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RESEARCH ARTICLE

A Novel Mantis Search Algorithm for Economic Dispatch in Combined Heat and Power Systems

GHAREEB MOUSTAFA[1], HASHIM ALNAMI[1], SULTAN H. HAKMI[1], ABDULLAH M. SHAHEEN[2], AHMED R. GINIDI[2], MOSTAFA A. ELSHAHED[3,4], AND HANY S. E. MANSOUR[5]
[1]Electrical Engineering Department, College of Engineering, Jazan University, Jazan 45142, Saudi Arabia
[2]Department of Electrical Engineering, Faculty of Engineering, Suez University, Suez, Egypt
[3]Electrical Engineering Department, Engineering and Information Technology College, Buraydah Private Colleges, Buraydah 51418, Saudi Arabia
[4]Electrical Power Engineering Department, Faculty of Engineering, Cairo University, Cairo 12613, Egypt
[5]Electrical Engineering Department, Suez Canal University, Ismailia 41522, Egypt

Corresponding author: Abdullah M. Shaheen (abdullah.mohamed.eng19@suezuni.edu.eg)

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ABSTRACT Economic dispatch in combined heat and power (CHP) schemes takes into account the trade-off between generating electricity and producing heat, ensuring that the system operates at the highest level of efficiency and cost-effectiveness. A Mantis Search Algorithm (MSA), in this paper, is developed to address the CHP economic dispatch taking into consideration valve points effect, feasible region constraints for CHP units, and power losses are considered all at once. The MSA draws its inspiration from the unique sexual cannibalism and foraging strategies of praying mantises including three stages of optimization which are hunting, attacking, and cannibalism. Moreover, various recent meta-heuristic optimization algorithms, such as the Aquila Optimizer (AO), Gradient-based Optimizer (GBO), Coot Optimizer (CO), and African Vultures Algorithm (AVO), are utilized for comparative analysis across the two test systems. The developed MSA is demonstrated to be superior across three power and heat loading levels for both a 7-unit system and a larger 84-unit system. In the case of the large 84-unit system, MSA exhibits a significant cost reduction, surpassing AVO, GBO, CO, and AO by 2.017%, 2.511%, 0.817%, and 0.126%, respectively. Simulation results confirm the remarkable efficiency of MSA as a promising solution for economic dispatch in combined heat and power schemes. Testing outcomes indicate that MSA outperforms several previously published methods in the literature, as well as the four adopted optimizers.

INDEX TERMS Mantis search optimization algorithm, economic dispatch, combined heat and power units, valve point loading effect.

I. INTRODUCTION

Combined heat and power (CHP) generation units, are the most effective way to concurrently produce thermal and electrical energy [1]. A substantial quantity of energy is lost as heat while converting fossil fuels into electricity in traditional thermal units [2]. On the other hand, this dissipated heat is utilized to supply the required thermal energy in CHP units. This utilization will result in the enhancement of energy efficiency to about 90 percent [3]. Additionally, CHP units can reduce environmental pollution by 13-18 percent and the whole fuel cost by 10-40 percent [4].

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Certainly, to effectively achieve the utilization of CHP units, the optimal economic dispatch problem is addressed. This optimization issue is solved to determine the optimal production scheduling of both heat and power units with minimizing the CHP fuel cost while maintaining operational limitations [5].

Recently, several mathematical approaches have been elaborated to address the optimal dispatch of CHP units' problem such as the benders decomposition approach [6], [7] normal boundary intersection approach [8], Lagrangian relaxation approach [9], [10], branch and bound approach [11], and sequential quadratic programming approach [12]. However, the efficacy of these approaches depends on the initial conditions, requires several iterations to reach an acceptable solution, and frequently does not converge toward a global solution. Thus, these approaches show a great degree of complexity and suffer from computational difficulties and sophisticated mathematical formulations. Subsequently, heuristic and metaheuristic techniques are effectively employed on the optimal dispatch of CHP units' issue. In [13], the combination of sustainable supply chain management (SSCM) covering its principles, and challenges with machine intelligence. This work highlighted numerous opportunities resulting from this synergy, including inventory management, improved demand forecasting, and waste reduction. The paper looked ahead to the future landscape of sustainable supply chains in the era of machine intelligence, discussing emerging trends, technological innovations, and ethical considerations that will shape the field. A case study of a decision-making framework in a food company has been employed to demonstrate the identification of the best supplier [14]. The findings emphasize the importance of considering suppliers' energy efficiency, and waste management. To handle the complexity and uncertainty linked to the influence performance and economic feasibility, a multi-criteria decision-making approach Through Inter-criteria Correlation (CRITIC) method is employed in [15]. Additionally, the neutrosophic set theory is integrated to manage uncertain information during the evaluation process.

In [16], the authors have depicted a comprehensive review of optimization techniques for optimal dispatch of CHP units. In [17], the particle swarm optimization (PSO) technique was suggested to address the CHP dispatch problem. Time-varying acceleration factors have been employed to overcome premature convergence of PSO and enhance the solution quality. The influence of valve-point is formulated in the polynomial cost function with the addition of a sinusoidal term. After using the PSO with time-varying acceleration factors, the authors have applied the Monte Carlo method to address the uncertainties of energy demand and renewable sources [18]. In [19], the PSO has also been proposed as an optimization technique to investigate the impact of economic dispatch of coal-fired CHP plants on the whole coal utilization of the CHP plant.

Additionally, an improved optimization technique based on the genetic algorithm (GA) [20] were illustrated to handle objective function of the CHP economic dispatch to minimize the whole fuel costs while sustaining the energy demand. Both valve-point and transmission loss impacts have been taken into consideration. In [21], an upgraded GA with new mutation and crossover have been presented to handle the studied problem. The non-dominated sorting GA II has presented to deal with both real and binary data of production scheduling [22]. Indeed, the benefits of energy storage integration into the system have been investigated. Furthermore, a hybrid non-dominated sorting GA and PSO have been engaged effectively to address the mentioned problem [23]. The multi-objective objective function has been designed to minimize both the whole fuel cost and air pollution results from the generation units. Transmission losses have been considered in the problem. However, their validation has been limited to small-scale networks of (5 and 7) units.

The cuckoo search optimizer (CSO) has been proposed to solve the optimal CHP economic dispatch problem as indicated in [24], [25], and [26] to minimize the whole fuel cost while sustaining the load demand considering the valve-point loading impacts and transmission power loss. In [24], the proposed method has been tested on small (5 units), medium (24 units), and large-scale (48 units) systems. The 5-unit test network has been considered for three demand levels of heat and power. In [25], the performance of CSO has been verified by applying on different scale six networks with 4, 5, 7, 11, 24, and 48 units. In [26], the suggested approach has been applied to five diverse test systems. Three of these systems with quadratic cost functions without considering the power loss, while the other two test systems with nonconvex cost functions.

A manta ray foraging optimizer [27] has been proposed to establish the optimum schedule of heat and power of cogeneration units while considering the effects of valve point and wind power. Two different scale systems: small with5 units and large with 96 units, have been addressed by considering two cases of peak and daily variation loading. The presence of wind power attains economical results in diverse cases with savings of 8%.

Myriads pf optimization techniques have also been proposed to address the optimal dispatch of CHP units' problem. These include heap-based optimization algorithm [28], gravitational search algorithm [29], group search optimizer [30], grey wolf optimizer [31], kho-kho optimizer [32], marine predators optimizer [33], multi-player harmony search algorithm [34], hybrid heap-based and jellyfish search approach [35], whale optimization algorithm [36], hybrid weighted vertices-based optimizer and PSO [37].

This paper utilizes the Mantis Search Algorithm (MSA) to address the CHPED problem and compares it with four other optimizers. The MSA is inspired by the unique behaviors of praying mantises, such as sexual cannibalism and foraging strategies, and it incorporates three optimization stages: hunting, attacking, and cannibalism [38], [39]. Each mantis represents a potential solution which is associated with a position in the search space, which corresponds to a candidate solution. The MSA iteratively improves the mantises' positions through a series of stages, including search, capture, consume, and reproduce, which emulate the hunting behavior of mantises. During the search stage, mantises explore the search space by adjusting their positions using an integration of global and local search strategies. This allows them to efficiently cover the solution space and locate promising regions [38]. The capture stage involves identifying the most favorable solutions, where mantises converge towards the best positions found so far. The consume stage involves evaluating the fitness of each mantis based on an objective function, which quantifies the candidate solution quality.

Finally, the reproduce stage involves generating new mantises through reproduction operators, such as mutation and crossover, to introduce diversity and explore diverse search space regions [39].

MSA has the ability to handle both continuous and discrete optimization problems, making it applicable to an extensive range of actual-world scenarios. Additionally, it exhibits strong exploration and exploitation capabilities by combining local and global search strategies, enabling efficient and effective exploration of the search space while converging towards optimal solutions. The algorithm also has the potential for parallelization, allowing for faster convergence and scalability to larger problem sizes. Therefore, the MSA's advantages lie in its versatility, exploration-exploitation balance, potential for parallelization, and applicability to various research objectives, making it a valuable tool for solving the CHPED non-convex optimization problem, is approached for the first time using four metaheuristic algorithms in this study. To ensure a realistic representation of the real-world counterpart, the problem formulation considers all practical constraints. Various algorithms in recent years are chosen for the study to be applied to CHP economic dispatch. The manuscript contributions can be demonstrated as follows:

- A penalty mechanism is employed to handle all practical constraints in the proposed non-convex CHP model, ensuring the feasibility of the optimal solution.
- The paper introduces new techniques, namely the African Vultures Algorithm (AVO) [40], Aquila Optimizer (AO) [41], Gradient-Based Optimizer (GBO) [42], and Coot Optimizer (CO) [43], which are applied for the first time to solve the non-convex economic dispatch of CHP problem.
- The tests conducted in this study include two distinct case studies: a 7-unit system with three loading levels and a larger 84-unit system, both subject to various constraints.
- When compared to existing approaches from literature and the newly introduced methods in this paper, the MSA consistently achieves the lowest total cost values for both test systems across all loading levels.

