Optimal Generation for Hydrothermal System with Pumped Storage Hydroelectric Plants Using Six Particle Swarm Optimization Algorithms

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ARTICLE INFO

Article history:
Received: 20 September 2021
Revised: 12 November 2021
Accepted: 29 November 2021

Keywords:
Pumped storage;
Hydroelectric plant;
Hhermal power plant;
Fuel expenditure;
Particle swarm optimization

ABSTRACT

In this paper, a hydrothermal system with one thermal power plant (TP) and one pumped storage hydroelectric plant (PHP) sis cooperated to produce and supply electricity to loads. The main objective of the study is to discharge water through hydro turbine and pump water back to the upper reservoir effectively so that reducing the total electric generation fuel expenditure (TFE) of TP as much as possible. The assumption is that there is no inflow to the reservoir of PHP and the requirement is that the volume should be the same for the beginning and the end of a scheduled day. A proposed particle swarm optimization (proposed PSO) and five other PSO variants are implemented. The simulation results indicate that appropriate discharge and pumped storage for PHP can reduce TFE for TP and the proposed PSO is the most effective PSO variant among six methods. The proposed PSO can reach the highest success rate avoiding time-consuming simulation and the best performance with a high number of good solutions. As compared to previous method, the proposed PSO is also more robust to find less TFE and valid optimal solution. As a result, it concludes that PHP is a very crucial power plant for giving benefit to power system and the proposed PSO is a good tool for power system with PHP.

1. INTRODUCTION

Optimal scheduling of hydrothermal system (HTS) is the power generation cooperation between thermal power plants (TPs) and hydroelectric plants (HPs) over periods [1-3]. The optimal scheduling problem of HTS concerns the objective of cutting the total fuel expenditure (TFE) of all TPs while the TFE of HPs is neglectable [4-5]. The optimal power generation problem for HTS is divided into long-term problem [6-7], medium-term problem [8-9] and short-term problem [10-16] in which the model of HPs is different but the model of TPs is the same in the problems.

Weather conditions play an important role in scheduling for HPs during different seasons in a year. The process of making long-term problem for hydropower plant considers many aspects in practice such as the unpredictable variation of load, the amount of water backs in the reservoir and the willingness to get online of generating sources including hydro and thermal generators. The short-term problem considers the range of time between a daylong and a weeklong in order to reach a specific objective in power system operation. In particular, if time range is a daylong, it will be scheduled in 24 smaller time intervals with one hour for each interval. Or, the schedule can be divided into 7 smaller time intervals in which each interval is a day. In addition, the scheduling must be associated strictly with the load demand at each single point of time, the amount of water remained in reservoirs, the willingness to get online of generating sources, etc. On the other hand, all constraints involving system operation must be met during operation time. The model of HPs in short-term problem is classified into constant head and variable head in which constant head model represents hydro generation as a discharge function [14-15] and the variable head model expresses the hydrogeneration as a volume and discharge function [17-20].

The HPs joined in HTS can be conventional type with the only generation mode while pumped storage hydroelectric plants (PHPs) have two separately modes, generation mode producing electricity and pump mode consuming electricity. The main task of the short-term hydrothermal scheduling problem with the integration of pumped hydro plants is to define an optimal power generation schedule (OPGS) for both pumped storage

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hydroelectric plants (PHPs) and thermal power plants (TPs). The OPGS will assign the particular power generated by operating power plants at each specific interval to meet the power demand of loads and cut the TFE of the TPs as much as possible. According to the assignment from OPGS, the operators of each pumped storage hydroelectric plant (PHP) in system need to calculate how much water discharged from its upper reservoir to the lower reservoir and pumped from the lower reservoir back to the upper reservoir so that all the hydraulic constraints especially reservoir volume constraint must be satisfied. Operators of each thermal power plant (TP) also comply with the scheduled power generation for the TFE reduction. In addition, both physical constraints belonging electrical devices and other involving constraints of the problem must be satisfied. Generally, PHPs integrated in the hydrothermal systems (HTSs) are utilized as an immediate backup source that improves the reliability of entire system to avoid the power lack and cut a high fuel expenditure due to high power generation from TPPs.

One of the earliest study about PHPs [21], the authors have solved the scheduling problem of a HTS with one classical hydroelectric plant (CHP), one PHP and one TP in which the applied method was to decompose the problem to hydro problem and thermal problem based on gradient theory. The constraints of CHP and PHP are totally different. In addition, the decomposed problems also considered each smaller interval in the whole timeline. That means, if the timeline needed to schedule is 24 hours, it will be broken into 24 smaller intervals. If the timeline is a weeklong, it will be divided into 7 smaller intervals. After that, using the mathematical methods in order to assign how much power must be generated by each hydro power plant and thermal power plant in the system. Specifically, the authors [21] implemented local variation method to define the optimal solution. However, these methods only demonstrated the satisfaction of all the constraints from CHP, PHP and TPs rather than showing the most effective TFE. In [22], two suggested methods for dealing with the selection of pump mode or generation mode for PHP were combined with a two computation phases (TCP)-based algorithm. The first method was flat volume level while the second method was based on the power demand of load. A system with one CHP, one PHP and one TP was optimally operated for reducing TFE of the sole TP. In addition, a nine-node transmission network was utilized to add the three power plants over twenty-four periods. As a result, the combination of TCP-based algorithm and the first method was more effective than the combination of TCP-based algorithm and the second method. The first combination could reach a convergence with a lower number of computation iterations and smaller TFE. The whole data of the system has not been shown in detail in the study, so the solved system has not been reminded in latter studies.

