\frac{\Gamma(1+\beta) \times \sin\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right) \times \beta \times 2^{\left(\frac{\beta-1}{2}\right)}}\right)^{\frac{1}{\beta}} \tag{29}$$

where, β is a constant value set to 1.5, μ, and υ are random values between [0,1].

Finally, the updating position of hawks is calculated as:

$$X(t+1) = \begin{cases} Y & F(Y) < F(X(t)) \\ Z & F(Z) < F(X(t)) \end{cases} \tag{30}$$

d: HARD BESIEGE WITH PROGRESSIVE RABID DIVES

When $r < 0.5$ and $|E| < 0.5$, the rabbit is weak, and the hawks hardly surround it. Similar, Levy flight (LF) concept is utilized to express this besiege as in (9) to (13), but Y is calculated using (31).

$$Y = X_{rab}(t) - E\left|J \times X_{rab}(t) - X_m(t)\right| \tag{31}$$

B. PROPOSED CHHO TECHNIQUES

In the section, the proposed CHHO techniques based on chaos theory are presented. Chaos maps have been used to predict unpredictable actions by formulating a set of chaotic equations [20]. For optimization techniques, chaotic maps are used to improve their convergence characteristics by applying the chaotic equation instead of utilizing random parameters. In this work, ten chaotic maps presented in Table 1 are applied for the conventional HHO to update the exploration parameter q instead of using random probability as follows:

$$q = y_{k+1} \tag{32}$$

where, y_{k+1} is the selected chaos map as presented in Table 1. The overall steps of CHHO are exhibited in the flowchart shown in Fig. 2.

IV. SIMULATION RESULTS AND DISCUSSION

The conventional HHO and proposed CHHO techniques have programmed by MATLAB (R2018a) using personal Intel Core i3-M370 CPU@2.40GHz with 4.00MB RAM Laptop. The optimal estimated parameters obtained by the proposed CHHO techniques have been validated using measured data of a commercial PEMFC stack provided in literature. The proposed CHHO with ten different chaotic functions introduced in the previous section have been validated via several operating scenarios. In this study, the following control variables have been adopted: the maximum number of iterations equals 500 iterations and the number of search agents equals

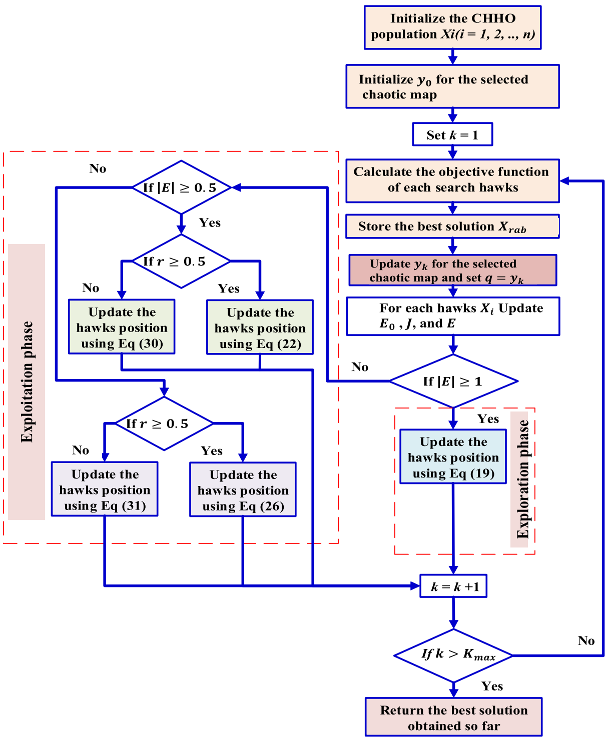

FIGURE 2. Flowchart of proposed CHHO techniques.

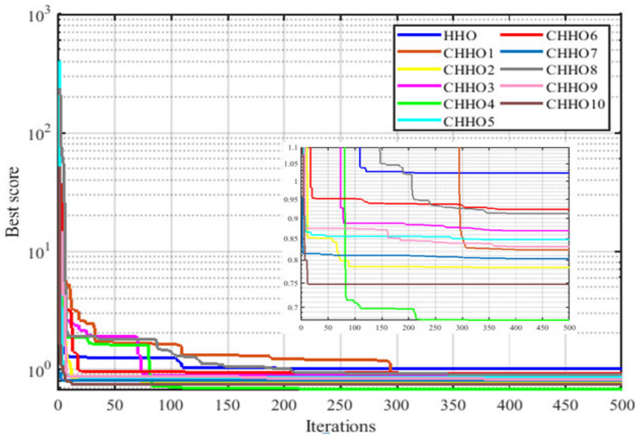

FIGURE 3. Convergence characteristics of CHHO and HHO.

30 search agents. In order to overcome the randomness of proposed optimization technique and examine the goodness of different chaotic functions, 50 independent executions have been carried out under each chaotic function as well as the conventional HHO and the best solution is taken as the minimum value of fitness function over the 50 runs. The results are carried out based on the measured data of the polarization curve of four different commercial fuel cell stacks, namely 250 W PEMFC stack, BCS-500W PEMFC, SR-12 500W PEMFC, and Temasek 1kW PEMFC which have the specifications provided in Table 2. The measured data of these fuel cell stacks [4], [5], are used as the input data for the optimization algorithm. Table 3 presents the search limits of the unknown parameters of PEMFC stacks.

TABLE 1. Chaotic maps.

