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Short-term scheduling of hybrid thermal, pumped-storage, and wind plants using firefly optimization algorithm

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ABSTRACT

This paper presents a novel method based on an enhanced firefly algorithm (EFA) to solve scheduling hybrid thermal, pumped-storage, and wind plants. Since the scheduling problem is inherently discrete, basic EFA and binary encoding/decoding techniques are used in the proposed EFA approach. Optimal power values of thermal and pumped-storage units are determined separately in the presence of uncertainty caused by wind speed. The proposed method is applied to a real plant, including four pumped-storage units, 34 thermal units with different characteristics, and one wind turbine plant. In addition, dynamic constraints of upstream and downstream sources and constraints regarding thermal and wind units are also considered for finding the optimal solution. In addition, the proposed EFA is successfully applied to a real plant, and the results are compared with those of the three available methods. The results show that the proposed method has converted to a more optimal cost than the other methods.

INTRODUCTION

Hydropower producers must bid their production into the day-ahead market in deregulated electricity markets. For price-taking producers, it is optimal to offer energy according to marginal costs, which for hydropower are determined by the opportunity cost of using water that could have been stored for future production. At the time of bidding, the uncertainty of future prices and inflows may affect the opportunity costs and thus also the optimal bids [1]. A modern power system consists of a large number of thermal and hydro plants connected at various load centers through a transmission network. An important objective in the operation of such a power system is to generate and transmit power to meet the system load demand at minimum fuel cost by an optimal mix of various types of plants. However, the hydro resources being limited, thus the worth of water is greatly increased. Therefore, an optimal operation of a hydrothermal system will lead to a huge saving in fuel cost of thermal power plants [2].

This research is a new optimization algorithm based on the light bulb algorithm (EFA) algorithm to solve the storage pump power plant scheduling problem. In addition, considering that in the pumping mode, all the units of this power plant operate at their constant power, while in the generating mode, these power plants have a continuous nature. Based on the results presented in the results section, it can be seen that the algorithm in the actual TaiPower power plant system will lead to a minimum cost. According to the results obtained from the binary warfare (EFA) algorithm method, when the required power of the consumer load decreases, the storage pump power plant starts to generate and store electricity and when it increases, the consumer load delivers it to the grid if the results obtained from the EPSO, EGA and PSO algorithms will be highly volatile.

Presenting an algorithm for optimal scheduling of hybrid plants comprising thermal units, pumped-storage, and wind units, and consistency of the results has always been one of the main problems in hydropower management systems [3-5]. This problem aims to minimize the total cost of consumed fuel considering all constraints of thermal, pumped-storage, and wind units. In conventional methods, decomposition-based methods are used to solve the independent scheduling of thermal and pumped-storage plants and wind plants. Then, in these methods, Lagrangian multipliers are used to find the optimal solution for hybrid plants. Generation scheduling for pumped-storage plants and thermal units in wind turbines is obtained through an iterative procedure [6]. One disadvantage of this method is that the obtained solution oscillates around its minimum and maximum values. Therefore, solutions obtained from these methods are usually trapped in local optima. However, optimizing a real plant's performance is an essential priority. Reducing a small percentage in generation costs results in significant savings. Various approaches and algorithms have been proposed for solving this problem in hybrid plants.

In previous studies, techniques based on PSO [7] and GA [8] were employed to solve scheduling of hybrid pumped-storage plants. Considering the obtained results in these studies, they have some disadvantages. Especially, early convergence of PSO and GA degrades their performance in searching for optimal solutions

Firefly algorithm (FA) is one of the metaheuristic algorithms based on swarm intelligence which is a proper candidate for various optimization problems due to its high performance in finding the global optimum. This algorithm was first presented in 2008 by Yang [9]. FA is developed based on fireflies which emit light and illuminate at night.

1) A firefly is attracted by other fireflies apart from its sex.
2) Attractiveness of each firefly is proportional to its illumination; therefore, fireflies with lower illumination are attracted by fireflies with higher illumination. However, as two fireflies get closer in this algorithm, attractiveness is reduced.
3) If the illumination of two fireflies is the same, other fireflies move towards each one randomly.

This paper presents a method based on EFA to solve short-term scheduling of hybrid pumped-storage, thermal, and wind plants. The proposed EFA method is based on a binary version of the firefly algorithm. In previous studies, various binary versions have been proposed for FA, and it has been applied to discrete binary problems like feature selection [11], and knapsack [10] and comparison results with binary GA and PSO indicate that binary FA performs better in finding the global optimum. Pumped-storage units (P/S units) of hybrid plants are designed in constant power pumping mode. In addition, an encoding/decoding method is used to manage discrete power characteristics in continuous pumping mode for a generation.

With the development of the electricity market and the introduction of pumped-storage plants, obtaining maximum profit and the performance of plants for maximizing profit have attracted attention [12-14]. In fact, the main purpose of this problem is to determine the pumping of Debi and Debi of water flowing through turbines for 24 hours [15]. PSO based on the coefficient of contraction, is used to solve this problem which outperforms GA in terms of saving costs and calculation time [16].

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Test results of the proposed method applied on the Taipower system are presented according to which EFA outperforms EGA, EPSO, and basic PSO. The timing of storage pump units is one of the most complex issues in locating thermal-hydropower plants. The timing of these power plants is aimed at minimizing the cost of fuel consumed for a power system while meeting the limitations of thermal and water units. The optimal solution to a storage pump power plant scheduling problem can be done by considering all the storage pump units and the combination of thermal units in each period. Classical solution methods for these nonlinear problems, integers, and hybrid optimization are usually based on decomposition methods in which we have this sub-problem for water units and a sub-problem for thermal units. These two subproblems are usually solved based on Lagrange multipliers. Due to the fluctuations in the solutions obtained by Lagrange coefficients, using this method to calculate the solutions of these two sub-problems does not seem reasonable. As a result, the cost corresponding to the answer obtained is often trapped at the local optimal point.

This research is a new optimization algorithm based on the light bulb algorithm (EFA) algorithm to solve the storage pump power plant scheduling problem. In addition, considering that in the pumping mode, all units of this power plant operate at their constant power, while in the generating mode, these power plants have a continuous nature.

METHOD

1. Problem Statement and Modelling

1.1. Modelling P/S unit

Pumped storage is mostly used and is one of the best methods of developing electrical energy. A 3-stage method is adopted to determine a practical limit to the proportion of pumped storage plant so that better use of other energy producing plant can be made. The first stage is feasibility assessment. The other two stages involved detailed examination. The method is also applicable for small hydraulic plant and is one of the best ways of determining the characteristics of future pumped storage plants. This method is also very flexible [17].

