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(Research Article)

Optimize power generation of thermal generating sources in solving the green energies-based economic load dispatch using Electric Eel Foraging Optimization

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Abstract

This research focuses on solving the green energies-based economic load dispatch problem (ELD) with the consideration of both solar and wind power to minimize the total electricity production cost (TEPC) of all thermal generating sources (TGSs) existing in the given power system. Two power systems, including a 6-TGS and a 15-TGS power system, were selected to conduct the research. Besides, the prohibited operating zones (POZs) of the TGSs are also considered while solving the GE-ELD problem. Golf optimization algorithm (GOA) and Electric Eel Foraging Optimization (EEFO) are applied to find the optimal power generation of TGSs to minimize the TEPC value and satisfy all the related constraints featured by the considered problem, especially the POZ constraints. The results obtained by GOA and EEFO in the two power systems are evaluated and compared using different criteria. The comparison indicates that EEFO is superior to GOA at all criteria, especially in the minimum value of TEPC (Min. TEPC) and the standard deviation (Std). In particular, EEFO is better than GOA 0.052($/h) on Min.TEPC and 98.34% on Std while applied in the first power system. The better values of EEFO over GOA in the second power system are 199.474 ($/h) and 78.703%. By considering these results, EEFO is considered a powerful search method and highly suggested for use to solve such GE-ELD problems.

Keywords: Economic load dispatch; Thermal generating sources; Prohibited operating zones; Solar and wind power; Production cost; Golf optimization algorithm

1. Introduction

Economic load dispatch (ELD) is the most concerning problem because its engineering and economic characteristics highly involve the power system operation [1-3]. In general, solving the ELD problem is to optimize the power generation of generating sources in the given power system so that the requirement of load demand for a minimum value of total electricity production cost (TEPC) is fulfilled [4]. Earlier, thermal generating sources (TGSs) were considered the only generating sources, accounting for a large proportion of electric production in most countries. However, the operation of these TGSs has released many toxic emissions that negatively affect residential areas and increase the damages of global warming to human living as well as the environment. Besides, most TGS-based power systems require different kinds of fossil fuels to maintain their operation. However, those fossil fuels become more expensive due to overuse and low reserve [5]. To unfold this situation, combining the use of green energies such as solar and wind in power systems with the traditional TGSs is acknowledged as a sustainable solution. As a result, the traditional ELD is also modified with the use of green energies and becomes the Green energies-based Economic load dispatch (GE-ELD).

By acknowledging the vital role of green energies while solving the GE-ELD, much research was proposed to solve the problem using different meta-heuristic algorithms. The use of meta-heuristic algorithms is mainly because of the characteristics of the GE-ELD problem, which is basically a non-convex and complicated problem, as mentioned in [6].

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In the past two decades, meta-heuristic algorithms have proven their high capability while dealing with different large-scale optimization problems in engineering and economic fields [7-11]. Therefore, the trend of using meta-heuristic algorithms to solve both ELD and GE-ELD is not an exception and also become more popular. Notably, the application of meta-heuristic algorithms to solve the mentioned problems, such as interior search algorithm (ISA) [12], Turbulent Flow of Water Optimization (TFWO) [13], whale optimization algorithm (WOA) [14], moth-flame optimization algorithm (MFO) [15], equilibrium optimizer (EO) [16], Grasshopper optimization algorithm (GOA) [17], chaotic bat algorithm (CBA) [18], Chaotic whale optimization algorithm (CWOA) [19], slime mould algorithm (SMA) [20], JAYA algorithm (YA) [21], bat-inspired algorithm (BIA) [22], multi-swarm statistical particle swarm optimization (MSPSO) [23], search and rescue optimization algorithm (SROA) [24], Harmony search algorithm (HSA) [25], the new meta-heuristic evolutionary programming (NMEP) [26], artificial cooperative search algorithm (ACSA) [27], A Multi-Objective Cross-Entropy Optimization (MOCEO) [28], particle oriented cat swarm optimization (POCSO) [29], the Online learning Honey Bee Mating Optimization (OLHBMO) [30], artificial bee colony algorithm (ABCA) [31], A Modified Teaching - Learning-Based Optimization (MTLBO) [32], improved water wave optimization algorithm (IWWOA) [33], Dragonfly algorithm (DA) [34], memetic sine cosine algorithm (MSCA) [35].

