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# Economic Dispatch of Multi-Microgrid Systems with Renewable Energy Sources Using Marine Predator Algorithm

**Adel A. Abou El-Ela[1], Ragab A. El-Sehiemy[2], Nora A. Abdel Aziz[1], Mohamed T. Mouwafi[1,*]**

*[1] Electrical Engineering Department, Faculty of Engineering, Menofia University, Egypt*
*[2]Electrical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Egypt*
*([*] Corresponding author: m_mouwafi@sh-eng.menofia.edu.eg)*

**ABSTRACT**

The optimal operation of multi-microgrids (MMGs) can be achieved by interconnection of them for power exchange between them and by reducing the total operation costs of different types of renewable energy resources (RERs) in MMGs. Therefore, solving the economic dispatch (ED) problem becomes one of the main challenges for the optimal operation of RERs by finding the optimal scheduling of these sources. This paper presents a procedure based on the marine predator optimizer (MPO) algorithm for solving the ED problem in MMGs. The minimization of total operating costs of RERs and battery energy storage (BES) is considered an objective function (OF) while satisfying the system constraints. The proposed algorithm is applied to two-microgrid systems connected together for solving the ED problem. The numerical results obtained for separate operation of MGs and MMGs using the proposed MPO are compared with other techniques such as jellyfish search (JS), particle swarm optimization (PSO), and differential evaluation algorithm (DEA) to prove the robustness of the proposed MPO for the economical operation of the MMGs.

***Keywords***: *Economic dispatch; multi-microgrids; renewable energy resources; battery energy storage; marine predator algorithm.*

## 1. Introduction

Consumption of electricity leads to an increasing requirement for renewable energy generation. Therefore, microgrids (MGs) enhance efficiency and decrease disruption[1,2]. MG is expected to provide a solution to a variety of challenges facing traditional centralized networks[3,4]. The benefits of small-scale power plants positioned directly on the load center include reduced power losses, improved efficiency, and less supply disruption. MGs are also believed to be better suited as renewable energy resources (RERs) for distribution system applications [5]. To handle the different issues in the islanded mode of MG, interconnection of two or more MGs is carried out [6]. The interconnection of multi-microgrid (MMG) systems improves the performance of the overall grid while keeping the flexibility of island model operation. By linking MMGs, the system becomes more resilient to severe weather and natural disasters and performs better as a whole, all the while retaining the ability to operate in an islanded model and reaping the rewards of MGs[7-9]. Various studies have been conducted with regard to the interconnection of several MGs into the system. Difficulties coordinating distribution networks in MMGs, which might be connected to the central grid, other MGs, or islands, were presented in [10].

ED seeks to identify the best-generating unit scheduling by considering certain operating constraints to minimize the cost of generation [11-13]. In [14], a distributed primal-dual consensus method was used to minimize a sum of quadratic generation cost functions that contain the supply-demand balance constraint, the individual constraint, the capacity constraint, and the ramp-rate constraint. In [15], a parallel and distributed computation method was applied for dynamical economic dispatch over a cyber-physical system. However, the proposed algorithm's convergence stages are dependent on the beginning points and only examine a single source of energy from thermal generators. In [16], particle swarm optimization (PSO) and genetic algorithm (GA) were used to solve the ED of MMG systems while meeting power system restrictions. In [17], an enhanced cuckoo search algorithm (CSA) was used to present a complete economic model for power dispatch optimization in MMGs. In [18], the PSO was applied to solve the ED problem in the MMG system.

The optimization issue of ED is very difficult, multi-constraint, and extremely nonlinear. Therefore, current metaheuristic optimization techniques such as GA [19], and PSO [20] were used to solve the ED problem. Recently, one of powerful metaheuristic optimization techniques called the marine predator algorithm (MPO) is used to solve different optimization problems with more effectively and efficiently than other optimization techniques, because of robustness, speed of convergence, and simplicity [21].

From the previous literature review, it can be concluded that, many published papers used old optimization techniques and ignored the RERs in solving the ED problem in MMGs. Therefore, this presents an appropriate MPO for solving the ED problem in separate MGs and MMGs by identifying the best scheduling of RERs and battery energy storage (BES). By comparing the acquired results with other methods such as jellyfish (JS) [22,23], differential evaluation algorithm (DEA) [24], and PSO. The main contributions of this paper are enumerated as follows:

(i) Applying the proposed MPO successfully for solving the ED problem in MMGs by finding the optimal scheduling of RERs considering the total costs of MMG operation.
(ii) Investigating two modes of MGs operation (two separate MGs and MMGs) for each objective function (OF) to prove the superiority of the proposed algorithm when compared with other methods.
(iii) Evaluating the proposed MPO for solving the ED problem in MMG by comparison the results of statistical analysis with other methods.
(iv) Proving the superiority of the proposed MPO for solving the ED problem in MMG by comparing the obtained results with other techniques such as DE, PSO, and JS.

This paper is structured as follows: Part 2 introduces the problem formulation by modeling of RERs, the OF, and system constraints at MG and MMG. The proposed MPO is depicted in Part 3. Part 4 presents the MPO approach for solving the ED problem in MMG. Part 5 contains applications with numerical findings and discussion, while Part 6 contains the paper's ultimate conclusion.