The paper is structured as follows: The MSA algorithm is explained in section II. For the CHP economic dispatch problem, a non-convex optimization model is formulated in section III. A detailed analysis and discussion of the numerical results are included in Section IV. Final conclusions can be found in chapter 5.

II. CHP ECONOMIC DISPATCH FORMULATION

The major goal of CHP Economic Dispatch is to meet demand for both power and heat while simultaneously lowering fuel costs for heat and power generators. In this way, the issue is defined as an objective function that is bound by a variety of constraints. Fig. 1 displays the schematic diagram of economic CHP dispatch issue.

The Cost Target Function (CTF) is simply defined as the whole cost of the power-heat combination, heat-only, and power-only units because the goal of the task is to minimize the total cost of production [36], [44]:

$$\text{Min } CTF = \sum_{i=1}^{N_p} C1_i(P_i^p) + \sum_{j=1}^{N_h} C2_j(H_j^h) + \sum_{k=1}^{N_C} C3_k(P_k^C, H_K^C)(\$/h) \quad (1)$$

where the term $C1_i(P_i^p)$ illustrates the cost of i^{th} power only units, whereas the term $C2_j(H_j^h)$ signifies the j^{th} heat only and the term $C3_k(P_k^c, H_k^c)$ establishes the k^{th} CHP. Moreover, the symbols N_p, N_h, and N_C characterize power-only units, heat-only units, and CHP units, respectively.

The three cost functions $C1_i(P_i^p)$, $C2_j(H_j^h)$, and $C3_k(P_k^c, H_k^c)$ can be demonstrated mathematically as follows:

1) $C1_i$ of i^{th} Power only units

$$C1_i(P_i^p) = \delta 1_i(P_i^p)^2 + \delta 2_i P_i^p + \delta 3_i + \left|\lambda_i \sin(\rho_i(P_i^{p\min} - P_i^p))\right| (\$/h) \quad (2)$$

2) $C2_j$ of j^{th} Heat only units

$$C2_j(H_j^h) = \gamma 1_j(H_j^h)^2 + \gamma 2_j H_j^p + \gamma 3_j(\$/h) \quad (3)$$

3) $C3_k$ of k^{th} CHP units

$$C3_k(P_k^c, H_k^c) = \alpha 1_k(P_k^c)^2 + \alpha 2_k P_k^p + \alpha 3_k + \alpha 4_k(H_k^c)^2 + \alpha 5_k H_k^c + \alpha 6_k H_k^c P_k^c(\$/h) \quad (4)$$

where the symbols ($\delta 1_i$, $\delta 2_i$, and $\delta 3_i$) depict the i^{th} power-only plant, whilst the symbols ($\gamma 1_j$, $\gamma 2_j$, and $\gamma 3_j$) indicate the cost coefficients of j^{th} heat-only plant $a_i b_i c_i$. In addition to this, the symbols ($\alpha 1_k$, $\alpha 2_k$, $\alpha 3_k$, $\alpha 4_k$, $\alpha 5_k$ and $\alpha 6_k$) refer to the cost coefficients of k^{th} CHP unit cost coefficients. The sinusoidal term described in Eq. (4) illustrates the valve-point impacts which determine the non-differentiability and non-convexity of this problem [45], [46].

A. CONSTRAINTS

When minimizing the given objective function, the following constraints are taken into consideration. Equation (7) can be used to determine the balance among power demand and generation:

1. *Power balance constraint*

$$\sum_{i=1}^{N_\text{p}} P_i^\text{p} + \sum_{k=1}^{N_\text{c}} P_k^\text{c} = P_{demand} \quad (5)$$

where P_{demand} illustrates the summation of power demand

2. *Limits of power–only units' capacity*

$$P_i^{p\min} \leq P_i^p \leq P_i^{p\max} \quad i = 1, \ldots, N_p, \quad (6)$$

3. *Heat balance constraint*

$$\sum_{i=1}^{N_c} H_i^c + \sum_{j=1}^{N_h} H_j^h = H_{demand}, \tag{7}$$

where H_{demand} illustrates thermal demand for the whole system.

4. *Limits of heat-only units' Generation*

$$H_j^{h\min} \leq H_j^h \leq H_j^{h\max} \quad j = 1, \ldots, N_h, \tag{8}$$

5. *Limits of CHP Capacity*

$$P_i^{C\min}(H_i^c) \leq P_i^c \leq P_i^{C\max}(H_i^c) \quad i = 1, \ldots, N_c, \tag{9}$$

$$H_i^{C\min}(P_i^c) \leq H_i^c \leq H_i^{C\max}(P_i^c) \quad i = 1, \ldots, N_c, \tag{10}$$

where "max" and "min" highlight the power and heat unit limitations.

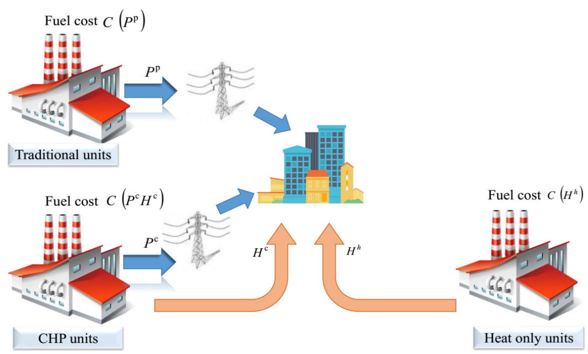

FIGURE 1. Schematic diagram of economic CHP dispatch.

III. MATHEMATICAL MODEL OF MANTIS SEARCH OPTIMIZATION ALGORITHM (MSA)

By deciding among searching for prey and attacking the prey in accordance with a predetermined probability value (p), the mantis optimizer creates an appropriate equilibrium among exploration and exploitation. The primary variables that determine the time difficulty of the proposed optimizer are N, D, and T, and the MSA time difficulty is O (N D T). Finally, Figure 2 presents the MSA flowchart.

A. INITIAL POPULATION

Each mantis, in the proposed MSA, characterizes a candidate solution for the CHPED. A matrix x with two-dimensional of size N solutions $\times$ search space dimension (D) will be generated. Besides, a vector is manifested to show the location of Mantis i at function t as depicted in Eq. (11). The vector is utilized with a random starting within the optimization issue boundaries:

$$\vec{x}_i^{\,t} = \vec{x}^{\,lb} * (1 - \vec{rv}) + \vec{rv} * \vec{x}^{\,ub} \tag{11}$$

where, rv_1, rv_2, rv_6, rv_7, rv_9, rv_{10}, rv_{12}, rv_{13} and r_{17} random values obtained by means of uniform distribution among zero and one. Moreover, $\vec{x}^{\,lb}$ lower bound of the j-dimension whilst $\vec{x}^{\,ub}$ upper limit of the j-dimension

B. EXPLORATION STAGE

Levy flight and the normal distribution are combined in the MSA to take into consideration for both small and large step sizes. The solution is often moved to a remote area by the normal distribution, which also excludes many other prospective solutions. The opposite end of the spectrum, the Levy flight produces small step sizes that necessitate extensive function analyses in order to reach the desired outcome; and consequently, it is rarely utilized exclusively. The combination of both the normal distribution and Levy flight has been conducted in order to provide a novel sequence of numbers that may accommodate both tiny as well as large numbers. This makes it possible to mimic the movements of pursuers searching for their victim. This behaviour can be scientifically stated in the following manner:

$$\vec{x}_i^{\,t+1} = \begin{cases} \vec{x}_i^{\,t} + (\vec{x}_i^{\,t} - \vec{x}_a^{\,t}) * \vec{\tau_1} + |\tau_2| * \vec{U} \\ *(\vec{x}_a^{\,t} - \vec{x}_b^{\,t}), \textit{ if } rv_1 \leq rv_2 \\ \vec{U} * \vec{x}_i^{\,t} + (\vec{x}_a^{\,t} + \vec{rv_3} * (\vec{x}_b^{\,t} - \vec{x}_c^{\,t})) \\ *(1 - \vec{U}), \quad \textit{otherwise} \end{cases} \tag{12}$$

where, $\vec{rv_3}$, $\vec{rv_4}$, $\vec{rv_5}$, $\vec{rv}_8$, $\vec{rv}_{16}$ and $\vec{rv}_{18}$ random vectors obtained by means of the uniform distribution among zero and one.

Moreover, $\vec{\tau_1}$ represents a numerical vector created according to the Levy flight approach, whilst $|\tau_2|$ manifests a random number according to the normal distribution with a mean of zero and a standard deviation of one. Furthermore, l represents a number which lessens and increases the striking velocity magnitude. Besides, $\vec{x}_i^{\,t}$ characterizes the position of the ith solution at function evaluation t, whereas $\vec{x}_a^{\,t}$, $\vec{x}_b^{\,t}$, and $\vec{x}_c^{\,t}$ random solutions extracted from the existing population.

