A Cooperative Dispatch Model for the Coordination of the Wind and Pumped-storage Generating Companies in the Day-ahead Electricity Market

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Abstract- Wind energy has generally intermittent and stochastic nature. In this regard, it is more desirable for both system and wind units' owners to operate in coordination with an energy storage unit to obtain some benefits. In this paper, the influence of coordination of wind units and pumped storage (PS) power plants, which is the most common type of large scale energy storage, is investigated. Nowadays, regard to incremental penetration of sources of uncertainty in power systems, construction of large-scale storage units which compensates and redresses probable curtailments and imbalances has assumed more importance. The independent system operator (ISO) requires a powerful intelligent calculational tool to optimize operation costs while clearing day-ahead market and determining hourly generation schedule. This tool can help the ISO to analyze advantages and disadvantages of coordination. The coordinated operation can help the wind units to increase their penetration and consequently their profit. The conclusions of numerical simulation clearly show the benefits of the presence of a storage unit in power system. It has been proved that coordination can decrease the market clearing price (*MCP*). It also diminishes commitment of expensive generating units while satisfying peak loads and decreases the generation cost of thermal units. In addition, the participation of an energy storage unit decreases the risk of commitment of wind units in the competitive wholesale electricity market.

Keywords: Coordination, Day-ahead market, Dispatchability, profitability, Unit commitment, Artificial neural network.

Nomenclature:

$p(i,t)$	The generated active power by thermal units
a, b, c	The cost function's coefficients
$C_T(i,t)$	The operation cost of each unit in each hour
$u(i,t)$	Thermal unit state (**1** unit is on; **0** unit is off)
RUR_i, RDR_i	Ramp up/down rate of unit i
MUT_i, MDT_i	Minimum up/down time
CST	Cold start-up time
CSC, HSC	Cold/hot start-up cost
SUC, SDC	Start-up/shut down cost
$y(i,t), z(i,t)$	Start-up/shut down indicator
A, B, C	The characteristics of wind turbines
P_r	The rated power of wind turbine
$V_{ci}\ V_{co}\ V_r$	The cut-in, cut-out, rated wind speed
η_w	The combined efficiency of gearbox
P_{WG}	Electric power output of the wind turbine
η^{PS}	The efficiency of variable/fix speed turbine
ρ	The density of water (kg/m^3)
H	The effective installation height of turbine
q	The flow of water (m^3/h)
$P_g(l,t)$	The generated power of PS unit
$P_p(l,t)$	The consumed power of PS unit

$Q_g(l,t)$	Water flow in generating mode
$Q_p(l,t)$	Water flow in pumping mode
$Vup(l,t)$	The volume of upper reservoir
$Vlow(l,t)$	The volume of lower reservoir
I_g, I_p	The state of PS unit (generation, pumping)
SRR	Spinning reserve required
$P_D(t)$	Demand at hour t
MCP	Market clearing price
$\rho_{reserve}$	Reserve price coefficient rate
$NegoRate$	Negotiated coordination rate

1. Introduction

In this study, the implication of coordinated operation of wind and pumped-storage (PS) units on profit of wind units and its influence on system profit in a day-ahead electricity market are investigated. When the structure of the power market is without any supporting policies for renewable generation resources, the uncertain wind generating units face some difficulties in order to participate in the wholesale energy market. The owners of wind units in restructured power system do not take risk of insufficient generation while they are devolved the responsibility of satisfying the specific portion of demand in power market clearance. In the case of inability to fulfill the assigned commitment by wind unit, this unit definitely would be penalized by the independent system operator (ISO). Due to the deficiency in the generation, they must redress the imbalance by buying needed energy from the spot market, which has certainly higher prices than day-ahead market clearing price (*MCP*). In addition, the existence of sources of uncertainty in power system confronts generation scheduling with some difficulties. Especially, whenever uncertain resources have to satisfy a significant amount of demand. In another word, they have large penetration in satisfying the total load. Hence, in order to mitigate the risk of participation in the wholesale market, uncertain units tend to have coordinated operation with a storage unit [1-3].

Nowadays, pumped-storage units, compressed air energy storage units, and ocean renewable energy storage units (ORES) are the most common type of large scale energy storages [4,5]. Nevertheless, more than 96% of total installed storage capacities around the world are pumped-storage units [6]. In addition, in term of efficiency as well as installation and maintenance costs (short-term and long-term costs), the pumped-storage facility is the leading technology in comparison with other emerging storage alternatives. On the other hand, storage units prevent commitment of expensive thermal units, especially gas units, during peak hours [7–10]. The wind energy is one of the most important uncertain resources, which undertakes a large share of demand satisfaction in the power system of some countries [11]. The wind units may generate more power than forecasted generation and the operator buys this excess power with lower price rather than *MCP* if it is legislated in market structure; otherwise, the excess wind generation would be dissipated. Wind units must have an exact anticipation of their next-day generation and must undertake the amount of power, which may be able to generate it. They use also state-of-the-art forecasting methods to reduce probable imbalances [12]. Forecasting methods have naturally some error, which may face wind units' owners with considerable detriments. Therefore, the owners prefer to have coordinated operation with energy storage units, when they decide to participate in the day-ahead power market [13]. The bidding strategies of wind units are different whenever they do not have coordination [14–16]. Consequently, if uncertain units are able to undertake part of demand satisfaction, the necessity of installation of new power plants will postpone to a future date and integration of sustainable renewable energy will rise, which has more benefits for both system and consumers [17,18].

