Apply three metaheuristic algorithms for energy storage-based integrated power system to reduce generation cost

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ABSTRACT

This research applies new computing methods to optimize the operation of a typical hydrothermal system for one day. The system consists of one thermal power plant (TPP) and one pumped storage hydropower plant (PSHP). The main target of the research is to determine the amount of water that must be discharged or pumped back to the reservoir to reduce the total electricity production cost (TEPC) of TTP. The volumes of water storage in the reservoir at the beginning and end points of the schedule must be the same. Three meta-heuristic algorithms are applied, including COOT optimizer (COOT), aquila optimizer (AO), and particle swarm optimizations (PSO) in which COOT and AO were proposed at early 2021. The results show that the effectiveness of COOT is better than AO, PSO and several methods in previous studies. Hence, COOT is considered a powerful computing tool for the problem.

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1. INTRODUCTION

Establishing an optimal schedule operation for the hydrothermal power system (HPS) is mainly about dispatching the power produced by both thermal power plants (TPPs) and hydropower plants (HPPs) in each interval to meet the assignment from the schedule [1]–[3]. Besides, the process of making an optimal schedule also focuses on minimizing the total electricity production cost (TEPC) caused by TPPs. On the other hand, the TEPC from HPPs is almost neglected due to the free water in rivers [4], [5]. Accordance to the intended time duration, the establishment of an optimal schedule for HPS is classified into the long-term duration [6], [7], the medium-term duration [8], [9], and the short-term duration [10]–[16]. In the short-term duration problem, the amount of power production is described in the form of a discharge function [14], [15], while the varying head uses a volume of discharge function in order to control the amount of power production [17]–[20].

The concepts of HPPs can be classified into the traditional HPPs, which only operate in generating mode and the pumped storage hydropower plant (PSPP), which can be operated in both generating mode and pumping mode. Developing an optimal power production schedule (OPPS) for the combined system with PSPP and TPP is the primary target associated with the short-term hydrothermal scheduling problem. A clear OPPS will manipulate the amount of power output belonging to each TPP in an entire system at a particular subinterval to fulfill the power demand while cutting TEPC used by TPP at least as possible. Following the OPPS, the operation board at PSPP will determine approximately the amount of water needed to release from the upper reservoir to the lower one. Also, the board must determine the volume of water needed to inject back to the upper reservoir in order to meet hydraulic constraints. On the other hand, the board at every TPP must also control the amount of power output as the OPPS given. Moreover, all engineering constraints and any mutual constraints related HPS problem must be imposed strictly. In summary, the presence of PSPP in the HPS concept is considered an instant contingency reserve to cope with the situation in which the mismatch is caused by the increase of the demand side over the supply side. This behavior not only enhances the reliability factor for the whole system but also contributes to the achievement of shortening the TEPC caused by the extra producing electricity process of TPP.

The early research considers the presence of PSPP in the combined system for cutting costs [21]. The method applied in [21] aims to reach a higher possibility that there is no violation in all constraints involving the hydrothermal system (HTS) problem. The study [22] introduces an algorithm called two phases of computations (TCP) in which the first phase presents two techniques to support the making decision of generating mode and pumping mode for PSPP. The results given by [21] have shown that the integration of TCP and the non-fluctuating water horizontal technique is more effective. Unfortunately, the system information was not declared in this study and there were no later studies replicating the system. The HPP in the study [16] is operated at two separate statuses: the generating status, which is represented by the release function of water and the pumping status, accompanied by a constant volume of pumped water and a fixed efficiency. In order to reach the OSPP and non-violation for all constraints, the gradient approach based on lagrange function (LF) is implemented. Several meta-heuristic methods can be listed such as evolutionary programming (EP) [23], and an improved Acceleration factor-based particle swarm optimization (AFPSO) [24]. The EP method in [23] performed better than LF method in [16] by reaching the lower value of TEPC. AFPSO is a modified version of the original particle swarm optimizations (PSO). But the study [24] did not apply the original PSO to present a clear view of the AFPSO performance. Therefore, we haven't seen any claim regarding AFPSO effectiveness in [24]. Aihara *et al.* [25] a solar power plant is added to the initial power system model while solving the HTS problem. In the new model, the PSPP is responsible for filling up the mismatch between the supply side and demand side caused by the decrease in solar radiation intensity. PSPP in [25] demonstrated the effectiveness in enhancing the reliability belonging power supply side while dealing with the uncertainty of other generating sources integrated with the system such as solar and wind. And this study did not focus on shortening TEPC value for TPP and there were no comparisons regarding its effectiveness of results over other studies.