## 2. Problem Formulation

This paper aims to solve the ED problem in MMG considering RERs by minimizing the total operation cost.

### *2.1 Modelling of generation sources*

Different types of generation sources such as conventional generators, wind, solar, and BES are considered. The modeling of these types is formulated as follows:

- *Modelling of conventional generators*

The optimal operation of conventional generators aims to minimize the total fuel cost. Therefore, the total fuel cost of conventional sources can be formulated as [25]:

$$Min\left(F_c\right) = \sum_{i=1}^{N_G} a_i P_i^2 + b_i P_i + c_i \qquad (1)$$

where, $P_i$ is the power generated from generation unit $i$, $a_i$, $b_i$, and $c_i$ are the coefficients of the fuel cost function for generation unit $i$, and $N_G$ is the total number of conventional generators.

- *Modelling of wind-power generation*

The output power of wind generation unit ($P_{wo}$) can be expressed as:

$$P_{wo}(t) = \begin{cases} 0 & if \;\; V_w \le V_{ci} \; or \; V_w \ge V_{co} \\ A \times V_w^3 - B \times P_{w,i}^r & if \;\; V_{ci} \le V_w \le V_r \\ P_r & if \;\; V_r \le V_w \le V_{co} \end{cases} \qquad (2)$$

where, $A = \left(\dfrac{P_{w,i}^r}{V_r^3 + V_{ci}^3}\right)$, $B = \left(\dfrac{V_{ci}^{\,3}}{V_r^{\,3} + V_{ci}^{\,3}}\right)$

where, $V_w$, $V_r$, and $V_{co}$ are the wind, rated, cut-in and cut-out speeds, respectively. $P_{wo}$ and $P_{w,i}^r$ are the output and rated power generated at wind speed $v$, respectively.

Now, the cost of wind turbine cost can be expressed as [26]:

$$F_w = 10 \times P_w \qquad (3)$$

- *Modelling of solar power generation*

The cost function of solar generation units can be cleared as [22]:

$$F_s = 2.5 \times P_s \qquad (4)$$

where, $P_S$ is the output power from PV units.

- *Modelling of BES*

The cost function of BES can be obtained as:

$$F_b = 2.5 \times P_b \tag{5}$$

where, $P_b$ is the stored power in kW.

*2.2 Objective function (OF)*

The OF in this paper aims to minimize overall cost of the MMG, which can be formulated as:

$$Min\ F = \sum_{m=1}^{N_{MG}} \left[ \sum_{t=1}^{T} \left( \sum_{i=1}^{N_d} F_c(t) + \sum_{j=1}^{N_s} F_w(t) + \sum_{k=1}^{N_w} F_s(t) + \sum_{l=1}^{N_b} F_b(t) \right) \right] \tag{6}$$

where, $F_c(t)$ is the total generation cost of conventional sources such as diesel. $F_w(t)$, $F_s(t)$, and $F_b(t)$ are the total generation cost of wind, solar, and battery units at time $t$, respectively. $N_{MG}$, $N_d$, $N_s$, $N_w$, and $N_b$ are the total number of *MGs*, diesel, solar, wind, and battery units, respectively. $T$ is the time horizon.

*2.3 System constraints*

The OF in Eq. (6) is minimized under the following constraints [27]:

$$\sum_{i=1}^{N_d} P_{di}(t) + \sum_{j=1}^{N_w} P_{wj}(t) + \sum_{k=1}^{N_s} P_{sk}(t) + \sum_{l=1}^{N_b} P_{bl}(t) = P_D(t), \quad t \in T \tag{7}$$

$$P_{di}^{\min} \le P_{di} \le P_{di}^{\max}, \qquad i \in N_d,\ t \in T \tag{8}$$

$$P_{wj}^{\min} \le P_{wj} \le P_{wj}^{\max}, \qquad j \in N_w,\ t \in T \tag{9}$$

$$P_{sk}^{\min} \le P_{sk} \le P_{sk}^{\max}, \qquad k \in N_s,\ t \in T \tag{10}$$

Eq. (7) aims to check the power balance constraint between generation sources and load demand. Eqs. (8), (9), and (10) represent the inequality constraints of the active power generated from diesel, wind, and solar at time $t$, respectively.

## 3. Marine Predator Algorithm

In this paper, three optimization techniques are applied to solve the ED problem in MMG system. The marine predator optimizer (MPO) was created by nature, with physiological connections based on Ramezani, Bahmanyar, and Razmjooy [28]. It conforms to principles for the best searching methods and meets rate procedures by using a certain search space.

$$X_0 = X_{\min} + rand \otimes \left( X_{\max} - X_{\min} \right) \tag{11}$$

where, $X_{min}$ and $X_{max}$ are the lower and higher bounds of control variables, respectively. *rand* is a random number from 0 to 1 and $\otimes$ is the dot product.

The fittest theory states that top predators ($X_{i,j}$ refers to the $j^{th}$ dimension of $i^{th}$ prey) are better hunters. By updating the original Prey matrix and duplicating the top member vector $n$ times, they create an Elite matrix depending on the position of the prey. This involves $n$ population numbers and $d$ dimensions. Depending on varying speed ratios, the MPO search process is separated into three parts.