No.	Name	Chaotic map formula
1	Chebyshev	$y_{k+1} = \cos\left(k \cos^{-1}\left(y_k\right)\right)$
2	Circle	$y_{k+1} = \operatorname{mod}\left(y_k + b_1 - \left(\frac{b_2}{2\pi}\right)\sin\left(2\pi y_k\right), 1\right)$ $b_1 = 0.5, b_2 = 0.2$
3	Gauss/mouse	$y_{k+1} = \begin{cases} 1 & y_k = 0 \\ \frac{1}{\operatorname{mod}\left(y_k\right)} & otherwise \end{cases}$
4	Iterative	$y_{k+1} = \sin\left(\frac{b\pi}{y_k}\right), b = 0.7$
5	Logistic	$y_{k+1} = by_k\left(1 - y_k\right), b = 4$
6	Piecewise	$y_{k+1} = \begin{cases} \frac{y_k}{H} & 0 \le y_k \le H \\ \frac{y_k - H}{0.5 - H} & H \le y_k \le 0.5 \\ \frac{1 - H - y_k}{0.5 - H} & 0.5 \le y_k \le 1 - H \\ \frac{1 - y_k}{H} & 1 - H \le y_k \le 1 \end{cases}, H = 0.4$
7	Sine	$y_{k+1} = \frac{b}{4}\sin\left(\pi y_k\right), b = 4$
8	Singer	$y_{k+1} = u\left(\begin{array}{l} 7.86 y_k^{1} - 23.31 y_k^{12} \\ -28.75 y_k^{3} - 13.302875 y_k^{4} \end{array}\right), u = 1.07$
9	Sinusoidal	$y_{k+1} = by_k^{1}\sin\left(\pi y_k\right), b = 2.3$
10	Tent	$y_{k+1} = \begin{cases} \frac{y_k}{0.7} & y_k < 0.7 \\ \frac{10}{3}\left(1 - y_k\right) & y_k \ge 0.7 \end{cases}$

A. CASE 1: ESTIMATION OF PEMFC PARAMETERS

To validate the robustness of proposed CHHO for the parameters identification of PEMFC stacks, a statistical analysis of the minimum values of fitness function (SSE) over 50 individual runs is presented. This analysis is demonstrated to give a clear assessment of ten chaotic functions and select the most accurate one. The comparisons between the CHHO based on different chaotic functions as well as the conventional HHO are carried out with respect to many metrics, mainly the best and worst values of SSE, mean value of SSE, Median, standard deviation (SD), relative error (RE), Root mean square error (RMSE), Mean absolute error (MAE) and efficiency. The mathematical expressions of these metrics are

TABLE 2. The considered specifications of PEMFC stacks.

PEMFC type	250 W stack	BCS 500W	SR-12 PEM 500W	Temasek 1kW
N (cells)	24	32	48	20
A (cm^2)	27	64	62.5	150
l (μm)	127	178	25	51
J_{max} (mA/cm^2)	860	469	672	1500
P_{H2} (atm)	1	1	1.47628	0.5
P_{o2} (atm)	1	0.2095	0.2095	0.5
T(K)	343.15	333	323	323

TABLE 3. The search limits of the unknown parameters.

Parameter	Min. value	Max. value
ξ_1	-1.1997	-0.8532
ξ_2	0.0008	0.006
ξ_3	3.6×10^{-5}	9.8×10^{-5}
ξ_4	-2.6×10^{-4}	-9.54×10^{-5}
λ	10	23
R_c	0.0001	0.0008
b	0..0136	0.5

presented in (33) to (37):

$$SD = \sqrt{\frac{\sum_{i=1}^{50}\left(SSE_i - \overline{SSE}\right)}{50-1}} \tag{33}$$

$$RE = \frac{\sum_{i=1}^{50}\left(SSE_i - SSE_{\min}\right)}{SSE_{\min}} \tag{34}$$

$$MAE = \frac{\sum_{i=1}^{50}\left(SSE_i - SSE_{\min}\right)}{50} \tag{35}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{50}\left(SSE_i - SSE_{\min}\right)^2}{50}} \tag{36}$$

$$efficiency = \frac{SSE_{\min}}{SSE_i} \times 100\% \tag{37}$$

where, SSE_i is the value of objective function obtained at the end of each run. SSE_{min} represents the minimum best value of SSE overall. $\overline{SSE}$ represents the mean value of SSE over the 50 launches of optimization process. The statistical results of proposed CHHO based on ten chaotic functions and HHO have been listed in Table 4. From this table, it can be observed that the smaller values of MAE and RMSE proved a well matching between the estimated and the measured parameters. The values of minimum SSE obtained by using 4th chaotic function is the best within all functions as well as the conventional HHO algorithm.

The optimized parameters of PEMFC model using ten chaotic functions are provided in Table 5. The results obtained from the proposed CHHO are compared with those obtained from HHO and other recent optimization techniques reported in literature (see Table 5).

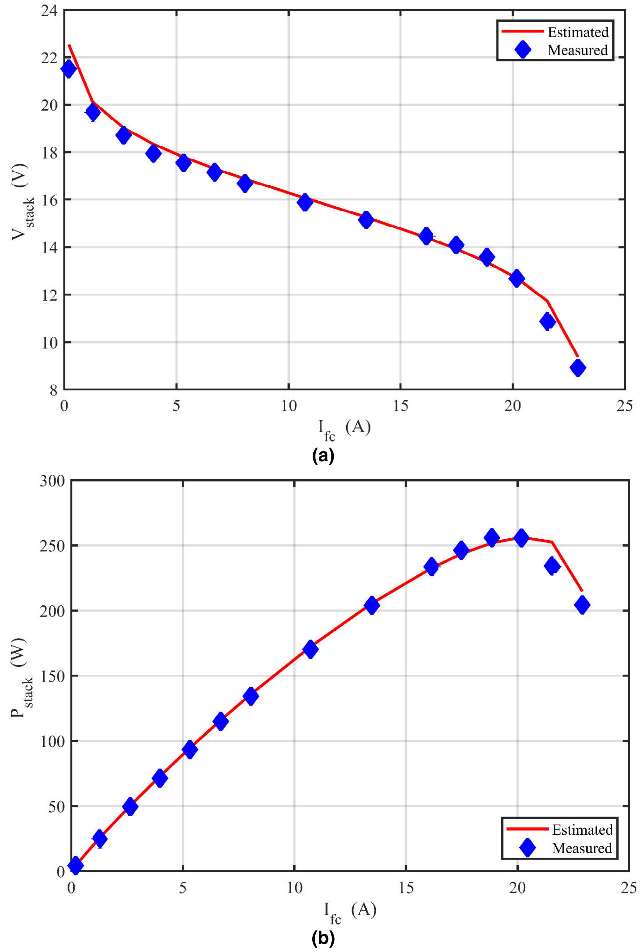

FIGURE 4. Polarization characteristics of 250W PEMFC using CHHO based on the 4th chaotic function: (a) I-V curve, (b) I-P curve.