2. The Models of System's Components

2.1. Thermal Power Plants

Thermal power plants, based on the amount of consumed fuel and generated power, have normally quadratic cost function which can be achieved by a simple curve fitting method. The cost function and its constraint are presented in Eq. (1) and (2) as below, where *a*, *b* and *c* stand for cost function coefficients. $C_T(i,t)$ shows the cost function of thermal units, and $P(i,t)$ represents generated active power by thermal units. t and i are the indices of time and thermal unit's number respectively.

$$C_T(i,t) = c_i .P(i,t)^2 + b_i .P(i,t) + a_i \quad (1)$$

$$P_{\min}(\mathrm{i})u(i,t) \le P(i,t)u(i,t) \le P_{\max}(\mathrm{i})\, u(i,t) \quad (2)$$

Ramp up/down rate limits can be shown as follows [19,20]:

$$P(i,t) - P(i,t-1) \le RUR_i \quad (3)$$

$$P(i,t-1) - P(i,t) \le RDR_i \quad (4)$$

Minimum up/down time (*MUT*/*MDT*) constraints and start-up/shutdown (SUC/SDC) constraints can be shown as below [21,22].

$$\begin{cases} \sum_{t=1}^{L_i}[1-u(i,t)] = 0 \\ \sum_{j=t}^{t+MTU_i-1} u(i,j) \ge MUT_i \times y(i,t), \forall t = L_i+1 \cdots T - MUT_i + 1 \\ \sum_{j=t}^{T}[u(i,j) - y(i,t)] \ge 0 \qquad , \forall t = T - MUT_i + 2 \cdots T \\ L_i = Min\{T, (MUT_i - U_i^0) \times u(i,0)\} \end{cases} \quad (5)$$

$$\begin{cases} \sum_{t=1}^{F_i} u(i,t) = 0 \\ \sum_{j=t}^{t+MDU_i-1}[1-u(i,j)] \ge MDT_i \times z(i,t),\ \forall t = F_i+1 \cdots T - MDT_i + 1 \\ \sum_{j=t}^{T}[1-u(i,j) - z(i,t)] \ge 0 \qquad ,\ \forall t = T - MDT_i + 2 \cdots T \\ F_i = Min\{T, (MDT_i - S_i^0) \times (1-u(i,0))\} \end{cases} \quad (6)$$

$$y(i,t) - z(i,t) = u(i,t) - u(i,t-1) \quad (7)$$

$$y(i,t) + z(i,t) \le 1 \quad (8)$$

$$SUC(\mathrm{i}) = \begin{cases} HSC(\mathrm{i}), & if \quad MDT(i,t) \le t \le MDT(i,t) + CST(i) \\ CSC(\mathrm{i}), & if \quad t \rangle MDT(i,t) + CST(i) \end{cases} \quad (9)$$

Where T denotes the total time intervals, which is equal to 24 hours. *CST* defines cold start-up time, and *CSC* and *HSC* are cold and hot start-up cost, respectively. The shutdown cost (*SDC*) is assumed to be $100 for all thermal units. $u(i,t)$ is a binary variable which represents the state of thermal unit i (value of **1** means the unit is on, **0** means the unit is off). As well, $y(i,t)$ and $z(i,t)$ show the start-up and shutdown indicators which are binary variables.

1.2. Wind Farms

1.2.1. Wind Turbines

The stochastic nature of wind has caused manageability controllability problems for wind units. The generated power of wind units depends on wind speed and wind turbines' characteristic. In a wind turbine, the generated power can be obtained by Eq. (10), where the amounts of A, B and C can be calculated according to Eq. (11) – Eq. (13), which are the characteristics of the wind turbine. P_r is the rated power of wind turbine. Furthermore, V_{ci}, V_{co}, and V_r are cut-in, cut-out and rated speed of the turbine respectively [23,24].

$$P_W = \begin{cases} 0 & 0 \le V < V_{ci} \\ \left(A + BV + CV^2\right) P_r & V_{ci} < V < V_r \\ P_r & V_r < V < V_{co} \\ 0 & V > V_{co} \end{cases} \tag{10}$$

$$A = \frac{P_r}{\left(V_{ci} - V_r\right)^2}\left[V_{ci}\left(V_{ci} + V_r\right) - 4\left(V_{ci} \times V_r\right)\left[\frac{V_{ci} + V_r}{2V_r}\right]^3\right] \tag{11}$$

$$B = \frac{P_r}{\left(V_{ci} - V_r\right)^2}\left[4\left(V_{ci} + V_r\right)\left[\frac{V_{ci} + V_r}{2V_r}\right]^3 - \left(3V_{ci} + V_r\right)\right] \tag{12}$$

$$C = \frac{1}{\left(V_{ci} - V_r\right)^2}\left[2 - 4\left[\frac{V_{ci} + V_r}{2V_r}\right]^3\right] \tag{13}$$

$$P_{WG} = P_W \eta_W \tag{14}$$

If a wind farm consists of several models of wind turbine, it will be possible to achieve the output power of the wind farm by having wind speed and wind turbines characteristics and summation of total power output of the turbines [25]. The subscript of w denotes the index of wind units. η_w shows the combined efficiency of the gearbox of the wind turbine. P_{WG} shows the wind output based on forecasted wind speed.

1.2.2. The Wind Speed Forecast by ANN

Artificial neural network (ANN) is a mathematical tool that is proposed based on imitation from the biological neural network, which has high flexibility to coincide with input data and discover trends of similarities. This tool can find the discipline and correlation among data and forecast the intended output regard to selected effective inputs [26-28]. In order to forecast the wind speed, a multilayer perceptron neural network is employed, which is tuned to have 20 neurons in 4 layers that use time series forecasting approach of nonlinear autoregressive with external input (NARX) classic mathematical method [29]. A four-year database of wind speed is employed as input data. These data provide hourly wind speed of 1460 days for ANN. These adequate amounts of data enable ANN to have large backward retrieving steps in daily data. In this paper, 26 days are selected as effective inputs to perform trainer matrix of ANN. The data are normalized by placing between 1 and -1. Then, the data are separated and segregated by linear, tangent hyperbolic and sigmoid activation functions. Finally, the weight of each interconnection can be calculated so that ANN be able to simulate the same as the real system based on the past behavior of it. By employment of a trained ANN, in which the weights of interconnections are determined, it is possible to forecast the future of a parameter by giving appropriate inputs to ANN [30].