A pumped-storage unit is comprised in plant management center, an upstream source and a downstream source which pumps a certain amount of water from the downstream source to the upstream source for storing energy in light load hours and pumps water from the upstream source to the downstream source at peak hours. Figure 1 shows performance and structure of a P/S plant. Discharged water from upstream source of a pumped-storage plant while generation is similar to a hydropower plant as shown in its power characteristic. Generated power of this unit is a function of volume of water of the upstream source and the volume of water transferred to the downstream source by the turbine which is determined using Eq. (1).

$$P_{hj}^{t} = f(Q_j^t, V_{j,u}^{t-1}) \tag{1}$$

Where P_{hj}^{t} is the generated power of the P/S unit at time t, $V_{j,u}^{t-1}$ is the volume of water at t-1 and Q_j^t is the volume of water transferred at time t by the turbine. The conventional model for a pumped-storage plant in generation mode is a second order function Q_j^t. This second-order function is given in Eq. (2).

$$P_{hj}^{t} = \alpha_j^{t-1}(Q_j^t)^2 + \beta_j^{t-1}Q_j^t + \gamma_j^{t-1} \tag{2}$$

Where α_j^{t-1}, β_j^{t-1} and γ_j^{t-1} in Eq. (2) depend on $V_{j,u}^{t-1}$. Since in previous studies, this dependency was demonstrated using a second order function, in this paper, α_j^{t-1}, β_j^{t-1} and

γ_j^{t-1} are calculated as a second order function with respect to $V_{j,u}^{t-1}$ according to Eq.(3), Eq. (4) and Eq. (5) [15].

$$\alpha_j^{t-1} = c_2 \tag{3}$$

$$\beta_j^{t-1} = c_3 V_{j,u}^{t-1} + c_5 \tag{4}$$

$$\gamma_j^{t-1} = c_1 (V_{j,u}^{t-1})^2 + c_4 V_{j,u}^{t-1} + c_6 \tag{5}$$

Where c_1 to c_6 are obtained through linear interpolation between two adjacent volumes. Figure 2 shows the characteristic of Eq. (1) for different values of $V_{j,u}^{t-1}$ from minimum to maximum which is plotted for 5 different levels of $V_{j,u}^{t-1}$ from minimum to maximum [5].

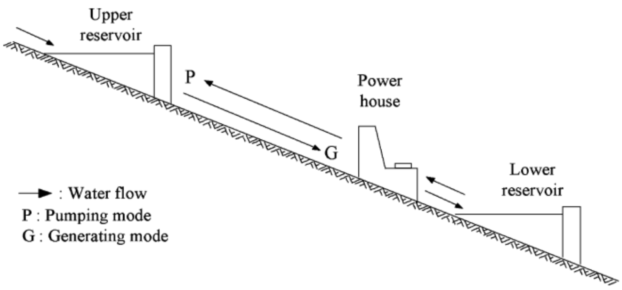

Figure 1. Performance and structure of the P/S unit

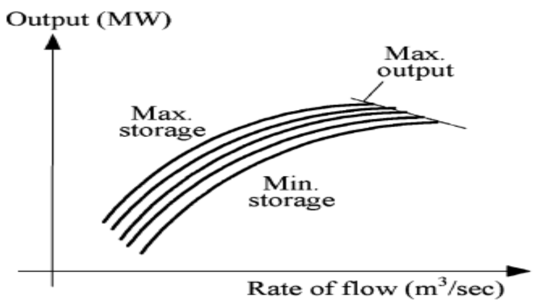

Figure 2. Input-Output feature by a typical pumped- storage plant in power generation mode

In addition, in pumping mode, since the advantage of a pump-turbine plant outside the nominal power area is reduced significantly, it is assumed that in practice, pumped-storage units in pumping mode operate at constant power. Therefore, the power of all units of the Taipower plant in pumping mode is equal to their nominal power. Feature function by a pumped-storage plant in pumping mode is inherently discrete, as illustrated in Figure 3.

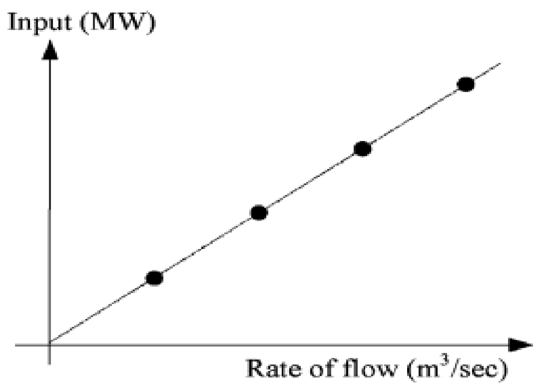

Figure 3. Input-output characteristic of a typical storage pump unit in pumping mode

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1.2. Modeling Wind Turbine Plant

Renewable energies especially wind energy, have attracted the attention of electricity utilizations due to being abundant and cheap. However, wind turbines should store energy generated by wind due to the high variability of wind and its stochastic nature. Hybrid P/S plants and wind plants are possible solutions to solve this uncertainty. The wind turbine plant also has an input-output characteristic described in Eq. (5) [1].

$$P_{WT}^{t} = 0.5\rho A C_p V_W^3 \tag{5}$$

where ρ is air density in $\frac{kg}{m^3}$, A is the area swept by turbine in m^2, C_p is efficiency of the wind turbine and V_W is the instantaneous wind speed in $\frac{m}{\sec}$. The studied turbine has a nominal wind speed of 14 m/s and nominal power of 1.5MW and power efficiency C_p of the wind turbine vs. instantaneous speed V_W is determined as shown in Figure 4.

Considering the wind's random characteristics, the wind turbine's output powerline is also random. Some probabilistic distributions like exponential and Gaussian distributions are usually used to model random disturbances. In [18], a scenario-based method using real data and the Weibull distribution function is proposed for the participation of wind power plants (WPPs) and considering their uncertain production. Also, considering WPPs may have surplus energy compared to the network load in the condition of high wind energy penetration, which will be lost without use, in the modeling of WPPs, a mathematical variable as the curtailed wind energy is considered. [19].

Weibull and Riley distributions are widely studied and analyzed, showing that Weibull distribution is better for simulating wind speed distribution. Therefore, in order to model wind speed distribution, Weibull distribution is used as shown in the following. [20]

$$f(V_W) = \frac{k}{c}\left(\frac{V_W}{c}\right)^{k-1} e^{-\left(\frac{V_W}{c}\right)^k} \tag{6}$$

Parameters k and c are distribution shape and scale parameters of Weibull distribution.