From this table, it is clearly noticed that the CHHO based on the 4th chaotic function (CHHO4) gives the minimum value of objective function (**0.674734884**) within all ten chaotic functions and other optimization techniques included in the comparison.

Accordingly, it is recommended to complete the simulation results based on the 4th chaotic function. The convergence characteristics of proposed CHHO techniques as well as the conventional HHO are shown in Fig. 3. The current-voltage (*I-V*) and current-power (*I-P)* polarization curves obtained by CHHO based on the 4th chaotic function compared with the experimentally measured data of 250W PEMFC stack are shown in Fig. 4*a-b*. From this figure, it can be observed that the computed polarization curves give a good agreement with the measured ones.

For more validation, the values of output voltage of PEMFC stack are compared with the corresponding measured one. The deviation between the estimated and measured data is evaluated by Individual Absolute Error (IAE) and Relative Error (RE) at each point of 15 data set. IAE and RE are mathematically calculated as given in (38) and (39), respectively. The calculated values of IAE and RE for the

TABLE 4. Statistical results of proposed CHHO compared with HHO and other recent methods for 250W PEMFC stack.

	Min	Max	Mean	Median	SD	RE	MAE	RMSE	Eff.
HHO	1.0227417	7.5612184	3.09433	1.9853482	206.80887	101.27622	2.0715883	2.9125468	45.381986
CHHO1	0.8234558	7.6402774	2.7376142	1.9421519	195.50701	116.22715	1.9141584	2.722105	41.719011
CHHO2	0.783442	7.6909196	2.8163307	1.9147513	213.29039	129.740858	2.0328887	2.9310288	40.824325
CHHO3	0.8686641	7.6040783	2.2696146	1.8428295	162.08809	80.638218	1.4009505	2.1301108	52.139509
CHHO4	0.6747349	10.337483	3.2981139	1.9322172	278.52156	194.40073	2.6233791	3.805837	35.241988
CHHO5	0.8477186	14.315273	3.5217301	1.9834018	338.51105	157.71811	2.6740115	4.2872056	40.640499
CHHO6	0.9228727	12.219179	3.3312623	2.0328524	259.3216	130.48331	2.4083896	3.5200304	40.675315
CHHO7	0.8035373	13.808912	2.7500121	1.8301066	248.00278	121.11913	1.9464748	3.1330961	44.45538
CHHO8	0.9122845	8.5530444	2.7172468	1.9528559	181.42461	98.925396	1.8049622	2.5462811	44.635729
CHHO9	0.8313804	15.698162	3.2972212	1.9917325	321.06195	148.29799	2.4658408	4.0227213	40.451848
CHHO10	0.7471126	12.156614	2.7743369	1.9056914	249.480195	135.670599	2.0272243	3.19518302	40.4864263

TABLE 5. Estimated parameters for 250W PEMFC stack using CHHO, HHO and other well-known optimization techniques.

	ξ_1	$\xi_2\times10^{-3}$	$\xi_3\times10^{-5}$	$\xi_4\times10^{-4}$	λ	b	$R_c\times10^{-4}$	SSE
CHHO1	-0.853990	2.41733037	5.46171532	-1.4245274	20.12083388	0.056695672	1.25432921	0.82345577
CHHO2	-1.017456	3.06348013	6.57312507	-1.3999476	22.34502578	0.057124896	1.89406215	0.78344198
CHHO3	-1.004724	2.54778708	3.67775929	-1.4166051	20.59107898	0.051198234	3.48094008	0.86866408
CHHO4	**-0.910176**	**2.96613751**	**7.78812841**	**-1.5238906**	**22.23690101**	**0.053665171**	**1.93212368**	**0.67473488**
CHHO5	-0.987716	3.54248583	9.79077192	-1.6124169	22.98544117	0.049506589	7.55546093	0.84771859
CHHO6	-0.853230	2.33780458	5.01901632	-1.3473694	17.47789646	0.052155949	3.60375395	0.92287265
CHHO7	-0.958829	2.67652872	5.03006123	-1.6482750	22.64253349	0.050862228	4.29017602	0.80353731
CHHO8	-0.853284	2.27606473	4.66449550	-1.3460856	17.46486219	0.051363644	3.38141009	0.91228454
CHHO9	-0.978190	3.26683190	8.42838000	-1.5320691	21.31088160	0.049414637	3.26063988	0.83138041
CHHO10	-0.974684	3.06359238	7.23019923	-1.4824184	20.21278880	0.052171220	3.13826777	0.74711216
HHO	-1.162001	4.01799947	9.74536802	-1.3345217	16.6810585563	0.047836035	7.00847713	1.02274171
SSO	-1.0554	3.7953	9.800	-1.1755	24	0.0136	1.0884	1.1508
ALO	-0.9438	3.4734	9.7898	-1.1811	24	0.0136	1.6530	1.1513
RGA	-1.1568	3.4243	6.4161	-1.1544	12.8989	0.0343	1.4504	8.4854
MPSO	-0.9479	3.0835	7.799	-1.8800	20.7624	0.0296	2.8666	9.7539
ARNA-GA	-0.9470	3.0586	7.6059	-1.8800	23.00	0.0329	1.1026	2.9518
JAYA-NM	-1.19966	3.55	6.00	-1.200	13.2287	0.03334	1.00	5.2513
HGA	-0.944957	3.01801	7.401	-1.880	23.00	0.02914489	1.00	4.8469
SGA	-0.9473	3.0641	7.7134	-1.9390	19.7650	0.0240	2.7197	5.6530
HADE	-0.8532	2.81009	8.09203	-1.2870	14.0448	0.0335374	1.00	7.9908
TLBO-DE	-0.853200	2.65052	8.001574	-1.360144	15.651416	0.0364609	1.00	7.2776677

output terminal voltage of 250W PEMFC stack are listed in Table 6.