A hydrothermal system with one PHP and one TP was mathematically formulated in [16]. In this study, the considered PHP is represented by two modes, generation mode with a discharge function and pump mode with a constant volume and a constant pump power. A gradient approach based on Lagrange function (LGA) was applied to reach the most optimal generation schedule with the satisfaction of all constraint. The study only showed a pump mode satisfying all the constraints of TPP and PHP rather than proving the best performance of the gradient approach. This system was then replicated for reducing TFE by using metaheuristic algorithms including Evolutionary Programming (EP) [23] and an improved Acceleration factor-based particle swarm optimization (AFPSO) [24]. EP [23] has shown a better result with smaller cost than LGA [16]; however, the verification of all constraints indicated that EP has used a higher power generation than the maximum generation of the PHP. In fact, the data shown in [16] was 300 MW for the maximum power generation of PHP but the solution of EP was 333.0154 MW for the PHP. Clearly, EP has provided an invalid solution for the system and it could not lead to the decision on the better performance of EP. AFPSO showed the same TFE as LGA [16] and the generation of PHP and TP between the two methods was slightly different. It is noted that AFPSO is a modified approach of PSO but PSO has not been replicated in [24] for comparison. Thus, the outstanding performance of AFPSO was not proved in the paper. In [25], photovoltaic systems were integrated with a HTS with the presence of PHPs in which the duty of PHPs is to supply the lack power due to the decrease of solar radiance. PHPs can improve the reliability of supply power sources that are influenced by uncertainty like wind and solar. The study did not concern the electricity generation cost reduction for TPs and there was no comparison to conclude the optimization for the proposed solution.

In this study, we reapply the system that has been solved in [16], [23] and [24]. In these studies, the results from the system only showed the optimal generation of thermal plant and hydro plant together with the obtained TFE rather than proving the meaning of the HTS with the presence of PHP. In addition, these studies did not show the major cause of reducing TFE for the HTS. Thus, the paper focuses on the shortcomings of the studies and clarify the following issues:

1) PHPs can reduce TFE for TPs. If only TPs supply electricity to loads, they must pay more money for fuel expenditure (FE). Meanwhile, inflows to PHPs are zeroes within the scheduled periods and power generated by TPPs is used to pump water back to upper reservoir for use in other times,
2) Thanks to the operation of PHPs, FE for each MWh in TPPs can be reduced.

The benefit of the HTS with the presence of PHPs is significant and PHPs should be built instead of conventional hydroelectric plants with only generation mode. In order to reach optimal solutions for study cases of the HTS with the presence of PHPs, different existing Particle swarm optimization variants are implemented together with a proposed PSO based on the velocity direction determination and inertia weight factor, called VWPSO. MPSO is a modified version of PSO, which was first developed in 1995 [26]. PSO was then improved and become constriction factor-based PSO (CPSO) and inertia weight factor-based PSO (WPSO) [27]. The combination of both weight factor and constrict factor was also another modified PSO (WCPSO) [28]. Another modified PSO focused on this method showing a better performance than PSO; however, IAF-PSO needs trials of tuning the initial and end points of the improved acceleration factors [29]. Several modified versions of PSO were successfully applied in [30-31] for different optimization problsems in engineering. However, these PSO methods were not highly effective for the system. So, a proposed PSO is first developed in the paper for cutting the TFE from TPs. The proposed method is formed by using two different formulas for updating new velocity and proposing a new criterion to select one out of two updates. In addition to the proposed method, five PSO methods including conventional PSO, WPSO, CPSO, IAF-PSO and CW-IAF-PSO (IAF-PSO with constriction and weight factors) are executed. In summary, the contribution of the paper are as follows:

1) Proposed an effective PSO with better results than other methods,
2) Implement PSO, CPSO, WPSO, IAF-PSO and CW-IAF-PSO,
3) Prove the effectiveness of PHPs in HTS.

In addition to the literature review, other parts of the paper are as follows. Section 2 presents TFE function and constraints regarding PHPs and TPs. Section 3 presents the structure of the proposed method. Section 4 shows the obtained results by different methods. Finally, conclusions are shown in Section 5.

2. PROBLEM FORMULATION

2.1. Problem description

In this paper, the short-term problem considers a daylong operation in power system. A daylong operation is broken into six small intervals with four hours for each. In order to determine the optimal solution for the problem, supposed that the load demand in each interval is predetermined and unchanged within an entire day. Moreover, the volume of water injected in the reservoir, the regulating coefficient of head variation and the amount of power output assigned for each generator are possibly adjusted following the schedule. On the other hand, the amount of water loss caused by the evaporation and excessing the capacity of reservoir is neglected.

