Annals of Electrical and Electronic Engineering, 2(2) 2019, Pages: 6-13

Published by IASE

Annals of Electrical and Electronic Engineering

Journal homepage: www.aeeej.org

Exploiting advanced genetic algorithm technique in optimal scheduling of pumped storage hydropower plant and wind farms in unit commitment program

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A R T I C L E I N F O

Article history:
Received 1 November 2018
Received in revised form
9 January 2019
Accepted 22 January 2019

Keywords:
Unit commitment
Optimal scheduling
Thermal units
Wind farms
Pumped storage hydropower plant
Advanced genetic algorithm technique

A B S T R A C T

Unit commitment problem has great importance in power system operation planning. Recently, with the restructuring process in power systems, and concern about economic and ecological issues, a need for efficient and green energy production with renewable resources such as wind power plants has risen. Wind energy does not impose any charge for its owners; but on the other hand, due to a variable and stochastic nature of wind speed, wind farm's generation changes, accordingly. Because of uncertainty in predicting wind power, even for short time, use of pumped storage hydropower plants alongside wind resources has been proposed to achieve higher maneuver power in units operation and benefit of energy exchange in power market. In this paper, a powerful advanced genetic algorithm is applied to solve common unit commitment problem at the presence of wind and pumped storage hydropower plants. The objective function of the optimization problem is maximizing the sum of electrical energy generation benefit of various power plants in the day-ahead power pool market, considering all operational limits. Proposed advanced genetic algorithm and its formulation with a coding procedure of unknown variable in a chromosome are explained and then, the numerical studies are performed on a typical test system under power pool market conditions, which its generation system consists of 10 thermal units, 1 wind farm, and 1 PSH power plants. Finally, the simulation results and the effectiveness of the proposed algorithm are evaluated.

1. Introduction

With regard to the vital role of power systems in modern human life, professional engineers have responsibility of proper operation of electrical resources or generators. To realize this goal, unit commitment, due to its great importance, has been studied more and more in recent decades. Solving this problem gives 24-hour or sometimes weekly ON/OFF state and Economic Dispatch (ED) of generating units in restructured power systems. In recent years, environmental concern and economic issues have more increased the need to use of power plants with high efficiency and low pollution level. With system restructuring, wind farms, due to their extensive advantages, have adsorbed attention of different countries. Since wind does not have any production cost, therefore, we attempt to maximize use of wind farms in optimal scheduling of power system for operation planning time interval. Since one of main characteristics of wind is its variable nature, therefore, the wind power prediction always includes uncertainty, even for short time. Hence, use of Pumped Storage Hydro Power Plant alongside wind farms is proposed as an effective solution to decrease uncertainties. A pumped Storage Hydro Power Plant is a set that stores energy in itself, with water cycling in its two lower and upper reservoirs. To store energy, pumps carry water from lower to upper reservoir and use it like a hydro power plant: Water is passed through hydro turbines and brought back to lower reservoir. Thus, surplus produced energy of wind farms can be stored in this way or its produced energy shortage can be compensated without fuel consumption. In power market with classical structure, thermal units and hydro power plants are coordinated to reduce fuel cost. Hence, today the pumped storage hydro power plants are utilized to provide peak load demand and then it is operated in low load period with pumping water to upper reservoir. With the appearance of competitive market and restructuring in power industry, some changes in operation planning problem have been formed. The most important change happens in its objective function which has turned to maximizing benefit from minimizing cost. Currently, these pumped storage hydro units can participate in market separately or can be used with companies which have either or both conventional units and wind power plants. Coordinating pumped storage power plant alongside wind resources which have high risk in energy generation can increase benefit and decrease the risk of wind resources in market. In recent years, numerous studies have been performed to investigate the impact of wind power generation on power system utilization. In Borghetti et al. (2008), wind farm and pumped storage hydro power plants combination is proposed. With this approach, PSH power plants can compensate the uncertainty in wind prediction. It also studies optimal scheduling of power system with wind farm and pumped storage units to minimize expected social cost in short-time market. In addition, uncertainty of load forecasting in scheduling was considered. In Aihara et al. (2011), a new method for operation pattern of PSH power plants is proposed, considering surplus power problem, resource reliability, generation cost reduction, which is presented with optimal solution of Pareto method. Reliability and fuel cost of each PSH power plant is estimated

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https://doi.org/10.21833/AEEE.2019.02.002

by Monte Carlo simulation method. Simulation results show that total cost of thermal units to maintain generating resources reliability by use of PSH power plants in power systems with high penetration of photovoltaic resources will increase. In Zhang et al. (2013), a simulation method for generation scheduling and its application for Chinese state PSH power plant capacity planning is proposed. Daily load dispatching between various types of power plants are simulated, using UC module. Simulation of wind farm operation was entered to the model for considering its variation effect on load daily dispatching. In Jiang et al. (2012), a robust optimization approach to overcome wind power uncertainty is represented, with the goal of providing robust unit commitment for thermal power plants in the day-ahead market under the worst scenarios of wind power. Robust optimization problem is modeled by use of an uncertainty set which includes the worst-case scenarios, and maintains these scenarios under the minimal increment of costs.

This paper proposes advanced Genetic Algorithm (GA) to solve UC optimization problem in presence of wind farm and PSH power plants in addition to thermal units. All types of power plants to provide network's load demand are scheduled in the day-ahead pool market with simultaneous clearing energy and reserve. First, the pumped storage power plants and wind farms are modeled to participate into the power market. Then, the solution procedure of optimization problem with advanced genetic algorithm technique by introducing unknown variables coding in chromosome is explained and finally, numerical studies using apocryphal data is applied on a test system, consisting of 10 thermal units, 1 wind farm, and 1 PSH power plant, and achieved results are evaluated. Rest of paper is organized as follows: In second part, the biding modeling of thermal units, wind farms and pumped storage power plants are presented under power pool market conditions. Advanced Genetic Algorithm Technique is completely introduced in third part of the paper which is applied to solve unit commitment, including thermal units, wind farms, and PSH power plants. Simulation studies on the typical test system are performed in fourth part of this paper and the conclusion has been is presented in last part of this paper.