$$IAE = |V_{measured} - V_{estimated}| \tag{38}$$

$$RE = (V_{measured} - V_{estimated})\,/V_{measured} \tag{39}$$

B. CASE 2: SIMULATION RESULTS UNDER DIFFERENT OPERATING CONDITIONS

In this subsection, the proposed CHHO4 is applied for extracting the unknown parameters of the BCS-500W FC, the SR-12 500W FC, and the Temasek 1kW PEMFC stacks. The statistical analysis based on 50 individual runs for the

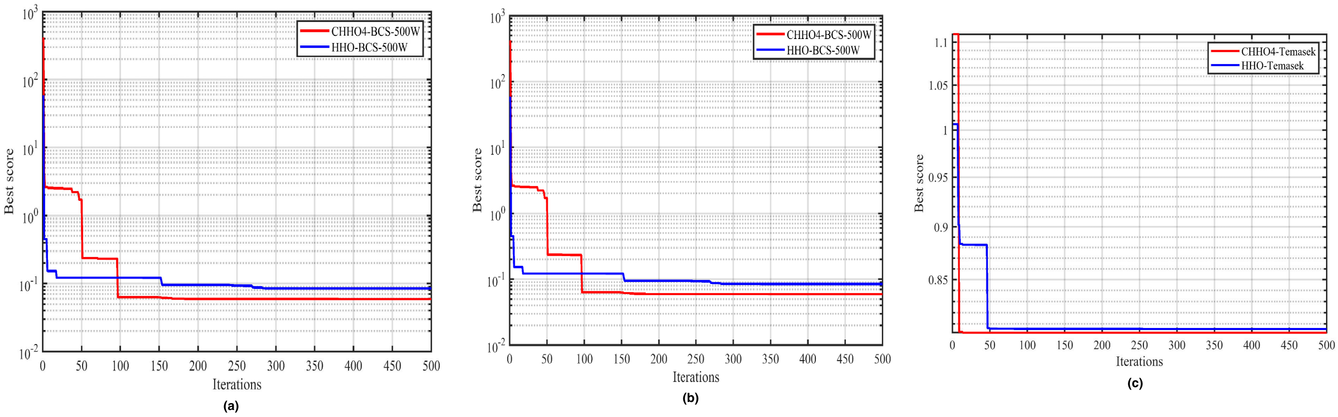

FIGURE 5. Convergence characteristics of CHHO4 and HHO;(a) BCS-500W PEMFC, (b) SR-12 500W PEMFC, and (c) Temasek 1kW PEMFC.

TABLE 6. Calculated voltage, absolute error, and relative error of CHHO4 for 250W PEMFC stack.

Item	I_L (A)	$V_{measured}$ (V)	$V_{estimated}$ (V)	IAE	$(IAE)^2$	RE
1	0.4717	21.63	21.45591	0.174088	0.030307	0.008114
2	2.149	19.68	19.34705	0.332945	0.110852	0.017209
3	2.83	18.78	18.91517	0.135167	0.01827	-0.00715
4	3.983	17.88	18.33575	0.45575	0.207708	-0.02486
5	5.713	17.58	17.64617	0.066175	0.004379	-0.00375
6	7.075	17.12	17.18058	0.060584	0.00367	-0.00353
7	8.019	16.77	16.88028	0.11028	0.012162	-0.00653
8	11.16	15.92	15.94204	0.022044	0.000486	-0.00138
9	13.73	15.22	15.17939	0.040615	0.00165	0.002676
10	16.56	14.42	14.26283	0.157171	0.024703	0.01102
11	17.56	14.02	13.89677	0.123232	0.015186	0.008868
12	19.03	13.52	13.28316	0.236836	0.056091	0.01783
13	20.34	12.82	12.60125	0.218745	0.04785	0.017359
14	22.01	10.86	11.23257	0.372566	0.138805	-0.03317
15	22.96	9.058	9.109156	0.051156	0.002617	-0.00562
SSE					0.674736	

TABLE 7. Statistical measurement of BCS-500W, SR-12 500W PEMFC, and Temasek 1kW stacks using CHHO4.

	SR-12 500W stack		BCS 500W stack		Temasek 1kW stack	
	CHHO4	HHO	CHHO4	HHO	CHHO4	HHO
Min	1.05716011067	1.059306438052	0.05928851295237	0.0845623593972	0.8023415657917	0.8055280146566
Max	32.6062726887	103.6034672929	10.9180555373455	13.187934228702	2.3886730844824	2.6453025773738
Mean	5.23070468393	7.784009253065	4.99988006734876	4.7057696142008	1.1338435450094	1.1649031850625
Median	1.10864496932	1.100576789454	5.39221581804628	4.0401720555184	1.1461098199254	1.2187486547846
SD	826.242275322	1732.499425349	352.728199473206	398.25376410706	26.636061909010	32.592254378167
RE	197.394156812	317.4106459401	4166.56727279115	2732.4256842763	20.658407425928	22.306807700478
MAE	4.17354457325	6.724702815013	4.94059155439639	4.6212072548035	0.3315019792176	0.3593751704058
RMES	9.18263314430	18.42210480146	6.04998585224186	6.0744506280932	0.4235830285071	0.4829611863891
Eff.	65.5605968054	70.96336979681	7.26588169658100	8.8095680563294	73.874541377062	73.049943163809

three fuel cell stacks using CHHO4 and the conventional HHO are reported in Table 7. The convergence characteristics of proposed CHHO4 and HHO for these fuel cell stacks are shown in Fig. 5a-c. The estimated parameters for the BCS-500W PEMFC stack obtained by CHHO4, HHO and other optimization techniques are listed in Table 8. Similarly, Tables 9 and 10 present the results of estimated parameters of SR-12 500W and Temasek 1kW PEM fuel cell stacks