In this research, we again implemented the same system specifications used in [16], [23], [24]. The common point that can be seen from these studies is that they only intended to present the optimal value of power output for HPP and TPP accompany with TEPC value more than interpreting the real contribution of PSPP in the HTS problem. Moreover, they did not recognize the key factor to shortening the TEPC in HTS problem. In addition, we have applied a PSO [26] and two novel metaheuristic algorithms comprising COOT optimizer (COOT) [27] and aquila optimizer (AO) [28]. Briefly, the main inspiration of forming COOT optimization algorithm (COOT) came from the simulation of moving practice on the water surface toward food supply area of the bird flock, called COOT. On the other hand, the Aquila optimization is developed by simulating nature behavior of Aquila species while they are hunting for prey. In summary, the novelty and contribution of the paper are as follows: i) apply new metaheuristic algorithms COOT and AO; ii) demonstrate the real performance of COOT over the other methods applied in this research and previous publications; and iii) avoid and eliminate all problems in previous studies but also achieve the optimal results, and reduce the TEPC for the system effectively.

2. PROBLEM FORMULATION

2.1. Objective function

In the concept of HTS, *m* TPPs and *n* HPPs are working to supply electricity to loads and the main target is to cutting TEPC of *m* TPPs. Normally, the TEPC caused by TPPs is approximately described by a quadratic function and the objective function is as follows [29], [30]:

$$Cutting\ TEPC = \sum_{l=1}^{TS}\sum_{i=1}^{m} tl_l.(\gamma_{1i}+\gamma_{2i}PG_{i,l}+\gamma_{3i}PG_{i,l}^{2}) \quad (1)$$

where TS is the number of subintervals; γ_{1i}, γ_{2i} and γ_{3i} are the fuel expenditure coefficient of the i^{th} TPP; $PG_{i,l}$ is the power produced by the i^{th} TPP in subinterval l; and tl_l the time length of the subinterval l.

2.2. Constraints

Power balance of supply and demand: this constraint is the relationship between the total power output produced by supply side and consumed by demand side (PRD). The constraint is as follows [16].

$$\sum_{i=1}^{m} PG_{i,l} + \sum_{j=1}^{n} PH_{j,l} - \sum_{j=1}^{n} PSG_{j,l} - PRD_l - Ploss_l = 0 \quad (2)$$

where $PH_{j,l}$ is the active power of the HPP j in subinterval l; and $PSG_{i,l}$ is the used power by the HPP j in subinterval l. Released water volume: the volume of water available to release directly to hydro turbine for producing power is shown as follows [13]:

$$WR_{j,l} = tl_l \times RW_{j,l} \quad (3)$$

where $WR_{j,l}$ is the released water volume from the upper reservoir to turbines of hydroelectric plant j at the *lth* subinterval; and $RW_{j,l}$ is the released water rate of the HPP j at subinterval l and it is obtained by [13]:

$$RW_{j,l} = \alpha_{1j} + \alpha_{2j} PH_{j,l} + \alpha_{3j} PH_{j,l}^2 \quad (4)$$

where α_{1j}, α_{2j} and α_{3j} are respectively the given coefficients in the HPP j.