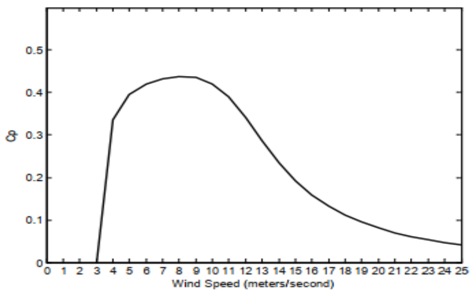

Figure 4. Efficiency of the turbine vs. instantaneous wind speed

1.3. Objective Function and Constraints

The proposed hybrid plant scheduling aims to find the best generation schedule for thermal and P/S units considering the limitations of wind, hydro and thermal plants. The current study's purpose is the short-term scheduling of a hybrid plant. Therefore, the scheduling problem can be formulated as a nonlinear optimization issue as follows:

$$Minimize\left(\sum_{t=1}^{T}\sum_{i=1}^{N_s} F_i^t\left(P_{si}^t\right)\right) \tag{7}$$

$$F_i^t\left(P_{si}^t\right) = a_i\left(P_{si}^t\right)^2 + b_i P_{si}^t + c_i \tag{8}$$

such that the following constraints are met:

1. Power Balance

$$\sum_{i=1}^{N_s} P_{si}^t + \sum_{i=1}^{N_h} P_{hj}^t + P_{WT}^t - P_L^t = 0 \tag{9}$$

Where P_{si}^t, P_{hj}^t, P_{WT}^t and P_L^t are the power produced through ith thermal unit, the power generated through jth P/S plant, the power generated by the wind unit and power consumption of the load at time t.

2. Dynamic balance of Upstream and Downstream Sources

$$V_{j,u}^t = V_{j,u}^{t-1} + Q_{j,pump}^t - Q_j^t + I_j^t \tag{10}$$

$$V_{j,l}^t = V_{j,l}^{t-1} - Q_{j,pump}^t + Q_j^t \tag{11}$$

Where $V_{j,u}^t$ and $V_{j,l}^t$ are volume of water in the upstream and downstream sources of the jth P/S unit at time t, $Q_{j,pump}^t$ and Q_j^t are the volume of pumped water of the jth P/s unit at time t.

3. Ramp rate and Power generation of Thermal Units

$$Max\left(\underline{P_{si}}, P_{si}^{t-1} - DR_i\right) \le P_{si}^t \le Min\left(\overline{P_{si}}, P_{si}^{t-1} + UR_i\right) \tag{12}$$

Where $\underline{P_{si}}$ and $\overline{P_{si}}$ are lower and upper limits of power generation of the ith thermal unit, DR_i and UR_i are decrease and increase in power generation of the ith thermal unit.

4. Water Discharge

$$\underline{Q_j} \le Q_j^t \le \overline{Q_j} \tag{13}$$

Where $\underline{Q_j}$ and $\overline{Q_j}$ lower and upper limits of water discharged by the jth P/S unit.

5. Water Pumping

$$\underline{Q_{j,pump}} \le Q_{j,pump}^t \le \overline{Q_{j,pump}} \tag{14}$$

Where $\underline{Q_{j,pump}}$ and $\overline{Q_{j,pump}}$ are lower and upper limits of the water pumped by the jth P/S unit.

6. Upstream and Downstream Sources [21]

$$\underline{V_{j,u}} \le V_{j,u}^t \le \overline{V_{j,u}} \tag{15}$$

$$\underline{V_{j,l}} \le V_{j,l}^t \le \overline{V_{j,l}} \tag{16}$$

Where $\underline{V_{j,u}}$ and $\overline{V_{j,u}}$ are lower and upper limits of the jth P/S unit, $\underline{V_{j,l}}$ and $\overline{V_{j,l}}$ are lower and upper limits of the downstream source of the jth P/S unit.

7. Wind Turbine Power

$$\underline{P_{WT}} \le P_{WT}^t \le \overline{P_{WT}} \tag{17}$$

8. Cyclic reserve of the hybrid plant

$$\sum_{i=1}^{Ns} P_{Rsi}^t\left(P_{si}^t\right) + \sum_{i=1}^{Nh} P_{Rhj}^t\left(P_{hj}^t\right) + P_{Rwt}^t(P_{wt}^t) \ge P_{Rreq}^t \tag{18}$$

2. The Proposed EFA Methodology

2.1. Principles of the Firefly Algorithm

Figure 5 shows general flowchart of the firefly algorithm. First, consider a D-dimensional (120><816) optimization problem. In this algorithm, first, a set of N fireflies that are all

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candidates for the optimization problem are randomly initialized in the D-dimensional space. Assume that x_j is position of the j[th] firefly in the solution space of the problem. Then fitness value for position of each firefly is calculated and sorted. After sorting fitness values, the best firefly is determined. In the next step, attractiveness of position of each firefly is updated; fireflies move towards their new position considering attractiveness in the D-dimensional space of the problem. Position of a firefly is updated considering attractiveness of position of each firefly using the following rule.

$$x_j(t+1) = x_j(t) + \beta_0 e^{-\gamma r^2}(x_i(t) - x_j(t)) + \alpha\varepsilon_i \quad (19)$$

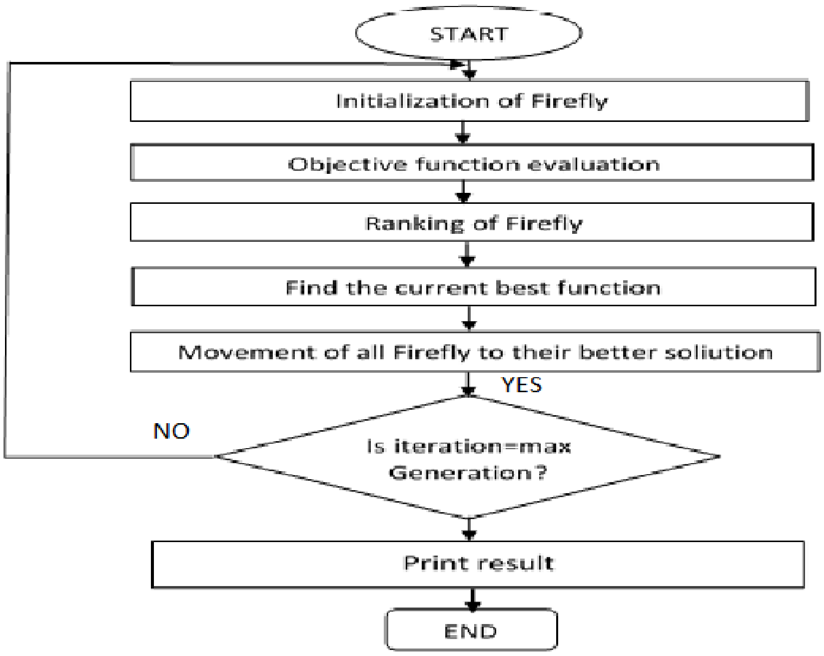

Figure 5. General flowchart of the Firefly Algorithm

Where $\beta_0 e^{-\gamma r^2}(x_i(t) - x_j(t))$ corresponds to the attractiveness of position of the j[th] firefly and its random term is associated to $\alpha\varepsilon_i$ and $x_i(t)$ is position of the most attractive firefly. Attractiveness of each firefly is proportional to its fitness value which can be represented as follows:

$$\mathrm{I(r)} = \mathrm{I_0 e^{-\gamma r_{ij}{}^2}} \quad (20)$$

Where γ is light absorption coefficient which is constant and I_0 is attractiveness at $r_{ij} = 0$. r_{ij} is Euclidean distance of two fireflies which is determined as follows:

$$r_{ij} = \sqrt{\sum_{k=1}^{D}(X_{jk} - X_{ik})^2} \quad (21)$$

Where D is dimension of the optimization problem. According to Eq. (21), fireflies with less attractiveness move towards more attractive fireflies. Figure 6 shows exploration mechanism using conventional FA and updating fireflies' position law. Considering Eq. (20), the position of each firefly is updated using three terms. The first term is only comprised of position of the j[th] particle, $x_j(t)$. Attraction towards other fireflies is shown in the second term and the third term indicates a random procedure with parameter α where numbers generated using this procedure are in the range of [0,1]. On the other hand, when $\beta_0 = 0$, fireflies would move randomly. In addition, parameter γ affects convergence rate of the algorithm. This variable might take any value but it usually varies between 0.1 to 10. Performance of the FA is generally controlled by three parameters including random parameter α , attractiveness β and attraction coefficient γ . FA shows two types of asymptotic behavior in $\gamma \to 0$ and $\gamma \to \infty$. If $\gamma \to 0$, attractiveness would be $\beta = \beta_0$. Therefore, attractiveness would be fixed in the whole search space which shows a specific case of PSO. If $\gamma \to \infty$, second term of Eq. (19) would be eliminated and the firefly would move randomly. In this paper, FA is implemented between these two asymptotic cases [22].

The brightness of a firefly is determined by the value of the objective function. The basic rules of this algorithm were designed to primarily solve continuous problems. To design the Firefly algorithm properly, two critical issues need to be defined: the attractiveness and the variation of the light intensity [23].

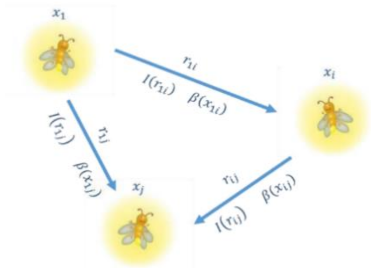

Figure 6. General flowchart of FA

2.2. Binary Encoding

In this paper, the only variables which can optimize the cost function (7) are the discharge rate of the P/S units, which are negative in pumping mode and positive in generation mode. The advantage of using this variable instead of generated power of the P/S unit is considering dynamic constraints of the volume of water in upstream and downstream sources. In conventional FA, these control variables are considered as fireflies, while in the proposed EFA, these variables are considered as a binary sequence of fireflies.

Optimization is a process of determining the best solution to make something as functional and effective as possible by minimizing or maximizing the parameters involved in the problems. Several categories of optimization problem such as discrete, chaotic, multi-objective and many more are addressed by inspiring the behavior of fireflies [24].

For instance, regarding a pumped-storage unit with four plants, figure 7 shows a binary sequence of fireflies, each unit's discharge rate control variable in binary form. To find optimal scheduling for each 1-hour period, a binary sequence with 5 bits is allocated; therefore, the total number of bits of this problem is 120. In this 5-bit sequence, the first bit is used to detect the pumping or generation mode of the P/S unit. The rest 4 bits are used to illustrate the normalized discharge rate q_j^t in generation mode or number of pumping units in pumping mode. In order to determine discharge rate in generation mode, it is assumed that there is a linear relationship between q_j^t and Q_j^t .

Hour	1	2	.....	24
	1 0 0 0 1	0 0 0 1 1	.....	1 0 0 1 0

Figure 7. Binary sequence for scheduling P/S plant

2.3. Binary Sequence Decoding

After encoding a solution as a binary sequence of fireflies, the Fitness value should be calculated using the decoded sequence. The following steps describe the details of decoding the binary sequence.

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Step 1) The first bit of each 24 binary sequence is decoded according to Table 1 to determine operational mode of the plant (pumping or generation).

Table 1. Decoding the binary sequence at time t.

Hour t				
b_0	b_1	b_2	b_3	b_4

If the value of the first bit is $b_0 = 0$, the plant is operating in pumping mode, otherwise, it is operating in generation mode.

Step 2) If the P/S plant is operating in pumping mode, go to step 3 otherwise go to step 6.

Step 3) The rest 4 bits of the binary sequence shown in Table (1) are used to calculate number of pumps of the plant N^t_{pump} and volume of the pumped water $Q^t_{j,pump}$ as follows.

$$N^t_{pump} = \sum_{n=1}^{4} b_n ; b_n \in \{0,1\} \tag{22}$$

$$Q^t_{j,pump} = Q_{j,sp} \times N^t_{pump} \tag{23}$$

anywhere $Q_{j,sp}$ is a fixed capacity pumped by each plant.

Step 4) upper limit of pumped water is calculated using the following equation.

$$\overline{Q^t_{j,pump}} = Min\left(\overline{Q_{j,pump}}, (V^{t-1}_{j,l} - \underline{V_{j,l}})\right) \tag{24}$$

If total volume of the water pumped by the P/S exceeds its upper limit, the number of pumping units is reduced until the upper limit is met.

Step 5) Pumping power in MW can be determined using the following equation.

$$P^t_{hj} = -\left(P_{j,sp} \times N^t_{pump}\right) \tag{25}$$

anywhere $P_{j,sp}$ is the fixed power of the pumped-storage plant in pumping mode. Then go at step 10.

Step 6) other 4 bits for normalized discharge coefficient q^t_j are converted into real value.

$$q^t_j = \sum_{n=1}^{4} \left(b_n \times 2^{-n}\right) ; b_n \in \{0,1\} \tag{26}$$

Step 7) upper limits of the discharged water is determined using the following equation.

$$\overline{Q^t_j} = Min\left(\overline{Q_j}, (\overline{V_{j,l}} - V^{t-1}_{j,l})\right) \tag{27}$$

Step 8) using the following equation, normalized value of q^t_j is converted to real value of Q^t_j .

$$Q^t_j = \underline{Q_j} + q^t_j \left(\overline{Q^t_j} - \underline{Q_j}\right) \tag{28}$$

Step 9) using Eq. (2), generated power of the P/S plant is determined.