In this research, two novel meta-heuristic algorithms, including the Golf optimization algorithm (GOA) [36] and Electric Eel Foraging Optimization (EEFO) [37], are employed to solve the GE-ELD problem. GOA is inspired by rules and behaviors players must respect in a golf match, while EEFO is proposed based on the foraging behavior of the electric eel. Before being published, GOA and EEFO are tested by different optimization problems in both theories and real optimization problems, reaching higher performance than many previous methods. This research applies the two algorithms in the two power systems, including the 6-TGS and the 15-TGS power systems, with a photovoltaic generator (PVG) and a wind power generator (PWG). Moreover, the constraints of prohibited operating zones of TGSs are also considered an extra term for judging the performance of the two applied algorithms.

The main novelties and the critical contributions of the research can be summarized as follows:

- Successfully apply two novel optimization algorithms to optimize the power generation of TGSs to reach the minimum value of TEPC while solving the GE-ELD problem.
- Indicate the most effective algorithm between the two, which is EEFO, while solving the considered problem using different comparisons.
- Successfully integrated solar and wind power into the power system and employed the POZ constraints of traditional TGSs using the newly applied algorithms.
- Offer another effective method while solving optimization problems in power systems, especially the GE-ELD with solar and wind.

2. Problem description

2.1. Objective function

As mentioned, the study concentrates on minimizing the total electricity production cost (TEPC) of thermal generating sources (TGSs) in the given power system. Typically, TEPC is formulated by a quadratic function as below:

$$Minimize\ TEPC = \sum_{k=1}^{N_{TGSs}} \varphi_{1,k} + \varphi_{2,k} TP_{TGS,k} + \varphi_{3,k} TP_{TGS,k}^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$with\ k = 1, \ldots, N_{TGSs}$$

where $TEPC$ is the total electricity production cost of TGSs in the system; $\varphi_{1,k}$, $\varphi_{2,k}$, and $\varphi_{2,k}$ are, respectively the fuel usage coefficients of TGSs k; $TP_{TGS,k}$ is the power generated by TGS k; and N_{TGSs} is the number of TGS existing in the given power system.

2.2. Constraints

The *constraints of power balance in the system*: This constraint concerns the balance of power produced by all the TGSs compared to the amount of power required by loads and losses in the transmission process. The mathematical expression of the constraints is given as follows:

$$\sum_{k=1}^{N_{TGS}} TP_{TGS,k} + P_{PVG} + P_{WPG} - P_{DM} - P_{LSS} = 0 \ldots\ldots\ldots (2)$$

In the equation above, $\sum_{k=1}^{N_{TGS}} TP_{TGS,k}$ is the total power produced by all TGSs; P_{PVG} and P_{WPG} are, respectively, the power produced by photovoltaic generator and wind power generator; P_{DM} is the amount of power required by loads, and finally, P_{LSS} is the power losses caused by the transmission process.

The term P_{LSS} stated in Equation (2) is calculated as follows:

$$P_{LSS} = \sum_{k=1}^{N_{TGS}} \sum_{h=1,h\neq k}^{N_{TGS}} TP_{TGS,k} B_{kh} TP_{TGS,h} + \sum_{k=1}^{N_{TGS}} B_{0k} TP_{TGS,k} + B_{00} \dots \quad (3)$$

where, B_{kh}, B_{0k}, and B_{00} are, respectively the loss factors

The constraints of TGS's operating boundaries: The constraint controls the power output produced by TGSs so that all TGSs will operate within their physical boundaries between the largest and the smallest of power productions.

$$TP_{TGS,k}^{smt} \leq TP_{TGS,k} \leq TP_{TGS,k}^{lar} \qquad (4)$$

in the equation above, $TP_{TGS,k}^{smt}$ and $TP_{TGS,k}^{lar}$ are respectively the smallest and largest values of power output produced by TGS k, $TP_{TGS,k}$ is power output produced by TGS k. While the constraint about the prohibited operational zones (POZs) of the TGSs are employed, Equation (4) are revised as follows [18]:

$$TP_{TGS,k} \in \begin{cases} TP_{TGS,k}^{smt} \leq TP_{TGS,k} \leq TG_{TGS,k,1}^{m} \\ TP_{TGS,k,z-1}^{n} \leq TP_{TGS,k} \leq TP_{TGS,k,z}^{m}; z = 2, \dots, n_i; \forall z \in \Omega \dots \dots \dots (5) \\ TP_{TGS,k,n_i}^{n} \leq TP_{TGS,k} \leq TP_{TGS,k}^{lar} \end{cases}$$

where, n_i is the number of the POZs of the TGSs.