The pumped hydro power plant in this research uses power generated by TPs to pump water back to the upper reservoir. The pumped water in upper reservoir is discharged through turbines for producing electricity at necessary periods. The generated power from PHP aims to reduce the TFE of TPs at high power demand of loads. Thus, the objective in optimal scheduling of the combined power system with PHPs and TPs is to reduce the TFE of the TPs plant during a daylong operation. The mathematical expression for a daylong scheduling is described as follows:

2.2. Objective function

In the concerned HTS, there are n_1 TPs and n_2 PHPs working in power system. The core target is to cut TFE of n_1 TPs. In general, the operation cost of TPs is modeled as a quadratic function formed by the relationship between fuel consumption and generated power output. The final mathematical expression of the operation cost function in the short-term hydropower schedule is presented as follows:

$$\text{Cut TFE}=\sum_{l=1}^{Ti}\sum_{x=1}^{n_1} td_l.\,(\sigma_{1x}+\sigma_{2x}TG_{i,k}+\sigma_{3x}TG_{x,l}^2) \tag{1}$$

where, Ti is the number of time intervals in the whole schedule; σ_{1x},σ_{2x} and σ_{3x} are the fuel expenditure coefficient of the x^{th} TP; $TG_{x,l}$is the active power of the x^{th} TP in time interval l; and td_l the time duration of the interval l.

2.3. Constraints

The power balancing between the generating side and the consuming side: This constraint aims to guarantee the balance between the amount of power generated by all generating sources and the amount of power consumed by loads. Besides, the amount of power loss caused by the lines' impedance is also taken into account. The official expression of the constraint is presented as follows:

$$\sum_{x=1}^{n_1} TG_{x,l}+\sum_{y=1}^{n_2} HG_{y,l}-\sum_{y=1}^{n_2} PHG_{y,l}-PCL_l-PL_l=0 \tag{2}$$

where $HG_{y,l}$ is the active power generated by the PHP y in time interval l; and $PHG_{y,l}$ is the active power consumed by the PHP y in time interval l for pumping water.

The constraint regarding the amount of water discharged from reservoir: The amount of water in reservoir, which is ready to discharge to the downstream via penstocks to the hydro turbines in order to produce electricity, is calculated by the expression below:

$$WO_{y,l}=td_l\times RD_{y,l} \tag{3}$$

where, $WO_{y,l}$ is the volume of water flushed out from the reservoir of the hydro power plant y at time interval l, $RD_{y,l}$

is the rate of the water flushed out of hydropower plant y at time interval l.

$$Dr_{y,l}=\tau_{1y}+\tau_{2y}HG_{y,l}+\tau_{3y}HG_{y,l}^2 \tag{4}$$

where, τ_{1y}, τ_{2y} and τ_{3y} are respectively the coefficient of flushed rate corresponding to the amount of active power generated by the PHP y.

The water volume constraint in reservoir: This constraint is about the relationship among the amount of water remained in reservoir, the water pumped back to reservoir, the water flushed out and the volume of spillage. This relationship is formulated by the equation below:

$$WR_{y,l-1}-WR_{y,l}+WI_{y,l}-WO_{y,l}-WP_{y,l}=0 \tag{5}$$

$WR_{y,l-1}$ and $WR_{y,l}$ are volume of water in the reservoir y in the *lth* and *(l-1)th* period; $WI_{y,l}$ is the water flowing to the *yth* reservoir in the lth period; $WO_{y,l}$ is the water discharged via the y^{th} PHP in the l^{th} period; and $WP_{y,l}$ is the water pumped back to the y^{th} PHP in the l^{th} period.

The water remained in reservoir at the beginning point and the ending point: The water in the reservoir at the beginning and the end of day must be constrained by:

$$WR_{y,0}=WR_{y,beg};WR_{y,Ti}=WR_{y,ulti} \tag{6}$$

where, $WR_{y,beg}$ and $WR_{y,ulti}$ are respectively the amount of water storage in reservoir belonging the hydropower plant y at the beginning point and the ultimate point of the schedule; $WR_{y,0}$ and $WR_{y,Ti}$ are the amount of water in the *yth* reservoir at *the 0th* and *Tith* period.