Reservoir water volume balance: the condition is considered every subinterval to guarantee the volume of the reservoir does not exceed limits. Inflows, discharge and pumped water are also constrained by [13]:

$$WSt_{j,l-1} - WSt_{j,l} + WB_{j,l} - WR_{j,l} + IW_{j,l} = 0 \quad (5)$$

where $WSt_{j,l-1}$ and $WSt_{j,l}$ are reservoir water volume in the l^{th} and $(l-1)^{th}$ subinterval; $WB_{j,l}$ is the amount of water brought back to the upper reservoir belonging HPP j in subinterval l; and $IW_{j,l}$ is the inflows to the jth HPP at the *lth* subinterval. The beginning and end volume constraints: the water level stored in reservoir must be restricted by [24]:

$$WSt_{j,0} = WSt_{j,str}; WSt_{j,TS} = WSt_{j,end} \quad (6)$$

where $WSt_{j,str}$ and $WSt_{j,end}$ are respectively available reservoir water volume at the beginning and remaining reservoir water volume at the end of the day; $WSt_{j,0}$ and $WSt_{j,TS}$ are the reservoir water volume at starting time and the last hour.

Reservoir volume limits: reservoir volume at each hour should be within the minimum and maximum allowable limits as follows [16]:

$$WSt_{j,min} \le WSt_{j,l} \le WSt_{j,max} \quad (7)$$

where $WSt_{j,min}$ and $WSt_{j,max}$ are minimum and maximum amount of water in the j^{th} reservoir. Released water limit: discharged water over one hour should be within the minimum and maximum allowable discharge rate of turbines as follows [23]:

$$RW_{j,min} \le RW_{j,l} \le RW_{j,max}$$
$$j=1, 2, \ldots, n ; l=1, 2, \ldots, TS \quad (8)$$

where $RW_{j,min}$ and $RW_{j,max}$ are minimum and maximum released water rate in the j^{th} reservoir. Generating and pumping limits: power generation and pump power of power plants must satisfy the inequality constraints below [16]:

$$PG_{i,min} \le PG_{i,l} \le PG_{i,max} \quad (9)$$

$$PH_{j,min} \le PH_{j,l} \le PH_{j,max} \quad (10)$$

$$PSG_{j,min} \le PSG_{j,l} \le PSG_{j,max} \quad (11)$$

where $PG_{i,min}$ and $PG_{i,max}$ are the smallest and highest power generation the i^{th} TPP; $PH_{j,max}$ and $PH_{j,min}$ are the highest and smallest power generation of the j^{th} HPP; and $PSG_{j,min}$ and $PSG_{j,max}$ are the smallest and highest pumping power of the j^{th} PSHP.

3. THE ENTIRE COMPUTING PROCESS OF COOT

3.1. The initialization

At the beginning point, COOT produces a set of solutions by using the model below:

$$S_i = rd.(S^{max} - S^{min}) + S^{min}; i = 1, 2, \dots, Po \tag{12}$$

where S_i is the *ith* solution within the lower and upper boundaries, S^{min} and S^{max}; and Po is population size. In COOT, the whole population is ranked separate into a quantity of leaders (*N*) and a quantity of COOT members (*M*). *N* is equal to 10% of the population, while 90% of the population is *M*. Each solution in leader group and its fitness function are represented by NP_j and FN_j. Similarly, each solution in COOT member group and its fitness function are MP_q and *FM*.

3.2. New solution updates

As mentioned earlier, COOT separates the initial population into two groups. Therefore, the new solution update (new position update) must be implemented differently for the two groups. The update of new position for each COOT in the two groups is presented as follows.