2. Biding modeling of thermal units, wind farms and PSH power plants in power pool market

In this unit commitment, in addition to thermal units, wind farms and pumped storage hydro power plants are considered in power pool market. Objective function of optimization problem is maximizing the shareholders' benefit in a day-ahead pool market according to Eq. 1:

$$\mathrm{MAX}\ (\mathrm{Rtotal}) = \mathrm{R_{TH}} + \mathrm{R_W} + \mathrm{R_{PS}} \tag{1}$$

Total demand of consumers should be provided by various types of energy producers. Also according to Eq. 2:

$$\mathrm{PG_{TH}(ti) + PG_{Wi,t}(ti) + PG_{gP,t}(ti) = P_{D,t}(ti) + P_{DpP,t}(ti)}\ \forall \mathrm{ti} \in \mathrm{T} \tag{2}$$

For entering these power plants to the day-ahead power market energy exchange, they should be correctly modeled. In subsections, PSH power plants, wind farms and thermal units are modeled, separately.

2.1. Biding modeling of thermal units

In general, achieved benefit from thermal power plants with regard to energy generation and maintaining spinning reserve for reliability management in power pool market is calculated as follows from (3) to (15):

$$\mathrm{R_{TH}} = \textstyle\sum_{ti=1}^{24}(\mathrm{PG_{Income-TH}(ti) + SR_{income-TH}(ti)}) - \mathrm{OC_{total-TH}(ti)} \tag{3}$$

$$\mathrm{OC_{total-TH}(ti)} = \textstyle\sum_{g=1}^{Gi}(\mathrm{OC_{TH}(Gi,ti)}) \tag{4}$$

$$\mathrm{PG_{Income-TH}(ti)} = \textstyle\sum_{g=1}^{Gi}(\mathrm{PG_{TH}(Gi,ti).MCP_t(ti)}) \tag{5}$$

$$\mathrm{PG_{TH}(Gi,ti)} = \mathrm{PG_{TH_{min}}(Gi)} + \textstyle\sum_{K=L1}^{Li}(\mathrm{PGL_{TH}(Gi,Li,ti).u_{TH}(Gi,ti)}) \tag{6}$$

$$\mathrm{OC_{TH}(Gi,ti)} = \mathrm{A_{TH}(Gi)} \times \mathrm{u_{TH}(Gi,ti)} + \textstyle\sum_{K=L1}^{Li}(\mathrm{PGL_{TH}(Gi,Li,ti)} \times \mathrm{SGL_{TH}(Gi,Li,ti)}) \tag{7}$$

$$\mathrm{PGL_{TH}(Gi,Li,t)} \le (\mathrm{KGL_{TH}(Gi,Li,ti) - PG_{min-TH}(Gi)}),\ \mathrm{Li = L1} \tag{8}$$

$$\mathrm{PGL_{TH}(Gi,Li,t)} \le \mathrm{KGL_{TH}(Gi,Li,ti) - KGL_{TH}(Gi,Li-1,ti)},\ \mathrm{Li = L2,.,NL(Gi,ti)-1} \tag{9}$$

$$\mathrm{PGL_{TH}(Gi,L,ti)} \le \mathrm{PG_{max-TH}(Gi) - KGL_{TH}(Gi,Li-1,ti)},\ \mathrm{Li = NL(Gi,ti)} \tag{10}$$

$$\mathrm{PGL_{TH}(Gi,Li,ti)} \ge 0,\ \mathrm{Li} = 1,\ldots.\mathrm{NL(Gi,ti)},\ \forall\ \mathrm{ti}\ \varepsilon\ \mathrm{T},\ \forall\ \mathrm{Gi}\ \varepsilon\ \mathrm{GENCOs} \tag{11}$$

$$\mathrm{A_{TH}(Gi)} = \mathrm{SGL_{Fix-TH}(Gi)} \times \mathrm{PG_{min-TH}(Gi)},\ \forall \mathrm{Gi}\ \varepsilon\ \mathrm{GENCOs} \tag{12}$$

$$\mathrm{PG_{min-TH}(Gi).u_{TH}(Gi,ti)} \le \mathrm{PG_{TH}(Gi,ti)} \le \mathrm{PG_{max-TH}(Gi).u_{TH}(Gi,ti)} \tag{13}$$

To maintain power system reliability, thermal units bid unloaded part of their synchronized capacity to provide spinning reserve with a percentage of highest marginal cost of energy generation as Eqs. 14 and 15:

$$\mathrm{SR_{income-TH}(ti)} = \textstyle\sum_{g=1}^{Gi} \mathrm{sr_{genco-TH}(Gi,ti).SR_{Price-TH}(Gi,ti)} \tag{14}$$

$$\mathrm{sr_{genco-TH}(Gi,ti)} \le \mathrm{PG_{max-TH}(Gi).u_{TH}(Gi,ti) - PG_{TH}(Gi,ti)} \tag{15}$$

Cost function is usually proposed by power plants owner in pool market in several segments based on unit's marginal price. Fig. 1 shows a piecewise linear production cost of a thermal unit in three segments to participate in a day-ahead pool market.

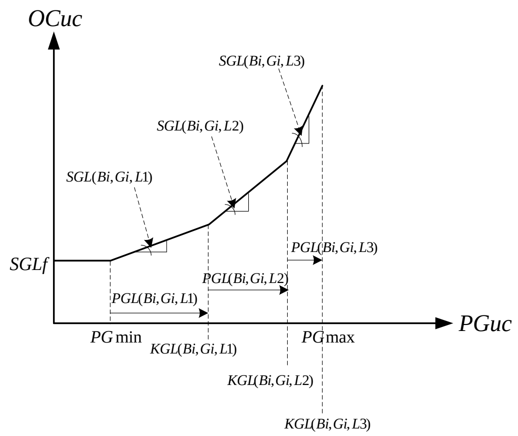

Fig. 1. Piecewise linear production cost of a thermal unit in three segments.

