Marine Predator Optimization Algorithm for Economic Load Dispatch Target Considering Solar Generators

Hai Son Hoang[1], Van Binh Nguyen[2], Van Duc Phan[2], and Hoang Nam Nguyen[3,*]

ARTICLE INFO

Article history:
Received: 28 December 2020
Revised: 23 February 2021
Accepted: 3 March 2021

Keywords:
Marine predator optimization algorithm
Solar generator
Brownian distribution
Levy flights distribution

ABSTRACT

This paper implements Marine predator optimization algorithm (MPA) to seek the optimal solutions of thermal plants (TPs) for a conventional ELD problem and a hybrid ELD (HELD) problem considering solar generators. MPA has a strong and stable search ability by using Brownian distribution and Lévy flights distribution. For testing MPA, four test systems with different constraints and difficult levels are used. In which, the last two systems formed from the first two ones, are first proposed and utilized to analyze the effectiveness of renewable energy resources as installed on the power system. The optimal solutions obtained by running MPA on Systems 1 and 2 are employed to compare with many previous optimization methods. As a result, it can lead to a conclusion that MPA is more effective and stronger than compared methods in terms of solution quality and stable search ability. MPA successfully solves Systems 3 and 4 of the HELD problem considering solar generators. In addition, from analyzing cost reduction level of cases with and without solar generators, it can offer a useful idea that the use of renewable energy resources significantly decreases a cost of buying fossil fuels for TPs.

1. INTRODUCTION

The more the country develops, the more the demand for electrical energy for production and daily life increases. To meet the increasing demand, the expansion of grid and the installation of more power plants is inevitable. This makes the operation and management of a power system become complicated. Economic load dispatch (ELD) is considered as an effective measure for solving the mentioned issue. ELD is a strategic problem of power generation scheduling for available thermal power plants (TPs) in the aim of reducing the cost and meeting the steady working requirements of TPs [1, 2].

Up to now, there has been a huge number methods proposed by scholars to apply for finding the best solution of such problem. They are Hopfield modeling (HM) [1], Tabu search (TS) [2], biogeography-based optimizer (BBO) [3], group search optimizer (GSO) [4], backtracking search (BS) [5], cuckoo search (CS) [6-8], charged system search algorithm (CSSA) [9], firefly optimizer (FO) [10], improved FO (IFO) [10], FO with an adaptive parameter α (APFO) [10] and memetic FO (MFO) [10], modified FO (MFO) [11], modified FO (MFO) [12], modified stochastic search (MSS) [13], Moth swarm algorithm (MSA) [14] and Social Spider optimizer (SSO) [15, 16], particle swarm optimization (PSO) [17]. Among these methods above, only HM and TS are not the members of the meta-heuristic method's family. HM is based on neural network and Lagrange function while TS is based on single solution and heuristic algorithm. In [1], HM has been conquered disadvantages of classical HM [18] like the difficulty in selecting weighting factors of energy function (EF) and big computational dimension by using a linear input-output model for updating neurons. In addition, a new EF including power mismatch, total fuel cost and transmission line losses has been proposed. However, the real performance of such method only proved on a 3-unit system and a 20-unit system taking single fuel cost function and simple constraints into account. In fact, the method did not deal with the ELD problem with large test system dimension, nonconvex function and complex constraints having valve point effects and prohibit zones etc.

Unlike HM, the mentioned remaining algorithms were successfully applied for coping with the complicated

[1]Faculty of Mechanical, Electrical, Electronic and Automotive Engineering, Nguyen Tat Thanh University, 300A Nguyen Tạt Thanh Street, Ward 13, District 4, Ho Chi Minh City, Vietnam.
[2]Faculty of Automobile Technology, Van Lang University, 45 Nguyen Khac Nhu Street, Co Giang Ward, District 1, Ho Chi Minh City, Vietnam.
[3]Modeling Evolutionary Algorithms Simulation and Artificial Intelligence, Faculty of Electrical & Electronics Engineering, Ton Duc Thang University, 19 Nguyen Huu Tho Street, Tan Phong Ward, District 7, Ho Chi Minh City, Vietnam.
*Corresponding author: Hoang Nam Nguyen; Phone: +84-28-37755028. E-mail: nguyenhoangnam@tdtu.edu.vn.

problem. However, each method has not solved all optimization problems and existed strengths and weaknesses. So, a combination of two or more methods is a great choice to get their strong points to form a better one. From this view, some of methods to be hybrid Nelder–Mead method and pattern search (NMPS) [19], genetic algorithm (GA) with quadratic programming (GA-QP) and GA with interior points (GA-IP) [20], PSO with double elitist breeding (PSO-DEB) [21] and modified grey wolf optimizer with β-hill climbing optimizer (MGWO-βHCO) [22] have been recommended to value ELD problem. In [22], the strong point of each member algorithm is exploited effectively. Grey wolf optimizer (GWO) has an effective global search ability while β-hill climbing optimizer (βHCO) has a good local search ability. So, this combination makes MGWO-βHCO ensure the balance between narrow zone and large zone searches. Results obtained from the method are very impressive as compared to previous ones on five test systems from 3 units to 80 units. However, execution time for whole searching process of the method was not reported in comparison tables of test cases. It is fact that time-consuming disadvantage is the main weakness of hybrid methods. Recently, the hottest issue that gets the concern of social, researchers and environmentalist, is exhausted of energy resources (ERs) and pollution emission (PE).

Using renewable energy resources (RERs) to replace with traditional ERs and reduce, PE is regarded as an excellent alternative. Therefore, ELD problem should be expanded and added RERs. In [23, 24], ELD problem taking both solar-based power plants (SBPs) and wind-based power plants (WBPs) into account has been resolved by chaos PSO and backtracking search, respectively while other authors from [25, 26] have addressed ELD problem only considering SBPs utilizing PSO and Dragonfly optimizer (DO), in turns. In [27], mixed systems with SBPs and TPs with the consideration of seasonality and prohibited operating zones is valued using DO. Clearly, the presence of RERs makes ELD problem to be complexed. To handle this problem, it requires a robust and strong tool for getting a global minimum in shorter execution time and fewer generation evaluations. In this paper, Marine predator optimization algorithm (MPA) is applied for dealing with the considered problem ELD and HELD. MPA was developed in 2020 for solving engineering design problems such as pressure vessel design, welded beam design, compression spring design, operating fan schedule for demand-controlled ventilation, building energy performance and its results were better than other methods such as PSO, GA, Gravitational Search Algorithm (GSA), CS, Salp Swarm Algorithm (SSA), Covariance Matrix Adaptation Evolution Strategy (CMA-ES). The superiority of MPA over other compared methods has attracted a huge number of readers and researchers. As a result, there are a lot of published papers using MPA for different problems such as ELD problem and HELD [28], forecasting confirmed cases of COVID-19 [29], diagnosing COVID-19 [30], designing photovoltaic model [31] and reconfiguring photovoltaic array system [32]. The remarkable point of MPA was demonstrated by the practice results as opposed to other previously reported methods about convergence speed and performance.

Solar energy has a huge contribution to the significant decrease of employing fossil fuels for TPs in the hybrid economic load dispatch problem considering solar generators [23-27]. Solar energy has been used widely and increasingly in the last years [33]. In addition, the use of solar energy can avoid polluted emission generated by TPs [37], reduce power losses in transmission lines [38], improve the voltage profile [39], and reduce the costs of consumed electric energy [40]. This study recommends MPA for the ELD problem of an integrated power system involving the solar energy source. The task of MPA in the paper is to certify the optimal operation point to diminish total costs of the standard test system with 6 units and 20 units, modified test system 1 with 6 thermal units and 2 solar generators and modified test system 2 with 20 units and 2 solar generators. As result, this paper provides some main information for readers as follows:

1) Propose modified test systems based on standard test systems for testing ELD problem with existing SBPs
2) Designate the best proper control parameters for MPA to standard test systems and modified test systems,
3) Give details of the weakness and strengths of the MPA's organization,
4) Provide a useful view for operators and managers' power system to value the effectiveness of RERs in hybrid power systems.