3.2.1. Position update for COOTs

There are three methods to update new location for each COOT member. The selection of method is dependent on the comparison of a random number with a balance parameter, which is selected to be 0.5. In addition, the order of COOT is also a condition in choosing a method. The three methods are presented in (13-15). If the random number is not higher than the balance parameter (i.e. $rd \leq 0.5$) and the considered COOT is not the first COOT in the group (i.e. $q \neq 1$), (13) is applied. If the random number is still not higher than the balance parameter but the COOT is the first one, (14) is applied. For other cases (i.e. $rd > 0.5$), (15) is applied.

$$MP_q^{m+1} = MP_q^m + \left(\frac{MI-m}{MI}\right).rd.\left[(rd.(S^{max} - S^{min}) + S^{min}) - MP_q^m\right] \tag{13}$$

$$MP_q^{m+1} = 0.5 \times \left(\left(MP_{q-1}^m + MP_q^m\right)\right) \tag{14}$$

$$MP_q^{m+1} = NP_{EL}^m + 2.rd \times \cos(2G\pi) \times \left(NP_{EL}^m - MP_q^m\right) \tag{15}$$

where MP_q^m and MP_q^{m+1} are new and old locations of the q^{th} COOT; *EL* is a selected leader among the existing leaders; NP_{EL}^m is position of the EL^{th} leader at the m^{th} iteration; *MI* and *m* are maximum and current iterations; and MP_{q-1}^m is position of the $(q\text{-}1)^{th}$ COOT individual nearby the q^{th} COOT.

3.2.2. Position update for leaders

The determination for new position of each leader at the next iteration is performed by:

$$NP_j^{m+1} = (2 - \tfrac{m}{MI}).rd.\cos(2G\pi).\left(BestPos - NP_j^m\right) + BestPos \ if \ rd < 0.5 \tag{16}$$

$$NP_j^{m+1} = (2 - \tfrac{m}{MI}).rd.\cos(2G\pi).\left(BestPos - NP_j^m\right) - BestPos \ if \ rd \geq 0.5 \tag{17}$$

In the two above, NP_j^{m+1} and NP_j^m are the new and old positions of the leader *j; G* is a randomly priduced number within -1 and 1; and $BestPos$ is the best position of all COOTs.

4. THE ENTIRE COMPUTING PROCESS OF COOT

In this part, the implementation of COOT, PSO [27] and AO [28] is accomplished to determine the best solution for the considered problem. The coding and simulation are executed on a personal computer

(2.2 GHz of central processor unit and 8 GB of RAM). MATLAB platform is used to code the solving program by using the three methods. The system and results are described in the next sections.

4.1. The system descriptions

The solved system has one TPP and one PSPP working over one day with six periods. The highest generation of the hydro plant is 300 MW and the highest pumping power is also 300 MW. The plant must discharge 800 acre-ft/h via turbine to produce the highest generation, but it only pumps back 600 acre-ft/h when using the pump power of 300 MW. So, the efficiency of pumped storage is 3/4. The initial volume and end volume are constrained to be the same and equal to 8,000 arce-ft. It is supposed that there are no inflows to the reservoir. Hence, the hydro plant has two options for operation. The first option is to pump water and used the stored water for producing electricity. The second option is to discharge the available water to produce electricity and then pumps back water for return used water. Data of the hydro plant, thermal plant and loads are from [16].

4.2. The results and discussions

In this section, three methods are run fifty trials to find out the best solutions to the considered problem by setting 10 to population size and 50 to the maximum quantity of iterations. Figure 1 shows TPEC of the fifty trials. These values were sorted from the smallest to the largest TPEC values. COOT is the most effective method and AO is the worst method because, among 50 independent runs, COOT can reach more optimal values than both PSO and AO.