2.2. Biding modeling of wind farms

Proposed strategy for wind farms is presented as a probabilistic optimization problem. Therefore, by maximizing (16), bidding energy of wind farms to daily energy market in each hour in a day can be calculated. Eqs. 17, 18, and 19 are constraints of the optimization problem. Eqs. 17 and 18 are used to calculate binary variables, and (19) shows maximum biding energy of wind farms to market (Singh and Erlich, 2008; Fabbri et al., 2005).

$$\mathrm{R_W} = \textstyle\sum_{t=1}^{24}\{(\mathrm{MCP_t(ti).P_{Wb,t}(Wi,ti)}) + (1 - \mathrm{bi,t(Wi,Si,ti)}).\mathrm{MCP_t^{up}(Wi,ti)}.\textstyle\sum_{Si}(\mathrm{P_{Wi,t}(Wi,Si,ti)} -$$

$$P_{Wb,t}(Wi,ti)\ ).\ P_i(Wi,Si,ti)) - b_{i,t}(Wi,Si,ti).\ MCP_t^{down}(Wi,ti).\ \textstyle\sum_{Si}(\ P_{Wb,t}(Wi,ti) - P_{Wi,t}(Wi,Si,ti)\ ).\ P_i(Wi,Si,ti) \quad (16)$$

$$P_{Wb,t}(Wi,ti) - P_{Wi,t}(Wi,Si,ti) \le M(Wi).\ b_{i,t}(Wi,Si,ti), \forall i \in I \quad (17)$$

$$P_{Wi,t}(Wi,Si,ti) - P_{Wb,t}(Wi,ti) \le M(Wi).\left(1 - b_{i,t}(Wi,Si,ti)\right), \forall i \in I \quad (18)$$

$$0 \le P_{Wi,t}(Wi,Si,ti) \le P_{W\,max}(Wi) \quad (19)$$

2.3. Biding modeling of PSH power plants

The goal of this section is biding modeling of pumped storage hydro power plants in daily energy pool market. Scheduling time period is selected one day. Stored energy in upper reservoir of PSH power plant at the end of a day equals to its stored energy at the beginning of that day. Objective function is maximizing daily benefit as in Eq. 20:

$$R_{PS} = \sum_{t=1}^{24} MCP_t(ti).\ P_{gp,t}(PSHPPi,ti) - \textstyle\sum_{t=1}^{24} C(PSHPPi).\ (\ P_{gp,t}(PSHPPi,ti) + P_{pP,t}(PSHPPi,ti)) - \sum_{t=1}^{24} MCP_t(ti).\ P_{pP,t}(PSHPPi,ti) \quad (20)$$

$$E_{u,t}(Bi, PSHPPi, ti) = (\ E_{u,t-1}(PSHPPi,ti) + (\eta(PSHPPi).\ P_{pP,t}(PSHPPi,ti)) - P_{gP,t}(PSHPPi,ti)) \quad (21)$$

$$E_u^{min}(PSHPPi) \le E_{u,t}(PSHPPi,ti) \le E_u^{max}(PSHPPi) \quad (22)$$

$$(P_{gP}^{min}(PSHPPi).\ m_{g,t}(PSHPPi,ti)) \le P_{gP,t}(PSHPPi,ti) \le (P_{gP}^{max}(PSHPPi).\ N.\ m_{g,t}(PSHPPi,ti)) \quad (23)$$

$$(P_{pP}^{min}(PSHPPi).\ n_{p,t}(PSHPPi,ti)) \le P_{pP,t}(PSHPPi,ti) \le (P_{pP}^{max}(PSHPPi).\ n_{p,t}(PSHPPi,ti)) \quad (24)$$

$$m_{g,t}(PSHPPi,ti)\left(\frac{1}{N}\right). + n_{p,t}(PSHPPi,ti) \le 1 \quad (25)$$

$$m_{gP,t-1}(PSHPPi,ti-1) + \left(\frac{1}{N}\right).\ n_{p,t}(PSHPPi,ti) \le 1 \quad (26)$$

$$m_{gP,t}(PSHPPi,ti) + \left(\frac{1}{N}\right).\ n_{p,t-1}(PSHPPi,ti-1) \le 1 \quad (27)$$

$$E_u^0(PSHPPi,ti) = E_u^{end}(PSHPPi,ti) \quad (28)$$

$$P_{gP,t}(PSHPPi,ti) - P_{pP,t}(PSHPPi,ti) = P_{Pb,t}(PSHPPi,ti) \quad (29)$$

Eq. 21 shows hourly expected stored energy in upper reservoir of pumped storage hydro power plant and Eq. 22 shows its minimum and maximum energy limits. Lower reservoir of PSHPP is, in fact, larger than upper reservoir. Hence, its minimum and maximum energy stored limits are ignored. Eqs. 23 and 24 show permission energy generation and consumption limits in PSH power plant, respectively. Eq. 25 guarantees that whenever one of PSHPP units is pumping, the generation mode is not reachable. Eqs. 26 and 27 model PSHPP's state-change time, the way that usually power plant's state-change from production to consumption, and vice versa, takes several minutes which causes losing participation opportunity of power plant in the one-hour market. Eqs. 28 and 29 show stored energy balance in upper reservoir, and biding energy in daily market, respectively (Lu et al., 2004; Brown et al., 2008).

3. Advanced genetic algorithm technique

Genetic algorithm is one of search and optimization methods which is based on principles and mechanisms of natural genetic and selection of the fittest. Since this algorithm follows the superior survival principle, it provides conditions to reach desirable solution. In some cases, especially facing complicated optimization problems with multiple local optimal points that the conventional optimization methods do not lead to reliable results, genetic algorithm can be a very reliable alternative. Classic mathematical methods have two main weaknesses: first, they consider the local optimal point as the global optimal point. Second, each classic method is useful for a particular problem. Genetic algorithm application, because of its stochastic nature, gives us the chance of reaching the global optimal point and for this reason in this paper it is proposed to solve unit commitment, including thermal units, wind farms, and PSH power plants. Coding procedure of unknown variables in chromosome is explained in following subsection.

3.1. Chromosome structure

First step in problem solving using GA is Chromosome definition for problem which shows unknown variable coding. Here we use binary-real combined method where in binary each gene takes two values 0 or 1, which shows ON/OFF state of generating unit in hour ti, And in real case each gene takes a real value which shows marginal clearing price in hour ti. In this way, in a chromosome that expresses problem's variables, first N genes shows ON/OFF state of each unit with the same gene number in hour ti and gene number (N+1), which is last gene of chromosome, shows MCP in hour ti. Therefore, the gene number of problem's chromosome is (N+1).T. An example of defined chromosome is shown in Fig. 2.