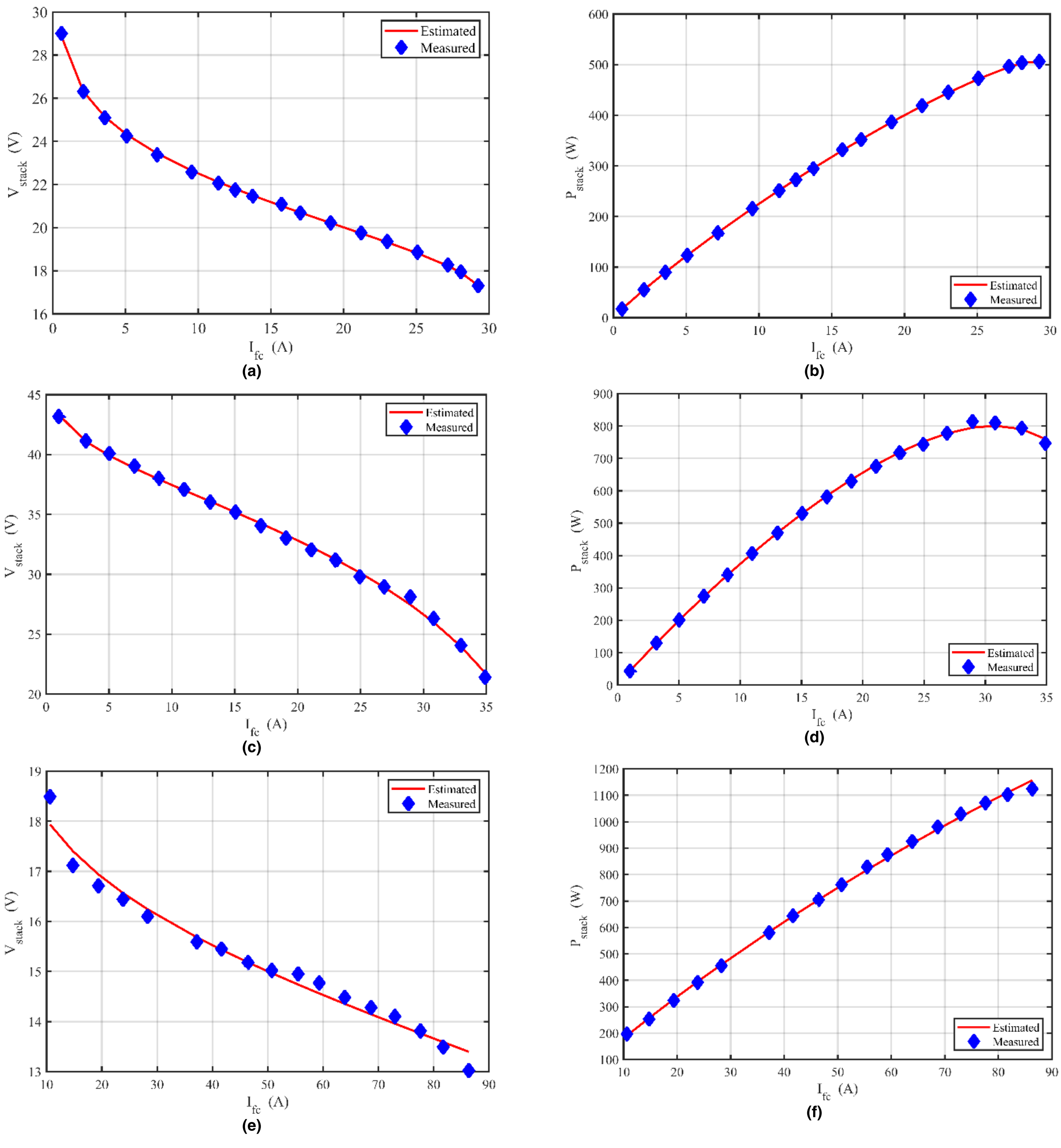

FIGURE 6. Polarization characteristics of different fuel cell stacks: (a) I-V curve for BCS 500W stack, (b) I-P curve for BCS 500W stack, (c) I-V curve for SR-12 500W FC, (d) I-P curve for SR-12 500W FC, (e) I-V curve for Temasek 1kW stack, (f) I-P curve for Temasek 1kW stack.

obtained by CHHO4, HHO and other optimization algorithms.

The *I-V* and *I-P* polarization characteristics of the BCS-500W FC, the SR-12 500W PEMFC, and the Temasek 1kW PEMFC stacks based on the estimated parameters obtained by CHHO4 method are shown in Fig. 6a-f. From this figure, it can be observed a good matching between the estimated and measured values.

Moreover, in this subsection, various cases of stack temperature and reactants' pressure at inlet channels of the PEMFC stack are studied to validate the accuracy of proposed CHHO4 technique. Based on the estimated parameters in the previous subsection, the polarization characteristics of 250W PEMFC stack under different temperatures are demonstrated.

In this case, the values of hydrogen and oxygen pressure at the input channels are kept constants at the values reported in the datasheet of 250W PEMFC stack. Fig. 7a-d show the polarization characteristics of the 250W FC stack and BCS-500W PEMFC at 323K, 343K, and 363K. The impact of reactants pressure (H_2 and O_2) at the inputs of fuel cell stack