*Phase 1*: Prey accepts Brownian motion, predator focuses on exploratory behavior. The mathematical model described at $Iter < \frac{1}{3}\ Max\_Iter$ as follows:

$$\overrightarrow{stepsize_i} = \overrightarrow{R_B} \otimes (\overrightarrow{Elite_i} - \overrightarrow{R_B} \otimes \overrightarrow{\mathrm{Pr}ey_i}), \quad i = 1, 2, ......, n \tag{12}$$

$$\overrightarrow{\mathrm{Pr}ey_i} = \overrightarrow{\mathrm{Pr}ey_i} + P.\vec{R} \otimes \overrightarrow{stepsize_i} \tag{1}$$

where, $\overrightarrow{R_B}$ is a Brownian random number vector within the range [0,1], $P$ is a constant, $\vec{R}$ is a vector of random numbers in [0,1], *Iter*, and *Max_Iter* refer to the current iteration, and the maximum number of iterations, respectively.

*Phase 2*: This phase investigates Lévy prey and Brownian predator movements, examining exploration and exploitation processes. The mathematical model cleared at $\frac{1}{3}\ Max\_Iter \le Iter < \frac{2}{3}\ Max\_Iter$ as:

(*i*) The first part of the population shows the behavior as:

$$\overrightarrow{stepsize_i} = \overrightarrow{R_L} \otimes (\overrightarrow{Elite_i} - \overrightarrow{R_L} \otimes \overrightarrow{\mathrm{Pr}ey_i}), \quad i = 1, 2, ....., n/2 \tag{2}$$

$$\overrightarrow{\mathrm{Pr}ey_i} = \overrightarrow{\mathrm{Pr}ey_i} + P.\vec{R} \otimes \overrightarrow{stepsize_i} \tag{3}$$

where, $\overrightarrow{R_L}$ is a Lévy distribution-based vector of random integers that perform Lévy movement.

(*ii*) The other part of the population shows in the exploratory behaviors:

$$\overrightarrow{stepsize_i} = \overrightarrow{R_B} \otimes (\overrightarrow{R_B} \otimes \overrightarrow{Elite_i} - \overrightarrow{\mathrm{Pr}ey_i}) \tag{4}$$

$$\overrightarrow{\mathrm{Pr}ey_i} = \overrightarrow{Elite_i} + P \times CF \otimes \overrightarrow{stepsize_i} \tag{5}$$

where, $CF$ is an adaptive parameter that sets the size of the predator step, which can be expressed as:

$$CF = \left( 1 - \frac{Iter}{Max\_Iter} \right)^{\left( 2 \frac{Iter}{Max\_Iter} \right)} \tag{6}$$

*Phase 3*: Predators hunt prey faster than goals as clarified at $Iter \ge \frac{2}{3}\ Max\_Iter$ as follows:

$$\overrightarrow{stepsize_i} = \overrightarrow{R_L} \otimes (\overrightarrow{R_L} \otimes \overrightarrow{Elite_i} - \overrightarrow{\mathrm{Pr}ey_i}), \quad i = 1, 2, ..., n \tag{7}$$

$$\overrightarrow{\mathrm{Pr}ey_i} = \overrightarrow{Elite_i} + P.CF \otimes \overrightarrow{stepsize_i} \tag{20}$$

Lévy method uses predator movement, combining Elite and step size, to predict predator behavior. Environmental factors like eddy formation and fish aggregating devices (FADs) impact predator behavior, requiring longer steps.

$$\vec{Prey}=\begin{cases}\vec{Prey}+CF\left[\vec{X}_{\min}+\vec{R}\otimes\left(\vec{X}_{\max}-\vec{X}_{\min}\right)\right]\otimes\vec{U} & if \quad r\le FADs\\ \vec{Prey}+\left[FADs(1-r)+r\right]\left(\vec{Prey}_{r1}-\vec{Prey}_{r2}\right) & if \quad r> FADs\end{cases} \quad (21)$$

FADs are binary vectors with a 0.2 probability of modifying the optimization process, with dimensions, and prey matrix random indexes (*r1* and *r2*). The flow chart of the proposed MPO to solve the ED problem in MG is shown in Figure 1. In this paper, the MPO is used to solve the ED problem in MGs by finding the best scheduling of RERs in both isolated MG and MMG modes of operation considering the minimizations of the total operation cost as OF. The steps of MPO to find the optimal solutions are presented as follows:

*Step 1*: Insert MG configuration with predicted power output, RER characteristics, network characteristics, cost, bids, load curve, and the OF, and set MPO parameters and constants.