3.2. Generation procedure of initial population

Naturally, initial population generation with regard to defined limits at the first time is difficult. For this reason, load behavior was used. Here, we act intelligently: for the peak load, maximum number of generators is selected ON state and also for off and low load, small generators are selected OFF state. Marginal clearing price of previous day market at the same time are used as initial guesses for today MCP.

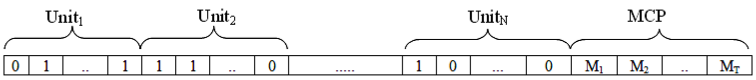

Fig. 2. An example of defined chromosome to solve UC.

3.3. Selection operator

Criterion for individual selection in each population is based on their fitness. They appear in new population based on their fitness of total fitness. In better words, here, elite selection criterion is used.

3.4. Crossover operator

If crossover operator is implemented in its standard form, because of UC constraints such as minimum up and down time, it is possible aforementioned constraints are not satisfied by chromosome changing. To solve this problem like Fig. 3, only, particular places are predicted to apply this operator which consists of the bound between the unit's scheduling time and other units. In Fig. 3, crossover place is the bound between scheduling time of unit 2 and unit 3.

3.5. Mutation operator

Here, multiple places mutation operator is used that during it one gene of total genes related to each unit can change in case of having necessary conditions. But because of aforementioned reason, mutation operator, like crossover operator, cannot be applied to each gene in each chromosome. Meaning that in scheduling time of each unit, if unit is in the ON state for a particular hour and for next hour is in the OFF state therefore this unit by applying mutation can turn off in that particular hour and on the next hour. But in the 00 or 11 combinations, with change in each gene to 0 or 1, the probability of violating Eq. 4 will increase.

3.6. Shift operator

One of new operators used in this study is shift or replace operator which gives special variety to genetic operators. Use of this operator results each chromosome's gene shifting one unit to right or left. Fig. 3 shows an example of shift to right. Fig. 4 also shows this operation for MCP genes separately.

$$\mathrm{Fitness(id)} = \mathrm{F_{Rh}(id)} / \big(\big(1 + \alpha.\mathrm{VT(id)} + \beta.\mathrm{VP(id)} + \gamma.\mathrm{VR(id)}\big) + \mathrm{F_p(id)} + \mathrm{F_{p1}(id)} + \mathrm{F_{p2}(id)} + \mathrm{F_{p3}(id)} \big) \qquad (30)$$

Fitness function of proposed Genetic algorithm is presented as Eq. 30. In genetic algorithm, goal is maximizing the fitness function. So, fitness function should be designed the way that the variables of UC optimization problem can be computed by applying proposed genetic algorithm. Since here the goal is maximizing exchange benefit of power plants under a day-ahead pool market condition, therefore, the benefit of all types of the power plants will participate directly in fitness function. Here, $\mathrm{F_{Rh}(id)}$ is summation benefit of all types of power plants in the market. Since all types of power plants have technical limits for participation in power market, therefore, these limits should be entered in fitness function as penalty factors that if violations of their technical limits occurred, then power plants benefits in power market will decrease.

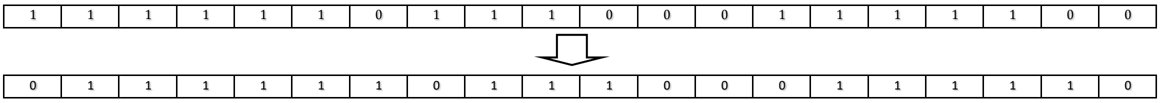

Fig. 3. An example of shift operator application related to binary genes (to right).

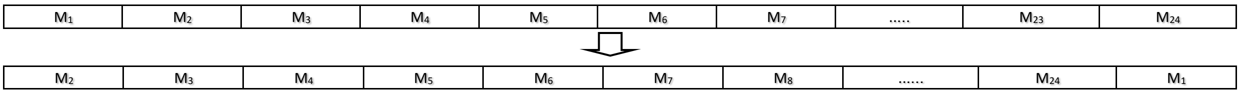

Fig. 4. An example of shift operator application related to real genes (to right).

For this reason, penalty factors are entered in denominator of fitness function of proposed advanced model of genetic algorithm. To compensate some small penalty factors, they were multiplied by coefficients such as α, β and γ. To prevent denominator of fitness function becoming zero when technical limits of all types of power plants are satisfied in UC problem solving, number 1 is added to sum of penalty factors. In fitness function, index id is the number of chromosomes. Index $\mathrm{VT(id)}$ is thermal unit penalty for violation from minimum up and down time limitation. Index $\mathrm{VP(id)}$ is the penalty of generation and load demand unbalances. Index $\mathrm{VR(id)}$ is penalty of spinning reserve shortage when lower than the predetermined amount. Indexes $\mathrm{F_p(id)}$ and $\mathrm{F_{p1}(id)}$ are penalties for violation from its minimum and maximum stored energy in the upper reservoir of pumped storage hydro power plants, respectively. Index $\mathrm{F_{p2}(id)}$ is penalty for violation from ON/OFF limitation of pumped storage hydro power plants. Index $\mathrm{F_{p3}(id)}$ is penalty for violation from stored energy equality at the beginning and end of scheduling period of power market in the upper reservoir of pumped storage hydro power plants. Fig. 5 shows the flowchart of proposed advanced genetic algorithm which is used to solve unit commitment optimization problem in presence of all types of power plants. In first step, coding Chromosomes of UC problem, considering above descriptions, are designed. In second step, initial population should be created and then, fitness chromosomes evaluations are performed in next step of proposed algorithm. Applying selection operator and choosing individuals equal to chromosomes number of initial population are done in fourth step. In the three next steps of proposed algorithm, crossover operator with rating Pc, shift operator with rating PSH and mutation operator with rating Pm are applied. If the targets are satisfied, then best population is selected as final UC solution. Otherwise, new population is created and then the algorithm returns to step 3, and repeats from step 3, again.