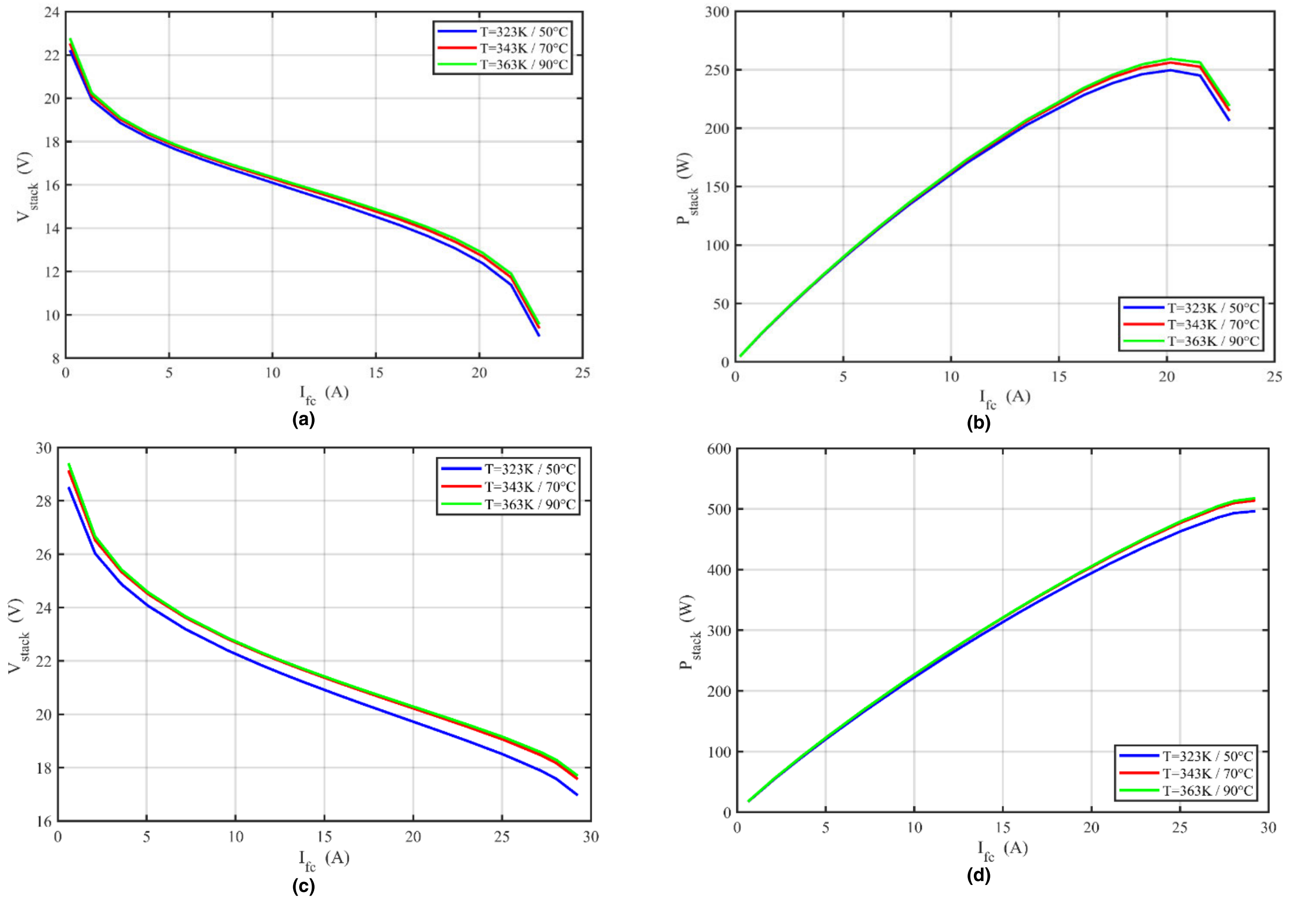

FIGURE 7. Dynamic operation of PEMFC stacks under change in cell temperature: (a) I-V plot for 250W PEMFC, (b) I-P plot for 250W PEMFC, (c) I-V plot for BCS-500W PEMFC, (d) I-P plot for BCS-500W PEMFC.

TABLE 8. Estimated parameters for BCS-500W PEMFC obtained by CHHO4, HHO and other optimization techniques.

	ξ_1	$\xi_2\times10^{-3}$	$\xi_3\times10^{-5}$	$\xi_4\times10^{-4}$	λ	β	$R_c\times10^{-4}$	SSE
CHHO4	**-1.165963**	**3.9095335**	**8.1088029**	**-1.8046841**	**19.3423812**	**0.0136016893**	**6.49013988**	**0.059288512**
HHO	-1.120679	3.444191	6.224088	-1.792572	16.196307	0.013601	1.000054	0.0845624
GWO	-1.0180	2.3151	5.240	-1.2815	18.8547	0.0136	7.503	7.1889
SSO	-1.018	2.3151	5.240	-1.2815	18.8547	0.0136	7.5036	7.1889
CS-EO	-1.1365	2.9254	3.7688	-1.3949	18.5446	0.013600	8.00	5.5604

TABLE 9. Estimated parameters for RS-12 500W PEMFC obtained by CHHO4, HHO and other optimization methods.

	ξ_1	$\xi_2\times10^{-3}$	$\xi_3\times10^{-5}$	$\xi_4\times10^{-4}$	λ	β	$R_c\times10^{-4}$	SSE
CHHO4	**-0.85320**	**3.09184126**	**8.2387726**	**-0.9540**	**22.9115599**	**0.17623745**	**6.24684705**	**1.05716011067**
HHO	-0.85331	2.417357	4.2487878	-0.95412	15.341289	0.177946	3.716654	1.059306
GWO	-0.9664	2.2833	3.400	-0.954	15.7969	0.1804	6.6853	1.517
SSO	-0.9664	2.2833	3.400	-0.954	15.7969	0.1804	6.6853	1.517
CS-EO	-1.0353	3.3540	7.2428	-0.954	10	0.1471	7.1233	7.5753

on the performance of FC stack is demonstrated while the cell temperature is maintained constant at the value given in the datasheet of the manufacturer. The *I-V*, *I-P* polarization curves of SR-12 500W PEFC and Temasek 1kW stack at pressures of 1/0.2075bar, 2.5/1.5bar and 5/3bar while maintaining the stack temperature at 343.15K are shown in