The constraint regarding water remained capability of reservoir: The reservoir capability of hydropower plants is restricted by their upper and lower boundaries:

$$\begin{gathered}WR_{y,min}\le WR_{y,l}\le WR_{y,max}\\ y=1,2,\ldots,n_2+1;l=1,2,\ldots,Ti\end{gathered} \tag{7}$$

where, $WR_{y,min}$ and $WR_{y,max}$ are minimum and maximum amount of water in the *yth* reservoir; and $RD_{y,min}$ and $RD_{y,max}$ are minimum and maximum values of flushed water in the *yth* reservoir

The constraint regarding the rate of flushed water from reservoir: The allowed value of the rate is located inside the minimum value and the maximum value as follows:

$$\begin{gathered}RD_{y,min}\le RD_{y,l}\le RD_{y,max}\\ y=1,2,\ldots,n_2;l=1,2,\ldots,Ti\end{gathered} \tag{8}$$

The constraint about generating capability of TPs and HPs: The amount of power generated by TPs and PHPs must be determined between its minimum and maximum allowed value. Any violation of these values will cause the damage and unstable state in the system operation. Thus, generators must be constrained by:

$$TG_{x,min}\le TG_{x,k}\le TG_{x,max} \tag{9}$$

$$HG_{y,min}\le HG_{y,k}\le HG_{y,max} \tag{10}$$

$$PHG_{y,min}\le PHG_{y,k}\le PHG_{y,max} \tag{11}$$

$TG_{x,min}$ and $TG_{x,max}$ are minimum and maximum generation of the x^{th} TP; $HG_{y,min}$ and $HG_{y,max}$ are minimum and maximum generation of the y^{th} PHP; and $PHG_{y,min}$ and $PHG_{y,max}$ are minimum and maximum consumed power of the y^{th} PHP for pumping water.

3. THE PROPOSED METHOD FOR THE CONSIDERED PROBLEM

3.1. Conventional Particle Swarm Optimization

In 1995, an algorithm, called Particle Swarm Optimization (PSO), was introduced for the first time by Kennedy and Eberhart [26] in order to determine the optimal solutions for different testing functions. After that, PSO was modified to enhance its ability in term of seeking optimal solutions and avoiding time consuming manner when dealing with various optimization problems [27-28]. There are three crucial elements that seriously affects to the efficiency of PSO: the velocity, the position and the fitness function. While both position and velocity are the main factors regarding producing new positions, the fitness function is a factor to assess the quality for the found positions. The three equations below present the relationship between these crucial elements via mathematical expressions:

$$\begin{gathered}V_f^{new}=V_f+af_1.rd.\left(Lo_f-Po_f\right)\\ +af_2.rd.\left(Po^*-Po_f\right);f=1,\ldots,n_3\end{gathered} \tag{12}$$

$$Po_f^{new}=Po_f+V_f^{new};f=1,\ldots,n_3 \tag{13}$$

$$F_f^{new}=F(Po_f^{new}) \tag{14}$$

where, V_f^{new} and V_f are the newly updated and old velocities of the f^{th} particle; Po_f and Lo_f are the present and the best positions of the f^{th} particle; Po_f^{new} and Po_f are newly updated and old positions of the f^{th} particle; Po^* is the most optimal position among the whole population; rd is a random value within 0 and 1; af_1 and af_2 are acceleration factors; F_f^{new} is new fitness of the f^{th} particle; and n_3 is the particle number.

3.2. Modified Particle swarm optimization algorithms

Because of the low efficiency of the velocity element during the whole searching process of the original PSO, C factor and W factor were added in order to shrink the search space and facilitate for the purpose of reaching the global solution more productively [20-21]. Hence the, the presence of C [20] and W [21] in newly updated velocity is considered as follows:

$$V_f^{new}=C[V_f+af_1.rd.(Lo_f-Po_f)+af_2.rd.(Po^*-Po_f)] \quad (15)$$

$$V_f^{new}=[W.V_f+af_1.rd.(Lo_f-Po_f)+af_2.rd.(Po^*-Po_f)] \quad (16)$$

$$.C=\frac{2}{2-\left(\sqrt{(af_1+af_2)^2-4(af_1+af_2)}+(af_1+af_2)\right)} \quad (17)$$

$$W=\frac{W_{max}-W_{min}}{IT_{max}}W_{max}IT \quad (18)$$

where, W and C are weight and constriction factors; W_{max} and W_{min} are the highest and lowest values of inertia weight factor; IT_{max} and IT are the highest and the current iterations.

The modified version with the application of C factor as shown in Eqs. (15) and (17) is called constriction particle swarm optimization (CPSO) and that shown in Eqs. (16) and (18) is called weight particle swarm optimization (WPSO).

In addition to CPSO and WPSO, PSO was also suggested to be modified by improving af_1 and af_2 [29]. The two coefficients were varied from the lowest to the highest value similarly to W in Eq. (18). And, based on that the velocity update is regulated as follows:

$$V_f^{new}=V_f+maf_1.rd.(Lo_f-Po_f)+maf_2.rd.(Po^*-Po_f) \quad (19)$$

where

$$maf_1=af_{1,s}+(af_{1,e}-af_{1,s})\frac{IT}{IT_{max}} \quad (20)$$

$$maf_2=af_{2,s}+(af_{2,e}-af_{2,s})\frac{IT}{IT_{max}} \quad (21)$$

where, maf_1 and maf_2 are modified acceleration factors of af_1 and af_2, $af_{1,s}$ and $af_{2,s}$ are initial acceleration factors; $af_{1,e}$ and $af_{2,e}$ are final acceleration factors.