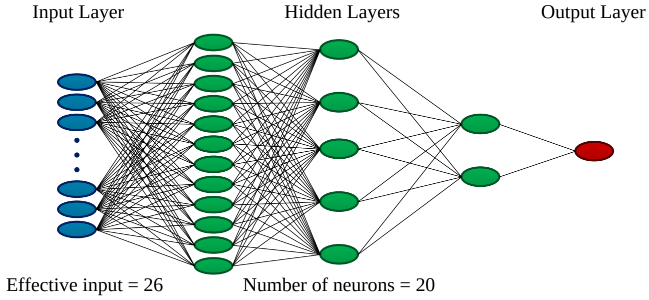

Fig. 1. The employed artificial neural network's structure

In order to consider the effect of stochastic nature of wind, a noise signal is added to ANN before training. This signal consists of the standard deviation of all input data (σ) multiplied by a random number within -1 and 1. This helps the ANN to consider the effect of intermittency. Hence, the ANN must be run many times for each hour (each time step). As a consequence, many forecasted outputs will be obtained which are considerably close to each other and are not too much scattered. The maximum and minimum obtained values for wind speed are called optimistic and pessimistic forecast respectively. These generation forecasts will be applied in bidding strategies of wind units in the day-ahead market ($P_{wt}^{pessimistic}$). The term of σ_t defines the standard deviation of wind speed for the 4-year wind speed database [31].

$$\begin{aligned} & input\left[f\left(t-1,\ldots,t-14,t-365,t-730\right)\right] = \\ & output\left[t + \sigma_t \times random\left\{-1:1\right\}\right] \\ & t = \left\{1:1460\right\} \end{aligned} \tag{15}$$

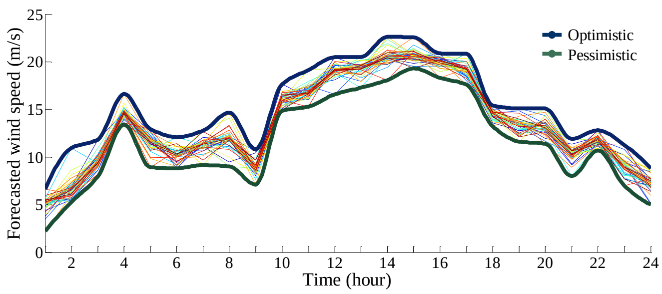

Fig. 2. Optimistic and pessimistic forecasted wind speed

1.3. Pumped-Storage Power Plants

The duty of pumped-storage units is to store low-priced off-peak power in large-scale, which is bought from thermal or nuclear power plants, and generate high-price peak electricity. The storing process is performed by pumping water from a lower reservoir to an upper reservoir. PS units have three operation modes of pumping, generating and idle. l represents the index of PS units. The generation equation of PS unit is given in Eq. (16), where g defines gravitational constant [32, 33]. η^{PS} is the efficiency of the turbine in the PS unit, and H shows the effective installation height of turbine from upper reservoir. In addition, ρ_{water} indicates on the density of water (kg/m^3). The subscripts of p and g are the indices of generation and pumping modes in the PS unit. $P_g^{PS}(l,t)$ and $P_p^{PS}(l,t)$ are the generated and the consumed power of *PS* unit l at time t. Furtheremore, $Q_g(l,t)$ and $Q_p(l,t)$ are water flow in generating and pumping modes (m^3/h). Moreover, $V_{up}(l,t)$ and $V_{low}(l,t)$ are volumes of upper and lower reservoirs. $I_g(l,t)$ and $I_p(l,t)$ are binary variables for showing the states of PS units (generating/Idle/pumping modes).

$$\begin{cases} P_g^{PS}(l,t) = \eta^{PS} \times \rho_{water} \times g \times H \times Q_g(l,t) \\ P_p^{PS}(l,t) = \rho_{water} \times g \times H \times Q_p(l,t) \end{cases} \tag{16}$$

$$P_{\min\_g}(l) \times I_g(l,t) \le P_g^{PS}(l,t) \le P_{\max\_g}(l) \times I_g(l,t) \tag{17}$$

$$P_{\min\_p}(l) \times I_p(l,t) \le P_p^{PS}(l,t) \le P_{\max\_p}(l) \times I_p(l,t) \tag{18}$$

$$\mathrm{Q}_{\min\_g}(l) \times I_g(l,t) \le Q_g(l,t) \le \mathrm{Q}_{\max\_g}(l) \times I_g(l,t) \tag{19}$$

$$\mathrm{Q}_{\min\_p}(l) \times I_p(l,t) \le Q_p(l,t) \le \mathrm{Q}_{\max\_p}(l) \times I_p(l,t) \tag{20}$$

$$\mathrm{V}_{\min\_up}(l) \le V_{up}(l,t) \le \mathrm{V}_{\max\_up}(l) \tag{21}$$

$$\mathrm{V}_{\min\_low}(l) \le V_{low}(l,t) \le \mathrm{V}_{\max\_low}(l) \tag{22}$$

$$V_{up}(l,t+1) = V_{up}(l,t) - Q_g(l,t) \times I_g(l,t) + Q_p(l,t) \times I_p(l,t) \tag{23}$$