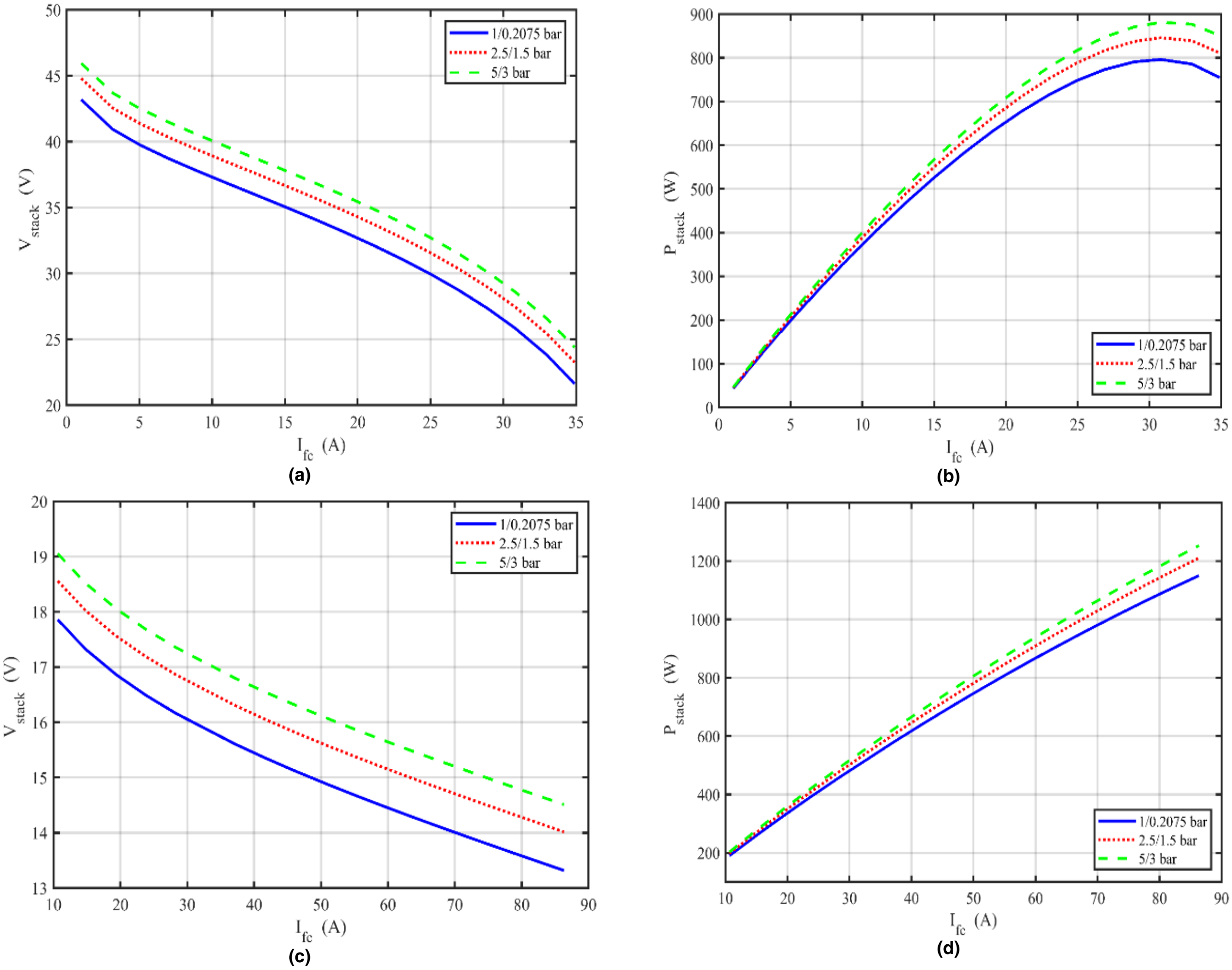

FIGURE 8. **Dynamic operation of PEMFC stacks under change in reactants' pressure: (a) I-V plot for SR-12 500W, (b) I-P plot for SR-12 500W, (c) I-V plot for Temasek 1kW, (d) I-P plot for Temasek 1kW.**

TABLE 10. **Estimated parameters for Temasek-1kW PEMFC obtained by CHHO4, HHO and other optimization methods.**

	ξ_1	$\xi_2 \times 10^{-3}$	$\xi_3 \times 10^{-5}$	$\xi_4 \times 10^{-4}$	λ	β	$R_c \times 10^{-4}$	SSE
CHHO4	**-1.09437461**	**4.4282264785**	**8.76558444**	**-2.1464994**	**18.63921**	**0.1015594**	**1.8910748**	**0.8023415657**
HHO	-0.853200	3.499113108	7.21117502	-2.4404920	22.999633	0.0712389672	1.82651477	0.8055280146
GWO	-1.0299	2.4105	4.00	-0.9540	10.0005	0.1274	1.0873	1.6481
SSO	-1.0299	2.4105	1.00	-0.9540	10.0005	0.1274	1.0873	1.6481

Fig. 8a-d. From Figs. 7 and 8, the reader can notice that the pressure ratio (P_{H2}/P_{O2}) at the supply inlet as well as the cell temperature play a significant role in the operation of PEMFC stack. When the input pressures of reactants and/or the cell temperature are increased, the output terminal voltage and the stack output power will be raised.

V. CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, an efficient optimization algorithm, called CHHO, has been proposed and applied for estimating the optimal effective parameters of different proton exchange membrane fuel cell stack models. The proposed CHHO algorithms are based on the conventional Harris Hawks Optimization HHO and ten chaotic functions. The best CHHO algorithm has been applied for finding the optimal parameters of four different commercial PEMFC stacks under a wide range of operating scenarios. The mathematical model of PEMFC has been precisely described and defined. This model has been used for optimizing and estimating parameters of PEMFC models. The 250W PEM fuel cell stack, three various commercial fuel cell stacks, namely, BCS 500W, SR-12 500W, and Temasek 1kW have been used to evaluate the effectiveness of CHHO algorithm. The optimal estimated data obtained by the proposed CHHO shown a good agreement with the experimental data of different commercial PEM fuel cell stacks. The results obtained by CHHO have been compared with different recent metaheuristic optimization algorithms. In all case studies, the obtained results from the proposed CHHO shown high accuracy in estimating the optimal parameters of PEM fuel cell stacks. Moreover, a statistical measurement has been performed to prove the superiority and accurateness of the CHHO in solving the studied optimization problem. During the simulation process, the most obtained values of objective function of CHHO are in the range of minimum value of SSE, and there are a few numbers of obtained values in the range of maximum value of SSE. The proposed CHHO can be considered as an efficient optimization technique for solving the problem of PEMFC parameter's estimation. In the future work, the proposed technique could be applied for solving other optimization problems.