The modified version with the application of Eqs. (19)-(21) is called improved acceleration factors based PSO (IAF-PSO). For the case that W, C and modified acceleration factors are combined in a modified version as follows:

$$V_f^{new}=C\left[W.V_f+maf_1.rd.(Lo_f-Po_f)+maf_2.rd.(Po^*-Po_f)\right] \quad (22)$$

The method with the application of Eq. (22) can be called constriction, weight and modified acceleration factors-based PSO (CW-IAF-PSO).

3.3. The proposed PSO

We have presented the structure of five existing PSO methods including PSO, WPSO, CPSO, IAF-PSO and CW-IAF-PSO in the two sections above. The five methods have been applied for different optimization problems and they have reached promising results as well as unexpected results. PSO has tended to fall into local optimal zones with low quality solutions while IAF-PSO and CW-IAF-PSO have coped with the difficulties of setting values to advanced parameters. IAF-PSO and CW-IAF-PSO have the same difficulty of setting values to $af_{1,s}$, $af_{1,e}$, $af_{2,s}$ and $af_{2,e}$ whereas both WPSO and CW-IAF-PSO have the same difficulty of setting values to W_{max} and W_{min}. If the selection of values for these parameters is not the most suitable, the two methods cannot reach the most effective solutions. On the contrary to these PSO methods, CPSO can be applied more easily because C parameter can be calculated by using Eq. (17). However, CPSO copes with the shortcoming of using narrow jumping steps due to the use of C parameter and it needs more iterations for reaching the best solutions. So, if the number of iterations is not high enough, CPSO will be hard to reach the best solution. For another case with high enough iteration number, CPSO can reach the best solution but its stability may not be high. To tackle the shortcomings of the five mentioned PSO methods, we apply a proposed PSO method. In the proposed PSO method, we use one more new velocity update formula as follows:

$$V_f^{new'}=WV_f+af_1.rd.(Lo_f-Po_f)+af_2.rd.(Po^*-Po_f)+rd.(Po^*-Po_{rd}) \quad (23)$$

In the equation, Po_{rd} is a position of a particle randomly picked up from the current population. The new velocity applies the weight factor and add one more changed interval by using Po^* and Po_{rd}. So, comparing the new velocity to other versions, it can expand the search space for the case that particles tend to approach to the same small zone or the same point. The proposed $V_f^{new'}$ is integrated to the new formula below:

$$Po_f^{new}=Po^*+V_f^{new'} \quad (24)$$

In addition, new velocity computation by using Eq. (16) and new position computation using Eq. (13) are also applied in the proposed PSO. However, the applications of either Eq. (23) and Eq. (24) or Eq. (16) and Eq. (13) are dependent on the quality of the current whole population. In the first step, the mean fitness of the whole population is calculated by:

$$F_{mean}=\sum_{f=1}^{n_3}F_f \quad (25)$$

For the case that F_f is smaller fitness than F_{mean}, Eq. (16)

and Eq. (13) are applied to update new velocity and new position. For other cases, i.e. F_f is higher than F_{mean} or equal to F_{mean}, Eq. (23) and Eq. (24) are applied.

As a result, the implementation of the proposed PSO for a typical problem can be summarized as follows:

Step 1: Choose the population n_3 and the iteration number IT_{max}

Step 2: Randomly produce the set of initial position and velocity for the initial population

Step 3: Calculate F_f for the initial population and determine Po^*

Step 4: Set Po_f to Lo_f and set iteration IT to 1

Step 5: Calculate F_{mean} using Eq. (25)

Step 6: Update velocity and position

If $F_f < F_{mean}$, using Eq. (16) and Eq. (13). Otherwise, using Eq. (23) and Eq. (24)

Step 7: Calculate new fitness for new position

Step 8: Compare new and old particles to find Lo_f

Step 9: Determine the best particle Po^*

Step 10: If $IT< IT_{max}$, set $IT= IT$+1 and go to Step 5. If $IT= IT_{max}$, stop the search procedure.

4. NUMERICAL RESULTS

In this section, the proposed PSO and five other PSO methods including PSO, CPSO, WPSO, IAF-PSO and CW-IAF-PSO are simulated on a hydrothermal system for reaching fifty optimal and valid solutions. The six methods are coded in Matlab program language and run on a personal computer with a processor of 2.0 Ghz and 4 GB of Ram. The employed system and numerical results are presented in the following sections.

4.1. The applied system

The applied system is comprised of one PHP and one TP scheduled in one day. The optimal generation cooperation of the two power plants supplies electricity to loads over one day divided into six periods with four hours for each. The maximum generation of the PHP is 300 MW while the pump power is -300 MW. Accordingly, the pumped water volume is -600 acre-ft/h. The volume of reservoir at the beginning and the end of the scheduled horizon is equal to 8,000 arce-ft while the water flowing to reservoir of PHP in the system is zero, i.e. $WI_{y,l} = 0$. The whole data of the system are taken from [16] and also given in Table 1, Table 2 and Table 3.