The first method in Eq. (12) uses hybrid-based motions to extensively search the search area so as to pinpoint the most probable areas that potentially have the nearly ideal solution. Additionally, it is recommended to use the second method for creating sudden orientation employing three options chosen at random from the present population.

$$\vec{U} = \begin{cases} 0 & \textit{if } \vec{rv_4} < \vec{rv_5} \\ 1 & \textit{otherwise} \end{cases} \tag{13}$$

The jth element of the $\vec{U}$ binary vector set to zero if the preceding vector has a tiny value, else it set to one. Each jth dimension of the two specified vectors is contrasted to one another.

The creation of archives that contain the precise location of several secret locations imitates the predators' foraging activities. The local best solutions for each mantis are stored in an archive of size A, and when it fills up with the best local solutions for every mantis, a randomly chosen solution is taken from there and replaced with a new one. Mathematically, this behaviour can be estimated using the following formula:

$$\vec{x}_i^{\,t+1} = \vec{x}_i^{\,t} + \alpha * (\vec{x}_{ar}^{\,t} - \vec{x}_a^{\,t}) \tag{14}$$

$\overrightarrow{x}^{t}_{ar}$ characterizes solutions that are selected randomly from the archive in order to designate the ith mantis location. To let it to protect the ambuscade distance, the parameter (α) is used to regulate the mantis' head position.

The parameter (α) can be mathematically evaluated according to Eq. (15):

$$\alpha = \mu * \cos(\pi * rv_6) \tag{15}$$

A distance factor (μ) can be evaluated according to the next equation:

$$\mu = (\frac{1-t}{T_m}) \tag{16}$$

where, T_m represents maximum iteration.

The mantis may attack its prey because of its fast movements as it scans its surroundings for nourishment. The following equation can be used to evaluate how the prey is moved to the ambuscade distance:

$$\overrightarrow{x}^{t+1}_{i} = \overrightarrow{x}^{t}_{ar} + \mu * (2 * rv_7 - 1) * (\overrightarrow{x}^{l} + \overrightarrow{rv_8} \times (\overrightarrow{x}^{u} - \overrightarrow{x}^{l})) \tag{17}$$

As observed in Eq. (17), the prey is far away from the invisible sites at the beginning of the optimization process. The prey is transferred around the way of the mantis; therefore, this distance gradually gets smaller as the current iteration is raised. The ambuscade behaviour of mantises and their prey is described mathematically as depicted in Eq. (18):

$$\overrightarrow{x}^{t+1}_{i} \begin{cases} \overrightarrow{x}^{t}_{i} + \alpha * (\overrightarrow{x}^{t}_{ar} - \overrightarrow{x}^{t}_{a}), \ if \ rv_9 \leq rv_{10} \\ \overrightarrow{x}^{t}_{ar} + \mu * (2 * rv_7 - 1) * (\overrightarrow{x}^{l} + \overrightarrow{rv_8} \\ \times (\overrightarrow{x}^{u} - \overrightarrow{x}^{l})), \ otherwise \end{cases} \tag{18}$$

where $x^t_{i,j}$ manifests the current location for the jth dimension of the ith mantis.

The patterns of behaviour of spearers and pursuers is subsequently incorporated in the optimizer with use of the recycling control factor, which splits up the optimization process into segments and helps in assessing the probable search space of an optimization issue. The following equation provides a numerical representation of this factor:

$$F = 1 - t\%(T_m/P)/(T_m/P) \tag{19}$$

where the symbol (%) signifies the remainder operator. Additionally, P manifests the number of cycles, and it is employed to generate an exchange among Eqs. (12) and (18).

C. ATTACKING THE PREY: EXPLOITATION STAGE

The computation of the striking distance and the strike velocity are two crucial pillars that support the effective execution of the hunting process. The striking distance represents the distance between the prey and predator. The mantis' natural hunting habit and efficient approaches of catching prey are imitated by the numerical forms created to design the optimization technique that was presented. As soon as it sees its victim, the mantis begins using its excellent methods for capturing and devouring it. These strategies entail figuring out the velocity and range of the prey's strike. A mathematical formula to determine the striking velocity magnitude of a mantis' front legs' v_s towards its victim is given below:

$$v_s = 1/(1 + e^{l*\rho G}) \tag{20}$$

ρG represents the mantis' strike gravitational acceleration level.

When the mantis achieves a number of 0, mantis realizes that it is not the correct time for assaulting the prey. However, when it reaches a value of one, it moves quickly to assault the intended prey and consumes it before escaping. The equation that follows adjusts how each mantis behaves when snatching its prey:

$$x^{t+1}_{i,j} = \frac{x^t_{i,j} + x^*_j}{2} + v_s * d^t_{si,j} \tag{21}$$

where $x^t_{i,j}$ designates the position of the prey and it is used to educe the distance among them and hasten the attacking process. The praying mantis's size determines the variation in the strike distance. In simple terms, as the size of the mantis increases, the strike distance increases. The following equation is used in the MSA to determine $d^t_{si,j}$:

$$d^t_{si,j} = -(x^t_{i,j} - x^*_j) \tag{22}$$

where x^*_j illustrates the jth dimension of the prey

In accordance with Eq. (22), when $x^t_{i,j}$ is far from the prey, the strike distance is large. Sometimes, following a missed blow, the mantis must change its course in order to be successful. Consequently, using the equation in Eq. (23), the mantis alters its orientation in response to the interchange of dual mantises selected arbitrary from the entire population.

$$x^{t+1}_{i,j} = rv_{12} * (x^t_{a,j} - x^t_{b,j}) + x^t_{i,j} \tag{23}$$

At function evaluation t +1, the term $x^{t+1}_{i,j}$ illustrates the latest location for the mantis jth dimension of i, whilst x^t_a and x^t_b two random mantises that are selected from the current population.

If the mantis strike fails, the neighborhood optima has already trapped the mantis. To get out of the local optima, individuals are required to be skilled at exploration and exploitation. In the next mathematical framework, the algorithm is modified to avoid the mantises choosing new areas where to attack their prey, preventing the algorithm from reaching the local optima.

$$x^{t+1}_{i,j} = x^t_{i,j} + e^{2l}.\cos(2l\pi).\left|x^t_{i,j} - \overrightarrow{x}^{l}_{ar,j}\right| + (2rv_{13} - 1).(x^u_j - x^l_j) \tag{24}$$

The recommended approach uses Eq. (24) with a failure probability to accelerate convergence to the best solution and to avoid stucking in local minima.

The probability in Eq. (25) is intended to gradually decrease with collective current function assessment in order to slow down the exploration phase and eventually accelerate convergence to the nearly optimum result.

$$P_f = a * (\frac{T_m - t}{T_m}) \tag{25}$$

A low value for the variable (a) results in more exploitation at the expense of less exploration. Equation (24) is applied after equation (21) to comply with the probability specified by equation (21) in MSA, whilst Equation (21) and equation (23) are randomly exchanged. The three mathematical equations are included in the MSA to address the problem of local minima and to match the capacity for exploration and exploitation.

D. SEXUAL CANNIBALISM

In praying mantises, sexual cannibalism takes place when the females eat the males immediately during or shortly afterward intercourse. As the initial activity of this behaviour, female mantises pull males to the observes according to the following formula:

$$\vec{x}_i^{t+1} = \vec{x}_i^t + \vec{rv}_{16} * (\vec{x}_i^t - \vec{x}_a^t), \tag{26}$$

where $\vec{x}_i^t$ stands for the female praying mantis, whilst $\vec{x}_a^t$ represents a result that is randomly selected from the population to represent the male chosen to use the female for reproduction and consumption.

Compared to virgin females, who are more likely to do so, mated females seldom drew male attention. At the beginning of the optimization process, mate attraction is likely to occur in order to entice the male to the location of the female. This probability, denoted P_t, is typically mathematically represented as follows:

$$P_t = rv_{17} * \mu \tag{27}$$

where P_c sexual cannibalism percentage.

Then, the male and female mate using the standard crossover operator of the genetic operators to create a new child, which is represented by the formula as follows:

$$\vec{x}_i^{t+1} = \vec{U} * \vec{x}_i^t + (x_{11}^t + \vec{rv}_{18} * (\vec{x}_i^t - x_{11}^t)) * (1 - \vec{U}), \tag{28}$$

The female that consumes the male following or during mating can be mathematically formulated as depicted in Eq. (29):

$$\vec{x}_i^{t+1} = \vec{x}_a^t.\mu.\cos(2\pi l), \tag{29}$$

where $\vec{x}_a^t$ stands for the male, μ is the portion of the male that has been consumed, and the part ($\cos(2\pi l)$) signifies the female freedom to turn the male throughout the consuming procedure.

The computational complexity of the employed methods may be calculated through the multiplication of the number of search agents, total amount of control variables, and the maximum amount of iterations using the commonly used Big O notation. In light of this, each case study's computational complexity is noted as $O(N*D*T_m)$.

TABLE 1. 7-Unit test system considering loading levels.

Loading Levels	Heat	Power
7-unit system (Case 1)	150 MWth	600 MW
7-unit system (Case 2)	175 MWth	250 MW
7-unit system (Case 3)	220 MWth	460 MW

IV. SIMULATION RESULTS

Two test systems, which are the 7-unit test systems and the large 84-unit test system, are evaluated and assessed by the novel MSA. To determine the effectiveness of the proposed MSA, the attained results for the CHP Economic Dispatch are compared with African Vultures Algorithm (AVO) [40], Aquila Optimizer (AO) [41], and Coot Optimizer (CO) [43]. The demonstrated techniques are tested on 7-unit test systems with three loading levels and the large 84-unit test system. The power and heat loading's peak, moderate, and low loading fluctuations are represented by the three loading levels, demonstrating the suggested technique's superiority over the others under all circumstances.