*Step 2*: The MPO starts with a random population matrix ($X$) as:

$$X=[X_1,X_2,X_3,....,X_{N_p}]^T \quad (22)$$

Each element ($X_i$) can be formed as:

$$X_i=[\left\{P_{i_1},P_{i_2},...,P_{i_{N_d}}\right\},\left\{P_{j_1},P_{j_2},...,P_{j_{N_w}}\right\},\left\{P_{k_1},P_{k_2},...,P_{k_{N_s}}\right\},\left\{P_{l_1},P_{l_2},...,P_{l_{N_b}}\right\}] \quad (8)$$

where, $P_i$, $P_j$, $P_k$, and $P_l$ are the outage powers from diesel, wind, solar, and battery in MG, respectively. Every element points to a solution within 24 hours as:

$$P_i=P_i^{\min}+rand\times(P_i^{\max}-P_i^{\min}) \quad (9)$$

*Step 3*: The initial global best solution of the OF ( $F_{best}^{initial}$ ) and corresponding control variables ( $x_{best}^{initial}$ ) can be determined among the accepted solutions.

*Step 4*: Create Elite and Prey matrix and accomplish memory saving.

*Step 5*: Determine the top predator from Elite and Prey for updating the position and velocity of the prey for successive iterations.

*Step 6*: Apply Lévy flight that can construct the algorithm limited out of the local ideal

*Step 7*: Apply three phases

*Step 8*: If the termination requirements are not met, repeat from step 3.

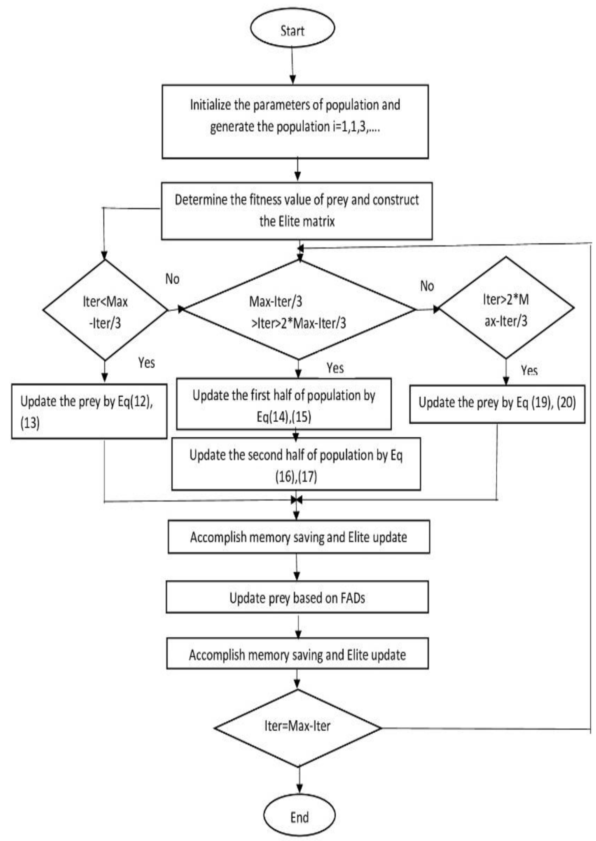


Figure 1 Flow chart of MPO of single MG

## 4. Applications

### *4.1 Description of MGs*

The proposed algorithm is applied to isolated MG and MMG systems to determine the optimal scheduling of RERs for reducing the total operating costs. Specific information concerning isolated MG, output power from solar and WT for the isolated MG based on 24-hour data are obtained from [29]. Figure 2 depicts the estimated load power for a single isolated MG via 24-hour data. Table 1 displays the cost coefficients of conventional generators. The BES system produces 344 kWh [30], and operates for 12 hours during charging and 12 hours during discharging.

The MMG system used in this paper consists of two MGs, including RERs such as solar units, wind units, and BES. The load data for the two MGs are founded in [25,26].

Table 1 coefficients of fuel cost functions for all generators for isolated MG

| Units | CHP ($G_1$) | Diesel generator ($G_2$) | Natural gas generator ($G_3$) |
|---|---|---|---|
| *a* (S/MW$^2$h) | 0.00024 | 0.000435 | 0.000315 |

| | | | |
|---|---|---|---|
| *b* (S/MWh) | 0.21 | 0.3 | 0.306 |
| *c* (S/h) | 15.3 | 14.88 | 9 |

*4.2 Results and comments*

- *Results of single MG*

Table 2 shows the best scheduling of various generation units for minimizing total operating costs for single MG. The overall operating cost achieved using the suggested MPO is less than that acquired using the PSO method. Therefore, this comparison reflects the great capability of the proposed MPO to solve the ED in MG. Figure 3 shows the convergence curves of the proposed MPO, JS, PSO, and DE for single MG. The proposed MPO can reach the optimal value of the OF with a lower number of iterations.

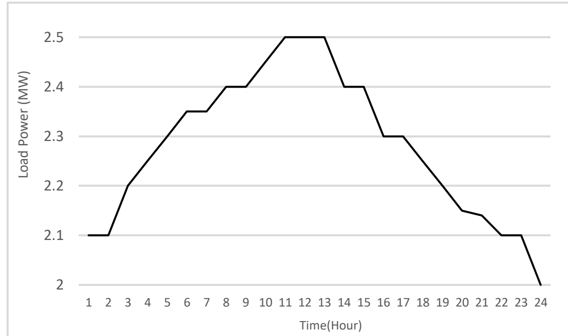


Figure.2 Expected load power for every hour per day

Table 2 Optimal scheduling of generation units for minimizing total cost for single MG