$$V_{low}(l,t+1) = V_{low}(l,t) + Q_g(l,t) \times I_g(l,t) - Q_p(l,t) \times I_p(l,t) \tag{24}$$

$$I_g(l,t) + I_p(l,t) \le 1 \tag{25}$$

$$I_g(l,t) \text{ and } I_p(l,t) = 0 \tag{26}$$

$$Q_g(l,t) \text{ and } Q_p(l,t) = 0 \tag{27}$$

$$P_g^{PS}(l,t) \text{ and } P_p^{PS}(l,t) = 0 \tag{28}$$

3. Problem Definition and Proposed Approach

3.1. Unit Commitment Problem

Unit commitment (UC) is a mixed integer non-linear programming (MINLP) with multiple variables and constraints, which is included in difficult problems of engineering. In this study, all constraints and equations are convex and smooth. The problem is solved using GAMS optimization software and employing the SBB solver to solve MINLP parts, and the CPLEX solver for finding the solution of MIP parts of the problem [34]. The SBB solver is capable of using semi-continuous variables, which can be equal to zero or be limited between a minimum value and a maximum value. The insufficiency of reserve confronts the system with the risk of load shedding of sensitive loads. Besides, at the worst condition, black-out of the system may be occured, which imposes a significant detriment to the system. The operation reserve is divided into two categories as spinning and non-spinning reserve. The spinning reserve required (*SRR*) is an unloaded synchronous capacity that can deliver power within ten minutes. The non-spinning reserve is the unsynchronized power that can generate within ten minutes. It can be hydro units or gas units or any type of storage units that are able to response to the need of system quickly. Required reserve of the system is determined based on various standards [35,36]. These standards can contain a specific percentage of maximum forecasted demand for a certain hour plus by a specific percentage of sources of uncertainty in the same hour. A specific amount of power for considering the loss of load probability (*LOLP*) can be also added to *SRR*. Moreover, it should be more than largest grid-connected power plant [37,38]. Furthermore, the reserve sources must be diffused around the system topologically, in order to prevent bottling and let the system to operate in islanding mode rather than brown-outs. To provide *SRR* by PS units, if PS unit is stated in generation mode, it can increase its generation up to P_{g_max}; if PS unit is stated in pumping mode, it can stop its pumping and start to generation up to needed power; finally, if it is stated in idle mode it can start generation [39]. The equations below illustrate objective function and system constraints, where N, L and W are the number of thermal, *PS* and wind farms respectively. Fig. 3 illustrates a quick overview on following parts of study. $P_D(t)$ is the demand of hour t.

$$\min: Total\ cost = \sum_{t=1}^{T}\sum_{i} C_T(i,t) + SUC_i \times y(i,t) + SDC_i \times z(i,t) \tag{29}$$

$$\sum_{i=1}^{N} P(i,t)u(i,t) + \sum_{i=1}^{L}(P_g^{PS}(i,t)I_g(l,t) - P_p^{PS}(i,t)I_p(l,t)) + \sum_{w=1}^{W} P_w(t) = P_D(t) \tag{30}$$

$$\sum_{i=1}^{N} P_{max}(i,t)u(i,t) + \sum_{i=1}^{L} P_{\max\_g}(l,t) - \sum_{i=1}^{L}(P_g^{PS}(i,t)I_g(l,t) - P_p^{PS}(i,t)I_p(l,t)) - P_D(t) \ge SRR(t) \tag{31}$$

3.2. Scenario Description

The day-ahead market mechanism and coordination between market participants is investigated through 5 scenarios [40,41]. The minimization of operation cost and maximization of profit of wind units while collaborative operation of wind and storage units are investigated [42]. All generation companies have a prediction of their trading for the next day. Hence, five scenarios are proposed on the IEEE 118-bus, 54-unit test system [43].

- ➢ Only thermal units have commitment,
- ➢ Wind and thermal units have commitment,
- ➢ Commitment of thermal, wind and *PS* units without coordination,
- ➢ Commitment of thermal, wind and *PS* units with coordination,
- ➢ Commitment of thermal, wind and *PS* units with coordination along with wind supporting policies.

In the first scenario, the thermal units are only called to satisfy the demand. The total operational cost can be obtained by Eq. (32).

$$TotalOperation\ \mathrm{Cost} = \left(\begin{array}{l} \sum_t \sum_i (cP_{it}^2 + bP_{it} + a + SUC_{it} + \\ SDC_{it}) + \sum_t \rho_{reserve} \times SRR_t \end{array} \right) \tag{32}$$