A. IMPLEMENTATION FOR 7-UNIT TEST SYSTEM

The test system under consideration comprises of four thermal generation units, two CHP units, and a heat-only unit. System statistics, including coefficients of losses, the cost of fuel, and heat/power limits, can be obtained from Reference [36] and [47]. In the appendix, the details of the parameters of MSA for the CHP problem and the cost coefficient of the participated units is the 7-unit system are tabulated. The proposed MSA, African Vultures Algorithm (AVO) [40], Aquila Optimizer (AO) [41], and Coot Optimizer (CO) [43] are employed for solving the CHP economic dispatch to minimize targets of fuel costs for this test system. Tabel 1 depicts the several power and heat requirements to be investigated. According to Table 1, there are three different power and heat loading levels that are taken into consideration.

The proposed MSA is employed on Case 1 of the 7-unit system to show the superiority of the MSA. The demand of heat and load, in this case, are 150 MWth and 600 MW, respectively. Table 2 illustrates the operating points provided by MSA, CO, AVO, and AO, where they provide a minimum fuel cost of 10091.93 \$/hr, 10092.95 \$/hr, 10094.58 \$/hr, and 10220.62 \$/hr, respectively. It is worthy illustrated from the table that all the operating points that extracted by MSA, CO, AVO, and AO are inside their permissible limits without any violation. The key benefit of the MSA optimizer's output is that it is able to identify feasible operating points in this large system for each unit.

The convergence characteristics for the MSA are compared with recently developed techniques (CO, AVO, and AO) as manifested in Figure 3. It is worth noted that the proposed MSA has evolution capability for improving the solution quality with reaching the minimum value of 10091.93 \$/hr

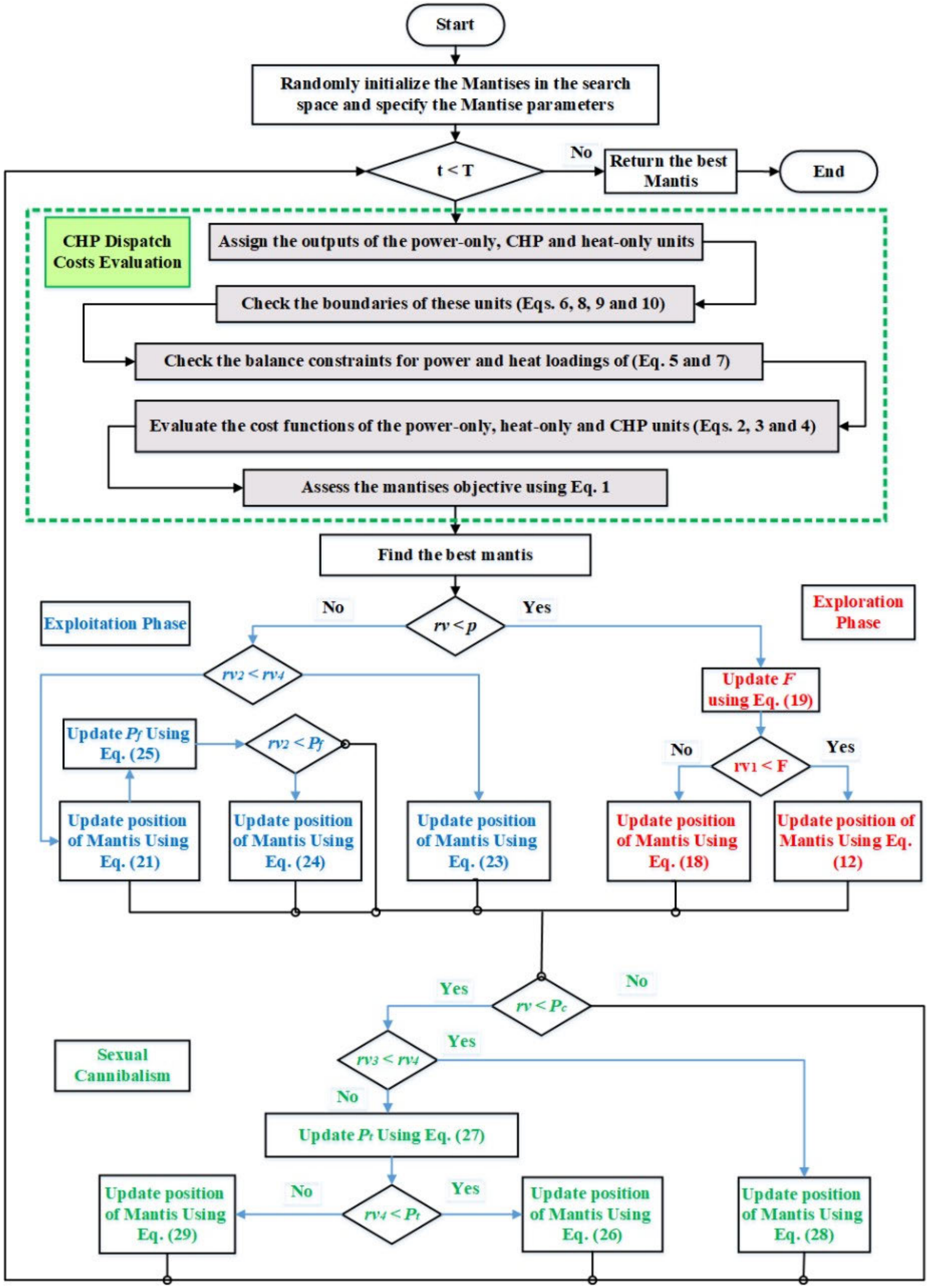

FIGURE 2. Flowchart of MSA.

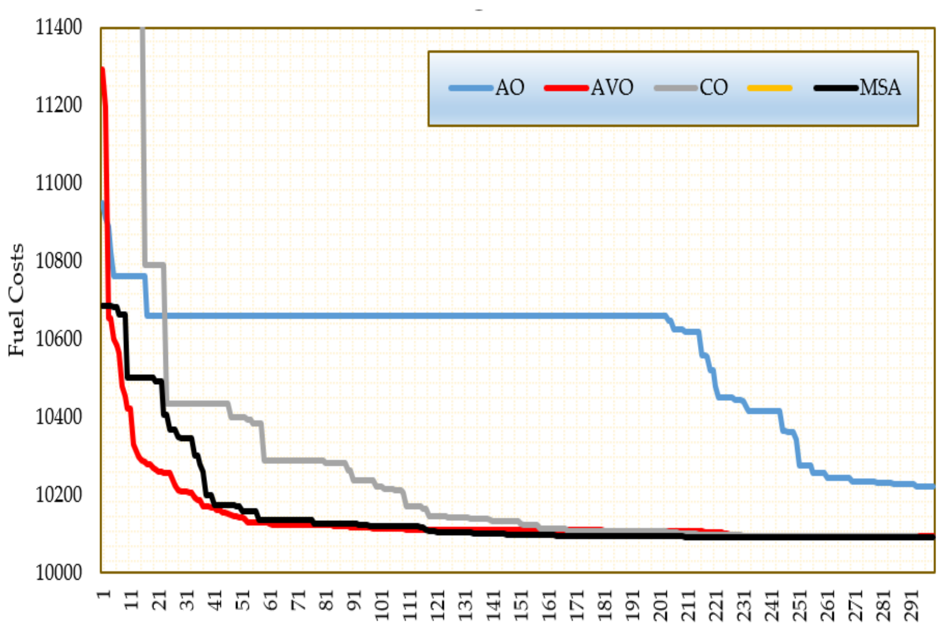

FIGURE 3. Convergence rates for the proposed CO, AVO, AO, and MSA for the 7-unit system (Case 1).

TABLE 2. Results of CO, AVO, AO, and MSA for 7-unit system (Case 1).

Outputs		AO	AVO	CO	MSA
Power only units	Pg1 (MW)	74.80225	45.84584	45.55776	44.86485
	Pg2 (MW)	91.42406	98.54249	98.53915	98.541
	Pg3 (MW)	175	112.6735	112.6734	112.6731
	Pg4 (MW)	124.9242	209.8158	209.8147	209.8158
CHP 1	Pg5 (MW)	93.77399	93.10668	93.41447	94.105
	Hg5 (MWth)	31.82824	33.51435	31.71127	27.64073
CHP 2	Pg6 (MW)	40.07545	40.01564	40.00047	40.00026
	Hg6 (MWth)	74.45646	74.75412	74.99106	74.99558
Heat only unit	Hg7 (MWth)	43.7153	41.73153	43.29767	47.36369
Total Pg		600	600	600	600
Total Hg		150	150	150	150
Costs ($/h)		10220.62	10094.58	10092.95	10091.93

in the 120 iterations compared to other technique which take more iterations and could not find a solution less than the MSA.

The statistical data, through thirty runs, for the proposed MSA and other algorithms proves the effectiveness of the proposed MSA to obtain the result as illustrated in Figure 4, where the proposed MSA obtains the minimum values in each run.