4. Simulation study

In this part of the paper, simulation studies are applied for three different cases. The results of different cases are compared and finally, conceptual achievements are presented.

For the base case study (case1), simulation study has been performed on generation system of a typical test system including 10 thermal units, 1 pumped storage hydro power plant, and 1 wind farm. For Case2, under similar conditions with base case study, the simulation has been repeatedly implemented by one change. Only 1 pumped storage hydro power plant has been ignored from generation system. For Case3, under similar conditions with base case study, only 1 wind farm has been ignored from generation system. The complete information of power plants characteristics which are bided in unipolar power pool market such as max and min amount of real power generation, primary production state, coefficients of cost function of thermal units, min and max amount of stored energy in PSHPP's upper reservoir, min and max capacity of power generation/pumped of PSH power plant, wind farm's generation capacity and hourly load demand profile have been shown in the Tables 1-3.

In base case study (case1), Proposed advanced genetic algorithm has been applied for optimal scheduling of all types of power plants under a day-ahead power pool market conditions. Thermal generation companies bide power-price curve to Independent System Operator (ISO) in three segments. In addition to power-price curve biding into the unipolar power pool market, to control frequency and system reliability management during sudden forced outages of generating units, thermal generation companies proposes their unloaded synchronized capacity to ancillary services market to participate in spinning reserve provision.

Price of spinning reserve for each thermal GENCO is considered as 15% of their highest incremental cost of energy production. To support participation of PSH power plants and wind farms in power pool market, it is assumed that market clearing price or MCP is paid to them by ISO. Positive and negative unbalances of wind farms for active power generation in power pool market with cost coefficient equal to τ have been incentivized and punished by (1+τ).MCP ($) and (1-τ).MCP ($), respectively.

To run this simulation, coefficient τ was set 0.5. Probabilistic generation scenarios of wind farm are used according to Singh and Erlich (2008) based on probability distribution function. The number of chromosomes to solve UC optimization problem is determined 5. Penalty coefficients α, β and γ in proposed advanced genetic algorithm are equal to 10, 4, and 2, respectively. Simulation study has been performed in Matlab software. For base case (case1), simulation results in Figs. 6-8 show convergence curve of fitness function for proposed advanced genetic algorithm while the goal is maximizing partnership benefit in a day-ahead power pool market at the presence of PSH power plans and wind farms in addition to thermal units.

Table 1
Information of all existent type generation companies.

GENCOs (thermal units)	PG_{min} (Gi)		PG_{max}(Gi)		$inital_{state}$(Gi)	
G1	150 MW		455 MW		+8	
G2	150 MW		455 MW		+8	
G3	25 MW		162 MW		- 5	
G4	20 MW		130 MW		- 5	
G5	20 MW		130 MW		- 6	
G6	25 MW		85 MW		-3	
G7	20 MW		80 MW		-3	
G8	10 MW		55 MW		-1	
G9	10 MW		55 MW		-1	
G10	10 MW		55 MW		-1	
GENCOs (wind farm)		PG_{min} (Wi)			PG_{max}(Wi)	
Wind1		0 MW			50 MW	
GENCOs (PSHPP)	P_{gp-min} (PSHPPi)	E_{min} (PSHPPi)	P_{gp-max}(PSHPPi)	E_{max}(PSHPPi)	P_{pp-min} (PSHPPi)	P_{pp-max}(PSHPPi)
PSHPP1 (N=4)	10 MW	100MWh	40 MW	650 MWh	10 MW	40 MW

Table 2
Coefficients for piecewise linear production cost of thermal units.

Gencos	a(Bi, Gi) $	b(Bi, Gi) $/Mwh	c(Bi, Gi) $/Mwh^2
G1	1000	16.19	4.8×10^{-4}
G2	970	17.26	3.1×10^{-4}
G3	700	16.6	20×10^{-4}
G4	680	16.5	21.1×10^{-4}
G5	450	19.7	39.8×10^{-4}
G6	370	22.26	71.2×10^{-4}
G7	480	27.74	7.9×10^{-4}
G8	660	25.92	41.3×10^{-4}
G9	665	27.27	22.2×10^{-4}
G10	670	27.79	17.3×10^{-4}

Total benefit of all generation companies to provide network load demand in 24 hours of power pool market equals 72616$ which for thermal units, wind farm, and pumped storage hydro power plant are equal to 59477$, 13058$, and 81$, respectively. As expected, thermal GENCOs will achieve the most benefit of power pool market, because the biggest part of daily generation to provide total load demand is assigned to these units during market clearing time interval. After thermal units, wind farms receive second priority in power pool market scheduling for energy production because they do not impose any cost for energy injection to power system. So, wind farms will earn benefit much more than PSH power plants GENCOs, but, lower than thermal GENCOs.

And, finally, the lowest benefit in power pool market goes to PSH power plants GENCOs that are only utilized at critical moments to flatten load profile curve and storing energy of wind farms in unwanted time of power market scheduling. They are scheduled the way that produce energy at peak load hours and consume energy and pump water to upper reservoir at off-peak and low-load. As can be seen from simulation results in Fig. 4, for base case study (case1), energy stored in PSHPP's upper reservoir does not change at the beginning of scheduling time from period 1 to 10 (OFF state), but it reduces from 400 to 399 in periods 10 and 11, indicating its generation mode, and then it does not change from period 12 to 23 (OFF state), and it increases from 399 to 400 in periods 23 and 24, which shows the pumping mode of PSHPP. As can be seen in Fig. 5 for base case study (case1), wind farm is scheduled for energy generation in power pool market from hour 9 with energy production equal to 47MW and it continues to operate until hour 16 (ON state), then it turns off from hour 16 until hour 20 (OFF state). In periods 21 and 22, it is again scheduled for energy generation in power pool market with 35MW and 20MW (ON state), respectively; after these times, it is not scheduled for energy generation in time periods 23 and 24, again. For base case (case1), unit commitment has been solved by use of proposed advanced genetic algorithm and load economic dispatch (ED) on all types of generation companies which are present in power pool market, shown in Fig. 9.