The operational constraints of PVG and PWG: Comparable to TGSs, both PVGs and WPGs are also constrained in their power output within the allowed operational boundaries:

$$P_{PVG}^{smt} \leq P_{PVG} \leq P_{PVG}^{lst} \dots \dots \dots \dots \dots (6)$$

$$P_{PWG}^{smt} \leq P_{PWG} \leq P_{PWG}^{lst} \dots \dots \dots .. (7)$$

where P_{PVG}^{smt} and P_{PVG}^{lst} are the smallest and the largest amount of power produced by PVGs; P_{PWG}^{smt} and P_{PWG}^{lst} are the are the smallest and the largest amount of power produced by PWGs, and finally, P_{PVG} and P_{PWG} are amount of power produced by the PVG and PWG.

3. The solving methods

3.1. Golf Optimization Algorithm

As mentioned earlier, GOA is proposed based on the rules and behaviors of the player while playing golf. According to the author, the execution of GOA is separated into 2 phases, and the mathematical expressions of each phase will be given as follows:

Phase 1: The exploration phase

In this phase, the new solutions are updated using the following equation:

$$G_i^{new,P1} = G_i + Rn \times (BG - I \times G_i) \dots \dots \dots \dots (8)$$

where, $G_i^{new,P1}$ is the new solution updated in Phase 1, Rn is the random number in the interval between 0 and 1; BG is the best solution at current time; I is the random factor and its value is randomly set by 1 or 2.

After the update process in Phase 1 is completed, the refining procedure to retain the high quality solution is carried out using the following equation:

$$G_i = \begin{cases} G_i^{new,P1}, \text{ if } F_{G_i^{new,P1}} < F_{G_i} \\ G_i, \text{ otherwise} \end{cases} \ldots\ldots\ldots \quad (9)$$

Phase 2: The exploitation phase

All the solutions will be updated in this phase using the following mathematical expression:

$$G_i^{new,P2} = G_i + (1 - 2 \times Rn) \times \frac{LB + Rn \times (UB - LB)}{CI} \ldots\ldots\ldots \quad (10)$$

where, $G_i^{new,P2}$ is the new solution updated in Phase 2; LB and UB are the lowest and highest boundaries of the search space, respectively; CI is the current iteration index.

Similar to Phase 1, all the new solutions updated in Phase 2 will go through the refining procedure as follows:

$$G_i = \begin{cases} G_i^{new,P2}, \text{ if } F_{G_i^{new,P2}} < F_{G_i} \\ G_i, \text{ otherwise} \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

3.2. Electric Eel Foraging Optimization

Unlike GOA, EEFO is a nature-inspired algorithm particularly EEFO is suggested based on the foraging behavior of the electric eel in the two stages, including the interaction stage, the resting stage, the hunting stage, and the migration stage. The mathematical formulation of the last two stages is also the update mechanism for new solutions of the EEFO, which will given as follows:

The interaction stage

In this stage, the movement of the eel in the search space relies on its direction, the reference between the current position and the random eel in the search space, and the neighborhood eel. The mathematical expression of the eel's movement in this stage is given as follows:

$$E_i^{IS} = \begin{cases} \begin{cases} E_j + rand * DV_1 * (RE - E_i), if\ PB_1 > 0.5 \\ E_j + rand * DV_2 * (RE - E_i), if\ PB_1 \le 0.5 \end{cases} if\ F_{E_j} < F_{E_i} \\ \begin{cases} E_j + rand * DV_1 * (RE - E_i), if\ PB_2 > 0.5 \\ E_j + rand * DV_2 * (RE - E_i), if\ PB_2 \le 0.5 \end{cases} if\ F_{E_j} < F_{E_i} \end{cases} \ldots\ldots (12)$$

where E_i^{IS} is the position of the i^{th} eel in the interaction stage with i =1, 2 … N_{pz} and N_{pz} is the population size; E_j is the position of the neighborhood eel; DV_1 and DV_2 are the direct vectors while the eel is moving; RE is the random eel selected in the population; PB_1 and PB_2 is the possibility of selecting the moving method; F_{E_j} and F_{E_i} are the fitness values of the neighborhood eel and the current eel.