2. MATHEMATIC MODEL

2.1 The objective of the problem

The fundamental goal of ELD problem regarding the solar energy generators has exploited the power as fully as possible from solar plants to reduce the total cost (TTC) of purchasing fossil fuels for each thermal plant (TP). The objective function (OF) [1] can be mathematically formulated as follows:

$$Lessening\ TTC = \sum_{g=1}^{N_g} FG_g \tag{1}$$

where FG_g is the generation function of the *gth TP* that can be constructed as the following quadratic function equation [5].

$$FG_g = m_g + n_g \times RP_g + o_g \times RP_g^2; g=1,...,N_g \quad (2)$$

2.2 Constraints of the problem

The OF is under the following constraints:

Working limits: The generation of each *TP* should be limited for safety [5] as bellows:

$$RP_{g,min} \leq RP_g \leq RP_{g,max} \quad (3)$$

Power balance restriction: The total generation come from power output of TPs and SBPs must be equal to the sum of the load side power (*LSP*) and power losses (*PL*) [27].

$$\sum_{g=1}^{N_g} RP_g + \sum_{j=1}^{N_{sl}} RSP_j = LSP + PL \quad (4)$$

The second term *PL* in Eq. (4) is power losses computed by employing Krone's reduction technique [5].

$$PL = \sum_{g=1}^{N_g}\sum_{j=1}^{N_g} RP_g \times B_{gj} \times RP_j + \sum_{g=1}^{N_g} B_{0g} \times RP_g + B_{00} \quad (5)$$

2.3 Power output of solar plant

The power output from SBPs is obtained dependent on energy conservation function from solar radiation as shown in equation (6) below [25]

$$RSP(A_m) = \begin{cases} RSP_{rated} \times \frac{(A_m)^2}{A_{std} \times R_c} & 0 < A_m < R_c \\ RSP_{rated} \times \frac{A_m}{A_{std}} & A_m > R_c \end{cases} \quad m=1, 2,...,T \quad (6)$$

3. MARINE PREDATOR OPTIMIZATION ALGORITHM AND FLOW CHART

MPA was proposed by Afshin Faramarzi et al in 2020 [28]. MPA was developed inspiring the hunting action of predators. In such MPA, the walks from Lévy flights and from Brownian motion were applied for the prey foraging strategy. In which, Brownian walk takes over the task of searching solutions in local spaces whilst Lévy flight walk is in charge of that of searching ones in large spaces. The real power of MPA has been valued by executing on some benchmark test functions and engineering design problems. Besides, MPA was used for implementation in different optimization fields such as forecasting, diagnosing, reconfiguring. The procedure for producing new solutions of MPA is constructed dependently on the comparison of velocity of praise and predators. As a result, there are three happened cases. Case 1, called the first stage, happens as preys have higher velocity than predators. Case 2, called the second stage, takes place as preys and predators have the same velocity. Case 3, called the last stage is opposite to Case 1. The detail of these three stages is explained as follow:

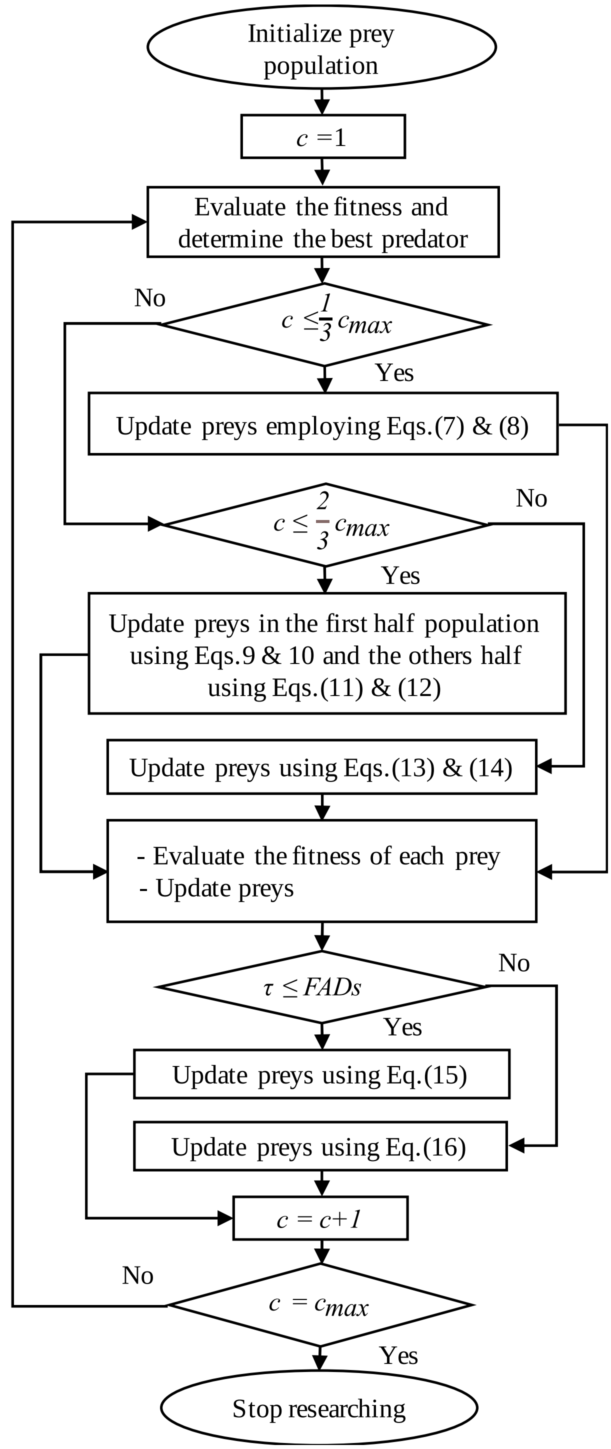

Fig. 1. The search process of MPA.

The first stage: The first stage is applied until $c \leq \frac{1}{3} c_{max}$. It is comprised of the two following equations.

$$X_g = X_g + \gamma * \theta \times \Delta_g \,; \quad g=1 \ldots S_{pop} \tag{7}$$

$$\Delta_g = \partial \times \left(X_{best} - \partial \times X_g\right) \tag{8}$$

The second stage: The stage is implemented as $\frac{1}{3}c_{max} < c < \frac{2}{3}c_{max}$. To ensure the balance ability of exploration and exploitation search mission, two mechanisms are recommended. Two equal population groups withdrawn from S_{pop} have taken over the mentioned work.

The work of group 1 is done by

$$X_g = X_g + \gamma * \theta \times \Delta 1_g; \quad g=1 \ldots S_{pop}/2 \tag{9}$$

$$\Delta 1_g = \varepsilon \times \left(X_{best} - \varepsilon \times X_g\right) \tag{10}$$

The work of group 2 is carried out by using Eqs. (11) and (12)

$$X_g = X_{best} + \vartheta \times K \times \Delta 2_g; \quad g=S_{pop}/2 \ldots S_{pop} \tag{11}$$

$$\Delta 2_g = \eta \times \left(\eta \times X_{best} - X_g\right) \tag{12}$$

The last stage: The stage starts from $c \geq \frac{2}{3}c_{max}$ to $c=c_{max}$ and is carried out by:

$$X_g = X_{best} + \vartheta \times K \times \Delta 3_g; \quad g=1 \ldots S_{pop} \tag{13}$$

$$\Delta 3_g = \eta \times \left(\eta \times X_{best} - X_g\right) \tag{14}$$

Updated solutions of each stage will continue being updated thanks to a comparison criterion as the following equations

$$X_g = X_g + [X_{min} + \sigma \times (X_{max} - X_{min})] \times \varphi \times K \quad if\ \tau \leq FADs \tag{15}$$

$$X_g = X_g + [FADs\ (1-\tau) + \tau] \times (X_{r1} - X_{r2}); \quad if\ \tau > FADs \tag{16}$$

The solutions searching steps of MPA for the considered ELD problem are specified in Figure 1

4. NUMERICAL RESULTS

In this section, MPA method has been suggested for ELD and HELD problems with the presence of solar energy resource. MPA is run for four test systems considering several various constraints. The first two systems without solar generators are shown and the two last ones consider the real effect of appearing solar generators in the power system. In which, systems 1 and 2 are conventional system with 6 and 20 units, respectively. Systems 3 and 4 are the modified systems of two mentioned ones. The data of the first two systems are, respectively, taken from [10] and [1], and shown in Table A1 and Table A2. The whole codes for MPA are written in a programming language of MATLAB 2018 and run on a personal laptop with 2.4 Ghz processor and 4GB RAM. To compare with other methods, fifty independent trial runs are implemented for each test system. Additionally, the selection for parameters of MPA to be population dimension (S_{pop}) and the maximum iteration number (c_{max}) is determined for each case.