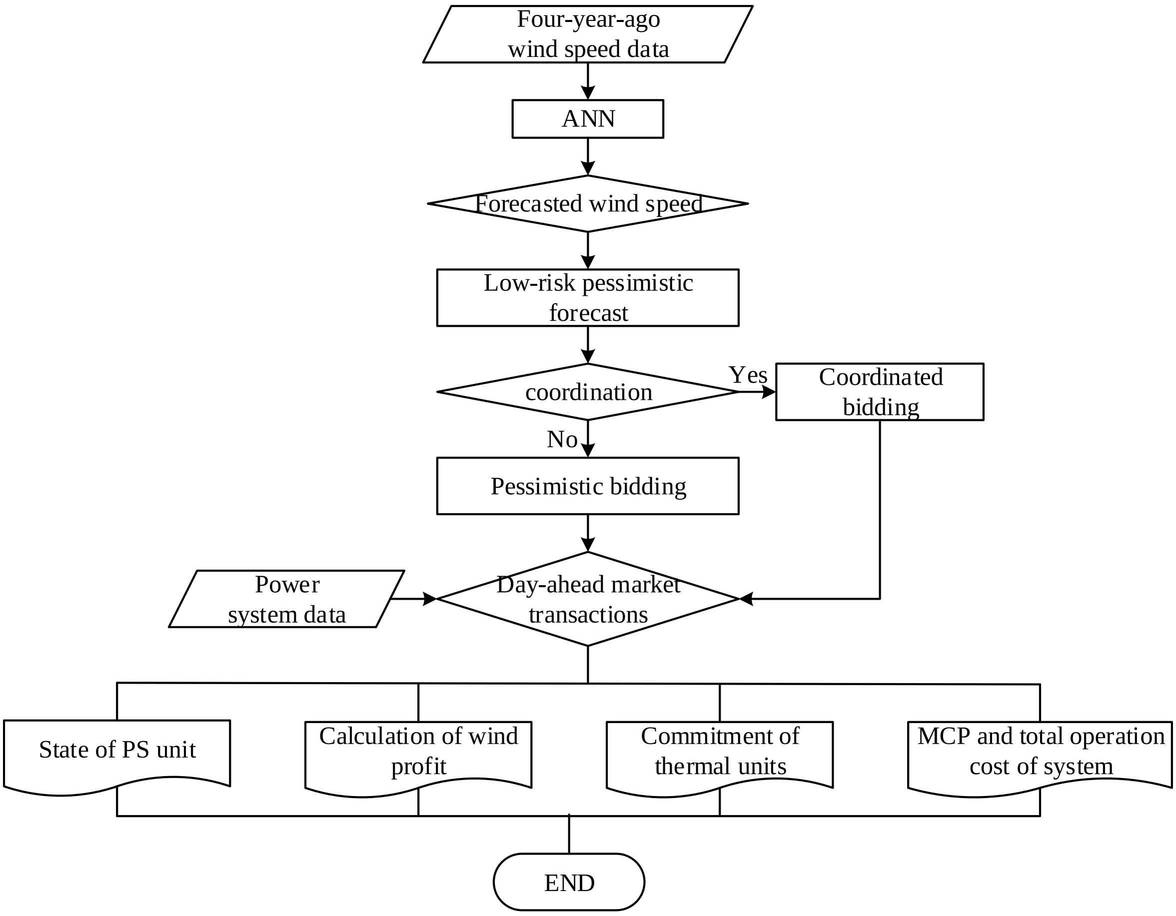

Fig. 3. Flowchart of simulations

In the second scenario, the wind units and thermal units commit in the generation, but the PS unit is not committed. Thus, wind owners adopt a low-risk policy in order to participate in the day-ahead electricity market. Hence, they bid pessimistic forecasted power so as to reduce the risk of penalization by ISO and buying from the spot market. In other words, the wind units' owners must be cautious for bidding. Nevertheless, if they generate more than forecasted amount, they sell excess generated power (curtailment) to the ISO with a different predetermined price, as it is supposed for this market. ISO buys the excess power of wind units with a lower price. However, the *MCP* must be paid to ISO by consumers, and ISO earns a surplus as the profit of system, which should be spent for expansion of the system. The expensive thermal units, which are shut down because of excess generation of wind resources may receive part of this surplus (called merchandizing surplus) if it is legislated in market structure rules. Because of containing uncertainty, the wind units are not allowed to participate in the ancillary service market. In power system with large penetration of wind units, the owners of wind units may be forced to shut down some of their turbines or reduce generation by controlling the output power of turbine with gearbox control system, when excess power is generated.

$Scenario\,2:$

$$Wind\ \ profit = \left(\begin{array}{l} \sum_t \sum_w P_{wt}^{pessimistic} \times MCP_t + \\ \sum_t \sum_w Penalty \times Curtailment \times MCP_t \end{array} \right) \tag{33}$$

$$Total\ Operation\ Cost = \left(\begin{array}{l} \sum_t \sum_i (cP_{it}^2 + bP_{it} + a + SUC_{it} + SDC_{it}) \\ + \sum_t \rho_{reserve} \times SRR_t \\ + \sum_t \sum_w P_{wt}^{pessimistic} \times MCP_t \end{array} \right) \tag{34}$$

In the third scenario, the wind and PS units operate independently so as to decrease total operation cost of the system. There is no supporting policy for wind resources. Also, they bid pessimistic forecasted generation to market operator. The market structure forces the ISO to buy the excess generated power of wind units with a specific reducing coefficient. In this case, the commitment of PS units helps to prevent commitment of expensive units, normally gas units, during peak hours. In this case, the PS units buy the electricity from the power system and sell it back to the net during peak hours. The difference between *MCP* of off-peak and peak hours determines the profit of PS unit. In this regard, the reserve cost have fallen considerably, because the *MCP* is decreased and the reserve cost is proportional to *MCP*. In other words, the reserve price ($\rho_{reserve}$) follows the day-ahead price trend. In addition, some of the reserve capacity is provided by PS units instead of expensive thermal units.