Additionally, to illustrate the superiority of the proposed MSA, a comparative study is conducted between the proposed MSA and other reported optimizers as manifested in Table 3. The proposed MSA, in this table, is compared with Differential Evolution (DE) [48], CPSO [49], Improved Artificial Ecosystem Algorithm (IAEA) [50], time varying acceleration coefficients based PSO (TVAC-PSO) [17], WVO-PSO [37], ECSA [25], CSO [51], improved Mühlenbein mutation based real coded genetic algorithm (RCGA-IMM) [20], Manta Ray Foraging (MRF) optimizer [52], CSO&PPS [53], teaching learning based optimization (TLBO) [49], Bee Colony Optimization (BCO) [54], LCA [55], AIS [56], IGA-NCM [21], and TVAC- particle swarm optimization (PSO) [18]. The proposed MSA achieves the highest performance by using the suggested technique for this problem, as demonstrated in the table, and achieves the lowest generation cost over different optimizers. The comparison validates the suggested MSA approach's effectiveness and superiority. This table reveals that the suggested MSA performs best when used for the CHP economic dispatch issue, obtaining the best generation cost across various optimizers.

For the second loading level of the 7-unit system, the proposed MSA is employed to show the superiority of the MSA. The demand of heat and load, in this case, are 175 MWth and 250 MW, respectively. Table 4 illustrates the operating points provided by MSA, CO, AVO, and AO, where they provide a minimum fuel cost of 9422.40 $/hr, 9428.92 $/hr, 9427.73 $/hr, and 9455.08 $/hr, respectively. It is worthy illustrated that all the operating points that extracted by MSA, CO, AVO, and AO are inside their permissible limits without any violation. The key benefit of the MSA optimizer's output is that it is able to identify feasible operating points in this large system for each unit.

The convergence characteristics for the MSA is compared with recently developed techniques (CO, AVO, and AO) as

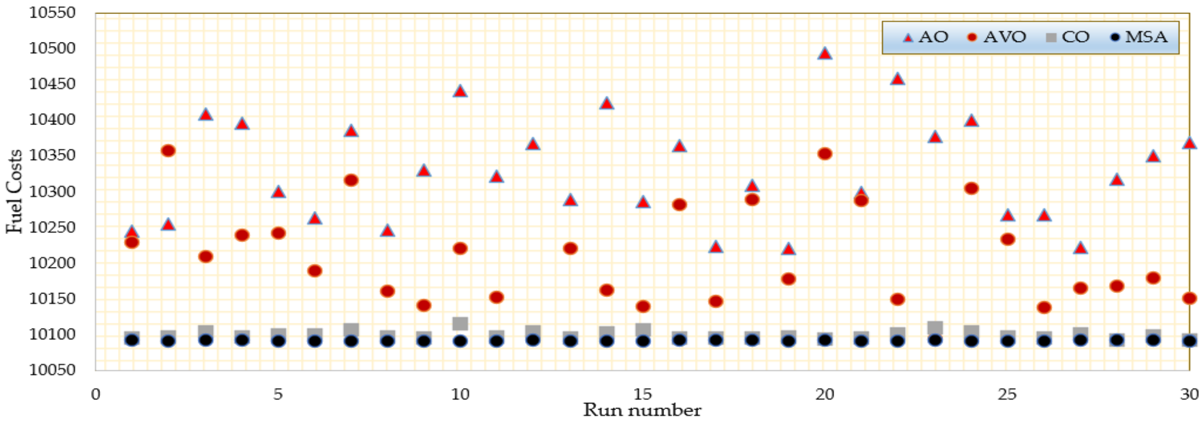

FIGURE 4. Thirty runs of the proposed CO, AVO, AO, and MSA for 7-unit system (Case 1).

TABLE 3. Comparison of the proposed MSA with the reported optimizers for 7-unit system (Case 1).

Optimizer	FC ($/hr)
MSA	10091.93
AO	10220.62
AVO	10094.58
CO	10092.95
IAEA [50]	10,092.18153
HT[28]	10091.9966
DE[48]	10317
TVAC-PSO[17]	10100.32
BCO [54]	10317
RCGA-IMM[20]	10094.0552
CPSO[49]	10325.33
CSO[51]	10094.1267
TVAC-PSO[18]	10244.002
ECSA[25]	10121.9466
LCA[55]	10104.38
TLBO[49]	10094.84
CSO&PPS[53]	10111
WVO-PSO[37]	10310372.015
AIS[56]	10355
MRF[52]	10092.33
IGA-NCM[21]	10107.9071

TABLE 4. Results of the proposed CO, AVO, AO, and MSA for 7-unit system (Case 2).

Outputs		AO	AVO	CO	MSA
Power only units	Pg1 (MW)	18.54192	25.88511	26.65324	28.05061
	Pg2 (MW)	21.0752	20.34919	20.00019	20.03942
	Pg3 (MW)	34.85516	30.18444	30	30.06028
	Pg4 (MW)	40.5671	40	93.3459	40.00244
CHP 1	Pg5 (MW)	94.92229	93.58126	40.00047	91.84326
	Hg5 (MWth)	23.09543	30.72018	32.10592	40.95872
CHP 2	Pg6 (MW)	40.03832	40	40	40.00398
	Hg6 (MWth)	74.75291	75.00086	74.97843	74.98593
Heat only unit	Hg7 (MWth)	77.15167	69.27896	67.921	59.05535
Total Pg		250	250	250	250
Total Hg		175	175	175	175
Costs ($/h)		9455.08	9427.73	9428.92	9422.40

manifested in Figure 5. It is worth noted that the proposed MSA has evolution capability for improving the solution quality with reaching the minimum value of 9422.40 $/hr in the 180 iterations compared to other technique which take more iterations and could not find a solution less than the MSA.

The statistical data, through thirty runs, for the proposed MSA and other algorithms proves the effectiveness of the proposed MSA to obtain the result as illustrated in Figure 6, where the proposed MSA obtains the minimum values in each run.

For the third loading level of the 7-unit system, the proposed MSA is employed to show the superiority of the MSA. The demand of heat and load, in this case, are 220 MWth and 160 MW, respectively. Table 5 illustrates the operating points provided by MSA, CO, AVO, and AO, where they provide a minimum fuel cost of 10190.13 $/hr, 10192.18 $/hr, 10202.71 $/hr, and 10226.55 $/hr, respectively. It is worthy illustrated that all the operating points that extracted by MSA, CO, AVO, and AO are inside their permissible limits without any violation. The key benefit of the MSA optimizer's output is that it is able to identify feasible operating points in this large system for each unit.

The convergence characteristics for the MSA is compared with recently developed techniques (CO, AVO, and AO) as manifested in Figure 7. It is worth noted that the proposed MSA has evolution capability for improving the solution quality with reaching the minimum value of 10190.13 $/hr in the 170 iterations compared to other technique which take more iterations and could not find a solution less than the MSA.

The statistical data, through thirty runs, for the proposed MSA and other algorithms proves the effectiveness of the proposed MSA to obtain the result as illustrated in Figure 8, where the proposed MSA obtains the minimum values in each run.

B. THE 84-UNIT TEST SYSTEM

The proposed MSA is employed on the Large 84-unit system to show the superiority of the MSA. The demand of heat and load, in this system, are 5000 MWth and 12700 MW,

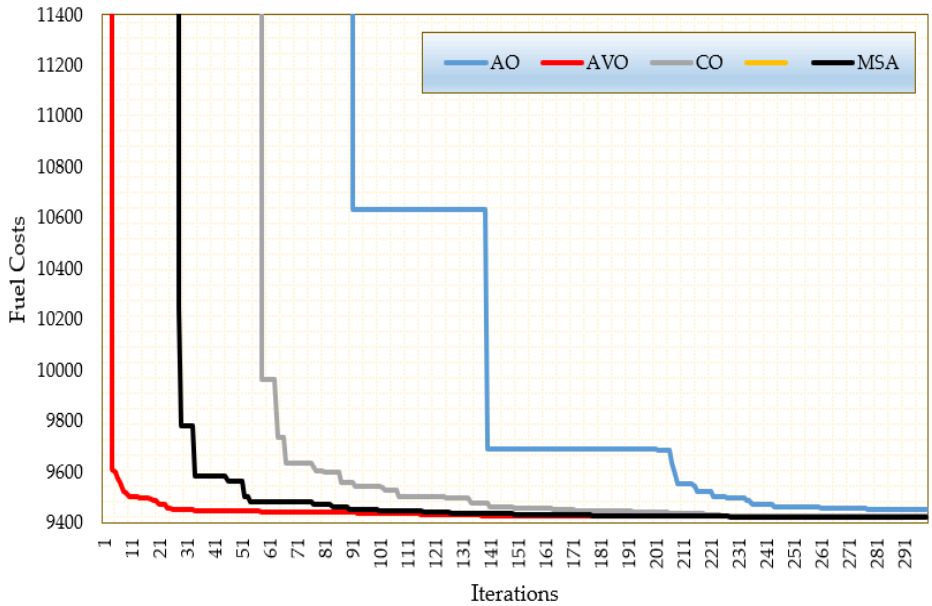

FIGURE 5. Convergence rates of the proposed CO, AVO, AO, and MSA for 7-unit system (Case 2).