4.1. The impact analysis of the MPA parameters on System 1

4.1.1. Choosing the best appropriate parameters of MPA method

As showing the strong search of MPA, the smallest cost ($Cost_{min}$) and standard deviation cost (std) are obtained for comparisons with other methods. So, S_{pop} and c_{max} need to have the most effective values. For solving the four considered systems, these parameters are selected based on the system dimension and the settings of previously applied methods for obtaining good results and ensuring a fair comparison. The two parameters influence final obtained solutions and computation time. Normally, high values of these parameters support applied methods to find verry good results but it takes high computation time. On the contrary, applied methods have to suffer from bad results if low values are set for these parameters. But short computation time is a major advantage of this case. So, S_{pop} and c_{max} are selected to reach both good result and suitable computation time. For each run, MPA produces [2.($S_{pop}.c_{max}$)] solutions whereas other ones produce either the same or smaller than the number of solutions, which is ($S_{pop}.c_{max}$) solutions. The setting of S_{pop} and c_{max} when solving the four systems always make sure that MPA produces smaller number of new solutions than other compared methods. And MPA is really more robust than others if it has the same or better results than others.

This work has been done by two ways. In the first way, the value of S_{pop} is kept constant while that of c_{max} is changed. In another, the value of c_{max} is not changed while that of S_{pop} is altered. Load side power levels of System 1 are 600,700 and 800 MW. To each load side power, these parameters have been investigated separately. For *LSP* of 600 MW, collected results are displayed in Figures 2, 3 and 4.

As observing the results from three figures, $Cost_{min}$ found by MPA at c_{max} = 10 of Figure 4 is smaller than that in Figures 2 and 3 and $Cost_{min}$ of 31445.623$/h is the most optimal at c_{max} = 30 in Figures 2 and 3 and c_{max} = 20 in Figure 4. If c_{max} continues to increase, this value is the same and it is no longer improved. However, we also need to assess robustness level of MPA through the value' std. The std value is the smaller, the algorithm is considered to be the most stable. From this viewpoint, only cases with std

≤ 1 are displayed in Figures. The minimum std value obtained from MPA is approximately zero at c_{max} = 90 in Figure 2, c_{max} = 60 in Figure 3 and c_{max} = 40 in Figure 4, respectively.

Finally, the most possible results such as Cost_{min}, $\text{Cost}_{\text{mean}}$ (the mean cost), Cost_{max} (the highest cost), STD, S_{pop} and c_{max} are summarized in Table 1 for *LSP* of 600MW.

Differences of S_{pop} and c_{max} also get the same Cost_{min}. But if we consider the number of generations, that of S_{pop} = 10 and c_{max} = 100 is the smallest. These values have been employed for setting MPA for System 1. Table 2 offers Cost_{min}, $\text{Cost}_{\text{mean}}$, Cost_{max} and STD with S_{pop} = 10 and c_{max} = 100 for *LSP* levels of System.

4.1.2. Result comparisons for System 1

The results gotten from MPA as reported in Table 1 were compared to FO [10], IFO [10], APFO [10], MFO [10] and MFO [11] regardless of Cost_{min}, $\text{Cost}_{\text{mean}}$, STD, S_{pop} and c_{max} for three *LSP*s. All compared results are tabulated in Tables 3-5, respectively. Such tables show that the Cost_{min} and $\text{Cost}_{\text{mean}}$ of MPA are approximately equal. Two costs are better than those from other ones except for MFO [11], because it only reported $\text{Cost}_{\text{mean}}$.

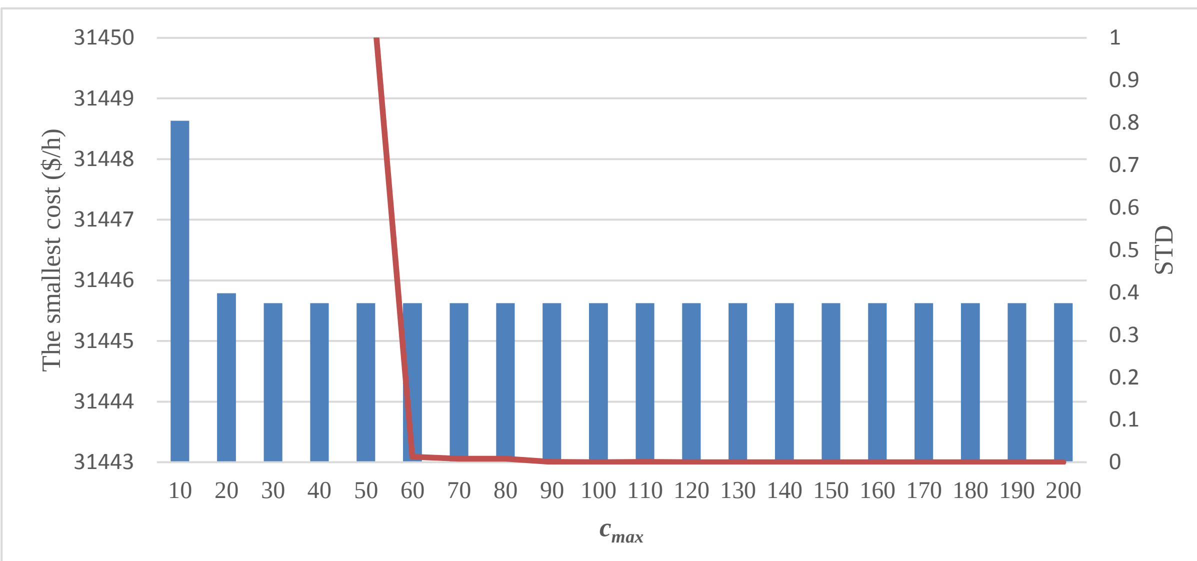

Fig. 3. The smallest cost and STD cost given by 50 trial runs with S_{pop}=20.

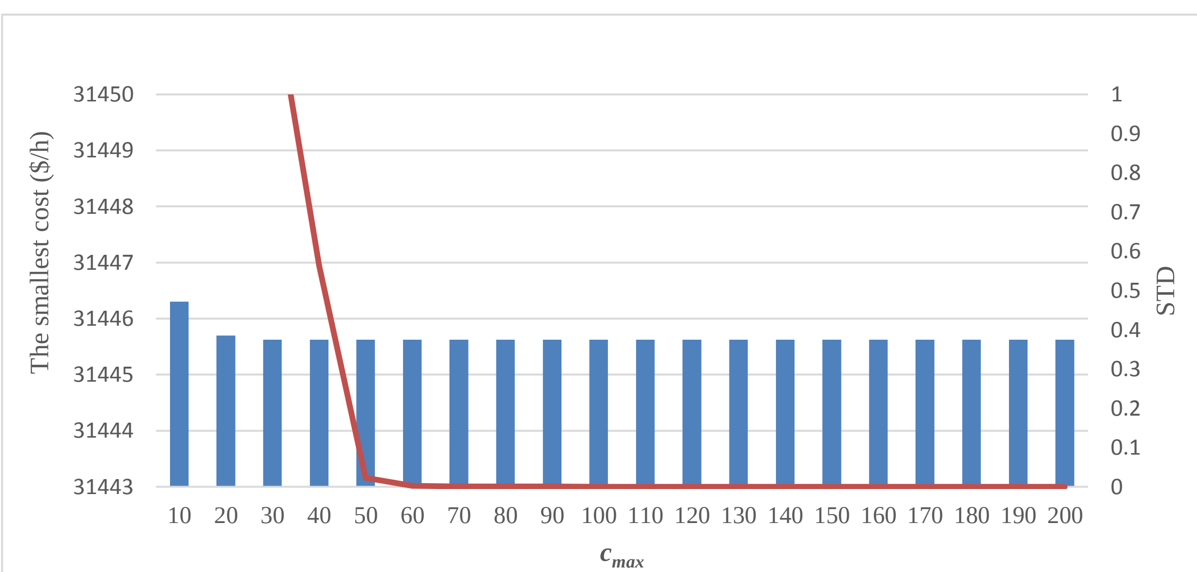

Fig. 4. The smallest cost and STD cost given by 50 trial runs with S_{pop}=30

Table 1. The best final results given by 50 trial runs for *LSP* of 600MW

$Cost_{min}$ (\$)	$Cost_{mean}$ (\$)	$Cost_{max}$ (\$)	STD	S_{pop}	c_{max}
31445.623	31445.626	31445.640	0.004	10	100
31445.623	31445.627	31445.665	0.007	20	60
31445.623	31445.631	31445.746	0.020	30	50