The resting stage

In this stage, the movement of each eel in the population is simulated as follows:

$$E_i^{RS} = E_R + Rn * (E_R - E_i), \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

n Equation (12), E_i^{RS} is the position of the i^{th} eel in the resting stage; E_R is where the eel will come and take a reset there in the search space.

The migrating stage

In this stage, the eel will move based on the measurement between its position and the prey's position as given by the following equation:

$$E_i^{MS} = -Rnd \times E_i + Rnd \times R - LF \times (R - E_i) \dots (14)$$

in the above equation, E_i^{MS} is the new position of the eel in the migrating stage; R is the position of the prey; LF is the value of the Levy flight function.

The hunting stage

The mathematical expression of the eel in the hunting stage is formulated as follows:

$$E_i^{HS} = R + AF \times R \times E_i \dots\dots\dots (15)$$

where E_i^{HS} is the new position of the i^{th} eel in the hunting stage; AF is the amplifying factor and its value is randomly between 0 and 1.

4. Results and evaluation

In this section, GOA [36] and EEFO [37] are employed to solve the GE-ELD to minimize the value of TEPC with the presence of both PVG and PWG in two power systems with consideration of the POZ constraints as described in Section 2. The first power system consists of 6 TGSs, while the second has 15 TGSs. The load demand required by the two power systems is 1263 and 2650 MW, respectively. Besides, a PVG and a PWG with rated power supplied 30 and 50MW are also integrated into those systems to reduce the reliance on TGSs and partly mitigate environmental damages. For judging the actual performance of GOA and EEFO, these methods use the same population size (NPz) settings and a maximum iteration (MI) while solving the considered problem in the two power systems. Moreover, the two methods are also operated with 50 trial runs for the best solution. The results obtained by GOA and EEFO are discussed and analyzed through different criteria for choosing the best method to apply to the problem.

All coding and related simulation for the study is performed in a computer with 2.3 GHz of the central processing unit (CPU) clock speed and 8GB of random access memory (RAM). MATLAB software version R2018a is used to conduct the whole work of the research.

4.1. The results obtained by the GOA and EEFO in System 1

In this subsection, the results obtained by GOA and EEFO in System 1 will be presented and evaluated. GOA and EEFO are applied with the same settings, with 30 for NPz and 50 for MI. Figure 1 describes the TEPC values after 50 trial runs. The pink line represents the results determined by GOA, while the green one describes the similar values achieved by EEFO. It is straightforward to realize that EEFO is the only method for reaching more optimal values of TEPC throughout 50 trial runs. At the same time, the results from GOA highly fluctuate with less time to reach the optimal values. Moreover, EEFO provides surprise stability while solving the considered problem with low fluctuation among the runs compared to GOA.

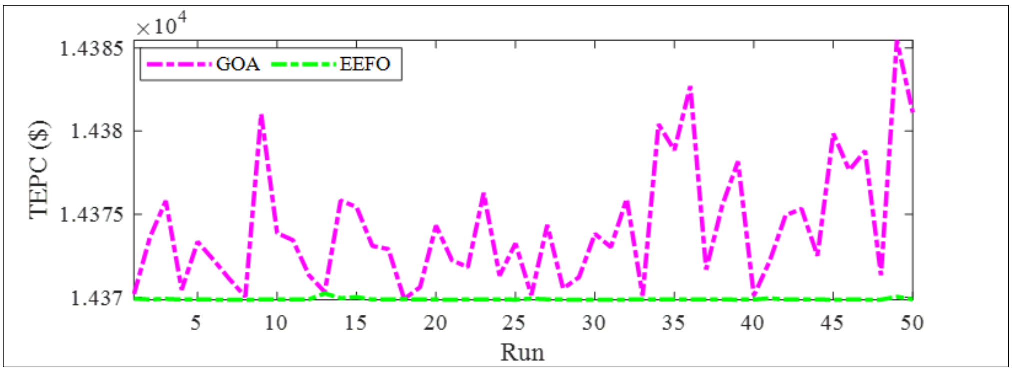

Figure 1 The results obtained by GOA and EEFO after 50 trial runs in System 1

Figure 2 provides more detail about the performance of GOA and EEFO while solving the GE-ELD in terms of different convergences, including the minimum, average, and maximum convergences. Regarding the minimum convergence described in Figure 2a, EEFO reaches the optimal value of TEPC after around 35 iterations for the best runs. At the same time, GOA cannot provide the same capability even though the difference of TPEC achieved by GOA compared to EEFO is not that much. However, while considering the average and maximum convergences, the difference in TPEC found by the two applied methods becomes clearer. Based on this evidence, EEFO provides a higher capability and effectiveness while dealing with GE-ELD than GOA.