Table 1. Data of TP

σ_{1x}	σ_{2x}	σ_{3x}	ε_x	τ_x	TG_x^{max} (MW)	TG_x^{min} (MW)
3877.5	3.9795	0.00204	0	0	2500	200

Table 2. Data of PHP

τ_{1y}	τ_{2y}	τ_{3y}	PHG_y (MW)	$WP_{y,l}$ (arce-ft/h)	HG_y^{max} (MW)	HG_y^{min} (MW)	$WR_{y,ulti}$ (arce-ft)	$WR_{y,beg}$ (arce-ft)
200	2	0	-300	-600	300	0	8000	8000

Table 3. Load demand of two applied systems

Period *l*	Load (MW)
1	1600
2	1800
3	1600
4	500
5	500
6	500

4.2. Results and discussions on obtained results

To run the six applied methods, population, iteration number and other parameters are selected as follows:

1) n_3=40; IT_{max}=4,000 for all methods. The values of population and iteration number are high enough for more effective methods but not high enough for worse methods reaching the most optimal solution. In addition, the values also make challenges to methods reaching the highest stability. The stability will be evaluated by using the average cost of fifty runs.

2) af_1=af_2=2.05 for all methods [27].

3) W_{min}=0.3; W_{max}=0.9 for WPSO, CW-IAF-PSO and the proposed PSO. The settings can enlarge the search space at the first iterations and narrow the search space at final iterations.

4) $af_{1,s}$ = $af_{2,s}$=2.05; $af_{1,e}$ = $af_{2,e}$=0.5 for IAF-PSO and CW-IAF-PSO.

As pointed in previous studies [32-33], metaheuristic algorithms need a number of trial runs to reach the highest performance and to compare the stability of search ability. So, each method in the paper is run to reach 50 successful solutions satisfying all constraints and TFE of each obtained solution is recorded to report the fifty values of TFE. In addition, the summary of fifty solutions and success rate are also reported for comparison and discussion. The TFE of fifty solutions is sorted in ascending order and plotted in Figure 1. In the figure, the green curve of the proposed method seems to a be a straight line from the 1st solution to the 47th solution excluding the last three solutions. The second-best method may be WPSO with the pink curve but WPSO suffers from higher TFE values from the 35th solution to the last solution. Other remaining methods are much less effective than the proposed PSO, especially PSO and IAF-PSO. The first two solutions indicate that PSO has the first solution with much higher TFE than the first solutions of other methods. PSO, IAF-PSO and CW-IAF-PSO have the worst first two solutions and these solutions are not the global optimum.

The detail of fifty found solutions is depicted in Figure 2 and Figure 3. Figure 2 shows the minimum, the average and the maximum values of TFE obtained by the applied PSO methods. CPSO and WPSO also reach the same minimum TFE of $269642.40 as the proposed PSO but their mean and maximum TFE values are much higher. PSO, IAF and CW-IAF-PSO surfer from the worst results. Figure 3 provides good evidences for showing the best stable search capability and the highest performance of dealing with all constraints that the proposed PSO can reach. The success rate of the proposed method is the highest but its standard deviation is the smallest among six methods. It is emphasized that the success rate of PSO, CW-IAF-PSO, IAF-PSO, CPSO and WPSO is respectively 5%, 16%, 14%, 17% and 18% but that is much higher for the proposed PSO with 66%. These methods have to be implemented 1000, 313, 357, 295 and 278 runs for reach the fifty successful runs but the proposed method has been executed only 76 runs. The success rate is good evidence to conclude that the outstanding performance of the proposed method over other ones [34-35].

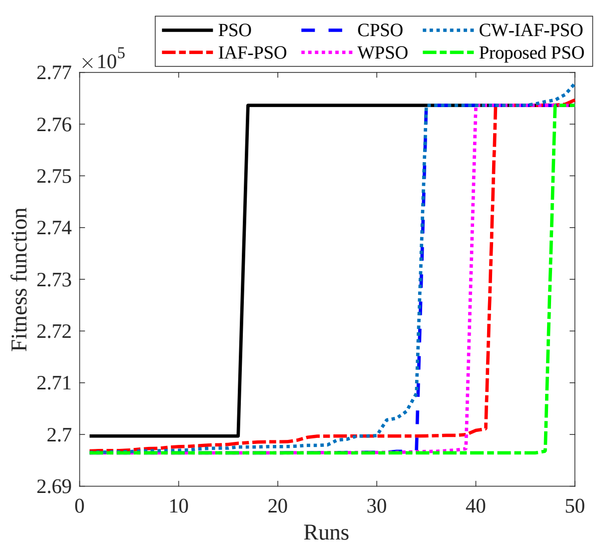

Fig. 1. TFE of fifty solutions arranged in ascending order.