| hr | MPO | | | | | | JS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P1 (MW) | P2 (MW) | P3 (MW) | Solar (MW) | Wind (MW) | BES (MW) | P1 (MW) | P2 (MW) | P3 (MW) | Solar (MW) | Wind (MW) | BES (MW) |
| 1 | 1.3202 | 0.2017 | 0.6011 | 0 | 0 | -0.0229 | 0.1081 | 0.9655 | 1.0494 | 0 | 0 | -0.0229 |
| 2 | 1.417 | 0 | 0.706 | 0 | 0 | -0.0229 | 0.1045 | 0.7574 | 1.261 | 0 | 0 | -0.0229 |
| 3 | 1.182 | 0.9597 | 0.0812 | 0 | 0 | -0.0229 | 0.9026 | 0.5168 | 0.8036 | 0 | 0 | -0.0229 |
| 4 | 1.2479 | 0 | 1 | 0 | 0.025 | -0.0229 | 0.755 | 0.0006 | 1.4923 | 0 | 0.025 | -0.0229 |
| 5 | 1.3271 | 0.8786 | 0.0923 | 0 | 0.025 | -0.0229 | 1.4365 | 0.8309 | 0.0305 | 0 | 0.025 | -0.0229 |
| 6 | 1.101 | 0.38 | 0.746 | 0 | 0.1 | 0.0229 | 1.3082 | 0.7995 | 0.1195 | 0 | 0.1 | 0.0229 |
| 7 | 1.0521 | 1 | 0 | 0.075 | 0.2 | 0.0229 | 0.8878 | 0.7245 | 0.4398 | 0.075 | 0.2 | 0.0229 |
| 8 | 0.918 | 0 | 0.9991 | 0.16 | 0.3 | 0.0229 | 0.5293 | 0.1444 | 1.2433 | 0.16 | 0.3 | 0.0229 |
| 9 | 1.2714 | 0.1464 | 0.2492 | 0.26 | 0.45 | 0.0229 | 0.2939 | 0.5221 | 0.851 | 0.26 | 0.45 | 0.0229 |
| 10 | 1.2748 | 0 | 0.2223 | 0.35 | 0.58 | 0.0229 | 0.011 | 0.0133 | 1.4728 | 0.35 | 0.58 | 0.0229 |
| 11 | 0.837 | 0.2029 | 0.3672 | 0.39 | 0.68 | 0.0229 | 0.7975 | 0.5027 | 0.1069 | 0.39 | 0.68 | 0.0229 |
| 12 | 1.1816 | 0 | 0.1705 | 0.425 | 0.7 | 0.0229 | 0.3584 | 0.5967 | 0.397 | 0.425 | 0.7 | 0.0229 |
| 13 | 1.0396 | 0.1198 | 0.1577 | 0.41 | 0.75 | 0.0229 | 0.0329 | 0.1165 | 1.1677 | 0.41 | 0.75 | 0.0229 |
| 14 | 1.0582 | 0.0705 | 0.0483 | 0.4 | 0.8 | 0.0229 | 0.0598 | 0.0825 | 1.0348 | 0.4 | 0.8 | 0.0229 |
| 15 | 0.3364 | 0.5033 | 0.4773 | 0.36 | 0.7 | 0.0229 | 0.5901 | 0.305 | 0.422 | 0.36 | 0.7 | 0.0229 |
| 16 | 0.9112 | 0.3812 | 0.1497 | 0.295 | 0.54 | 0.0229 | 0.1939 | 0.5077 | 0.7405 | 0.295 | 0.54 | 0.0229 |
| 17 | 0.8549 | 1 | 0.0222 | 0.2 | 0.2 | 0.0229 | 0.1005 | 0.2768 | 1.4998 | 0.2 | 0.2 | 0.0229 |
| 18 | 0.6359 | 0.4979 | 0.9841 | 0.075 | 0.08 | -0.0229 | 1.3116 | 0.8054 | 0.001 | 0.075 | 0.08 | -0.0229 |
| 19 | 1.4051 | 0.7928 | 0 | 0.025 | 0 | -0.0229 | 1.1723 | 1.0217 | 0.0039 | 0.025 | 0 | -0.0229 |
| 20 | 1.1729 | 0 | 1 | 0 | 0 | -0.0229 | 0.8544 | 1.3031 | 0.0154 | 0 | 0 | -0.0229 |
| 21 | 1.2436 | 0.8949 | 0.0244 | 0 | 0 | -0.0229 | 1.4175 | 0.6843 | 0.0611 | 0 | 0 | -0.0229 |
| 22 | 1.4254 | 0.2429 | 0.4546 | 0 | 0 | -0.0229 | 0.3999 | 1.4885 | 0.2346 | 0 | 0 | -0.0229 |
| 23 | 1.1229 | 1 | 0 | 0 | 0 | -0.0229 | 1.2856 | 0.0457 | 0.7916 | 0 | 0 | -0.0229 |
| 24 | 1.0248 | 0.1369 | 0.8612 | 0 | 0 | -0.0229 | 0.3502 | 0.1774 | 1.4954 | 0 | 0 | -0.0229 |
| **Total cost ($)** | **1022.80915** | | | | | | **1022.83818** | | | | | |

- *Results of MMG system*

Tables 3 and 4 show the best scheduling of various generation units and the total operation costs of the MMG using MPO, and JS, respectively. It is noted that, the total operation cost obtained using the proposed MPO is lower than that obtained using JS. In addition, the total cost obtained when solving the ED in MMG is lower than that obtained when considered individual MGs. For example, the total operating cost in MMG by using MPO is 2046.381 $, but by using isolated MGs, it is 1022.8091 $, meaning that the total cost of two MGs is equal to 2045.618 $, that means it saves about 1022.8091 $ (lower than total cost of the two isolated MGs). This comparison reflects the priority MPO than the other algorithms for solving the ED in MMGs.