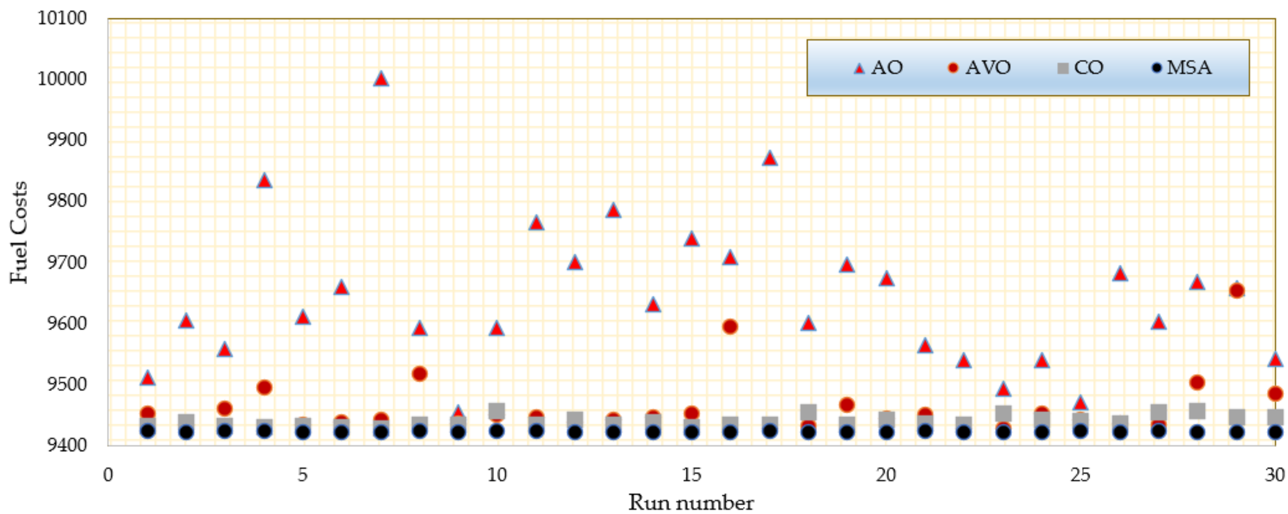

FIGURE 6. Thirty runs for the proposed CO, AVO, AO, and MSA for the 7-unit system (Case 2).

respectively. This system encompasses twenty-four CHP units, twenty heat-only units, and forty conventional thermal units and the unit data were derived from [36]. Table 6 illustrates the operating points provided by MSA, CO, AVO, GBO, and AO, where they provide a minimum fuel cost of 289154.3 \$/hr, 296414.4 \$/hr, 294987.1 \$/hr, 291515.7 \$/hr, and 289518.7 \$/hr, respectively.

It is worthy illustrated that all the operating points that extracted by MSA, CO, AVO, HBO, and AO are inside their permissible limits without any violation. The key benefit of the MSA optimizer's output is that it is able to identify feasible operating points in this large system for each unit.

The results of the proposed MSA, when applied to get the optimal generation cost forissue, are compared with the recently and reported techniques in the literature which are MSA, CO, AVO, HBO, AO, WOA [36], SDO [28], IMPA [28], MRF [52], MPA [28], HT [28], JFSO [35], and HHTJFSO [35] as illustrated in Table 7.

It can be characterized from Table 7 that the proposed MSA delivers the lowest minimum, average, worst of 289154.3 \$/hr, 292113.3 \$/hr, and 290746 \$/hr, respectively, while it provides a standard deviation of 705.9179 \$/hr. As manifested in this table, in accordance with the obtained results of the fuel costs, the suggested MSA outperforms the recently developed techniques and the reported techniques in the literature.

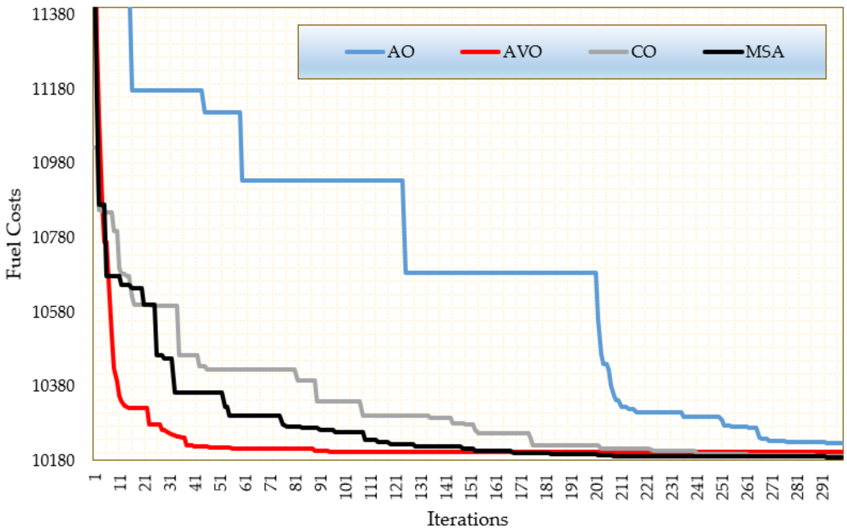

FIGURE 7. Convergence rates of the proposed CO, AVO, AO and MSA for 7-unit system (Case 3).

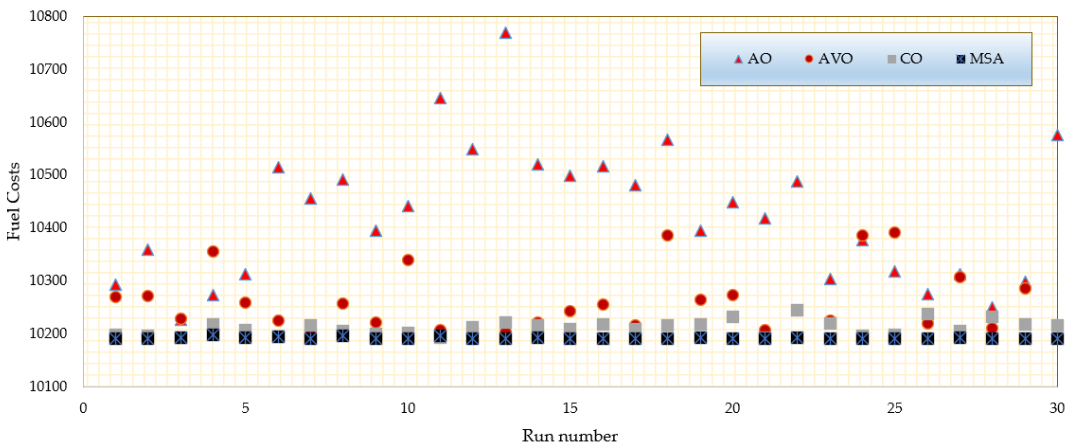

FIGURE 8. Thirty runs of the proposed CO, AVO, AO, and MSA for 7-unit system (Case 3).

TABLE 5. Results of the proposed CO, AVO, AO, and MSA for 7-unit system (Case 3).

Outputs		AO	AVO	CO	MSA
Power only units	Pg1 (MW)	74.55913	75	10.06264	10.0073
	Pg2 (MW)	98.6217	20.02156	86.87738	86.62808
	Pg3 (MW)	31.67218	113.0778	112.4821	112.6703
	Pg4 (MW)	125.7751	124.9079	124.7142	124.8706
CHP 1	Pg5 (MW)	89.26281	86.99276	85.82674	85.82065
	Hg5 (MWth)	56.69881	69.51089	76.37732	76.41341
CHP 2	Pg6 (MW)	40.10912	40	40.03702	40.00311
	Hg6 (MWth)	75.08621	75.00086	75.00244	74.99728
Heat only unit	Hg7 (MWth)	88.21497	75.48824	68.62024	68.5893
Total Pg		460	460	460	460
Total Hg		220	220	220	220
Costs ($/h)		10226.55	10202.71	10192.18	10190.13

Consequently, the MSA illustrates better practical ability, greater inclusiveness comparing to the recent and reported techniques. The convergence characteristics for the MSA is compared with recently developed techniques (CO, AVO, HBO, and AO) as manifested in Figure 9. It is worth noted that the proposed MSA has evolution capability for improving the solution quality with reaching the minimum value of 289154.3 $/hr in the 2300 iterations compared to other technique which take more iterations and could not find a solution less than the MSA. The statistical data, through thirty runs, for the proposed MSA and other algorithms proves the effectiveness of the proposed MSA to obtain the result as illustrated in Figure 10, where the proposed MSA obtains the minimum values in each run.

In order to conduct the statistical significance tests and the results have been accurately implemented, the t-test is performed for all cases studied and both systems. Table 8 records the p-value regarding the t-test which is used to compare the means of the AO, AVO and CO compared to the proposed MSA across the multiple runs. To evaluate the significance

TABLE 6. Results of the proposed CO, AVO, AO, GBO and MSA for 84-unit system.