Table 2. The results given by 50 trial runs for *LSP levels*

LSP (MW)	$Cost_{min}$ (\$)	$Cost_{mean}$ (\$)	$Cost_{max}$ (\$)	STD
600	31445.623	31445.626	31445.640	0.004
700	36003.124	36003.128	36003.160	0.006
800	40675.968	40676.060	40679.287	0.488

Table 3. The result comparisons of MPA and others of System 1 with *LSP* of 600MW

Method	FO [10]	IFO [10]	APFO [10]	MFO [10]	MFO [11]	MPA
$Cost_{min}$ (\$)	31489	31447	31576	31481	31445.62	31445.623
$Cost_{mean}$ (\$)	31842.75	31452.95	31945.7	31620.6	No	31445.626
STD	243.84008	2.9285348	244.08931	95.848784	No	0.004
S_{pop}	25	25	25	25	No	10
c_{max}	150	150	150	150	No	100

Table 4. The result comparisons of MPA and others of System 1 with *LSP* of 700MW

Method	FO [10]	IFO [10]	APFO [10]	MFO [10]	MFO [11]	MPA
$Cost_{min}$ (\$)	36075	36006	36036	36021	36003.12	36003.124
$Cost_{mean}$ (\$)	36353.7	36010.3	36212.2	36114.6	No	36003.128
STD	152.7413	2.5152168	75.797931	44.446775	No	0.006
S_{pop}	25	25	25	25	No	10
c_{max}	150	150	150	150	No	100

Table 5. The result comparisons of MPA and others of System 1 with *LSP* of 800MW

Method	FO [10]	IFO [10]	APFO [10]	MFO [10]	MFO [11]	MPA
$Cost_{min}$ (\$)	40739	40676	40701	40740	40675.97	40675.968
$Cost_{mean}$ (\$)	40982.05	40681.3	40886.6	40950.3	No	40676.060
STD	121.88065	2.6969769	77.10171	110.85605	No	0.048
S_{pop}	25	25	25	25	No	10
c_{max}	150	150	150	150	No	100

For reviewing the robustness of all compared methods, MPA is more stable than others due to owning the smallest STD. Specially, that of MPA is 0.004 whereas that of other ones is from 2.9285348 to 244.08931 with *LSP* of 600 MW. For case with *LSP* of 700 MW, that of MPA is 0.006 whereas that of other ones is from 2.5152168 to 152.7413. For the case with *LSP* of 800 MW, that of MPA is 0.048 whereas that of other ones is from 2.6969769 to 121.88065. In addition, MPA' S_{pop} and c_{max} are 2.5 and 1.5 times less than others', respectively. From here, it can give a comment that MPA has a more remarkable advantage than other methods for System 1.

4.2 Result comparisons for System 2

With the same manner as System 1, S_{pop} and c_{max} of MPA have been also investigated to find the best correct values for System 2. Finally, S_{pop} = 30 and c_{max} = 200 are adopted. For the data of System 2, readers can see in [1]. For testing the power of MPA, 50 successful trials are run and the collected results from the experiment process are used to compete with many available methods. Table 6 provides the optimal solutions attained from MPA and seven methods such as HM [1], BBO [3], GSO [4], BS [5], CS [6], MFO [12] and MSS [13] in respect of $Cost_{min}$,

For better view, Figure 5 is designed to show a $Cost_{min}$ comparison for seven mentioned methods. $Cost_{min}$ of 62456.6331 ($) is the best value of this system that only four methods to be MPA, GSO [4], CS [6] and MSS [13] can achieve. That of HM [1], BBO [3], BS [5] and MFO [12] is respectively 62456.634, 62456.793 and 62456.6925. Considering the remaining terms, only MPA and CS [6] has a report. Regarding the stable method, STD of CS [6] is 0.0004 and that of MPA is 0.01665187. MPA' S_{pop} is 20 and is bigger than that of CS [6]. MPA' c_{max} is 200 and is smaller than that of CS [6].

Table 6. The result comparisons of MPA and others of System 2

Method	HM [1]	BBO [3]	GSO [4]	BS [5]	CS [6]	MFO [12]	MSS [13]	MPA
$Cost_{min}$ ($)	62456.634	62456.793	62456.63	62456.6925	62456.6331	62456.638	62456.63	62456.6331
$Cost_{mean}$ ($)	No	62456.7928	62456.63	62457.1517	62456.63	No	No	62456.6433
$Cost_{max}$ ($)	No	62456.79.35	62456.63	62458.1272	62456.63	No	No	62456.7143
STD	No	No	No	No	0.00004	No	No	0.01665187
S_{pop}	No	No	400	No	10	20	10	20
c_{max}	No	400	300	20000	500	500	100	200

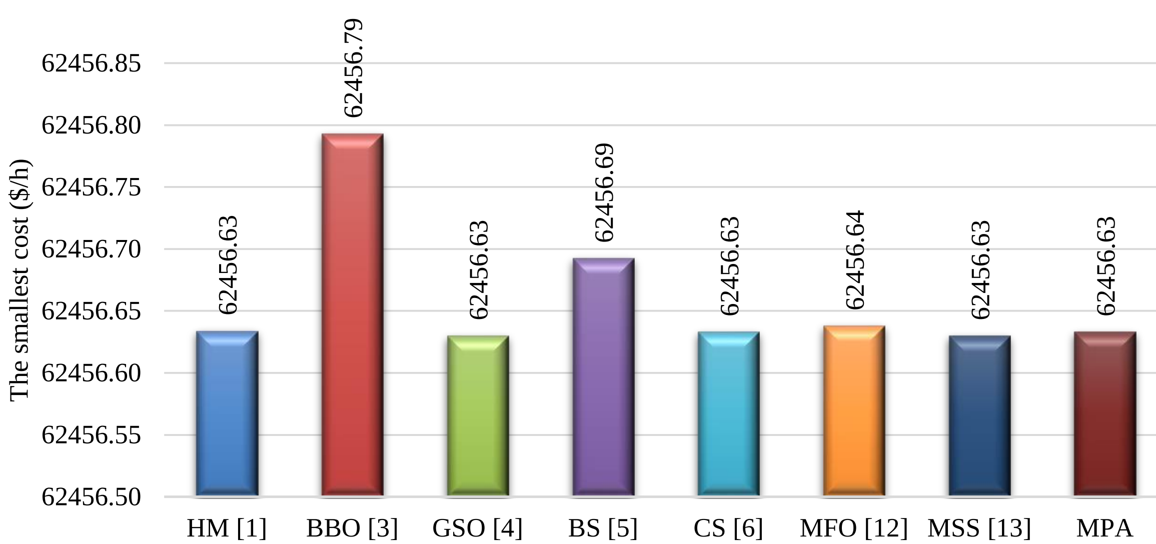

Fig. 5. The cost comparison of eight methods.