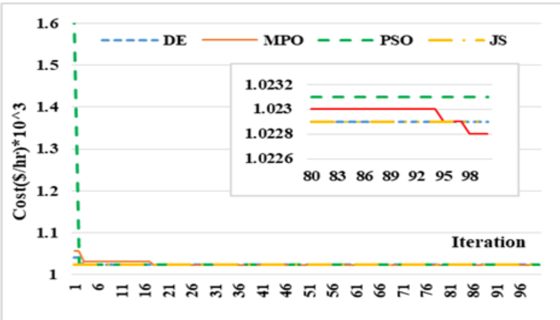


Figure 3 Convergence curves of the proposed MPO and other methods for single MG

Figure 4 shows the convergence curves of different techniques for minimizing total operation costs. The MPO reaches to the minimum cost than other techniques with a minimum number of iterations.

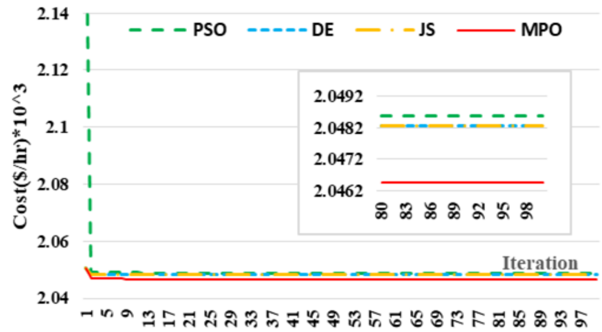


Figure 4 Convergence curves of the proposed MPO and other methods for MMG

Figure 5 shows a summary between the total operation costs of isolated MG and MMG using MPO and other techniques.

Table 3 Optimal scheduling of generation units for minimizing total cost for MMG using MPO

| hr | MG1 | | | | | | MG2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P1 (MW) | P2 (MW) | P3 (MW) | Solar (MW) | Wind (MW) | BES (MW) | P1 (MW) | P2 (MW) | P3 (MW) | Solar (MW) | Wind (MW) | BES (MW) |
| 1 | 0.8405 | 0.701 | 0.7963 | 0 | 0 | -0.0229 | 0.4673 | 0.943 | 0.4977 | 0 | 0 | -0.0229 |
| 2 | 1.0455 | 0.7851 | 0.8597 | 0 | 0 | -0.0229 | 0.41 | 0.693 | 0.4526 | 0 | 0 | -0.0229 |
| 3 | 1.3969 | 0.7658 | 0.912 | 0 | 0 | -0.0229 | 0.3391 | 0.4723 | 0.5598 | 0 | 0 | -0.0229 |
| 4 | 1.1108 | 0.7564 | 0.9778 | 0 | 0.025 | -0.0229 | 0.3527 | 0.6117 | 0.6865 | 0 | 0.025 | -0.0229 |
| 5 | 1.4569 | 0.7951 | 0.4039 | 0 | 0.025 | -0.0229 | 0.8893 | 0.4391 | 0.6117 | 0 | 0.025 | -0.0229 |
| 6 | 0.7547 | 0.6344 | 0.903 | 0 | 0.1 | 0.0229 | 0.783 | 0.8421 | 0.537 | 0 | 0.1 | 0.0229 |
| 7 | 0.952 | 0.6802 | 0.7729 | 0.075 | 0.2 | 0.0229 | 0.4289 | 0.6407 | 0.6295 | 0.075 | 0.2 | 0.0229 |
| 8 | 0.6166 | 0.7818 | 0.4215 | 0.16 | 0.3 | 0.0229 | 0.8142 | 0.7721 | 0.4279 | 0.16 | 0.3 | 0.0229 |
| 9 | 0.6792 | 0.7911 | 0.4 | 0.26 | 0.45 | 0.0229 | 0.7005 | 0.4697 | 0.2936 | 0.26 | 0.45 | 0.0229 |
| 10 | 0.7744 | 0.613 | 0.4 | 0.35 | 0.58 | 0.0229 | 0.4312 | 0.4771 | 0.2984 | 0.35 | 0.58 | 0.0229 |
| 11 | 0.551 | 0.6296 | 0.4 | 0.39 | 0.68 | 0.0229 | 0.5334 | 0.4093 | 0.2908 | 0.39 | 0.68 | 0.0229 |
| 12 | 0.3045 | 0.5787 | 0.4 | 0.425 | 0.7 | 0.0229 | 0.6271 | 0.4605 | 0.3334 | 0.425 | 0.7 | 0.0229 |
| 13 | 0.3163 | 0.6951 | 0.4 | 0.41 | 0.75 | 0.0229 | 0.4742 | 0.4178 | 0.3308 | 0.41 | 0.75 | 0.0229 |
| 14 | 0.3549 | 0.5941 | 0.4 | 0.4 | 0.8 | 0.0229 | 0.3249 | 0.3503 | 0.3299 | 0.4 | 0.8 | 0.0229 |
| 15 | 0.0167 | 0.5926 | 0.4 | 0.36 | 0.7 | 0.0229 | 0.8805 | 0.4312 | 0.3131 | 0.36 | 0.7 | 0.0229 |
| 16 | 0.5699 | 0.6407 | 0.4 | 0.295 | 0.54 | 0.0229 | 0.4665 | 0.4659 | 0.3412 | 0.295 | 0.54 | 0.0229 |
| 17 | 1.0117 | 0.7003 | 0.552 | 0.2 | 0.2 | 0.0229 | 0.6087 | 0.4394 | 0.4421 | 0.2 | 0.2 | 0.0229 |
| 18 | 1.2883 | 0.7687 | 0.5686 | 0.075 | 0.08 | -0.0229 | 0.8166 | 0.3965 | 0.3972 | 0.075 | 0.08 | -0.0229 |
| 19 | 0.9685 | 0.694 | 0.4408 | 0.025 | 0 | -0.0229 | 0.7811 | 0.9241 | 0.5875 | 0.025 | 0 | -0.0229 |
| 20 | 0.7865 | 0.6814 | 0.9116 | 0 | 0 | -0.0229 | 0.7653 | 0.7522 | 0.4488 | 0 | 0 | -0.0229 |
| 21 | 1.0841 | 0.6529 | 0.7194 | 0 | 0 | -0.0229 | 0.4927 | 0.8676 | 0.5091 | 0 | 0 | -0.0229 |
| 22 | 0.961 | 0.7374 | 0.491 | 0 | 0 | -0.0229 | 0.9793 | 0.5343 | 0.5429 | 0 | 0 | -0.0229 |
| 23 | 1.1695 | 0.6499 | 0.7873 | 0 | 0 | -0.0229 | 0.7598 | 0.46 | 0.4193 | 0 | 0 | -0.0229 |
| 24 | 0.9699 | 0.7912 | 0.906 | 0 | 0 | -0.0229 | 0.303 | 0.662 | 0.4138 | 0 | 0 | -0.0229 |
| **Total cost ($)** | **2046.381** | | | | | | | | | | | |