The best generation of TP obtained by the proposed method and the fuel expenditure for each period is also reported and the price for each MWh is reported in Table 4. In this Table, we also show the power, the expenditure and the price for the case that only the sole TP supplies electricity to loads. For the case not using the PHP, the sole TP must use $270864.6 to produce electricity and the price for each MWh is from $9.67 to $12.75 for different periods. As using PHP, the cost is cheaper and equal to $269642.40 while the price is from $9.61 to $10.45. For the first three periods, the sole TP must supply to full power of load, i.e. the generation of the sole TP and load is the same. Namely, load is respectively 1,600, 1,800 and 1,600 MW and generation of the sole TP is also 1,600, 1,800 and 1,600 MW respectively while the generations of TP in HTS are 1450.0660, 1450.0660 and 1449.9340 MW respectively. So, the fuel expenditure of the sole TP is much higher than that of the HTS. For the last three periods, the HTS must produce electricity for loads and for pumping water back to the upper reservoir. Hence, the fuel expenditure of the HTS is much higher. Namely, the sole TP generates 500 MW for the last three periods but the TP of HTS must produce 800 MW. However, the use of electricity to pump water back to the upper reservoir is more effective than the use of only TP. For better view of the significance of the PHP, the fuel expenditure of each period for the case of using only TP and using both TP and PHP is plotted in Figure 4.

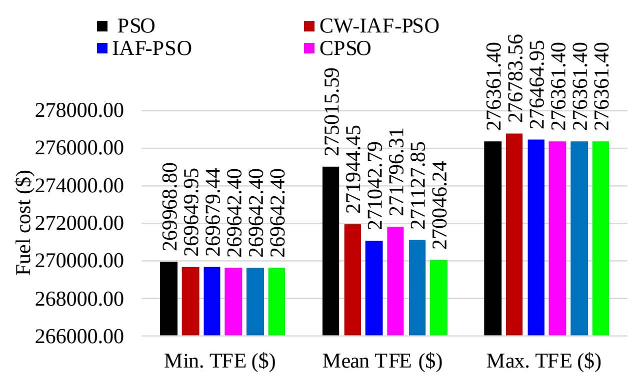

Fig. 2. Summary of fifty solutions obtained by applied method.

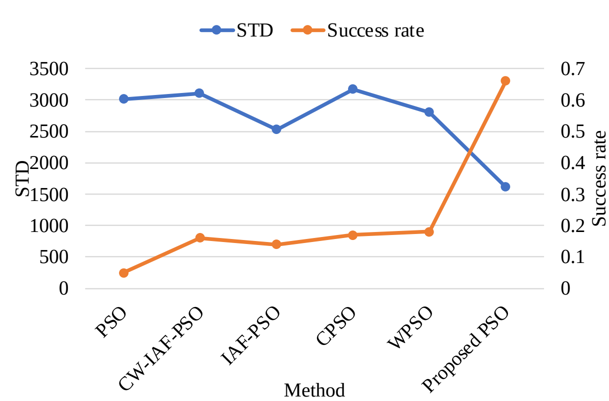

Fig. 3. Standard deviation of fifty solutions and success rate obtained by applied methods.

The volume and generation of PHP are shown in Figure 5. This figure shows the PHP uses water to generate electricity for the first three periods and the generation is respectively 149.9343, 300 and 150.0657 MW and –300MW for the last three periods. The minus power means that PHP implements the pump mode for the last three periods. At the beginning, the volume of the reservoir is 8,000 arce-ft and it is decreased to 6000.5256 arce-ft at the first period, to 2800.5256 arce-ft at the second period and 800 arce-ft for the third period. But, the water is then pumped back to the reservoir and the volume is increased to 3200 arce-ft at the fourth period and 5600 arce-ft at the fifth period and 8000 arce-ft at the last period. Clearly, the initial volume and end volume are the same as the requirement of the problem.

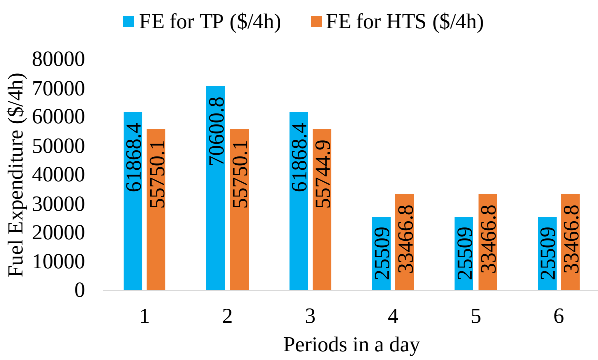

Fig. 4. Fuel expenditure of TP for two different cases.