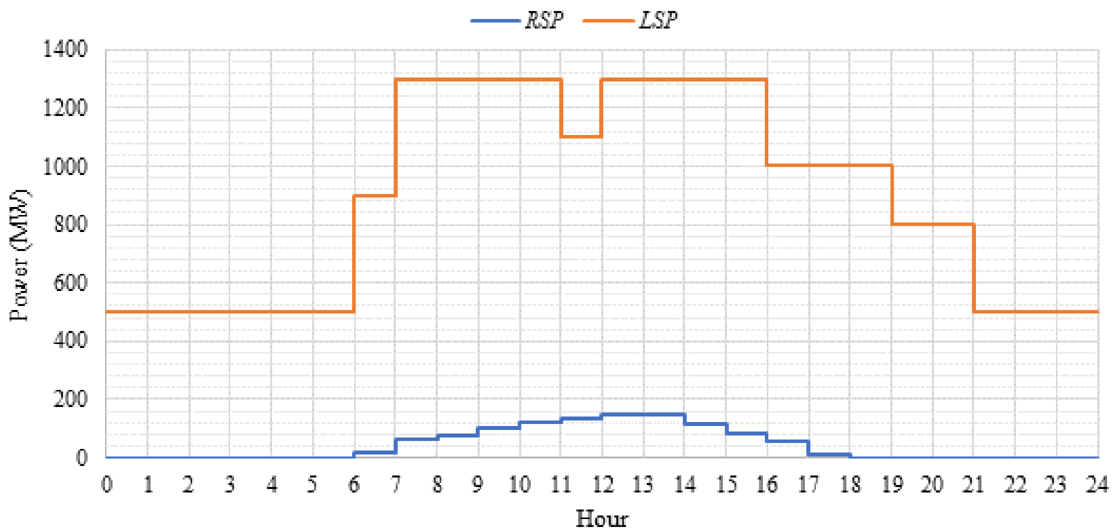

Fig. 6. Load-side power and power output of SBPs of System 3.

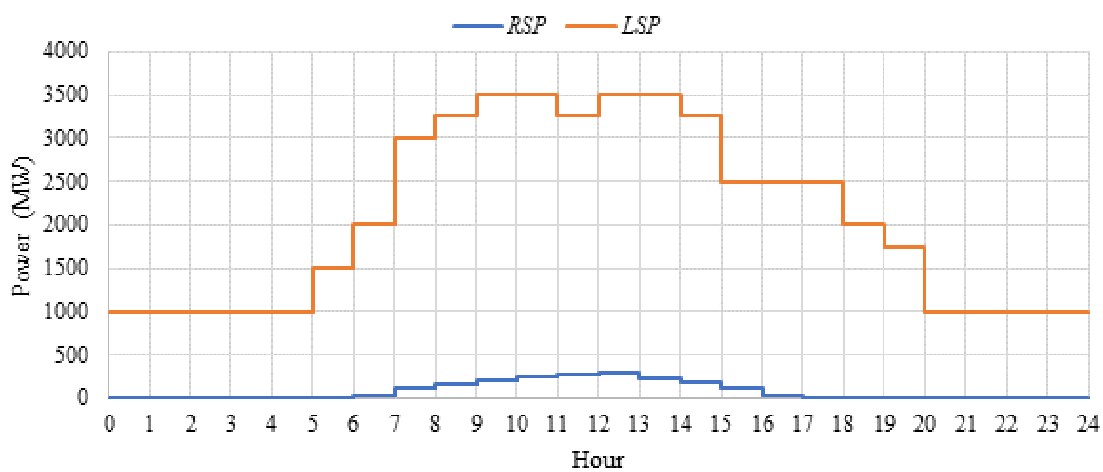

Fig. 7. Load-side power and power output of SBPs of System 4

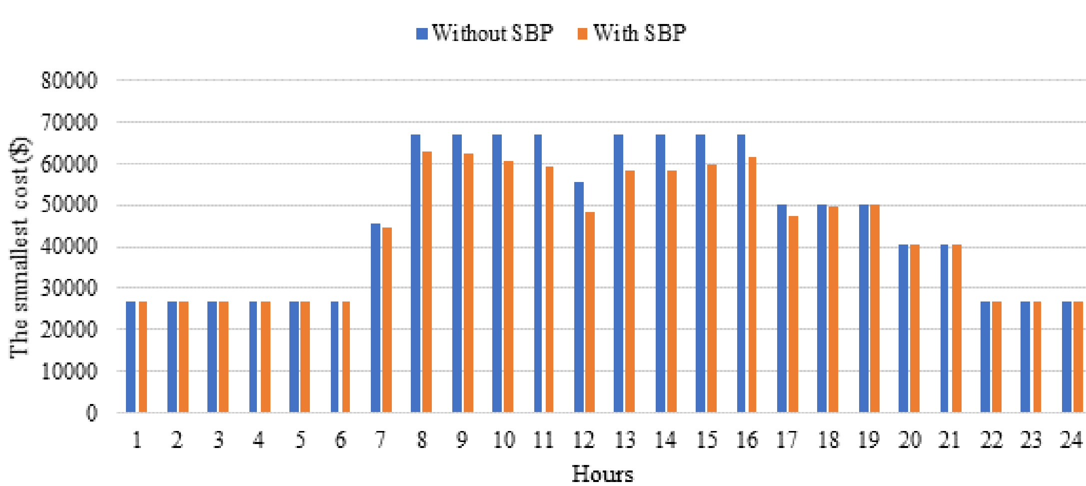

Fig. 8. Cost obtained from MPA of System 3 with and without SBP.

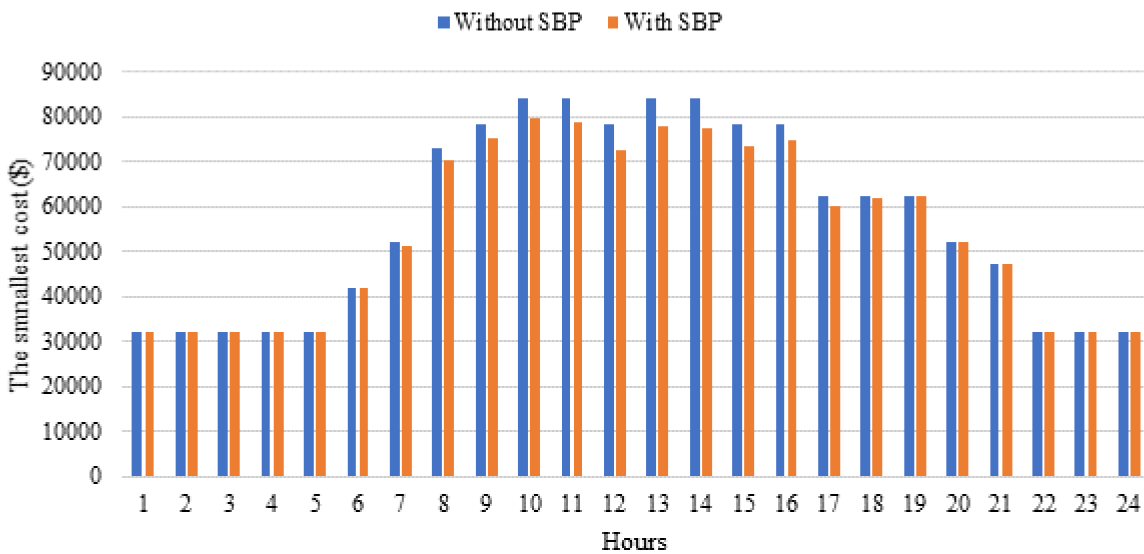

Fig. 9. Cost obtained from MPA of System 4 with and without SBP

4.3. Result comparisons for Systems 3 and 4

To further prove the MPA's search capabilities, we take it to implement Systems 3 and 4. A cooperation of operating thermal and solar units is shown in these systems. In which, System 3 is formed from System 1 whilst System 4 is created from System 2. So, data of TPs' operation parameters like the same as Systems 1 and 2 whereas solar radiation and power output of solar genarator is presented in Tables A3 and A4 in Appendix. Because solar radiation has changed according to interval times, power output of solar genarator is not constant. Figures 6 and 7 are plotted to offer load side power and power output of SBPs.

To value the effect of solar energy resource on the existing power system, we have applied MPA to two hybrid systems with and without SBPs in 24 periods with different *LSP* levels. Figures 8 and 9 display the optimal solutions obtained from MPA for Systems 3 and 4. As comparing two above cases with and without SBP, cost reduction is significantly decrease. Namely, that of System 3 is $ 65520.5 and that of System 4 is $ 47301.8.