In Figure 2, the best convergences owned by three methods are depicted. The COOT reaches the optimal value much faster than PSO and AO. Figure 3 show that COOT provides the best performance among the three methods. Moreover, the striking features owned by COOT is not only shown from the minimum fuel cost value (Min.Cost) but also can be observed from the other criteria such as the average fuel cost value (Aver.Cost), the maximum fuel cost value (Max.Cost) and the standard of deviation (Std). Particularly, the Min.Cost obtained by COOT is $269642.458, while the similar ones reached by PSO and AO are, respectively, $269643.226 and $269689.404. Regarding the Aver.Cost, the value obtained by COOT is $273318.073 while the values given by PSO and AO are $275725.268 and $279135.716. After converting into percentages, COOT can reach less cost than PSO and AO by 0.88% and 2.13%. Next, the Max.Cost reached by COOT is $276929.755, but the values reported by PSO and AO are $287389.894 and $286963.092. From the evidence, COOT proved itself the best method among the three methods applied for the problem and AO is the worst.

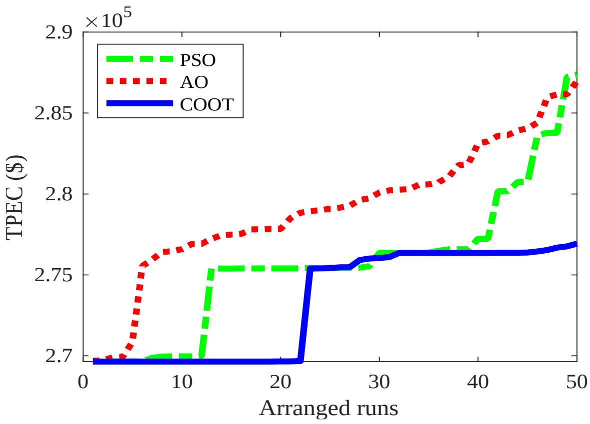

Figure 1. The cost of fifty solutions arranged in descending order

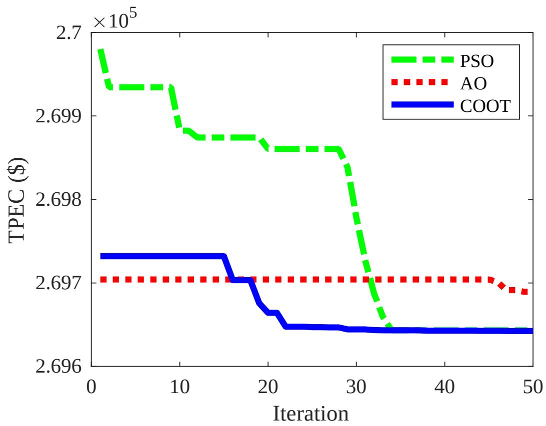

Figure 2. The convergence curves given by the three methods

The optimal operation solution of the PSPP is shown in Figure 4. The figure shows four major parameters regarding water in reservoir including reservoir volume, inflows to reservoir, discharge and stored water. Among the four parameters, discharge means the hydropower plant performs generation mode to produce electricity, while stored water means pump mode is carried out to move water from lower reservoir to upper reservoir. Looking at the green area from hour 0 to hour 24, we can see the water volume in the reservoir is 8000 acre-ft at the beginning of the day (i.e. hour 0) and it is also equal to 8,000 acre-ft at the last hour as the constraint that the initial and end volume must be the same. Inflows in orange cannot be seen in the figure due to these values are zero for all a day. So, it uses water available in the reservoir to produce electricity and then it must consume electricity from the TPP to move water in the lower reservoir to upper reservoir. In fact, volume decreases from hour 1 to hour 12 and it suffers from the lowest volume with 800 acre-ft at hour 12. The decrease of volume can be simply understood by observing discharge in yellow. The yellow area starts from hour 1 to hour 12 and it has four major values, including 500.9 for hour 1 to hour 4, 799.9 for hour 5 to hour 8 and 499.2 for hour 9 to hour 12. On the contrary, the power plant does not discharge water for the latter hours (i.e. from hour 13 to hour 24) but it needs to store water for compensating water used in hours before. Hence, we do not see the yellow area in the hours, but we see grey area with the same height of 600 acre-ft as the constraint of the power plant. The discharge is not higher than 800 acre-ft because the discharge limit is 800 acre-ft. In contrast, the pumped water is the same for all pumping mode hours as characteristic of the power plant. The volume increases from hour 13 to hour 24 by adding 600 acre-ft and it reaches 8,000 acre-ft.