Step 10) power of thermal units $P_{s,rm}$ is determined using the following equation.

$$P^t_{s,rm} = P^t_L - P^t_{hj} - P^t_{WT} \tag{29}$$

Step 11) continue scheduling calculations of P/S units in steps 1 to 10.

Step 12) determine optimal capacity for thermal units and thermal cost using Eq. (8). In this step, optimal capacity of thermal units in the proposed method is determined using conventional FA.

Step 13) steps 1 to 12 are repeated for each firefly.

In the proposed method, each sequence of particles shows a complete solution for scheduling of hybrid P/S, thermal, and wind plants. To determine the generation power of the thermal units, a UC package is used, using this package, scheduling of thermal units independently considering power of P/S and wind units can be determined optimally. This feature makes the proposed method attractive.

RESULTS AND DISCUSSION

1. Simulation Result

The proposed approach is implemented using MATLAB on a 5 core 3.2GHz PC. Then, the proposed method is implemented on a part of Taipower hybrid plant including 34 thermal units, one wind turbine and 4 P/S units. In addition to the constraints mentioned in section 2, Taipower has 4 important characteristics which make scheduling the hybrid plant more difficult.

1) Taipower plant is an isolated system. Cyclic reserve power at each hour should be 300MW.
2) Thermal units can hardly manage large changes in consumption load due to limitation in power changes.
3) Downstream source of the Ming-Hu pumped-storage unite has a low-capacity source.
4) Due to uncertainty of wind speed, power of the wind turbine is variable and scheduling of other plants should be done accordingly.

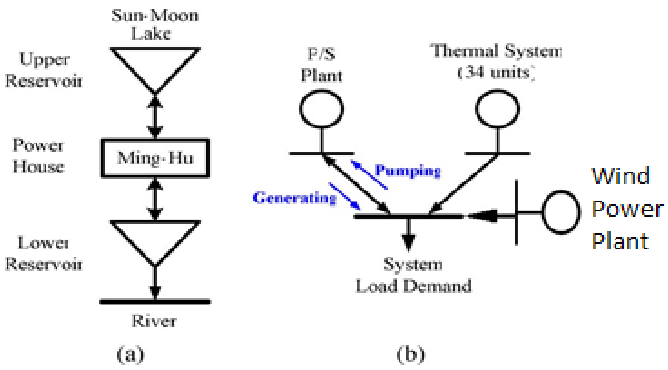

Figure 8. Real plant system. (a) Hydraulic diagram (b) electric diagram

Wind Power Plant

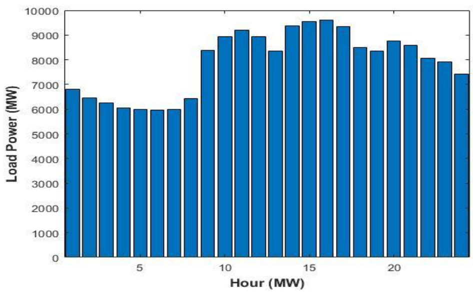

Figure 9. Load consumption pattern

Table 2. Characteristics of MING-HU P/S Plant

Installed Capacity	Maximal Discharge ($\frac{m^3}{sec}$)	Maximal Pumping ($\frac{m^3}{sec}$)	Lower reservoir		Efficiency
			Maximal Storage ($10^3 m^3$)	Minimal Storage ($10^3 m^3$)	
250×4	380	249	9756	1478	0.74

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Figure 8 shows a diagram of the system of interest. Table 2 represents information regarding the capacity of sources and generation power of each unit of the Ming-Hu plant which is comprised of 4 turbine-pump units. In pumping mode, each unit operates at its nominal power. Since the upstream source of this plant is Sun-Moon Lake, the constraint regarding volume of the upstream source can be neglected. On the other hand, since downstream source of the plant is small, its constraint should be considered. In addition, final volume of the downstream source should be equal to its initial volume. The number of thermal units considered in this paper is 34, given their characteristics in [6].

The proposed EFA method, EPSO, EGA, and PSO are applied to a real load consumption pattern on a summer day shown in Figure 9. Scheduling results using the mentioned algorithms for thermal units 31, 32, 33 and 34 and P/S unit are represented in Figures 10 and .11.

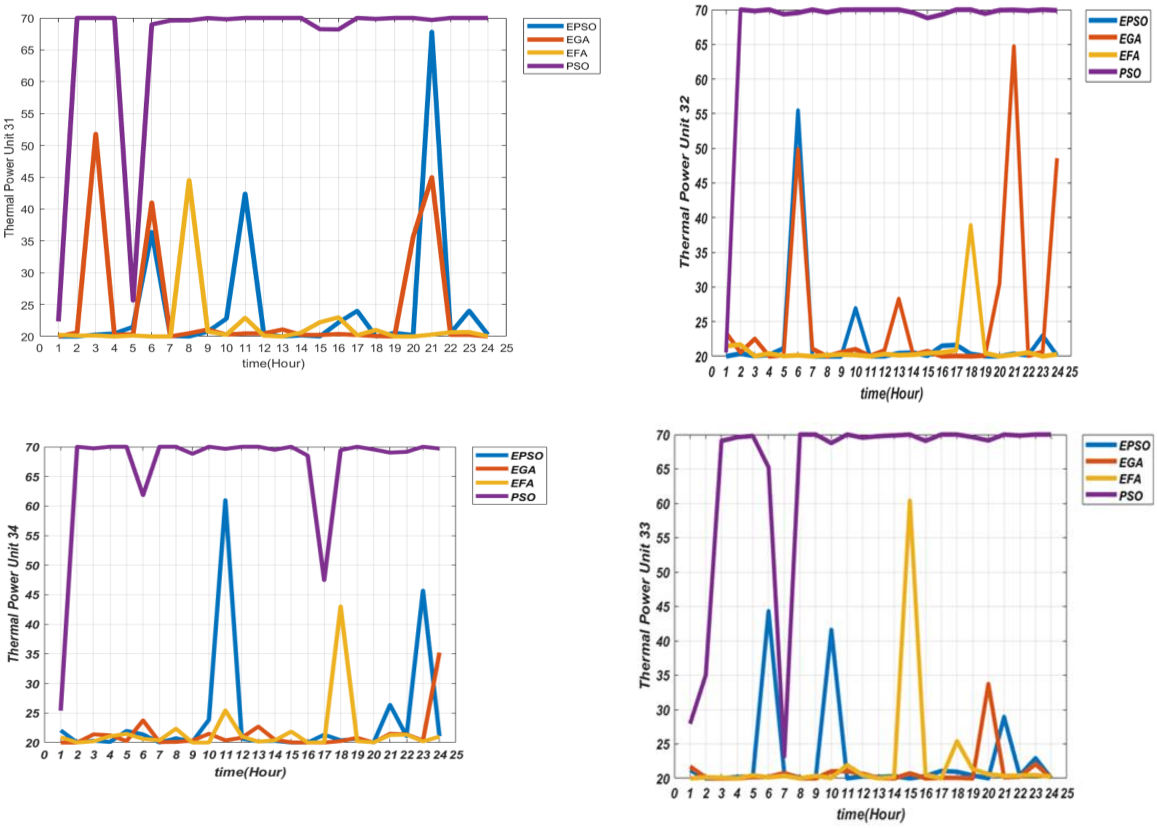

Figure 10. Power of thermal units 31, 32, 33, and 34 using EPSO, EGA, EFA, and PSO