$Scenario\,3:$

$$Wind\ \ profit = \left(\begin{array}{l} \sum_t \sum_w P_{wt}^{pessimistic} \times MCP_t + \\ \sum_t \sum_w Penalty \times Curtailment \times MCP_t \end{array} \right) \tag{35}$$

$$Total\ Operation\ Cost = \begin{pmatrix} \sum_t \sum_i (cP_{it}^2 + bP_{it} + a + SUC_{it} + SDC_{it}) \\ +\sum_t \rho_{reserve} \times SRR_t + \sum_t \sum_w P_{wt}^{pessimistic} \times MCP_t \\ +\sum_t \sum_L P_g{}^{PS}{}_{lt} \times MCP_t - \sum_t \sum_L P_p{}^{PS}{}_{lt} \times MCP_t \end{pmatrix} \quad (36)$$

$$Paid\ to\ PS = \begin{pmatrix} \sum_t \sum_L P_g{}^{PS}{}_{lt} \times MCP_t \\ -\sum_t \sum_L P_p{}^{PS}{}_{lt} \times MCP_t \end{pmatrix} \quad (37)$$

In the scenario 4, the PS and wind units want to increase their own profits. Therefore, they are passionate about singing a bilateral contract so that they can have coordination with each other. It produces a benefit for the system by decreasing the total operation cost of the system. They accept to trade power between each other according to negotiated prices. The wind units' owners will sell their excess power to the PS units with a specific predetermined price, which is more than buying price of the ISO but is lower than *MCP*. According to the contract terms, the PS units possess curtailments of wind units. If PS units are planned to generate a specific amount of electricity, they naturally decrease their current generation level, and instead the power will be provided by curtailments of wind units (excess generated wind power) with a price lower than *MCP* and is sold to demand with *MCP*. The wind unit cannot sell its high-risk uncertain power to the load through market transaction. The PS unit also may use part of its needed power for pumping by buying from wind units instead of totally from the system. It is noticeable that the PS units dedicate just some of their capacity for balancing curtailments. This dedicated capacity can be calculated by using probabilistic stochastic methods or having sufficient cognition from the wind curtailments at various times of a year. If the PS unit is stated in idle mode, they can start to pump, provided that the curtailment of wind unit be higher than minimum pumping range. The collaborative operation performs increase in profit of both wind and PS units. In the next day, if wind generation has deficit power, which is called negative imbalance, the PS unit will provide the needed power of wind unit at the real time and must be investigated in real time coordination in the spot market, which is beyond the scope of this research. In the real time, if the wind unit has negative imbalance, the PS unit will decrease or stop its pumping or start to generate in idle mode or increase the generation level in generating mode. Therefore, the wind units not only decrease the risk of commitment of uncertain resources but also increase their own profit. Compared with scenario 3, there is no difference between commitment scheduling of units and economic dispatch configuration. But the economic market transactions and profit of each unit are dissimilar in comparison with scenario 3. In following equations, *NegoRate* represents coordination price, which is negotiated between the wind and *PS* units. $\rho_{reserve}$ is symbolized for the reserve price. Besides, $P_{wt}^{pessimistic}$ indicates on the pessimistic forecast of wind generation at hour *t*.

In the scenario 5, the ISO is the owner of storage units, such as PS, and use them to make demand curve smoother and to redress uncertainty of wind units. It can be said that the ISO legislates some supporting strategies for uncertain units. Therefore, uncertain units do not penalize due to positive and negative imbalances. The purpose is to encourage investors to make an investment in renewable energy section. Thus, the wind units bid high-risk optimistic forecasted generation ($P_{wt}^{optimistic}$) to market operator.

$Scenario\,5:$

$$Wind\ \ profit = \left(\sum_t \sum_w P_{wt}^{optimictic} \times MCP_t \right) \quad (40)$$

4. Numerical Study: Simulation Results and Discussion

4.1. Economic Advantages of PS Units

In this part, a deregulated non-competitive power system is employed, in order to simulate the influence of PS units on system main parameters. The storage units are able to decrease the total cost of operation by transferring power from off-peak hours to peak hours. The PS unit buys the power to store at a lower price and sells it during peak hours with a higher price. Furthermore, such units prevent commitment of expensive units during peak hours that reduce operational cost and market clearing price in restructured power systems [44]. The utilization of PS unit also helps the ISO to have flatter thermal generation curve, which is more desired by the operator. In this part, the results of simulation are investigated by an IEEE 118-bus 54-unit test system through three scenarios.

$Scenario\,4:$

$$Wind\ \ profit = \begin{pmatrix} \sum_t \sum_w P_{wt}^{pessimistic} \times MCP_t & \\ +\sum_t \sum_w \left(Penalty \times Curtailment \times MCP_t\right) & [\forall t \,|\, I_p{}^{ps}{}_{lt} = 0] \\ +\sum_t \sum_w \left(NegoRate \times Curtailment \times MCP_t\right) & [\forall t \,|\, I_p{}^{ps}{}_t = 1 \ \ \& P_p{}^{ps}{}_{lt} \ge Curtailment] \\ +\sum_t \sum_w \begin{pmatrix} NegoRate \times P_p{}^{ps}{}_{lt} \times MCP_t + \\ Penalty \times (Curtailment - P_p{}^{ps}{}_{lt}) \times MCP_t \end{pmatrix} & [\forall t \,|\, I_p{}^{ps}{}_t = 1 \ \ \& P_p{}^{ps}{}_{lt} \le Curtailment]. \end{pmatrix} \quad (38)$$

$$TotalOperation\,\mathrm{Cos}\,t = \begin{pmatrix} \sum_t \sum_i (cP_{it}^2 + bP_{it} + a + SUC_{it} + SDC_{it}) \\ +\sum_t \rho_{reserve} \times SRR_t + \sum_t \sum_w P_{wt}^{pessimistic} \times MCP_t \\ +\sum_t \sum_L P_g{}^{PS}{}_{lt} \times MCP_t - \sum_t \sum_L (P_p{}^{PS}{}_{lt} - Curtailment) \times MCP_t \end{pmatrix} \quad (39)$$