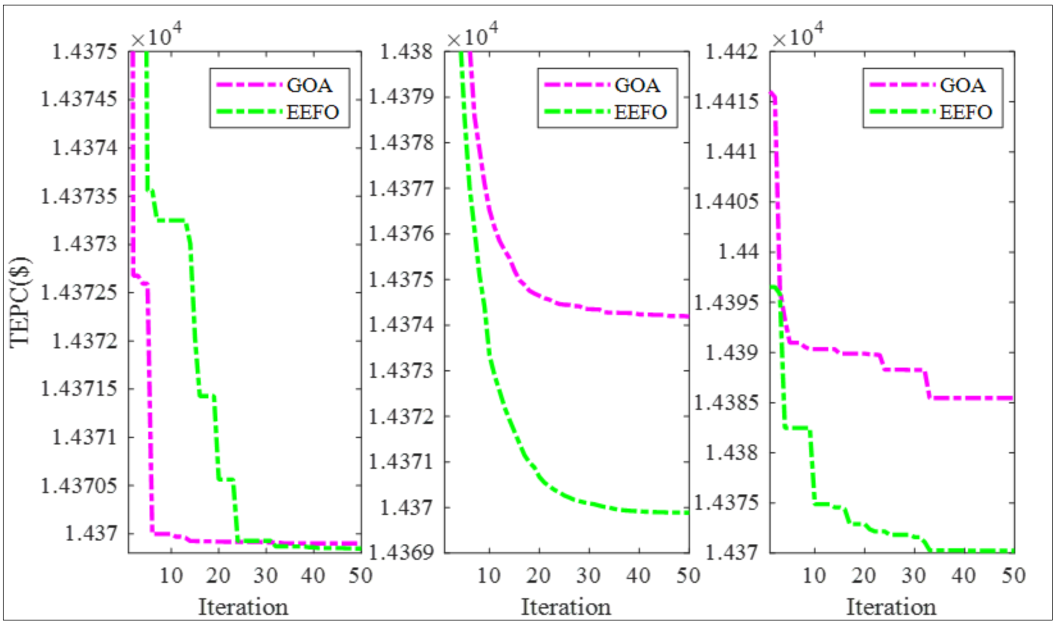

Figure 2 The minimum, average, and maximum convergences obtained by GOA and EEFO in System 1

Figure 3 presents a quantitative comparison between GOA and EEFO on different criteria, including the minimum TEPC (Min. TEPC), average TEPC (Aver. TEPC), maximum TEPC (Max. TEPC), and standard deviation (STD). As mentioned earlier, the difference between the first criterion is only 0.052 $/h, but the remaining criteria have shown huge differences. EEFO can save 4.302 $/h and 15.320 $/h compared to GOA over the Aver.TEPC and Max. TEPC. These values correspond to 0.03% and 0.11%, respectively. Moreover, EEFO completely outperforms GOA while considering the Std value. Specifically, the Std resulted by EEFO is only 0.062, while the similar GOA is up to 3.745. By converting percentage, EEFO is more effective than GOA at 98.34% in this criterion.