Unit	AO	AVO	CO	GBO	MSA	Unit	AO	AVO	CO	GBO	MSA
Pg1	112.9303	73.44392	109.078	113.6807	112.3718	Pg57	10.0857	29.99448	13.50891	18.9996	10.45587
Pg2	113.5818	76.84842	94.71494	113.4458	73.73106	Pg58	16.47404	11.57848	36.69099	23.41707	11.29778
Pg3	98.89659	111.5251	90.10443	96.12848	97.35785	Pg59	10.08371	17.98299	22.99403	16.09832	20.77163
Pg4	181.3366	183.7604	179.371	133.9634	129.7907	Pg60	17.7765	10.20646	42.96487	14.9864	10.52516
Pg5	89.95437	91.12012	76.04319	87.68001	87.79726	Pg61	78.38804	75.75407	45.37674	74.28107	53.72143
Pg6	111.2916	140	107.0307	139.999	139.7648	Pg62	57.35736	84.15999	84.25977	66.71939	35.06594
Pg7	259.7322	277.4208	277.2356	282.1243	259.6141	Pg63	35.79921	71.47788	39.86554	53.7046	44.71833
Pg8	284.7853	177.2329	285.5333	285.2583	285.1405	Pg64	42.53892	81.96059	68.38002	35.51324	58.40742
Pg9	284.088	286.6088	286.6867	291.8823	284.6022	Hg41	152.0668	117.3669	112.1868	166.6626	132.1614
Pg10	279.5615	275.5382	202.2588	277.8487	205.1206	Hg42	137.0974	140.6913	114.2461	130.9178	127.353
Pg11	243.6417	301.7237	242.0416	94	318.3837	Hg43	134.334	118.0854	134.6298	139.7959	113.7822
Pg12	244.8346	244.0655	316.6434	243.2088	243.5139	Hg44	120.0947	148.9054	128.6867	136.5777	125.9375
Pg13	394.3109	304.5858	387.3341	392.8991	394.2846	Hg45	84.82553	104.1811	94.99276	126.2356	89.51973
Pg14	394.2969	125.5657	309.1711	393.8365	394.1379	Hg46	76.90414	115.5389	96.28678	128.0484	95.91331
Pg15	394.2227	389.8286	307.5515	483.2122	394.2625	Hg47	94.17188	115.0018	91.24365	100.5074	89.32023
Pg16	394.3755	484.0392	480.7868	304.5121	394.3098	Hg48	99.35045	80.46205	86.56369	108.639	86.21463
Pg17	488.6774	494.0047	492.7146	399.5344	489.2983	Hg49	142.1256	136.7245	119.2939	125.3458	133.7497
Pg18	399.7904	499.9819	485.6608	489.2567	489.2748	Hg50	112.8267	109.4325	124.79	119.578	139.213
Pg19	512.3205	511.2821	527.4369	421.5196	511.4246	Hg51	134.4619	132.9746	134.6047	106.9414	122.4078
Pg20	511.9799	527.1609	505.6924	511.0379	511.4467	Hg52	124.1038	146.8592	153.2127	144.7383	147.0149
Pg21	523.9326	544.9031	430.9171	522.3615	524.0752	Hg53	82.67116	124.3826	87.39848	77.98408	96.67149
Pg22	526.4314	526.4581	523.3778	523.2815	523.281	Hg54	95.95263	101.5499	79.58578	76.76457	108.6191
Pg23	523.4525	526.0657	523.4335	523.2627	523.4097	Hg55	113.1362	84.47716	113.2622	109.4475	101.5701
Pg24	523.3527	525.1784	514.4749	523.2742	523.3693	Hg56	79.17505	95.35528	85.33739	96.61596	93.41527
Pg25	523.3814	528.7292	522.3427	523.2716	523.2292	Hg57	40.02176	48.56948	38.41497	43.8574	38.65994
Pg26	523.6753	532.9909	517.7571	523.2794	523.349	Hg58	42.61846	40.67681	49.65092	45.74645	40.55474
Pg27	12.02897	13.6045	24.57583	10.00445	12.09596	Hg59	39.98155	43.42171	44.55277	42.61399	44.60935
Pg28	10.38567	13.3602	14.1689	10.00036	10.10763	Hg60	43.18741	39.18548	51.48045	42.13746	40.22182
Pg29	10.34272	10.05025	18.83867	10.38125	10.01811	Hg61	39.50125	38.52502	14.88893	37.8519	28.34263
Pg30	91.49626	96.94382	90.12684	87.87278	87.90801	Hg62	30.14744	42.34584	39.198	34.41638	20.01485
Pg31	159.9151	174.0488	177.8	189.993	170.0826	Hg63	20.31772	36.5813	19.5977	28.50203	24.39999
Pg32	189.9045	145.8779	161.9946	189.9952	189.6642	Hg64	22.97963	41.33458	30.33198	20.23374	30.61318
Pg33	172.1171	110.8506	179.7584	159.7312	189.649	Hg65	377.1406	329.4876	360.2313	331.2062	334.4751
Pg34	199.8959	188.9296	184.7595	197.2413	164.7818	Hg66	378.7252	348.7063	475.5052	351.0053	387.4499
Pg35	173.5952	166.1083	190.6614	164.7978	164.8956	Hg67	369.0806	351.0604	351.7349	332.3729	398.444
Pg36	166.2299	183.1336	165.7417	199.5484	181.4373	Hg68	376.6617	351.6806	405.3827	355.9698	371.737
Pg37	103.2134	86.37738	90.46958	109.8321	109.9972	Hg69	59.97552	59.99976	52.00316	59.99998	59.70257
Pg38	92.63005	110	94.87563	109.7687	89.08379	Hg70	59.64363	60	41.64037	59.99787	59.98714
Pg39	92.3572	91.20645	95.23621	109.7903	89.75182	Hg71	59.91641	60	51.29129	59.99997	59.98494
Pg40	511.483	526.3835	524.4511	511.2756	511.2892	Hg72	59.86118	59.99927	59.02946	59.80447	59.96787
Pg41	165.7105	103.6636	112.8394	191.2467	129.7606	Hg73	59.93549	59.99997	59.17069	59.99925	59.36095
Pg42	138.6637	144.9561	107.8652	127.5407	121.1971	Hg74	59.48382	59.99994	58.81389	59.90457	59.89292
Pg43	133.8349	104.6727	135.2552	143.3596	97.01068	Hg75	59.93676	60	57.67098	59.99769	59.94224
Pg44	108.3515	159.5927	125.3073	137.9584	118.7998	Hg76	59.74407	59.99954	58.03681	59.97746	59.96899
Pg45	51.416	73.80288	64.9336	99.35108	56.82343	Hg77	119.7302	119.9998	113.6479	119.9957	119.7965
Pg46	42.28322	86.95985	67.75278	101.4511	64.23568	Hg78	119.923	96.45269	116.1935	119.9999	119.9956
Pg47	62.33353	86.33775	67.19565	69.54783	56.63051	Hg79	119.8293	119.9928	108.3423	120	119.9589
Pg48	68.35043	46.32635	56.96038	78.97772	53.04891	Hg80	119.7344	120	118.4424	120	119.227
Pg49	148.105	138.178	121.2504	117.8325	132.6037	Hg81	119.5256	119.9967	117.4028	119.9992	119.987
Pg50	95.74875	89.81802	130.0712	107.3322	142.7567	Hg82	119.7269	120	118.3697	119.7771	119.8826
Pg51	134.3363	138.3411	134.6358	84.81492	112.6393	Hg83	119.5221	119.9996	112.6557	119.8374	119.9731
Pg52	115.4629	184.7832	170.3193	152.1656	156.2398	Hg84	119.8504	119.9963	119.9978	119.9958	119.9858
Pg53	48.95778	97.20458	55.16503	43.49306	65.10409	Sum (Pg)	12700	12700	12700	12700	12700
Pg54	64.35291	70.75481	46.30104	42.10911	78.94742	Sum (Hg)	5000	5000	5000	5000	5000
Pg55	84.30841	50.97752	86.32983	80.06797	70.79563	TFC ($/hr)	289518.7	294987.1	296414.4	291515.7	289154.3
Pg56	44.85104	63.57905	54.92552	65.04026	61.33976						

of the results using these tests, the critical value or p-value associated with a chosen significance level is considered to be 0.01. As shown, all the p-values are below the significance level. Thus, it indicates that the observed differences are statistically significant.

V. CONCLUSION

A Mantis Search Algorithm (MSA) is proposed, in this article, for decreasing the whole fuel cost of the CHP Economic Dispatch. The Mantis Search Algorithm (MSA) has three stages of optimization which are hunting, attacking,

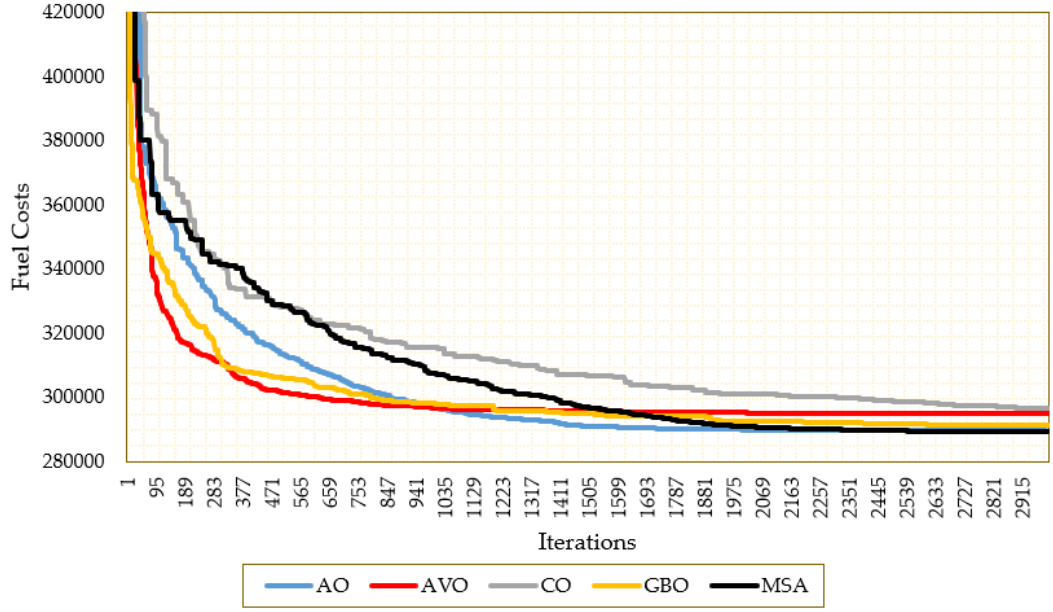

FIGURE 9. Convergence rates of the proposed CO, AVO, AO, GBO and MSA for 84-unit system.