Optimal solutions of four systems are shown in Tables A5 and A8 in Appendix

5. CONCLUSION

In this work, MPA was recommended for determining optimal operation parameters for two systems of the ELD problem and two systems of the HELD problem. In four test systems, the first two systems did not consider the presence of solar power generation while the last two systems regarded the operation scheduling of TPs and SBPs. The complicated levels of these systems were arranged from small to large systems and from simple to complex systems. The analysis results from employing MPA on Systems 1 and 2 were compared with some optimization methods. MPA can reach a good solution quality, fast convergence, and stabilization of searching ability. So, MPA is deserving of a positive optimization method for the HELD. The results show that the use of renewable energy sources is very effective for fuel cost reduction if they are incorporated into the power system. With advantages of the proposed method, in future research, MPA can be introduced to deal with ELD problems considering complicated models of thermal generating units [34], hydroelectric plants [35-36]. In addition, reducing power loss in the transmission line and [38] improving voltage profile [39] can be future interesting studies.

NOMENCLATURE

B_{gj}, B_{0g}, B_{00}	Coefficients of B-matrix for transmission power loss
m_g, n_g, o_g	Fuel burnt coefficients of cost function of the g*th* thermal unit
RP_g	Real power output of the *gth* thermal unit
RSP_j	Real power output of the *jth* solar genarator
RSP_{rated}	Rated real power output of solar genarator
$RP_{g,min}$; $RP_{g,max}$	Lower and upper limits of real power output of the *gth* thermal unit
T	Number of time intervals
A_m	Solar radiation of the *mth* time
A_{std}	Solar radiation corresponding to standard environmental condition
R_c	Radiation intensity in W/m^2
N_g	Number of thermal genarators

N_{sl}	Number of solar genarators
X_{best}	The best solution
X_g	The *gth* solution
c	Current iteration
γ	Predetermined factor
θ, ϑ	randomly selected number
$\partial, \varepsilon, \sigma, \varphi, \tau$	Brownian based random number
μ	Levy based random number
K	Decreased coefficient dependent on current iteration and highest iteration number
X_{min}, X_{max}	The minimum and maximum bounds of the solution
FADs	Fish aggregating equipment
P_{r1}, P_{r2}	Two randomly choosed solutions

REFERENCES

[1] Su, C.T.; Lin, C.T. 2000. New approach with a Hopfield modeling framework to economic dispatch. *IEEE transactions on power systems*, 15(2): 541-545.

[2] Pothiya, S.; Ngamroo, I.; Kongprawechnon, W. 2008. Application of multiple tabu search algorithm to solve dynamic economic dispatch considering generator constraints. *Energy Conversion and Management*, 49(4): 506-516.

[3] Bhattacharya, A.; Chattopadhyay, P. K. 2009. Biogeography-based optimization for different economic load dispatch problems. I*EEE transactions on power systems*, 25(2): 1064-1077.

[4] Moradi-Dalvand, M., Mohammadi-Ivatloo, B., Najafi, A.; Rabiee, A. 2012. Continuous quick group search optimizer for solving non-convex economic dispatch problems. *Electric Power Systems Research*, 93: 93-105.

[5] Modiri-Delshad, M.; Abd Rahim, N. 2014. Solving non-convex economic dispatch problem via backtracking search algorithm. *Energy*, 77: 372-381.

[6] Nguyen, T. T.; Vo, D. N. 2015. The application of one rank cuckoo search algorithm for solving economic load dispatch problems. *Applied Soft Computing*, 37: 763-773.

[7] Nguyen, T. T.; Vo, D. N.; Dinhhoang, B.; Pham, L. H. 2016. Modified cuckoo search algorithm for solving nonconvex economic load dispatch problems. *Advances in Electrical and Electronic Engineering*, 14(3): 236-246.

[8] Nguyen, T. T.; Nguyen, C. T.; Van Dai, L.; Vu Quynh, N. 2019. Finding optimal load dispatch solutions by using a proposed cuckoo search algorithm. *Mathematical Problems in Engineering.*

[9] Zakian, P.; Kaveh, A. 2018. Economic dispatch of power systems using an adaptive charged system search algorithm. *Applied Soft Computing*, 73: 607-622.

[10] Moustafa, F. S. El-Rafei, A.; Badra, N. M.; Abdelaziz, A. Y. 2017. Application and performance comparison of variants of the firefly algorithm to the economic load dispatch problem. *In 2017 Third International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB)*147-151, February.

[11] Thang, N. T.; Phuong, N. D.; Thanh, V. P.; Hien, C. T. 2018. An Effectively Modified Firefly Algorithm for Economic Load Dispatch Problem. *TELKOMNIKA*, 16, 2436-2443.

[12] Nguyen, T. T.; Nguyen, B. Q.; Nguyen, P. D., Hien, C. T. 2019. Minimizing Electricity Fuel Cost of Thermal Generating Units by Using Improved Firefly Algorithm. *Journal of Engineering and Technological Sciences*, 51(1): 133-147.

[13] Pham, L. H.; Duong, M. Q.; Phan, V. D.; Nguyen, T. T.; Nguyen, H. N. 2019. A high-performance stochastic fractal search algorithm for optimal generation dispatch problem. *Energies*, 12(9): 1796.

[14] Ha, P. T.; Hoang, H. M.; Nguyen, T. T.; Nguyen, T. T. 2020. Modified moth swarm algorithm for optimal economic load dispatch problem. *TELKOMNIKA*, 18(4): 2140-2147.

[15] Kien, L. C., Nguyen, T. T., Hien, C. T., & Duong, M. Q. 2019. A novel social spider optimization algorithm for large-scale economic load dispatch problem. *Energies*, 12(6): 1075.

[16] Yang, W., Cheng, T., Guo, Y., Yang, Z., & Feng, W. 2020. A Modified Social Spider Optimization for Economic Dispatch with Valve-Point Effects. *Complexity*.

[17] Chen, X.; Xu, B.; Du, W. 2018. An improved particle swarm optimization with biogeography-based learning strategy for economic dispatch problems. *Complexity*.

[18] Su, C. T.; Chiou, G. J. 1997. A fast-computation Hopfield method to economic dispatch of power systems. *IEEE transactions on Power Systems*, 12(4): 1759-1764.

[19] Hasan, K. M., & Raja, M. A. Z. 2018. Design of reduced search space strategy based on integration of Nelder–Mead method and pattern search algorithm with application to economic load dispatch problem. *Neural Computing and Applications*, 30(12): 3693-3705.

[20] Raja, M. A. Z.; Ahmed, U.; Zameer, A.; Kiani; A. K.; Chaudhary, N. I. 2019. Bio-inspired heuristics hybrid with sequential quadratic programming and interior-point methods for reliable treatment of economic load dispatch problem. *Neural Computing and Applications*, 31(1): 447-475.

[21] Wu, A. Yang, Z. L. 2018. An elitist transposon

quantum-based particle swarm optimization algorithm for economic dispatch problems. *Complexity*, 2018.

[22] Al-Betar, M. A.; Awadallah, M. A.; Krishan, M. M. 2019. A non-convex economic load dispatch problem with valve loading effect using a hybrid grey wolf optimizer. *Neural Computing and Applications*, 1-2

[23] Huynh, D.C.; and Nair, N. 2015. Chaos PSO algorithm based economic dispatch of hybrid power systems including solar and wind energy sources. In *2015 IEEE Innovative Smart Grid Technologies-Asia (ISGT ASIA)* 1-6 November.

[24] Tyagi, N.; Dubey, H.M. and Pandit, M. 2016. Economic load dispatch of wind-solar-thermal system using backtracking search algorithm. *International Journal of Engineering, Science and Technology*, *8*(4): 16-27.

[25] Augusteen, W. A., Geetha, S., & Rengaraj, R. (2016, March). Economic dispatch incorporation solar energy using particle swarm optimization. In 2016 3rd International Conference on Electrical Energy Systems (ICEES) (pp. 67-73). IEEE.

[26] Das, D.; Bhattacharya, A.; Ray, R. N. 2018. Solution of Probabilistic Economic Dispatch in Presence of Solar Power. In *2018 International Electrical Engineering Congress*, 1-4 March.