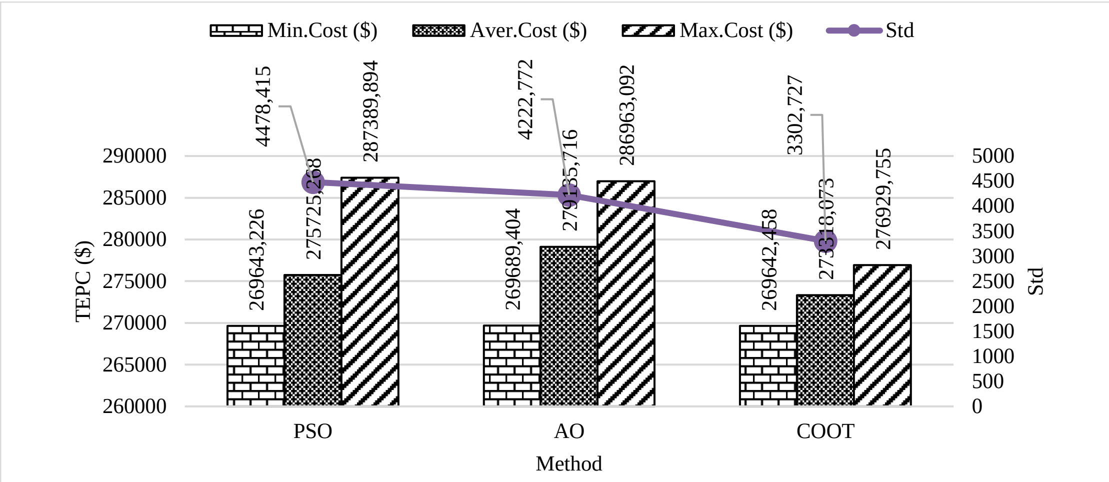

Figure 3. Summary of fifty solutions obtained by three methods

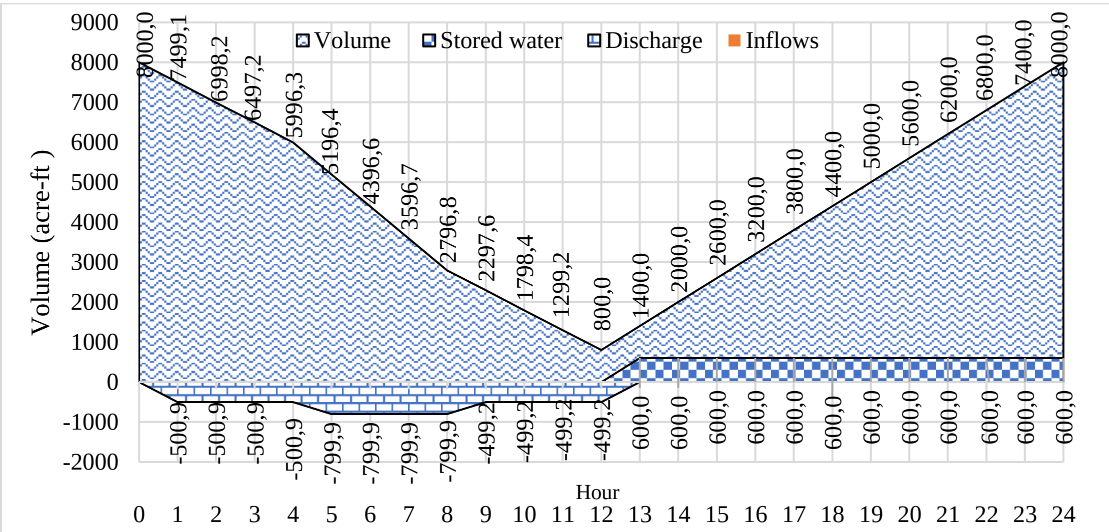

Figure 4. Operation solution of PSPP

4.3. Comparison with previous methods

Optimal generations of thermal and hydro plants and fuel cost obtained by methods are reported in Table 1. The cost of $269628.8 from EP [23] is the lowest among the methods, while other methods and COOT have approximately the same cost of $269642.458. However, EP has reported hydro generation with