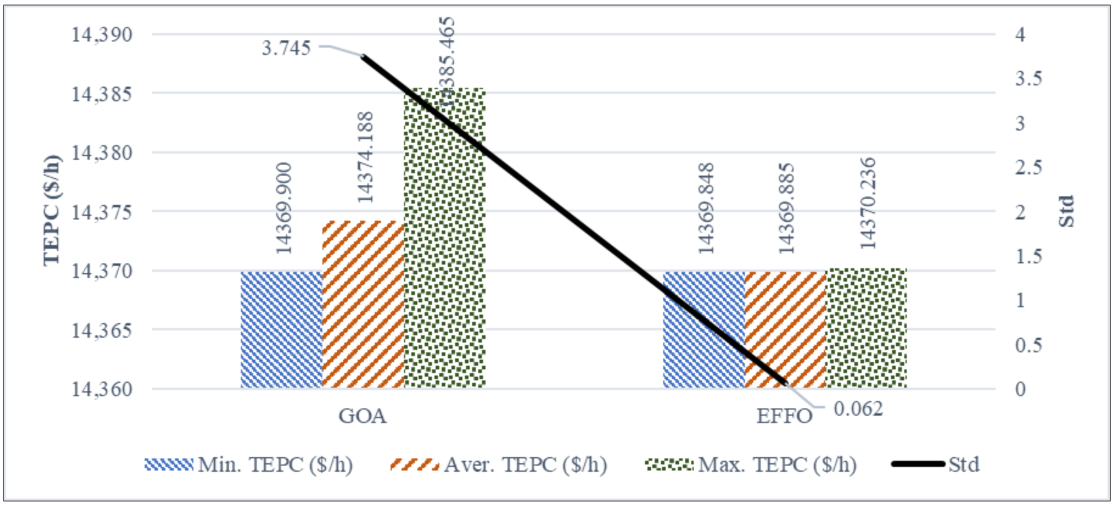

Figure 3 The comparison between GOA and EEFO on different criteria in System 1

The power supplied by each TGS in the system found by GOA and EEFO is given in Figure A1 of the Appendix.

4.2. The results obtained by the GOA and EEFO in System 2

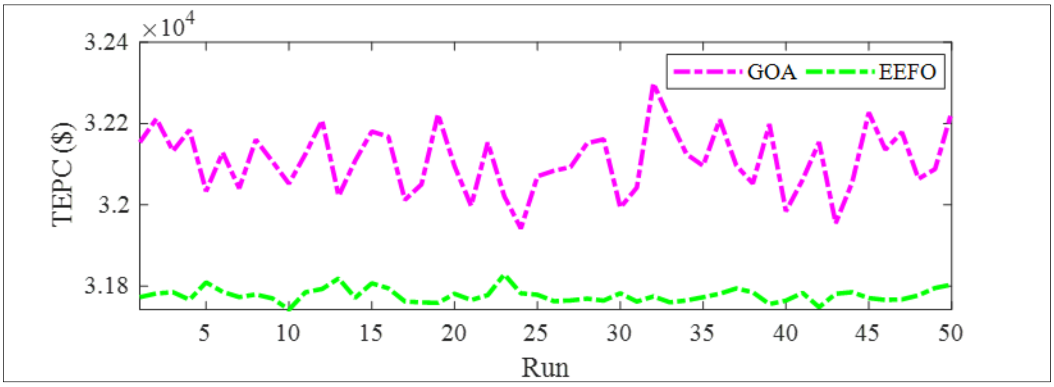

Figure 4 The results obtained by GOA and EEFO after 50 trial runs in System 2

Figure 6 presents the convergences achieved by the GOA and EEFO in terms of the minimum, average, and maximum convergence among 50 trial runs. Notably, the minimum convergences of GOA and EEFO are given in Figure 6a, where EEFO reaches the optimal value of TEPC after 95 iterations. In comparison, GOA is trapped in the local optima at around 45 iterations and cannot achieve the global optimization as EEFO. Additionally, the observation of the average and the maximum convergences of the two applied methods in Figure 5a and 5b, respectively, makes the superiority of the performance of EEFO over GOA clear. This also means that EEFO still maintains its high capability while dealing with the larger scale of the considered problem, while GOA starts to show its downsides and low effectiveness.