[27] Suresh, V.; Sreejith, S. 2017. Generation dispatch of combined solar thermal systems using dragonfly algorithm. *Computing*, 99(1): 59-80.

[28] Faramarzi, A.; Heidarinejad, M.; Mirjalili, S.; Gandomi, A. H. 2020. Marine predators algorithm: A nature-inspired Metaheuristic. *Expert Systems with Applications*, 113377.

[29] Al-Qaness, M. A.; Ewees, A. A.; Fan, H., Abualigah, L.; Abd Elaziz, M. 2020. Marine Predators Algorithm for Forecasting Confirmed Cases of COVID-19 in Italy, USA, Iran and Korea. *International Journal of Environmental Research and Public Health*, 17(10): 3520.

[30] Abd Elaziz, M.; Ewees, A. A.; Yousri, D.; Alwerfali, H. S. N.; Awad, Q. A.; Lu, S.; Al-Qaness, M. A. 2020. An improved Marine Predators algorithm with fuzzy entropy for multi-level thresholding: Real world example of COVID-19 CT image segmentation. *IEEE Access*, 8: 125306-125330.

[31] Yousri, D., Abd Elaziz, M., Oliva, D., Abualigah, L., Al-qaness, M. A.; Ewees, A.A. 2020. Reliable applied objective for identifying simple and detailed photovoltaic models using modern metaheuristics: Comparative study. Energy Conversion and Management, 223, 113279.

[32] Yousri, D.; Babu, T. S.; Beshr, E.; Eteiba, M. B.; Allam, D. 2020. A robust strategy based on marine predators algorithm for large scale photovoltaic array reconfiguration to mitigate the partial shading effect on the performance of PV system. *IEEE Access*, 8: 112407-112426

[33] Chowdhury, M. S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., ... & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews, 27, 100431.

[34] Van, T. P., Snášel, V., & Nguyen, T. T. (2020). Antlion optimization algorithm for optimal non-smooth economic load dispatch. International Journal of Electrical & Computer Engineering, 10(2), 1187-1199.

[35] Nguyen, T. T., Vo, D. N., & Dinh, B. H. (2018). An effectively adaptive selective cuckoo search algorithm for solving three complicated short-term hydrothermal scheduling problems. Energy, 155, 930-956.

[36] Nguyen, T. T., Vo, D. N., & Dinh, B. H. (2016). Cuckoo search algorithm using different distributions for short-term hydrothermal scheduling with reservoir volume constraint. International Journal on Electrical Engineering and Informatics, 8(1), 76

[37] Shahsavari, A., & Akbari, M. (2018). Potential of solar energy in developing countries for reducing energy-related emissions. Renewable and Sustainable Energy Reviews, 90, 275-291

[38] Routray, A., Mistry, K. D., & Arya, S. R. (2020). Power loss minimization in radial distribution systems with obstructed solar astronomical model and temperature effect using grey wolf optimization technique. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-20.

[39] Gampa, S. R., Makkena, S., Goli, P., & Das, D. (2020). FPA Pareto optimality-based multiobjective approach for capacitor placement and reconductoring of urban distribution systems with solar DG units. International Journal of Ambient Energy, 1-17. 10.1080/01430750.2020.1713887

[40] Daus, Y. V., Yudaev, I. V., & Stepanchuk, G. V. (2018). Reducing the costs of paying for consumed electric energy by utilizing solar energy. *Applied Solar Energy*, *54*(2), 139-143.

APPENDIX

Table A1. Parameters of System 1

Unit	$RP_{g,min}$	$RP_{g,max}$	m_g	n_g	o_g
RP_1 (MW)	10	125	756.79886	38.53973	0.1524
RP_2 (MW)	10	150	451.32513	46.15916	0.10587
RP_3 (MW)	35	225	1049.9977	40.39655	0.02803
RP_4 (MW)	35	210	1243.5311	38.30553	0.03546
RP_5 (MW)	130	325	1658.5596	36.32782	0.02111
RP_6 (MW)	125	315	1356.6592	38.27041	0.01799

Table A2. Parameters of System 2

Unit	$RP_{g,min}$	$RP_{g,max}$	m_g	n_g	o_g
RP_1 (MW)	150	600	1000	18.19	0.00068
RP_2 (MW)	50	200	970	19.26	0.00071
RP_3 (MW)	50	200	600	19.8	0.0065
RP_4 (MW)	50	200	700	19.1	0.005
RP_5 (MW)	50	160	420	18.1	0.00738
RP_6 (MW)	20	100	360	19.26	0.00612
RP_7 (MW)	25	125	490	17.14	0.0079
RP_8 (MW)	50	150	660	18.92	0.00813
RP_9 (MW)	50	200	765	18.27	0.00522
RP_{10} (MW)	30	150	770	18.92	0.00573
RP_{11} (MW)	100	300	800	16.69	0.0048
RP_{12} (MW)	150	500	970	16.76	0.0031
RP_{13} (MW)	40	160	900	17.36	0.0085
RP_{14} (MW)	20	130	700	18.7	0.00511
RP_{15} (MW)	25	185	450	18.7	0.00398
RP_{16} (MW)	20	80	370	14.26	0.0712
RP_{17} (MW)	30	85	480	19.14	0.0089
RP_{18} (MW)	30	120	680	18.92	0.00713
RP_{19} (MW)	40	120	700	18.47	0.00622
RP_{20} (MW)	30	100	850	19.79	0.00773

Table A3. Data of Solar generator and LSPs of System 3

Hour	A_m (W/m2)	RSP_1 (MW)	LSP (MW)	Hour	A_m (W/m2)	RSP_1 (MW)	LSP (MW)
1	0	0	500	13	703	141	1300
2	0	0	500	14	736	147	1300
3	0	0	500	15	586	117	1300
4	0	0	500	16	425	85	1300
5	0	0	500	17	291	58	1000
6	0	0	500	18	86	10	1000
7	111	16	900	19	0	0	1000
8	311	62	1300	20	0	0	800
9	375	75	1300	21	0	0	800
10	503	101	1300	22	0	0	500
11	617	123	1300	23	0	0	500
12	686	137	1100	24	0	0	500

Table A4. Data of Solar generator and *LSP*s of System 4

Hour	A_m (W/m2)	RSP_1 (MW)	LSP (MW)	Hour	A_m (W/m2)	RSP_1 (MW)	LSP (MW)
1	0	0	1000	13	703	281	3500
2	0	0	1000	14	736	294	3500
3	0	0	1000	15	586	234	3250
4	0	0	1000	16	425	170	3250
5	0	0	1000	17	291	116	2500
6	0	0	1500	18	86	20	2500
7	111	33	2000	19	0	0	2500
8	311	124	3000	20	0	0	2000
9	375	150	3250	21	0	0	1750
10	503	201	3500	22	0	0	1000
11	617	247	3500	23	0	0	1000
12	686	274	3250	24	0	0	1000

Table A5. Optimal solutions of System 1

Units	*LSP*=600 (MW)	*LSP*=700 (MW)	*LSP*=800 (MW)
RP_1 (MW)	21.190	24.972	28.763
RP_2 (MW)	10.000	10.000	10.000
RP_3 (MW)	82.074	102.656	123.246
RP_4 (MW)	94.385	110.625	126.875
RP_5 (MW)	205.359	232.699	260.029
RP_6 (MW)	186.993	219.047	251.089

Table A6. Optimal solutions of System 2

Units	*LSP*=2500 (MW)	Units	*LSP*=2500 (MW)
RP_1 (MW)	512.8019	RP_{11} (MW)	150.2317
RP_2 (MW)	169.0878	RP_{12} (MW)	292.7676
RP_3 (MW)	126.9004	RP_{13}(MW)	119.1109
RP_4 (MW)	102.9052	RP_{14} (MW)	30.7857
RP_5 (MW)	113.6926	RP_{15} (MW)	115.7923
RP_6 (MW)	73.5652	RP_{16} (MW)	36.2531
RP_7 (MW)	115.2959	RP_{17} (MW)	66.8733
RP_8 (MW)	116.4031	RP_{18} (MW)	87.9559
RP_9 (MW)	100.415	RP_{19} (MW)	100.8204
RP_{10} (MW)	106.0275	RP_{20} (MW)	54.2793