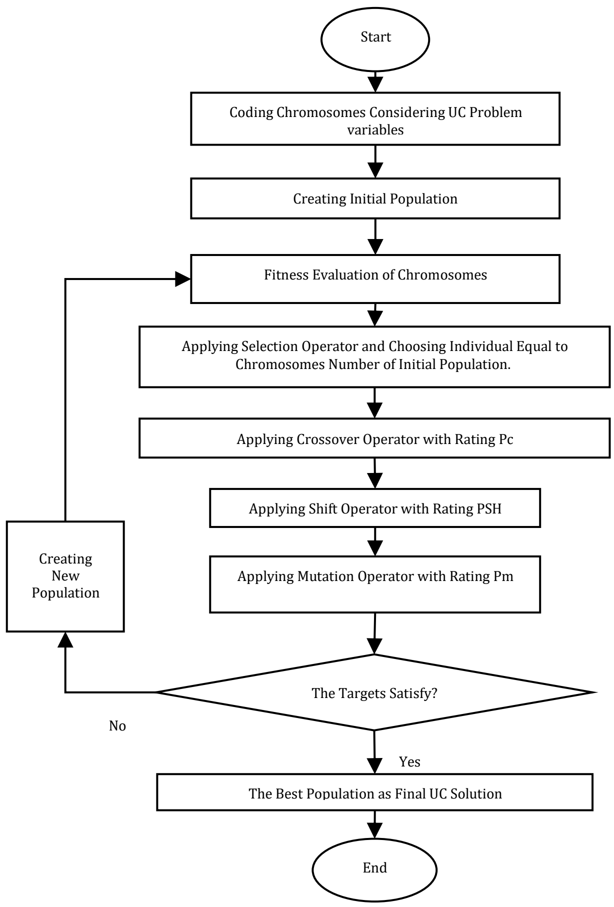

Fig. 5. The flowchart of proposed advanced genetic algorithm.

Table 3
Hourly load demand profile (LDC) of test network in a day-ahead power pool market.

T (hour)	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
Total Load (MW)	400	450	550	650	7000	800	850	900	1000	1100	1150	1200
T (hour)	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
Total Load (MW)	1050	1000	850	725	675	770	850	1050	1000	800	600	500

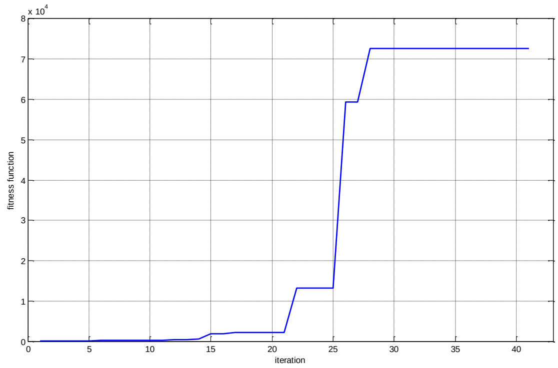

Fig. 6. Convergence curve of fitness function by proposed advanced genetic algorithm application (case1).

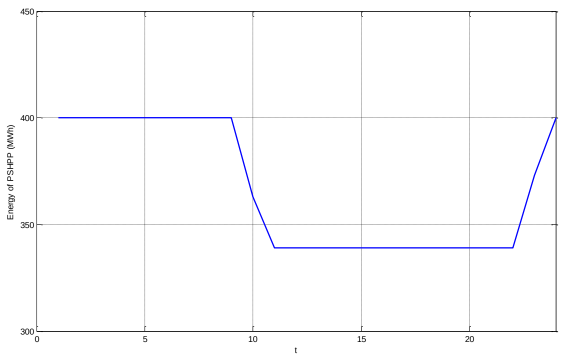

Fig. 7. Stored energy curve of PSHPP behind upper reservoir (case1).

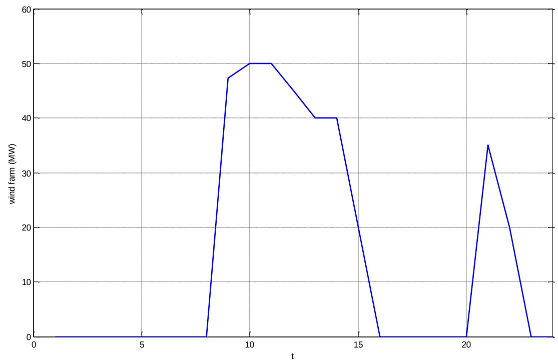

Fig. 8. Energy production curve of wind farm (case1).

Market clearing price $\mathbf{MCP_t(ti)}$ for each scheduling time period with regard to offered energy generation price by most expensive thermal unit is calculated which are presented in Table 4. Comparing total benefit in three case studies (case1, case2 and case3) and benefit of thermal units, wind farm and PSH power plant in Table 5 shows that when PSHPPs and wind farms are scheduled, simultaneously, not only the most aggregate benefit of power pool market clearing is achieved, but also each PSHPP and wind farm will earn maximum benefit of power production, compared to cases (case2 and case3) when one of them was not participating in power pool market. Furthermore, from Table 5, we can conclude that the total achieved benefit from power pool market clearing in the absence of wind farm decrease more compared to the condition of PSHPP not participating in power market. Because wind farm scheduling to provide a part of network load demand does not impose any operating cost to the market, while, PSHPP scheduling imposes consonant cost to the power pool market in either generating or pumping operating mode.