Table 1. The characteristics of thermal units

units	P_{MIN}	P_{MAX}	RDR	RUR	A	B	C	SUC	SDC	CST	MUT	MDT
1-3,8,9,32	5	30	30	30	31.67	26.243	0.06966	1040	100	1	1	1
4,36,40	150	500	500	500	6.78	12.887	0.01087	1440	100	3	8	8
5,10, 43,44,45	100	300	300	300	6.78	12.887	0.01087	1110	100	1	8	8
6,31,38	10	30	30	30	31.67	26.243	0.06966	1040	100	1	1	1
7,14,16,19,22,23,26,34,35,37,47,48,51-53	25	100	100	100	10.15	17.820	0.01280	1050	100	1	5	5
11	100	350	350	350	32.96	10.760	0.00300	1100	100	1	8	8
12,13,15,17,18	8	30	30	30	31.67	26.243	0.06966	1040	100	1	1	1
20,21	50	250	250	250	28.00	12.329	0.00240	1100	100	1	8	8
24,25	50	200	200	200	39.00	13.290	0.00440	1100	100	2	8	8
27,28	100	420	420	420	64.16	8.339	0.01059	1250	100	2	10	10
29	80	300	300	300	6.78	12.887	0.01087	1100	100	1	8	8
30	30	80	80	80	74.33	15.470	0.04592	1045	100	1	4	4
33	5	20	20	20	17.95	37.696	0.02830	1030	100	1	1	1
39	200	650	650	650	32.96	10.760	0.00300	1440	100	3	8	8
42	20	50	50	50	58.81	22.942	0.00977	1045	100	1	1	1
41,46,49	8	20	20	20	17.95	37.696	0.02830	1030	100	1	1	1
50,54	25	50	50	50	58.81	22.942	0.00977	1045	100	1	2	2

Table 2. The characteristics of pumped storage units

properties	PS unit 1	PS unit 2
P_{min_g}	29.58	16.35
P_{max_g}	233.6	220.88
P_{min_p}	37.3	21.04
P_{max_p}	265.22	252.32
Q_{min_g}	48	27
Q_{max_g}	357.5	340
Q_{min_p}	48	27
Q_{max_p}	357.5	340
V_{min_up}	50000	50000
V_{max_up}	6500000	7000000
V_{min_low}	100000	100000
V_{max_low}	200000000	200000000

Table 3. The characteristics of wind farms

properties	Wind farm 1 & 2
Number of turbines	40
$V_{cut\text{-}in}$	3 m/s
V_{Rated}	20 m/s
$V_{cut\text{-}out}$	25 m/s
P_{Rated}	8.3251 MW

The characteristics of thermal units are displayed in Table 1. The characteristics of pumped storage units and wind farms are represented in Tables 2 and 3 respectively.

- Scenario 1: The system has only thermal units
- Scenario 2: The system has thermal and wind units
- Scenario 3: The system has thermal, wind and *PS* units

The demand curve is illustrated in Fig. 4. The results are calculated based on Eq. (1) – Eq. (31). The results show that the total operation cost of system is decreased from \$1600705 to \$1594243 with presence of *PS* units. In addition, the average cost of operation with and without the presence of *PS* units are 14.0289 and 14.0858 \$/MW respectively.

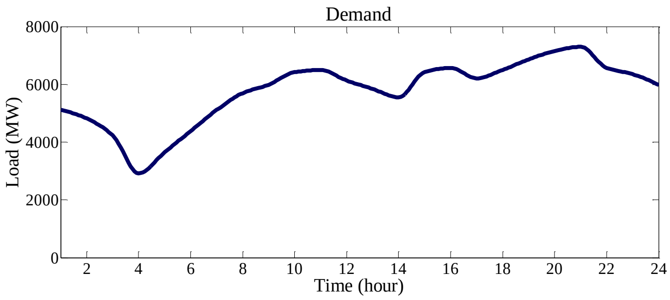

Fig. 4. Demand of system

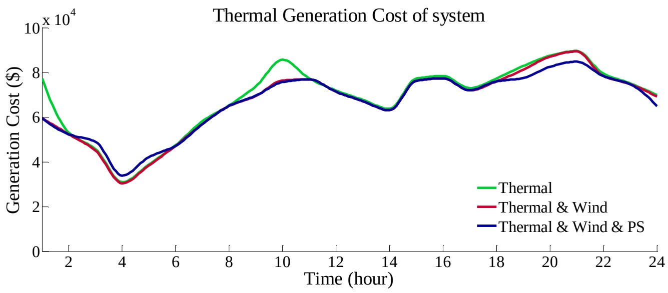

Fig. 5. Operation Cost of system for different commitment of generating units

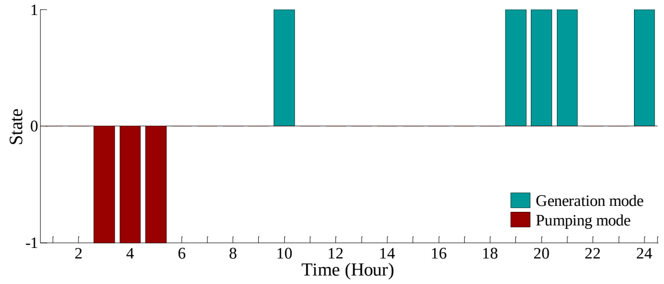

Fig. 6. States of *PS* unit for a day

4.2. Coordination in the Day-ahead Market

In this part, the ISO would like to minimize total cost while maximizing profits of providers. Table 4 demonstrates the results of simulation on the test system for proposed scenarios. The overall conclusions of all scenarios are depicted through Fig. 8 to 12 after the following discussion. As expected, in the first scenario, as the demand increases, more expensive units are committed. The total cost of thermal generation is $2099115 that is the most expensive scenario. The market clearing price, because of 100% contribution of thermal power plants in the generation, reaches the value of 19.45 $/MW that is higher than all scenarios. The total operation cost, which includes reserve cost, is $2193575 that results in the average cost of 15.86 $/MW and must be paid by consumers.