Table A7. Optimal solutions of System 3

Hour	1	2	3	4	5	6	7	8	9	10	11	12
RP_1 (MW)	17.41	17.41	17.41	17.41	17.41	17.41	31.92	81.49	76.24	65.74	56.40	34.77
RP_2 (MW)	10.00	10.00	10.00	10.00	10.00	10.00	10.00	81.31	73.76	58.66	45.20	14.06
RP_3 (MW)	61.51	61.51	61.51	61.51	61.51	61.51	140.43	225.00	225.00	225.00	225.00	155.90
RP_4 (MW)	78.11	78.11	78.11	78.11	78.11	78.11	140.49	210.00	210.00	210.00	210.00	152.72
RP_5 (MW)	178.04	178.04	178.04	178.05	178.04	178.04	282.83	325.00	325.00	325.00	325.00	303.37
RP_6 (MW)	154.93	154.93	154.93	154.93	154.93	154.93	277.90	315.00	315.00	315.00	315.00	301.99

Optimal solutions of System 3 (continuous)

Hour	13	14	15	16	17	18	19	20	21	22	23	24
RP_1 (MW)	49.35	47.57	58.94	72.14	34.01	35.75	36.10	28.76	28.76	17.41	17.41	17.41
RP_2 (MW)	35.05	32.49	48.86	67.86	12.97	15.47	15.98	10.00	10.00	10.00	10.00	10.00
RP_3 (MW)	225.00	225.00	225.00	225.00	151.80	161.23	163.16	123.24	123.24	61.51	61.51	61.51
RP_4 (MW)	210.00	207.74	210.00	210.00	149.48	156.93	158.45	126.90	126.90	78.11	78.11	78.11
RP_5 (MW)	325.00	325.00	325.00	325.00	297.93	310.45	313.01	260.00	260.00	178.04	178.04	178.05
RP_6 (MW)	315.00	315.00	315.00	315.00	295.61	310.30	313.30	251.10	251.10	154.93	154.93	154.93

Table A8. Optimal solutions of System 4

Hour	1	2	3	4	5	6	7	8	9	10	11	12
RP_1 (MW)	150.00	150.00	150.00	150.00	150.00	301.45	403.63	593.74	600.00	600.00	600.00	600.00
RP_2 (MW)	50.00	50.00	50.00	50.00	50.00	50.00	93.70	200.00	200.00	200.00	200.00	200.00
RP_3 (MW)	50.00	50.00	50.00	50.00	50.00	50.00	81.18	160.91	180.80	200.00	198.14	169.80
RP_4 (MW)	50.00	50.00	50.00	50.00	50.00	50.00	70.25	126.89	148.38	178.53	168.54	134.54
RP_5 (MW)	50.00	50.00	50.00	50.00	50.00	68.86	91.92	130.08	144.22	159.99	159.35	136.09
RP_6 (MW)	20.00	20.00	20.00	20.00	20.00	24.41	49.62	92.17	100.00	100.00	100.00	98.33
RP_7 (MW)	26.10	26.16	26.25	26.28	26.27	93.83	106.97	124.33	125.00	125.00	125.00	125.00
RP_8 (MW)	50.00	50.00	50.00	50.00	50.00	54.64	85.88	140.34	150.00	150.00	150.00	148.20
RP_9 (MW)	50.00	50.00	50.00	50.00	50.00	51.13	77.21	117.50	135.99	166.07	158.90	124.68
RP_{10} (MW)	30.00	30.00	30.00	30.00	30.00	56.07	85.05	128.12	149.98	150.00	150.00	139.18
RP_{11} (MW)	100.00	100.00	100.00	100.00	100.00	130.46	140.34	157.38	175.00	190.29	184.12	163.50
RP_{12} (MW)	150.00	150.00	150.00	150.00	150.00	247.12	272.03	307.68	325.22	352.47	345.37	313.36
RP_{13} (MW)	40.00	40.00	40.00	40.01	40.00	90.73	105.24	128.22	139.79	159.54	152.40	132.21
RP_{14} (MW)	20.00	20.00	20.00	20.00	20.00	20.00	27.39	33.47	47.11	66.86	61.59	37.39
RP_{15} (MW)	25.00	25.00	25.00	25.00	25.00	64.18	90.51	134.38	156.26	184.79	180.05	142.01
RP_{16} (MW)	24.56	24.50	24.41	24.38	24.38	32.60	34.47	37.56	39.25	41.29	40.14	38.17
RP_{17} (MW)	30.00	30.00	30.00	30.00	30.00	30.00	42.10	85.00	85.00	85.00	85.00	85.00
RP_{18} (MW)	30.00	30.00	30.00	30.00	30.00	39.08	63.38	104.57	119.99	120.00	119.99	111.41
RP_{19} (MW)	40.00	40.00	40.00	40.00	40.00	56.32	79.09	116.94	120.00	120.00	120.00	120.00
RP_{20} (MW)	30.00	30.00	30.00	30.00	30.00	30.00	30.00	72.58	89.97	100.00	100.00	79.45

Table A8. Optimal solutions of System 4 (Continued)

Hour	13	14	15	16	17	18	19	20	21	22	23	24
RP_1 (MW)	600.00	600.00	600.00	600.00	488.92	508.66	512.78	410.36	357.92	150.00	150.00	150.00
RP_2 (MW)	200.00	200.00	200.00	200.00	152.76	166.31	169.10	98.40	61.24	50.00	50.00	50.00
RP_3 (MW)	195.25	192.78	172.96	179.27	116.81	125.14	126.89	83.98	61.37	50.00	50.00	50.00
RP_4 (MW)	161.85	162.25	137.96	145.34	95.70	101.62	102.86	72.25	56.37	50.00	50.00	50.00
RP_5 (MW)	157.10	155.13	139.08	143.63	108.91	112.86	113.68	93.26	82.70	50.00	50.00	50.00
RP_6 (MW)	100.00	100.00	100.00	100.00	68.33	72.66	73.57	51.08	40.27	20.00	20.00	20.00
RP_7 (MW)	124.99	125.00	125.00	125.00	113.47	114.97	115.30	107.48	103.31	26.35	26.21	26.37
RP_8 (MW)	150.00	150.00	150.00	150.00	109.65	115.23	116.40	87.74	73.05	50.00	50.00	50.00
RP_9 (MW)	151.87	149.64	127.33	134.34	95.33	99.53	100.40	78.63	67.15	50.00	50.00	50.00
RP_{10} (MW)	150.00	150.00	144.57	149.95	101.42	105.22	106.04	86.34	76.76	30.00	30.00	30.00
RP_{11} (MW)	183.06	181.19	167.25	173.68	148.12	149.87	150.24	140.97	136.78	100.00	100.00	100.00
RP_{12} (MW)	340.50	340.79	315.98	321.28	288.28	291.99	292.77	273.32	262.91	150.00	150.00	150.00
RP_{13}(MW)	149.59	146.96	133.88	138.12	116.09	118.60	119.11	106.10	99.06	40.00	40.02	40.00
RP_{14} (MW)	58.14	57.26	40.85	43.56	30.18	30.73	30.83	27.66	25.52	20.00	20.00	20.00
RP_{15} (MW)	173.84	171.65	145.40	152.77	110.30	114.86	115.80	92.08	79.76	25.00	25.00	25.00
RP_{16} (MW)	40.23	40.01	38.55	39.33	35.87	36.19	36.26	34.58	33.82	24.32	24.44	24.29
RP_{17} (MW)	85.00	85.00	85.00	85.00	61.41	65.92	66.86	43.62	31.74	30.00	30.00	30.00
RP_{18} (MW)	119.99	120.00	114.31	120.00	82.58	87.04	87.97	64.91	53.22	30.00	30.00	30.00
RP_{19} (MW)	120.00	120.00	120.00	120.00	96.05	99.98	100.80	80.45	69.71	40.00	40.00	40.00
RP_{20} (MW)	99.91	99.50	83.04	88.75	48.94	53.38	54.30	31.36	30.00	30.00	30.00	30.00