- *Results of statistical analysis*

Table 5 shows statistical summary of different methods after 30 trials, showing best, worst, mean, SD, and standard error. It can be observed that a better performance is obtained using the proposed MPO because of the convergence to the best solution in most trials. This comparison reflects the capability of the proposed MPO to reach either optimum value or very near to it in every trial.

Table 4 Optimal scheduling of generation units for minimizing total cost for MMG using JS

| hr | MG1 | | | | | | MG2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P1 (MW) | P2 (MW) | P3 (MW) | Solar (MW) | Wind (MW) | BES (MW) | P1 (MW) | P2 (MW) | P3 (MW) | Solar (MW) | Wind (MW) | BES (MW) |
| 1 | 0.6304 | 0.9946 | 0.6 | 0 | 0 | -0.0229 | 0.7 | 0.6209 | 0.7 | 0 | 0 | -0.0229 |
| 2 | 0.8337 | 0.6127 | 0.8 | 0 | 0 | -0.0229 | 0.6994 | 0.7 | 0.6 | 0 | 0 | -0.0229 |
| 3 | 1.0517 | 0.7852 | 0.709 | 0 | 0 | -0.0229 | 0.6 | 0.6 | 0.7 | 0 | 0 | -0.0229 |
| 4 | 1.3604 | 0.6 | 0.731 | 0 | 0.025 | -0.0229 | 0.6295 | 0.6 | 0.6 | 0 | 0.025 | -0.0229 |
| 5 | 1.3464 | 0.8745 | 0.6 | 0 | 0.025 | -0.0229 | 0.6 | 0.6 | 0.6 | 0 | 0.025 | -0.0229 |
| 6 | 1.3277 | 0.6646 | 0.639 | 0 | 0.1 | 0.0229 | 0.6228 | 0.6 | 0.7 | 0 | 0.1 | 0.0229 |
| 7 | 0.9028 | 0.6941 | 0.8 | 0.075 | 0.2 | 0.0229 | 0.6457 | 0.6615 | 0.6 | 0.075 | 0.2 | 0.0229 |
| 8 | 1.0103 | 0.6083 | 0.6 | 0.16 | 0.3 | 0.0229 | 0.6 | 0.6156 | 0.7 | 0.16 | 0.3 | 0.0229 |
| 9 | 0.9812 | 0.6 | 0.6 | 0.26 | 0.45 | 0.0229 | 0.603 | 0.7 | 0.3 | 0.26 | 0.45 | 0.0229 |
| 10 | 1.484 | 0.3674 | 0.2818 | 0.35 | 0.58 | 0.0229 | 0.5303 | 0.5016 | 0.4091 | 0.35 | 0.58 | 0.0229 |
| 11 | 1.077 | 0.3 | 0.333 | 0.39 | 0.68 | 0.0229 | 0.6462 | 0.4608 | 0.6771 | 0.39 | 0.68 | 0.0229 |
| 12 | 1.2092 | 0 | 0.8 | 0.425 | 0.7 | 0.0229 | 0.6986 | 0.6964 | 0 | 0.425 | 0.7 | 0.0229 |
| 13 | 1.3249 | 0.1163 | 0 | 0.41 | 0.75 | 0.0229 | 0.6429 | 0.6 | 0.7 | 0.41 | 0.75 | 0.0229 |
| 14 | 1.3541 | 0.3 | 0.3 | 0.4 | 0.8 | 0.0229 | 0.6 | 0.3 | 0.3 | 0.4 | 0.8 | 0.0229 |
| 15 | 1.0593 | 0.1338 | 0.3 | 0.36 | 0.7 | 0.0229 | 0.6019 | 0.6392 | 0.6 | 0.36 | 0.7 | 0.0229 |
| 16 | 1.0123 | 0.2475 | 0.1805 | 0.295 | 0.54 | 0.0229 | 0.6843 | 0.6013 | 0.6983 | 0.295 | 0.54 | 0.0229 |
| 17 | 1.4183 | 0.0328 | 0.527 | 0.2 | 0.2 | 0.0229 | 0.6 | 0.6761 | 0.7 | 0.2 | 0.2 | 0.0229 |