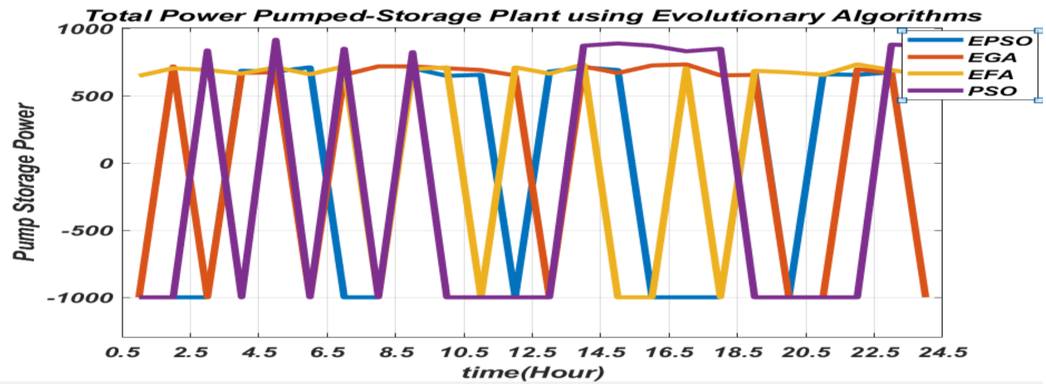

Figure 11. Generated/ pumped power of the P/S plant using EPSO, EGA, EFA and PSO

As can be seen in Figures 9, 10, 11, and 12 and Tables 3, 4, 5, 6, and 7, the following results are inferred.

1) Pumping/generation scheduling of the P/S plant using the proposed EFA usually follows load changes and considers a solution compatible with economic concerns.
2) In conventional PSO, power changes of thermal units are very large, while determined power using other algorithms has lower fluctuations.
3) Since the turbine operates at a nominal speed of 14m/s, the wind turbine's power is 1.5 MW.

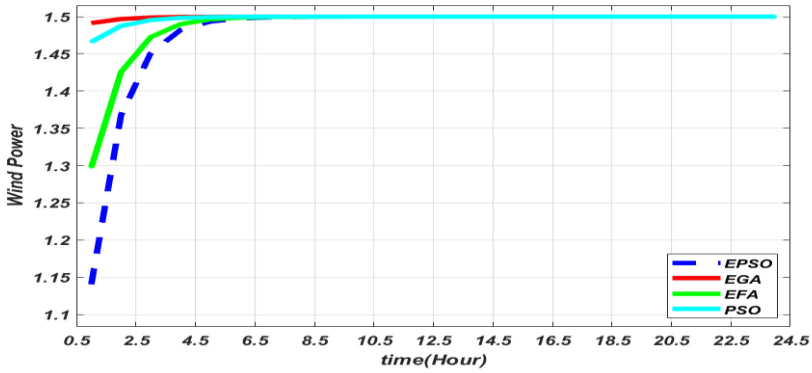

Figure 12. Power of the wind turbine (MW)

In this section, more detailed descriptions are given about superior performance of the proposed EFA compared to previous algorithms. Therefore, this paper uses EGA, EPSO and conventional PSO for comparison. Since in conventional PSO, discrete nature of pumped-storage unit in pumping mode cannot be managed, an intelligent method is considered to adjust pumping power of these units. For example, in conventional PSO, for pumping power among 375 and 625MW, power of the P/S unit is considered 500MW. Figure 11 shows scheduling results of the P/S units using EFA, EGA, EPSO, and PSO. Figure 13 shows total cost of the hybrid plant (thermal, wind and (P/S) using EFA and other methods. Considering these two figures, EFA has converted to a more optimal solution compared to the other methods. So, it is concluded that it is better to use EFA for scheduling Taipower hybrid plant.

Table 3. Scheduling P/S unit using EPSO

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Output EPSO(MW)	-1000	-1000	-1000	687.32	681.56	712.89	-1000	-1000
Hour	9	10	11	12	13	14	15	16
Output EPSO(MW)	706.01	649.38	657.03	-1000	681.26	712.57	692.86	-1000
Hour	17	18	19	20	21	22		24
Output EPSO(MW)	-1000	-1000	681.12	-1000	661.06	656.69	675.48	-1000
Cost (USD)					1.5497			

Table 4. Scheduling P/S unit using EGA

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Output EGA (MW)	-1000	137.20	-1000	671	676.08	712.89	-1000	657.14
Hour	9	10	11	12	13	14	15	16
Output EGA(MW)	719.84	705.84	692.96	652.89	-1000	719.62	670.52	726.92
Hour	17	18	19	20	21	22	23	24

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Output EGA(MW)	734.58	652.66	656.59	-1000	-1000	698.77	670.19	-1000
Cost (USD)	1.5863							

Table 5. Scheduling P/S unit using PSO

Hour	1	2	3	4	5	6	7	8
Output PSO(MW)	-1000	-1000	838.8	-1000	919	-1000	919	-1000
Hour	9	10	11	12	13	14	15	16
Output PSO(MW)	851.9	-1000	826.8	-1000	-1000	-1000	-1000	874.2
Hour	17	18	19	20	21	22	23	24
Output PSO(MW)	890.9	874.1	851.5	-1000	-1000	-1000	882.1	873.9
Cost (USD)	1.6131							

Table 6. Scheduling P/S unit using EFA

Hour	1	2	3	4	5	6	7	8
Output EFA (MW)	649.54	706.06	693.17	665.98	712.73	661.3	719.73	-1000
Hour	9	10	11	12	13	14	15	16
Output EFA (MW)	699.24	712.63	-1000	712.63	665.78	734.73	-1000	-1000
Hour	17	18	19	20	21	22	23	24
Output EFA (MW)	705.78	-1000	686.98	675.79	656.85	734.67	692.74	652.69
Cost (USD)	1.5462							