PG(Gi,t)	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
G1	250	300	400	455	455	455	455	455	455	455	455	455
G2	150	150	150	195	245	345	385	410	150	198	391	455
G3	0	0	0	0	0	0	0	0	128	130	0	0
G4	0	0	0	0	0	0	0	0	130	130	130	130
G5	0	0	0	0	0	0	0	25	25	25	25	40
G6	0	0	0	0	0	0	0	0	20	20	20	20
G7	0	0	0	0	0	0	0	0	25	25	25	25
G8	0	0	0	0	0	0	0	0	0	10	10	10
G9	0	0	0	0	0	0	10	10	10	10	10	10
G10	0	0	0	0	0	0	0	0	10	10	10	10
$P_{Wb,t}(Wi,ti)$	0	0	0	0	0	0	0	0	**47**	**50**	**50**	**45**
$P_{gP,t}(PSHPP1,t)$	0	0	0	0	0	0	0	0	0	**37**	**24**	0
$P_{pP,t}(PSHPP1,t)$	0	0	0	0	0	0	0	0	0	0	0	0
PG(Gi,t)	**t13**	**t14**	**t15**	**t16**	**t17**	**t18**	**t19**	**t20**	**t21**	**t22**	**t23**	**t24**
G1	455	455	455	455	455	455	455	455	455	455	455	381
G2	325	415	330	235	210	315	255	260	200	185	150	150
G3	0	0	0	0	0	0	130	130	130	0	0	0
G4	130	0	0	0	0	0	0	130	130	130	35	0
G5	25	25	25	25	0	0	0	25	0	0	0	0
G6	20	20	0	0	0	0	0	20	20	0	0	0
G7	25	25	0	0	0	0	0	0	0	0	0	0
G8	10	10	10	10	10	0	0	10	10	0	0	0
G9	10	0	0	0	0	0	0	10	10	0	0	0
G10	10	10	10	0	0	0	10	10	10	10	0	0
$P_{Wb,t}(Wi,ti)$	**40**	**40**	**20**	0	0	0	0	0	**35**	**20**	0	0
$P_{gP,t}(PSHPP1,t)$	0	0	0	0	0	0	0	0	0	0	0	0
$P_{pP,t}(PSHPP1,t)$	0	0	0	0	0	0	0	0	0	0	**-40**	**-31**

Fig. 9. Load economic dispatch on PSHPP, wind farm and thermal GENCOs.

Table 4
Market clearing price in a day-ahead pool market.

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
$\mathrm{MCP_t(ti)}$ \$	17.384	17.384	17.384	17.384	17.384	17.447	27.347	27.347	27.853	27.853	27.853	27.853
	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
	27.853	27.853	27.853	26.067	26.067	17.447	27.853	27.853	27.853	27.853	17.384	17.384

Table 5
Comparing total benefit in three case studies and benefit of thermal units, wind farm and PSH power plant.

Numerical studies for three cases	power pool market with simultaneous clearing of energy and reserve			
	Total Benefit ($)	Benefit of Thermal Units ($)	Benefit of PSHPP ($)	Benefit of Wind Farm ($)
Base case study (Case1)	72616	59477	81	13058
In absence of PSH power plant (Case2)	68481	55467	0	13014
In absence of wind farm (Case3)	66112	66064	48	0

5. Conclusion

In this paper, proposed advanced genetic algorithm was utilized to optimal scheduling of UC problem for a day-ahead power pool market. Simulation results indicated the effectiveness and applicability of proposed algorithm and its good convergence characteristic to optimal solution. In addition, we have also found that simultaneous scheduling of wind farms and PSH power plants brings maximum benefits to all market's shareholders in power pool market with simultaneous clearing of energy and reserve.