333.0154 MW, which is greater than the maximum generation of 300 MW. So, EP has not satisfied the generation constraint. AFPSO [24] did not exceed the generation limits for both thermal and hydro plants, but it has a significant error in power balance constraint. The power load is 1,600 MW for the 1st and 3rd intervals, but total power of the plants is 1599.99 and 1599.97 MW, respectively. The mismatch is 0.01 and 0.03 MW for the two intervals and it is too high to accept the effectiveness of AFPSO. Lamarckian genetic algorithm (LGA) [16] can be considered to be as effective as COOT; however, LGA [16] needs the approximation for fuel cost function and a lagrange optimization function. Especially, we have to take the partial derivative of the function with respect to variables. As a result, LGA is limited for problems where functions fail to be taken partial derivative. By acknowledging these unhandled issues from previous studies, the results obtained by COOT have several strong features as follows:

- Avoid the violation of hydro generation as [24] and the power mismatch as [23].
- All restrictions of LGA [16], such as requiring a high number of steps, using the partial derivative, establishing lagrange function are completely removed while applying COOT.

Table 1. Results comparison obtained by different methods

	Subinterval (l)	1	2	3	4	5	6	TEPC ($)
	PCL_l (MW)	1,600	1,800	1,600	500	500	500	
AFPSO [24]	$PG_{i,l}$ (MW)	1449.99	1,500	1,450	800	800	800	269642.4
	$PH_{j,l}$ (MW)	150	300	159.97	-300	-300	-300	
	Total power (MW)	1599.99	1,800	1599.97	500	500	500	
EP [23]	$PG_{i,l}$ (MW)	1466.4211	1466.9846	1466.5943	800	800	800	269628.8
	$PH_{j,l}$ (MW)	133.5789	333.0154	133.4057	-150	-300	-300	
	Total power (MW)	1,600	1,800	1,600	650	500	500	
LGA [16]	$PG_{i,l}$ (MW)	1,450	1,500	1,450	800	800	800	269642.4
	$PH_{j,l}$ (MW)	150	300	150	-300	-300	-300	
	Total power (MW)	1,600	1,800	1,600	500	500	500	
COOT	$PG_{i,l}$ (MW)	1450.005	1,500	1449.995	800	800	800	269642.458
	$PH_{j,l}$ (MW)	149.995	300	150.005	-300	-300	-300	
	Total power (MW)	1,600	1,800	1,600	500	500	500	

5. CONCLUSION

In this research, three meta-heuristic methods are implemented to determine the optimal total fuel cost for hydrothermal system. Among these methods, the performance of COOT is superior to the other remaining methods in the research over all aspects such as the lowest cost, the mean cost, maximum cost and fluctuations. In addition, the TEPC from fifty runs obtained by the three methods was also sorted and depicted for comparison. COOT has reached about forty-eight runs with the same quality as the most optimal solution, while OA and PSO could not reach one best optimal solution. Compared with the results reported by the previous research, COOT has found the same cost as other methods and a valid solution satisfying all constraints, while two other methods have violated the involved constraints. Consequently, COOT is regarded as a powerful metaheuristic method for solving the problem of optimal generation for pumped storage hydroelectric plants and TPPs in this research. In future work, we will apply the COOT and other new algorithms for more complicated systems with the contribution of additional renewable power plants to evaluate the efficiency of the applied methods.

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