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REFERENCES

[1] A. Fathy and H. Rezk, "Multi-verse optimizer for identifying the optimal parameters of PEMFC model," *Energy*, vol. 143, pp. 634–644, Jan. 2018.

[2] L. Zhang and N. Wang, "An adaptive RNA genetic algorithm for modeling of proton exchange membrane fuel cells," *Int. J. Hydrogen Energy*, vol. 38, no. 1, pp. 219–228, 2013.

[3] S. Xu, Y. Wang, and Z. Wang, "Parameter estimation of proton exchange membrane fuel cells using eagle strategy based on JAYA algorithm and Nelder–Mead simplex method," *Energy*, vol. 173, pp. 457–467, Apr. 2019.

[4] O. E. Turgut and M. T. Coban, "Optimal proton exchange membrane fuel cell modelling based on hybrid teaching learning based optimization-differential evolution algorithm," *Ain Shams Eng. J.*, vol. 7, no. 1, pp. 347–360, 2016.

[5] Y. Rao, Z. Shao, A. H. Ahangarnejad, E. Gholamalizadeh, and B. Sobhani, "Shark smell optimizer applied to identify the optimal parameters of the proton exchange membrane fuel cell model," *Energy Convers. Manage.*, vol. 182, pp. 1–8, Feb. 2019.

[6] Y. Chen and N. Wang, "Cuckoo search algorithm with explosion operator for modeling proton exchange membrane fuel cells," *Int. J. Hydrogen Energy*, vol. 44, no. 5, pp. 3075–3087, Jan. 2019.

[7] M. Guarnieri, E. Negro, V. Di Noto, and P. Alotto, "A selective hybrid stochastic strategy for fuel-cell multi-parameter identification," *J. Power Sources*, vol. 332, pp. 249–264, Nov. 2016.

[8] A. Askarzadeh and A. Rezazadeh, "A new heuristic optimization algorithm for modeling of proton exchange membrane fuel cell: Bird mating optimizer," *Int. J. Energy Res.*, vol. 37, no. 10, pp. 1196–1204, 2013.

[9] A. A. El-Fergany, "Electrical characterisation of proton exchange membrane fuel cells stack using grasshopper optimiser," *IET Renew. Power Gener.*, vol. 12, no. 1, pp. 9–17, 2017.

[10] M. Ali, M. A. El-Hameed, and M. A. Farahat, "Effective parameters' identification for polymer electrolyte membrane fuel cell models using grey wolf optimizer," *Renew. Energy*, vol. 111, pp. 455–462, Oct. 2017.

[11] A. Rowe and X. Li, "Mathematical modeling of proton exchange membrane fuel cells," *J. Power Sources*, vol. 102, nos. 1–2, pp. 82–96, Dec. 2001.

[12] J. M. Correa, F. A. Farret, L. N. Canha, and M. G. Simoes, "An electrochemical-based fuel-cell model suitable for electrical engineering automation approach," *IEEE Trans. Ind. Electron.*, vol. 51, no. 5, pp. 1103–1112, Oct. 2004.

[13] J. C. Amphlett, R. M. Baumert, R. F. Mann, B. A. Peppley, P. R. Roberge, and T. J. Harris, "Performance modeling of the Ballard Mark IV solid polymer electrolyte fuel cell I. Mechanistic model development," *J. Electrochem. Soc.*, vol. 142, no. 1, pp. 1–8, 1995.

[14] F. Z. Aouali, M. Becherif, H. S. Ramadan, M. Emziane, A. Khellaf, and K. Mohammedi, "Analytical modelling and experimental validation of proton exchange membrane electrolyser for hydrogen production," *Int. J. Hydrogen Energy*, vol. 42, no. 2, pp. 1366–1374, 2017.

[15] R. F. Mann, J. C. Amphlett, M. A. I. Hooper, H. M. Jensen, B. A. Peppley, and P. R. Roberge, "Development and application of a generalised steady-state electrochemical model for a PEM fuel cell," *J. Power Sources*, vol. 86, nos. 1–2, pp. 173–180, 2000.

[16] J. C. Amphlett, R. Baumert, R. F. Mann, B. A. Peppley, P. R. Roberge, and T. J. Harris, "Performance modeling of the Ballard Mark IV solid polymer electrolyte fuel cell II. Empirical model development," *J. Electrochem. Soc.*, vol. 142, no. 1, pp. 9–15, 1995.

[17] Z.-J. Mo, X.-J. Zhu, L.-Y. Wei, and G.-Y. Cao, "Parameter optimization for a PEMFC model with a hybrid genetic algorithm," *Int. J. Energy Res.*, vol. 30, pp. 585–597, Jun. 2006.

[18] B. Alatas, "Chaotic harmony search algorithms," *Appl. Math. Comput.*, vol. 216, no. 3, pp. 2687–2699, 2010.

[19] G. Kaur and S. Arora, "Chaotic whale optimization algorithm," *J. Comput. Des. Eng.*, vol. 5, no. 3, pp. 275–284, 2018.

[20] A. A. Heidari, S. Mirjalili, H. Faris, I. Aljarah, M. Mafarja, and H. Chen, "Harris hawks optimization: Algorithm and applications," *Future Gener. Comput. Syst.*, vol. 97, pp. 849–872, Aug. 2019.

[21] T. V. Nguyen and R. E. White, "A water and heat management model for proton-exchange-membrane fuel cells," *J. Electrochem. Soc.*, vol. 140, no. 8, pp. 2178–2186, 1993.

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