List of symbols

$\mathbf{ti}$ **:** Time period of scheduling a day-ahead power pool market.
$\mathbf{Gi}$ **:** Index for thermal units.
$\mathbf{Wi}$ **:** Index for wind farms.
$\mathbf{PSHPPi}$ **:** Index for pumped storage hydro power plants.
$\mathbf{Si}$ **:** Index for generation scenarios of wind farms.
$\mathbf{Li}$**:** Index for segment number of piecewise linear production cost curve of thermal units.
$\mathbf{R_{TH}(ti)}$**:** Total financial benefit of all thermal units in hour ti due to participation in active power generation and spinning reserve provision ($).
$\mathbf{MCP_t(ti)}$**:** Market clearing price in time period ti ($).
$\mathbf{R_W(ti)}$: Total financial benefit of all wind farms in hour ti due to participation in active power generation ($).
$\mathbf{R_{PS}(ti)}$: Total financial benefit of all pumped storage hydro power plants in hour ti due to participation in active power generation ($).
$\mathbf{PG_{Income-TH}(ti)}$: Total financial income of all thermal power plants due to energy production in hour ti into a day-ahead power pool market ($).
$\mathbf{OC_{total-TH}(ti)}$: Total operation cost of all thermal units in hour ti into a day-ahead power pool market ($).
$\mathbf{PG_{TH}(ti)}$**:** Total amount of active power bought by ISO from all thermal GENCOs in hour ti (MW).
$\mathbf{PG_{Wi,t}(ti)}$**:** Total amount of active power bought by ISO from all wind farms in hour ti (MW).
$\mathbf{PG_{gP,t}(ti)}$**:** Total active power generation of all pumped storage hydro power plants in hour ti (MW).
$\mathbf{P_{DpP,t}(ti)}$**:** Total active power consumption of all pumped storage hydro power plants in hour ti (MW).
$\mathbf{MCP_t(ti)}$ **:** Marginal clearing price in hour ti into a day-ahead power pool market ($).
$\mathbf{u_{TH}(Gi, ti)}$**:** Binary variable by which commitment state of thermal power plant Gi in hour ti is determined (where 1 means ON and 0 means OFF).
$\mathbf{KGL_{TH}(Gi, Li, ti)}$**:** Block Li upper limit of thermal power plant Gi offered cost in hour ti (MW).
$\mathbf{NL(Gi, ti)}$**:** Number of offered cost segments of thermal power plant Gi in hour ti into a day-ahead power pool market.
$\mathbf{SGL_{TH}(Gi, Li, ti)}$**:** Price of block Li of offered cost by thermal unit Gi in hour ti into a day-ahead power pool market ($).
$\mathbf{SGL_{Fix-TH}(Gi)}$**:** Fixed running cost of thermal unit Gi into a day-ahead power pool market ($/MWh).
$\mathbf{PGL_{TH}(Gi, Li, ti)}$**:** Power produced in block Li of the offered cost of thermal unit Gi in hour ti into a day-ahead power pool market (MW).
$\mathbf{PG_{min\_TH}(Gi)}$**:** Minimum active power generation capacity of thermal unit Gi (MW).
$\mathbf{PG_{max\_TH}(Gi)}$**:** Maximum active power generation capacity of thermal unit Gi (MW).
$\mathbf{SR_{Price-TH}(Gi, ti)}$**:** Cost of spinning reserve provision by thermal unit Gi in hour ti ($).
$\mathbf{SR_{genco-TH}(Gi, ti)}$**:** Spinning reserve contribution by thermal unit Gi in hour ti (MW).
$\mathbf{MCP_t^{up}(Wi, ti)}$, $\mathbf{MCP_t^{down}(Wi, ti)}$**:** Energy charge paid to wind farm Wi appropriate to active power production surplus (positive unbalance) and shortage (negative unbalance) in hour ti, respectively ($).
$\mathbf{bi, t(Wi, Si, ti)}$**:** Binary variable which equals 1 when active power bought by ISO from wind farm Wi in hour ti into a day-ahead power pool market is greater than that in generation scenario Si and zero otherwise.
$\mathbf{P_{Wb,t}(Wi, ti)}$**:** Amount of active power bought by ISO from wind farm Wi in hour ti into a day-ahead power pool market (MW).
$\mathbf{P_{Wi,t}(Wi, Si, ti)}, \mathbf{P_i(Wi, Si, ti)}$**:** Generation scenario Si for wind farm Wi based on wind power prediction in hour ti and the probability of each of them by a probability tree of wind farm generation.
$\mathbf{P_{W\,max}(Wi)}$**:** Maximum active power generation capacity of wind farm Wi (MW).
$\mathbf{P_{gP,t}(PSHPPi, ti)}$**:** Active power generation of pumped storage hydro power plant PSHPPi in hour ti into a day-ahead power pool market (MW).
$\mathbf{P_{pP,t}(PSHPPi, ti)}$**:** Active power consumption of pumped storage hydro power plant PSHPPi in hour ti into a day-ahead power pool market (MW).
$\boldsymbol{\eta}\mathbf{(PSHPPi)}$**:** Efficiency of pumped storage hydro power plant PSHPPi.
$\mathbf{C(PSHPPi)}$**:** Fixed operating cost of pumped storage hydro power plant PSHPPi ($).
$\mathbf{E_{u,t}(PSHPPi, ti)}$**:** stored energy in upper reservoir of pumped storage hydro power plant PSHPPi in hour ti (MWh).
$\mathbf{E_u^{max}(PSHPPi)}, \mathbf{E_u^{min}(PSHPPi)}$**:** Maximum and minimum energy storage limit of upper reservoir of pumped storage hydro power plant PSHPPi, respectively (MWh).
$\mathbf{P_{gP}^{max}(PSHPPi)}$, $\mathbf{P_{gP}^{min}(PSHPPi)}$**:** Maximum and minimum active power generation of pumped storage hydro power plant PSHPPi, respectively (MW).
$\mathbf{P_{pP}^{max}(PSHPPi)}$, $\mathbf{P_{pP}^{min}(PSHPPi)}$**:** Maximum and minimum active power consumption of pumped storage hydro power plant PSHPPi, respectively (MW).
$\mathbf{m_{g,t}(PSHPPi, ti)}$**:** Binary variable which equals 1 when pumped storage hydro power plant PSHPPi in hour ti is in generation state.
$\mathbf{n_{p,t}(PSHPPi, ti)}$**:** Integer variable showing the number of same units of pumped storage hydro power plant PSHPPi which are in consumption (pumping state). It varies between 0 and N.
$\mathbf{P_{D,t}(ti)}$**:** Total load demand of power system in hour ti into a day-ahead power pool market.
$\mathbf{E_u^0(PSHPPi, ti)}, \mathbf{E_u^{end}(PSHPPi, ti)}$**:** Stored energy in upper reservoir of pumped storage hydro power plant PSHPPi at the beginning and end of scheduling period into a day-ahead pool market (MWh).
N: Number of similar units in pumped storage hydro power plant PSHPPi.
$\mathbf{P_{Pb,t}}$ $\mathbf{(PSHPPi, ti)}$**:** Accepted power generation or consumption of pumped storage hydro power plant PSHPPi in hour ti into a day-ahead power pool market by ISO (MW).

References

Aihara R, Yokoyama A, Nomiyama F, and Kosugi N (2011). Optimal operation scheduling of pumped storage hydro power plant in power system with a large penetration of photovoltaic generation using genetic algorithm. In the IEEE Trondheim PowerTech, IEEE , Trondheim, Norway. https://doi.org/10.1109/PTC.2011.6019279

Borghetti A, D'Ambrosio C, Lodi A, and Martello S (2008). An MILP approach for short-term hydro scheduling and unit commitment with head-dependent reservoir. IEEE Transactions on power systems, 23(3): 1115-1124. https://doi.org/10.1109/TPWRS.2008.926704

Brown PD, Lopes JP, and Matos MA (2008). Optimization of pumped storage capacity in an isolated power system with large renewable penetration. IEEE Transactions on Power systems, 23(2): 523-231. https://doi.org/10.1109/TPWRS.2008.919419

Fabbri A, Roman TG, Abbad JR, and Quezada VM (2005). Assessment of the cost associated with wind generation prediction errors in a liberalized electricity market. IEEE Transactions on Power Systems, 20(3): 1440-1446. https://doi.org/10.1109/TPWRS.2005.852148

Jiang R, Wang J, and Guan Y (2012). Robust unit commitment with wind power and pumped storage hydro. IEEE Transactions on Power Systems, 27(2): 800-810. https://doi.org/10.1109/TPWRS.2011.2169817

Lu N, Chow JH, and Desrochers AA (2004). Pumped-storage hydro-turbine bidding strategies in a competitive electricity market. IEEE Transactions on Power Systems, 19(2): 834-841. https://doi.org/10.1109/TPWRS.2004.825911

Singh SN and Erlich I (2008). Strategies for wind power trading in competitive electricity markets. IEEE Transactions on Energy Conversion, 23(1): 249-256. https://doi.org/10.1109/TEC.2007.914179

Zhang N, Kang C, Kirschen DS, Xia Q, Xi W, Huang J, and Zhang Q (2013). Planning pumped storage capacity for wind power integration. IEEE Transactions on Sustainable Energy, 4(2): 393-401. https://doi.org/10.1109/TSTE.2012.2226067