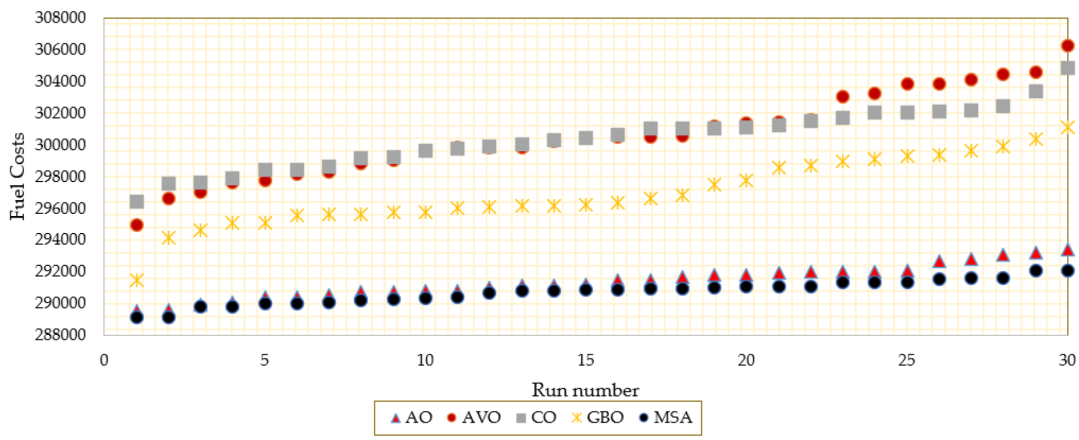

FIGURE 10. Thirty runs of the proposed CO, AVO, AO, GBO and MSA for 84-unit system.

TABLE 7. Comparison of the proposed MSA with the reported optimizers for 84-unit system.

Optimizer	OBC ($/hr)	Average	Worst	Std
MSA	289154.3	292113.3	290746	705.9179
GBO	291515.7	301133.1	296983	2149.608
CO	296414.4	304848	300395.6	1880.976
AVO	294987.1	306217.7	300618.8	2678.679
AO	289518.7	293439	291393.6	1042.976
HT	289822.4	290891	292342.5	886.4399
JFSO[35]	290323.8	292366.9	293747.4	988.0994
WOA[36]	290123.97	-	-	-
MPA[28]	294717.7	-	-	-
SDO[28]	292788.5	-	-	-
MRF[52]	291225.6	-	-	-
IMPA[28]	289903.8	-	-	-

and cannibalism. The proposed MSA is employed on the 7-unit test system with three load levels including varying power and heat load and considering valve point effect. Furthermore, the proposed MSA is employed on the Large

TABLE 8. P-value of the T-test of the compared algorithms.

		AO vs MSA	AVO vs MSA	CO vs MSA
7-unit system	Case 1	1.02E-24	3.00E-12	3.70E-10
	Case 2	4.31E-14	7.28E-05	1.23E-14
	Case 3	3.71E-14	2.33E-08	4.28E-10
84-unit system		9.20E-03	4.86E-27	1.09E-33

84-unit system to show the superiority of the MSA. Myriads of recent meta-heuristic optimizers are employed, for the first time, on the CHP economic dispatch which are AVO, GBO, AO, and CO. The statistical data, through thirty runs, for the proposed MSA and other algorithms shows the effectiveness of the proposed MSA to obtain the solution. Besides, the proposed MSA gets a high reduction in the total fuel cost considering the diverse loading levels. In accordance with the obtained results of the fuel costs, the suggested MSA outperforms the recently developed techniques and the

TABLE 9. Parameters settings of MSA and cost coefficients of the 7 unit-system.

Parameters settings of MSA

Symbol of Controlling parameter	Value
P_c	0.2
ρG	6
P	2
a	0.5
A	1.0
p	0.5

cost coefficients of the 7 unit-system

1. Cost coefficient of the power-only units

Generator	$\delta_{1,i}$	$\delta_{2,i}$	$\delta_{3,i}$	λ_i	ρ_i
1	0.010	2.0	25.0	100.0	0.040
2	0	1.80	60.00	140.0	0.040
3	0	2.10	100.00	160.0	0.040
4	0	2.00	120.00	180.0	0.040

2. Cost coefficient of the CHP units

CHP units	α_1	α_2	α_3	α_4	α_5	α_6
1	0.0345	14.50	2650.0	0.030	4.20	0.0310
2	0.0435	36.0	1250.0	0.0270	0.60	0.0110

3. Cost coefficient of the heat-only units

Heat-only units	γ_1	γ_2	γ_3
1	0.0380	2.01090	950.0

reported techniques in the literature. Moreover, the MSA illustrates better practical ability, greater inclusiveness compared to the recent and reported techniques.

APPENDIX

Table 9 provides the details of the parameters of MSA for the CHP problem and also the complete data of the cost coefficient of the participated units is the 7-unit system [57].

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GHAREEB MOUSTAFA received the bachelor's and master's degrees in electrical engineering from Suez Canal University, Egypt, in 1998 and 2003, respectively, and the Ph.D. degree in electrical engineering with cooperation channel system between Suez Canal University and Dresden Technical University (TUD), Dresden, Germany, in 2010. From 1998 to 2003, he was a Research and Teaching Assistant with the Electrical and Computer Engineering Department, Faculty of Engineering, Suez Canal University, then an Assistant Lecturer, from 2003 to 2007. From 2007 to 2009, he was a Researcher and a Ph.D. Student with the Institute of High Voltage and Current, TUD. From 2010 to 2013, he was a Lecturer with the Electrical Engineering Department, Faculty of Engineering, Suez Canal University. Since 2013, he has been an Assistance Professor with the Electrical Engineering Department, Faculty of Engineering, Jazan University, Jazan, Saudi Arabia. His research interests include high voltage and high current, electric connector, and power quality, and recently power system optimization.

HASHIM ALNAMI received the bachelor's degree in electrical engineering from Jazan University, Saudi Arabia, in 2013, the master's degree in electrical engineering, specialist in electrical power systems from Southern Illinois University, IL, USA, in 2018, and the Ph.D. degree in electrical engineering, specialist in electrical power systems from Wichita State University, KS, USA, in 2021. He was a Power Engineer with Saudi Aramco Company, Dhahran, Saudi Arabia, from 2013 to 2014. Since 2021, he has been an Assistance Professor with the Electrical Engineering Department, Jazan University, Jazan, Saudi Arabia. His research interests include power system distribution, power generation, power system analysis, renewable energy sources, and power control.

SULTAN H. HAKMI received the bachelor's degree in electrical engineering from the King Fahd University of Petroleum and Minerals, Saudi Arabia, in 2013, and the master's and Ph.D. degrees in electrical engineering, specialist in electrical power systems from Wichita State University, KS, USA, in 2017 and 2021, respectively. He was a Teaching Assistant with the Electrical Engineering Department, Jazan University, Jazan, Saudi Arabia, from 2013 to 2014. From 2016 to 2021, he was a Research Assistant while he was a Student with the Electrical Engineering Department, Wichita State University. Since 2021, he has been an Assistance Professor with the Electrical Engineering Department, Jazan University. His research interests include power system distribution, energy management, power system analysis, renewable energy sources, power markets, and recently power system optimization.

ABDULLAH M. SHAHEEN was born in Tanta, Egypt, in 1985. He received the B.Sc. degree from Suez Canal University, Port Said, Egypt, in 2007, and the M.Sc. and Ph.D. degrees from Menoufia University, Shebeen El-Kom, Egypt, in 2012 and 2016, respectively. He is currently with the Department of Electrical Engineering, Faculty of Engineering, Suez University, El-Suweis, Egypt. His research interests include power system operation, control, and planning; the applications of optimization algorithms in electric power systems; renewable integration; and smart grids.

AHMED R. GINIDI received the B.Sc. degree in electrical engineering from Fayoum University, Egypt, in 2007, and the M.Sc. and Ph.D. degrees from Cairo University, Egypt, in 2010 and 2015, respectively. He is currently an Associate Professor with Suez University. His main research interests include power system operation, control, and planning; the applications of optimization algorithms in electric power systems; renewable integration; and smart grids.

MOSTAFA A. ELSHAHED received the B.Sc., M.Sc., and Ph.D. degrees in electric power engineering from Cairo University, in 2005, 2008, and 2013, respectively. He was a Postdoctoral Researcher with the University of Porto, Portugal, and The University of Manchester, U.K. He is currently an Associate Professor with the Buraydah Private Colleges and on leave from Cairo University. His research interests include power quality, power systems stability, power systems operations, stochastic optimization, and integration of renewable energy sources.

HANY S. E. MANSOUR received the B.Sc. degree in electrical engineering and the M.Sc. and Ph.D. degrees in electrical engineering, specialist in electrical power systems from Suez Canal University, Egypt, in 2013, 2017, and 2021, respectively. He is an Assistance Professor with the Electrical Engineering Department, Suez Canal University. His research interests include power systems planning and operation, renewable energy resources, microgrids, optimization, and power control.