Table 7. Determined power of the thermal unit using EFA

Time(h)	DG sources					
	G1	G2	G3	G4	G5	G6
1	54.9099	63.6509	87.3650	38.1332	30.0658	90.2483
2	40.4797	62.8999	80.5971	29.2294	36.5692	68.0000
3	40.0720	61.5115	80.0000	24.1799	28.3843	68.0000
4	40.8088	60.1159	82.6615	25.0352	31.1241	68.7704
5	40.3707	61.9289	80.0000	25.5274	33.5257	68.4095
6	40.0000	66.3773	84.2326	25.6365	27.3607	68.0404
7	40.2997	60.3256	80.1132	30.4437	26.2368	70.4580
8	40.0000	60.2056	90.8289	32.2840	26.5603	68.0000
9	40.0000	79.6958	80.6179	24.7148	28.8948	75.7545
10	41.5179	62.9114	82.2850	29.0940	26.1411	68.0000
11	43.6163	61.4658	80.0882	26.3146	26.6885	68.8814
12	43.5698	60.0000	80.4981	37.2598	26.8305	68.1433
13	40.0000	60.0000	80.1062	25.5810	28.1203	68.0000
14	51.4140	61.3276	80.9974	27.9340	27.9049	68.1767
15	45.2400	61.4693	81.1085	24.3564	32.5188	68.0907
16	40.0000	60.6474	80.3452	24.7032	27.0032	69.6012
17	40.6069	63.6889	82.4809	24.6196	27.1755	68.0000
18	41.6311	60.0623	80.2948	26.0423	35.1846	68.5858
19	40.4030	63.4892	81.7469	34.0113	28.3021	68.9561
20	40.0000	76.1847	80.3802	29.2376	26.0000	68.5779
21	41.8228	60.0000	80.0000	25.9600	38.0383	102.3265
22	40.0000	68.1532	82.2870	27.5908	38.6113	69.2986
23	40.6751	60.4286	81.3292	28.1538	27.5674	71.3230
24	40.1540	62.4942	80.0000	34.2765	27.6995	68.0811

Time(h)	DG sources					
	G7	G8	G9	G10	G11	G12
1	110.0000	135.5908	135.3595	130.0000	140.0319	145.5680
2	110.0000	140.8620	136.0663	130.6801	94.0000	94.4159
3	110.0000	143.7927	135.3005	130.1932	95.7373	94.0000
4	110.0583	136.9356	135.1659	130.8662	94.5598	94.8309
5	110.0263	135.4777	135.5466	130.0000	94.5439	95.1908
6	110.6878	135.0000	135.8172	130.0000	94.4993	94.2741
7	110.0000	136.2023	135.0000	130.2876	94.8027	94.0000
8	111.4353	135.3237	135.8715	130.0000	94.1279	94.1184
9	111.2620	139.1401	135.7775	131.0291	95.1736	95.1034
10	110.8131	136.8991	135.5726	132.0971	94.0000	94.3562
11	110.5770	135.0000	135.3300	130.5077	94.0000	94.0000
12	110.0000	140.9830	139.1855	130.0000	94.0000	95.7814
13	112.9482	135.0000	146.9573	130.0000	94.0000	94.0000
14	110.0000	137.0315	138.5996	130.0000	94.0000	94.0000
15	110.0000	135.2352	135.0654	130.3988	95.7993	94.1066
16	112.7804	135.0000	135.7023	130.3955	96.4233	94.8170
17	120.2163	154.3520	135.7193	130.0000	95.7979	94.3891
18	110.5463	135.1262	135.5173	130.5643	94.1586	94.5679
19	112.0024	136.0801	135.7134	130.0808	94.2889	94.8631
20	110.6285	135.2286	135.2173	130.0752	94.3296	94.1422
21	110.8477	135.0000	135.2353	130.2723	95.1849	94.7405
22	111.5772	136.2422	135.6280	132.0314	94.4569	94.0000
23	112.1073	138.0432	135.0000	130.0000	95.5797	94.0000
24	112.7679	135.4952	135.6786	131.3662	94.0000	94.2719

Time(h)	DG sources					
	G13	G14	G15	G16	G17	G18
1	194.5427	192.5000	195.0674	195.4042	192.5000	251.0850
2	125.7426	125.0000	127.4595	126.4377	125.0000	220.9335
3	125.9909	125.6738	125.7405	125.9717	125.0000	220.4784
4	125.6447	126.8476	125.0000	125.0000	125.4014	221.1400
5	125.1836	126.3341	125.7322	125.0000	125.1151	220.2168
6	125.1779	126.7116	125.0000	125.3264	125.0000	220.1249
7	125.2138	125.0327	125.0000	125.3359	125.1609	220.2825
8	125.4027	125.0102	125.0000	125.8209	125.4298	221.1328
9	125.0000	125.3762	126.4064	125.1469	125.2463	220.0000
10	127.8176	126.7106	127.2001	125.0000	125.1547	223.6112
11	125.9522	125.6752	125.7287	125.5647	125.2647	221.1385
12	125.5498	125.9946	125.4090	125.2119	125.3678	220.0000
13	125.1477	126.0159	126.0252	126.7861	125.1500	220.0000
14	125.5494	125.3132	126.5457	125.1981	125.3685	220.0560
15	125.2064	125.0000	127.1388	125.0644	125.4369	220.0000
16	125.0995	126.3288	125.4664	125.8012	125.0000	220.7104
17	125.5629	125.0000	127.7835	125.0000	125.2163	220.7426
18	125.0000	125.6739	125.0081	126.2419	125.0000	221.0715
19	125.3166	125.2037	125.5662	125.7943	125.0000	220.4472
20	125.8391	125.0193	125.2332	126.2061	125.8238	222.1115
21	125.0000	125.0987	125.2738	125.1712	125.0000	220.2982
22	126.5818	125.0000	125.3438	125.0000	125.0000	220.0000
23	125.0000	125.0000	125.0342	125.0000	125.0996	220.6930
24	125.0000	125.0000	127.1277	125.0000	126.5767	220.9429

Time(h)	DG sources					
	G19	G20	G21	G22	G23	G24
1	251.2463	286.4063	286.0000	292.0000	292.0000	292.0000
2	224.1182	243.0645	243.2287	255.5493	254.5104	257.2931
3	221.1685	246.3662	243.7305	255.9968	254.0180	254.0000
4	221.1071	242.0000	242.0000	255.0176	254.0000	255.2733