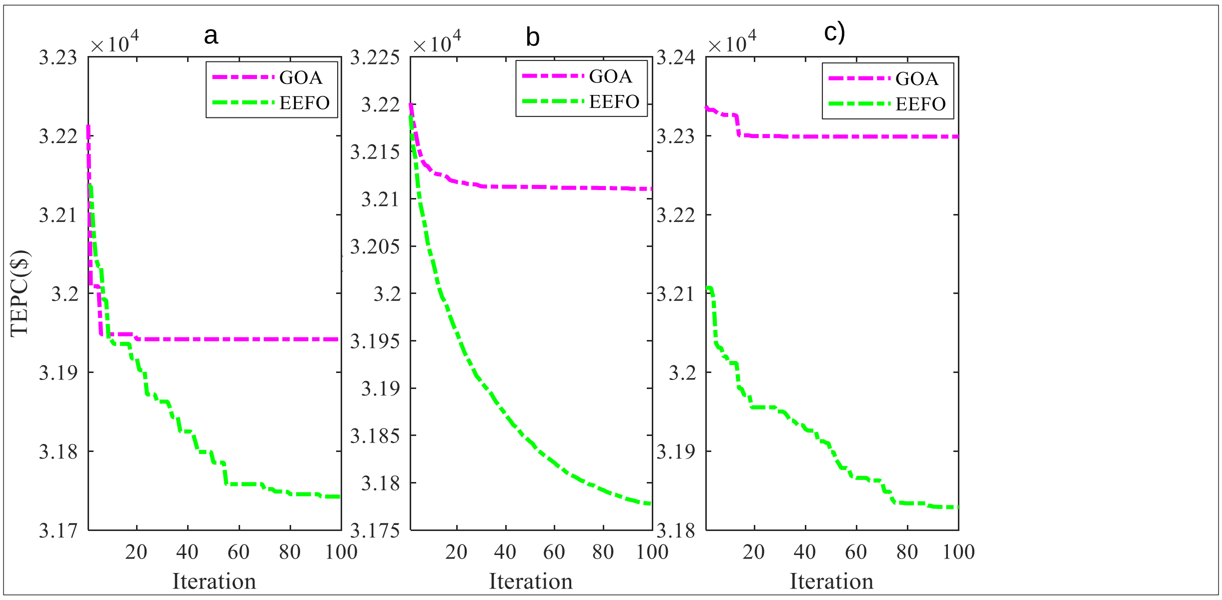

Figure 5 The minimum, average, and maximum convergences obtained by the GOA and EEFO in System 2

Figure 7 compares GOA and EEFO on different criteria, as conducted in Figure 3 of the first System. Firstly, the value of Min. TEPC achieved by GOA is 31941.975 ($/h), significantly larger than EEFO, which is only 31742.501 ($/h). Using a simple calculation, EEFO saves 199.474 ($/h) of TEPC, or 0.62%, compared to GOA. Additionally, the evaluation on other criteria, such as Aver. TEPC, Max. TEPC and Std also indicate the superiority of EEFO over GOA. In particular, the results obtained by EEFO on those criteria are 31777.680 ($/h) for Aver. TEPC, 31829.223 ($/h) for Max. TEPC, and only 17.006 for STD, while those of GOA are, respectively, 32110.552 ($/h), 32298.866 ($/h), and up to 79.848. The differences are enormous and very noticeable in each criterion. By converting into percentages, EEFO is better than GOA 1.037% for Aver. TEPC, 1.45% for Max. TEPC and 78.703% for Std.

The particular value of power generation for each TGS found by GOA and EEFO in System 2 are described in Figure A2 of the Appendix