| 18 | 1.1892 | 0.6059 | 0.5 | 0.075 | 0.08 | -0.0229 | 0.7 | 0.6941 | 0.6267 | 0.075 | 0.08 | -0.0229 |
| 19 | 1.1993 | 0.8389 | 0.5006 | 0.025 | 0 | -0.0229 | 0.6 | 0.6566 | 0.6003 | 0.025 | 0 | -0.0229 |
| 20 | 1.1562 | 0.7157 | 0.5 | 0 | 0 | -0.0229 | 0.6 | 0.7 | 0.674 | 0 | 0 | -0.0229 |
| 21 | 1.4449 | 0.5 | 0.5 | 0 | 0 | -0.0229 | 0.6213 | 0.6597 | 0.6 | 0 | 0 | -0.0229 |
| 22 | 1.163 | 0.5015 | 0.689 | 0 | 0 | -0.0229 | 0.6113 | 0.6811 | 0.6 | 0 | 0 | -0.0229 |
| 23 | 1.1732 | 0.6349 | 0.5665 | 0 | 0 | -0.0229 | 0.6 | 0.6 | 0.6713 | 0 | 0 | -0.0229 |
| 24 | 0.9026 | 0.691 | 0.8 | 0 | 0 | -0.0229 | 0.6406 | 0.7 | 0.3117 | 0 | 0 | -0.0229 |
| **Total cost ($)** | **2048.261** | | | | | | | | | | | |

Table 5 Statistical summary of the proposed MPO and other methods after 30 random trials

| Case# | Algorithm | Best solution | Worst solution | Average | SD | Standard error |
|---|---|---|---|---|---|---|
| MG | PSO | 1022.9613 | 1023.2481 | 1023.1297 | 0.00402192 | 0.0007343 |
| | DE | 1022.855 | 1023.0827 | 1022.983 | 0.00371039 | 0.00067742 |
| | JS | 1022.838 | 1023.25332 | 1022.98681 | 0.0140412 | 0.00256356 |
| | MPO | 1022.8091 | 1023.14 | 1022.914 | 0.00598567 | 0.0011 |
| MMG | PSO | 2048.524 | 2049.137 | 2048.651 | 0.035755 | 0.00652802 |
| | DE | 2048.231 | 2048.37 | 2048.309 | 0.001748 | 0.0003191 |
| | JS | 2048.261 | 2048.45 | 2048.372 | 0.00231168 | 0.000422 |
| | MPO | 2046.381 | 2046.644 | 2046.55 | 0.004094 | 0.00074504 |

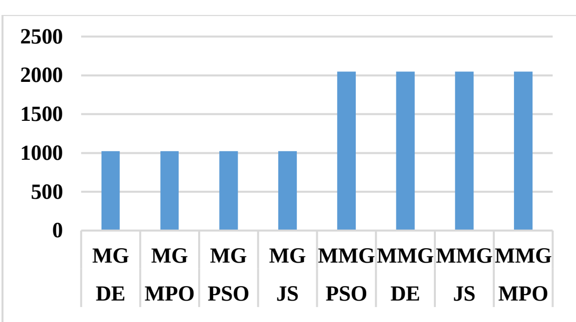


Figure 5 Comparison of total cost using different techniques for MG and MMG

## 5. Conclusion

In this paper, the MPO has been successfully developed and utilized to determine the best schedule for BES in both single-MG and MMG modes, as well as for renewable and nonrenewable energy resources. We present the MPO as a revolutionary approach to solving the ED problem in MMG. This approach draws its inspiration from the biological interactions between predators and prey in marine environments, where predators frequently employ the well-known foraging tactic known as Brownian and Lévy random movement. Additionally, the planned MPO's evaluation has been conducted by contrasting the outcomes of statistical analysis with other techniques.

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