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5	221.5240	242.5185	243.4576	256.4435	254.6134	257.4351
6	221.3956	242.1097	242.4534	254.5008	259.5599	254.9416
7	221.7822	244.3814	242.1021	255.7675	254.0000	254.6488
8	220.5248	242.0232	242.9296	254.0000	254.7978	254.3657
9	220.2881	244.7307	242.0000	256.9026	256.4495	254.0000
10	225.7218	242.0000	242.0000	259.6521	254.0000	254.0000
11	220.0000	242.0000	242.8450	254.0165	254.0000	254.1581
12	220.2537	242.0000	242.0000	256.1479	255.6522	258.2711
13	220.0000	242.3624	242.3347	254.0000	254.0000	254.7751
14	220.0000	242.0000	242.1384	254.0000	254.7755	255.6641
15	221.0360	243.2048	243.7745	254.6840	255.2679	254.0000
16	221.2585	242.2740	242.0810	256.2245	255.2777	254.3965
17	220.0000	243.0596	242.0000	254.7666	255.2053	254.0000
18	220.2693	242.0000	242.8618	254.5490	254.0000	254.5334
19	220.4257	242.3634	242.1916	255.3262	255.3119	255.0468
20	220.8979	242.6797	243.0917	254.7908	254.0000	254.0000
21	220.0000	242.2035	243.0549	254.0000	254.0000	254.0000
22	220.1102	243.0167	242.1497	255.5699	254.0000	258.4869
23	221.9359	242.2185	242.0100	258.9190	256.0663	255.1000
24	221.0247	242.8133	242.0000	255.8208	255.1545	255.0966

Time(h)	**DG sources**					
	G25	**G26**	**G27**	**G28**	**G29**	**G30**
1	292.8880	292.0000	292.7534	14.1633	10.9145	10.0000
2	257.3042	259.1333	255.0059	13.6947	10.3729	10.0000
3	271.4768	254.0000	254.0000	10.0000	10.2510	10.0000
4	254.0000	254.8566	255.0955	10.4934	10.4224	10.6597
5	255.0431	255.2403	256.2757	10.0812	10.4063	10.2366
6	254.0000	254.4983	256.1681	10.1363	10.8252	10.0000
7	254.0334	255.8372	255.2491	10.3928	10.4351	10.2153
8	254.0614	254.7753	256.0510	10.9680	100.4351	10.2142
9	254.9228	10.0443	10.0000	10.0443	10.0000	10.0000
10	254.0000	10.0000	10.0000	10.0000	10.0000	10.0132
11	254.4293	99.1884	97.7499	99.1884	97.7499	11.3232
12	254.6733	10.3574	11.2871	10.3574	11.2871	11.1266
13	254.8121	10.2886	10.0000	10.2886	10.0000	11.1098
14	254.0000	10.0000	10.4919	10.0000	10.4919	10.0000
15	254.4721	10.0704	10.0000	10.0704	10.0000	10.0000
16	254.2543	99.2940	100.0000	99.2940	100.0000	10.0000
17	255.1012	256.0953	254.0000	10.0000	10.8891	10.5057
18	254.5907	254.0000	254.4331	10.7379	10.8466	100.3563
19	254.0000	254.4663	256.1156	10.6908	10.0000	10.1677
20	255.2156	255.0166	257.9830	10.0000	10.3985	10.2515
21	258.1297	254.4616	256.1207	10.2856	10.1594	10.0551
22	254.2611	255.0448	254.0000	10.0712	10.0000	11.1545
23	254.0000	257.7377	256.0822	10.0000	10.0000	10.4696
24	255.2331	257.6940	254.0000	10.0000	10.8202	11.5010

Time(h)	**DG sources**			
	G31	**G32**	**G33**	**G34**
1	20.2470	21.4762	20.0000	20.8963
2	20.1273	21.6886	20.1478	20.0091
3	20.1523	20.0223	20.0954	20.2188
4	20.0000	20.3997	20.0000	21.0811
5	20.1461	20.0469	20.4222	21.4707
6	20.0000	20.1415	20.1438	20.6294
7	20.0000	20.0000	20.3557	20.3824
8	44.5293	20.1609	20.0000	22.3490
9	20.7654	20.2604	20.3511	20.0000
10	20.2750	20.1840	20.0492	20.0000

11	22.9225	20.0000	21.9240	25.4402
12	20.1341	20.3194	20.4525	21.0395
13	20.0000	20.1639	20.0000	20.1586
14	20.6034	20.2262	20.1834	20.3830
15	22.2200	20.4351	60.3638	21.8587
16	22.9931	20.5489	20.5228	20.0000
17	20.1989	20.8684	20.0000	20.0496
18	21.0155	38.8863	25.3787	43.0208
19	20.0000	20.4475	21.3585	20.2361
20	20.0000	20.0000	20.5916	20.0454
21	20.2901	20.2319	20.3511	21.2622
22	20.6536	20.5346	20.4007	21.3387
23	20.6809	20.0000	20.4573	20.1949
24	20.0338	20.2825	20.2534	21.0067

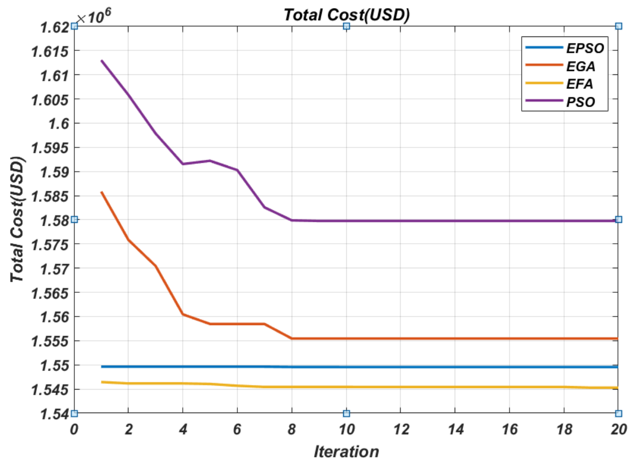

Figure 13. Final cost vs. number of iterations of EPSO, EGA, EFA and PSO

Table 8. The final cost of EGA, EPSO, PSO and EFA

Method	**Cost**	**Cost saving**
EFA	1.5462	-
EPSO	1.5449	**0.0013**
EGA	1.5839	**0.0401**
PSO	1.6131	**0.0669**

CONCLUSION

Scheduling hybrid plants based on P/S units in the presence of wind energy is more complicated than conventional P/S plants. This paper proposes a new approach based on EFA to solve the scheduling of hybrid plants. The proposed method uses encoding and decoding methods to consider discrete performance of pumped-storage plants but pumping mode and continuous performance in generation mode. In addition, dynamic constraints of upstream and downstream sources and constraints regarding thermal and wind units are also considered for finding the optimal solution. In addition, the proposed EFA is successfully applied to a real plant and the results are compared with those of the three available methods. The obtained results show that the proposed method has converted to a more optimal cost than the other methods.

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