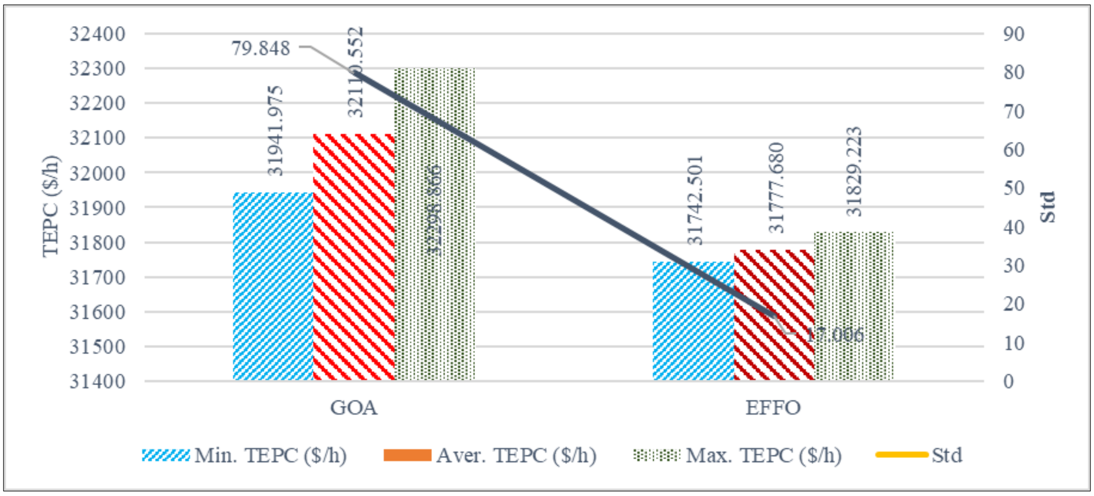

Figure 6 The comparison between GOA and EEFO on different criteria in System 2

5. Conclusions

In the research, two novel meta-heuristic algorithms, including Golf optimization algorithms (GOA) and Electric Eel Foraging Optimization (EEFO), are successfully employed to solve the Green energies – Economic load dispatch (GE-ELD). Notably, both photovoltaic (PVG) and Wind power generators (PWG) are simultaneously considered while solving the GE-ELD problem. Besides, the constraint of prohibited operating zones (POZs) of thermal generating sources (TGSs) is also applied to evaluate the actual performance of the two applied algorithms. Moreover, the applied algorithms are also tested on the two power systems, including a 6-TGS and a 15-TGS power system, with different criteria. In particular, the results obtained by GOA and EEFO are evaluated by Min. TEPC, Aver. TEPC, Max. TEPC and Std. The evaluation of these criteria in the two power systems reveals that EFFO is superior to GOA. Specifically, in System 1, EEFO not only reaches the best value of TEPC, but is also better than GOA 0.03 % on Aver. TEPC, 0.11% Max. TEPC, and 98.34% on Std. Additionally, the better percentages of EEFO over GOA are more noticeable. In particular, EEFO is more effective than GOA 0.62% in Min. TEPC, 1.037% on Aver. TEPC, 1.45% on Max. TEPC and 78.703% on Std. EEFO has proven its high effectiveness compared to GOA over various comparisons, in which the two essential criteria are the ability to reach the global optima and the degree of stability while solving the considered problem. Therefore, EEFO is considered a powerful search method, and it is highly recommended to solve such GE-ELD problems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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Appendix A

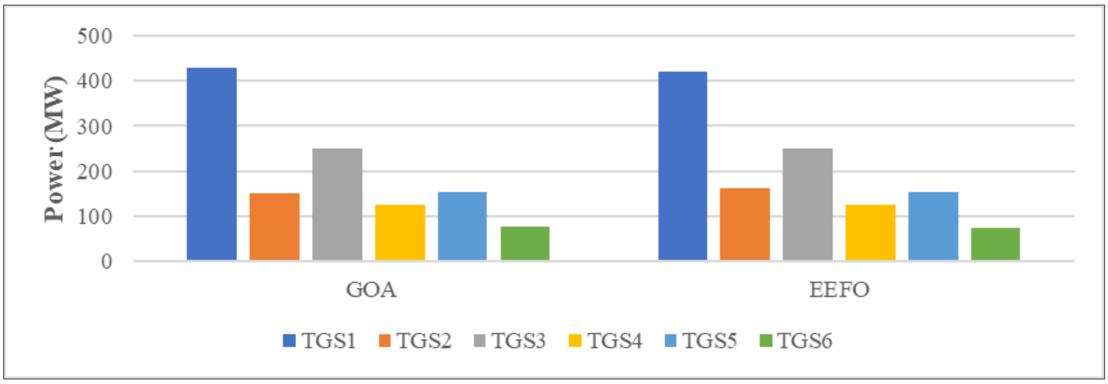

Figure A1 The power generation of all TGSs in System 1 found by GOA and EEFO

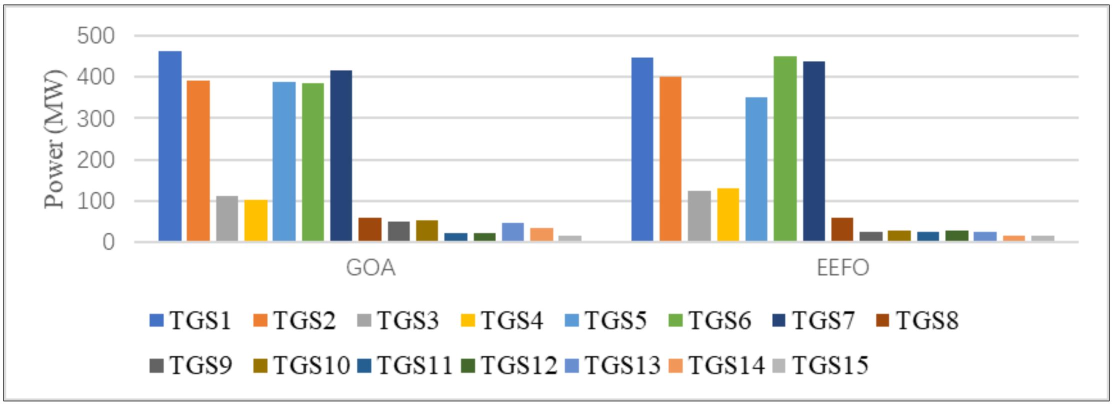

Figure A2 The power generation of all TGSs in System 2 found by GOA and EEFO