Table 4. Comparison of TFE for two different cases

l	Only TP supply to load		
	$TG_{x,l}$ (MW)	FE ($/4h)	Price($/MWh)
1	1600	61868.4	9.666
2	1800	70600.8	9.805
3	1600	61868.4	9.666
4	500	25509	12.754
5	500	25509	12.754
6	500	25509	12.754
TFE ($)	270864.6		
l	Optimal operation for HTS		
	$TG_{x,l}$ (MW)	FE($/4h)	Price($/MWh)
1	1450.066	55750.100	9.6116
2	1450.066	55750.100	9.6116
3	1449.934	55744.899	9.6116
4	800	33466.8	10.458
5	800	33466.8	10.458
6	800	33466.8	10.458
TFE ($)	269642.40		

Table 5. Result comparison obtained by different methods

Period (*l*)		1	2	3	4	5	6	Cost ($)
PCL_l (MW)		1600	1800	1600	500	500	500	
AFPSO [24]	$HG_{y,l}$ (MW)	150	300	159.9700	-300	-300	-300	269642.40
	$TG_{x,l}$ (MW)	1449.9910	1500	1450	800	800	800	
	$TG_{x,l}+HG_{y,l}$ (MW)	1599.9910	1800	1599.9700	500	500	500	
EP [23]	$HG_{y,l}$ (MW)	133.5789	333.0154	133.4057	-150	-300	-300	269628.80
	$TG_{x,l}$ (MW)	1466.4211	1466.9846	1466.5943	800	800	800	
	$TG_{x,l}+HG_{y,l}$ (MW)	1600	1800	1600	650	500	500	
LGA [16]	$HG_{y,l}$ (MW)	150	300	150	-300	-300	-300	269642.40
	$TG_{x,l}$ (MW)	1450	1500	1450	800	800	800	
	$TG_{x,l}+HG_{y,l}$ (MW)	1600	1800	1600	500	500	500	
Proposed PSO	$HG_{y,l}$ (MW)	149.8477	300	150.1523	-300	-300	-300	269642.40
	$TG_{x,l}$ (MW)	1450.1523	1500	1449.8477	800	800	800	
	$TG_{x,l}+HG_{y,l}$ (MW)	1600	1800	1600	500	500	500	

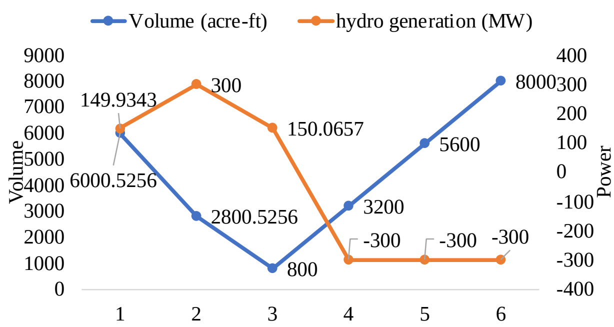

Fig. 5. Volume of reservoir and generation of PHP.

4.3. Comparison with previous methods

The comparisons of results obtained by AFPSO [24], EP [23], LGA [16] and the proposed PSO are given in Table 5. The optimal generation of TP and PHP, the TFE and the verification of power balance constraint are shown clearly in the Table. The comparison of TFE indicates that EP [23] reported the lowest cost, $269628.8 while that of others is $269642.4. The maximum generation for PHP given in Table 2 is 300 MW but the hydro generation at the second period of EP [23] is 333.0154 MW, which is higher than the maximum by 33.0154 MW. Obviously, EP [23] violated the constraint of generation limit and the reported TFE is not adopted for an optimal solution. On the contrary to EP [23], AFPSO [24] has not violated the generation limit but AFPSO has coped with a high error between generation side and consumption side. The load demand at the first period is 1,600 MW but the total generation is 1599.9910 MW. For the third period, the load demand and the total generation are 1,600 and 1,599.9700 MW. Clearly, the mismatch is high and the solution is not accepted as an optimal solution. LGA [16] can provide the same good solution as the proposed PSO; however, LGA [16] is a deterministic approach that needs a high number of steps. Especially, Lagrange function must be established and then taking partial derivative must be done. As a result, LGA is limited for problems where functions fail to be taken partial derivative. These metaheuristic algorithms were not reported for success rate and computation time whereas the success rate of the proposed PSO is 66% and average computation time is under two seconds. As a result, it is concluded that the proposed PSO is an effective for the optimal generation problem for hydrothermal systems with the presence of pumped storage hydroelectric plants.

5. CONCLUSIONS

In this paper, five existing and one proposed PSO methods have been applied to deal with an objective of cutting the total fuel expenditure for producing and supplying electricity to loads by thermal power plants in hydrothermal system. The role of the proposed method was to select suitable periods for pump operation and power generation operation for PHP for periods with the generation mode, and determine the effective power of TP for periods. The simulation results indicated that PHP could reduce TFE from $270864.6 to $269642.40 for one operation day. The saving money was $1,222.2 for one day and it was equivalent to 0.45%. If the scheduled horizon is one year, the saving money will become much bigger and it will be a huge benefit. Hence, power system should use PHP as a core power plant type. In addition, the proposed PSO has reached a huge achievement in optimizing operation of the HTS. The method has reached a higher success rate than other methods and it could reduce simulation time for finding fifty valid solutions. As a result, it was recommended that the proposed PSO was a strong optimization tool for the power system with PHP and TP.

ACKNOWLEDGEMENTS

This research was a part of the scientific research topic with No. CS2021-16. The authors would like to thank Sai Gon University and Ton Duc Thang University, Vietnam.

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