In the second scenario, the thermal generation cost is lower than scenario 1, as expected. The cost of $1980487 shows 5.6% reduction in thermal generation. Nevertheless, the reserve cost of the system is increased from $94460 in scenario 1 to $103142 in scenario 2 because of commitment of wind units. It is because a specific factor corresponded with uncertainty is considered in the calculation of *SRR*. The start-up and shutdown cost of the system is also increased to $41829 in the second scenario. Thus, the operation cost of the system, which must be paid by consumers, is increased to $2231108, because sufficient reserve for considering the uncertainty of wind speed must be provided. The wind units receive *MCP* for their commitment. Therefore, the average cost of the system in scenario 2 is increased to 16.13 $/MW. In this scenario, wind units' owners prefer to bid specific amount of power generation based on the cautious and pessimistic forecasted wind speed to avoid the obligation of compensation from the spot market. The wind units have earned the profit of $147478. The reserve price ($\rho_{reserve}$) is generally 10-20 times lower than *MCP* in the day-ahead energy market [45, *46*]. The penalty is a decreasing factor for buying excess generated power of wind farms by ISO.

In the third scenario, the total generation cost of thermal units is decreased to $1967738 compared to the second scenario. This reduction in thermal generation decreases the *MCP* to 19.0956 $/MW. The reduction in *MCP* results reduction in profit of wind units, because their profit is related to *MCP* and their revenue will be paid based on *MCP*. The commitment of PS units decreases total operation cost to $2198337, which results the reduction of average cost to 15.8998 $/MW. In scenario 3, the reserve cost and start-up and shutdown costs are $101060 and $41729 respectively.

In the fourth scenario, as expected, the profit of wind units is increased to $147176. The total operation cost is increased too. It is because the market competition gets far away from perfect competition, and because of the attempt of the wind and PS units to increase their own profit. In addition, according to Eq. (37) the generated power of PS must be paid to PS, and the pumped power, which is taken from the system, must be paid back to ISO by PS. Therefore, when PS takes some of its needed power for pumping from wind units, the second term of Eq. (37) decreases and consequently more money must be paid to PS. It can be said that merchandizing surplus of ISO is decreased and some of the profit of ISO is paid to PS and the wind back. The comparison of Eq. (36) and Eq. (39) illustrates the reason of increase of total operation cost in scenario 4 compared with scenario 3. Thus, the total operational cost of the system increased from $2198337 in scenario 3 to $2203917 in the fourth scenario. The average cost of the system is also increased to 15.94 *$/MW.*

As it is obvious in scenario 5, the results show a significant increase of $166869 in the profit of wind units. The share of wind units in demand satisfying is increased. Consequently, the thermal units have fewer commitments, and the thermal generation cost is decreased to $1930172. The increase in *MCP* to value of 19.154 $/MW because the last participated unit is gone away from its optimum operation point illustrated in Fig. 7. As can be seen, the reduction in generated power may sometimes increase generation cost.

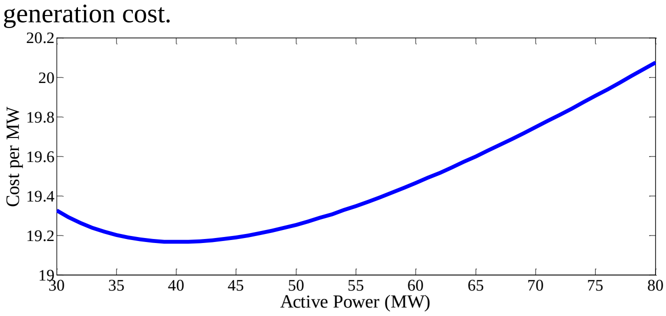

Fig. 7. Optimum point of unit number 30, which is at 40 *MW*

Table 4. Results of Simulation for all Scenarios

Operational parameters	Senario 1	Senario 2	Senario 3	Senario 4	Senario 5
Thermal Costs	2099115	1980487	1967738	1967738	1930172
MCP	19.4539	19.4197	19.0956	19.0956	19.1540
Wind Profit	0	147478	145781	147176	166869
Operation Costs	2193575	2231108	2198337	2203917	2204816
Average Costs	15.8654	16.1368	15.8998	15.9402	15.9467
Reserve Costs	94460	103142	101060	101060	104272
SUC & SDC	39539	41829	41729	41729	42889

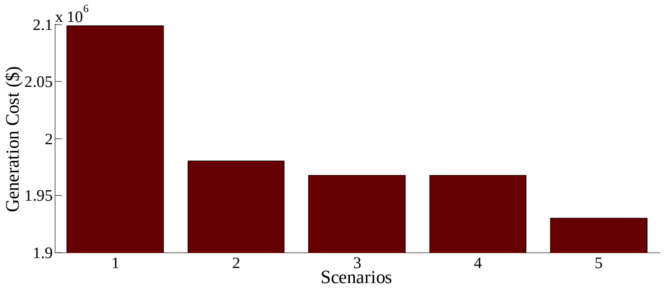

Fig. 8. Thermal generation costs

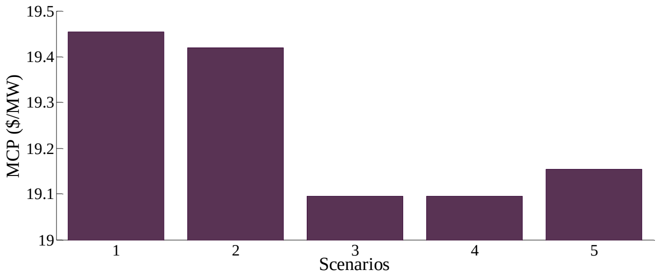

Fig. 9. Market clearing price

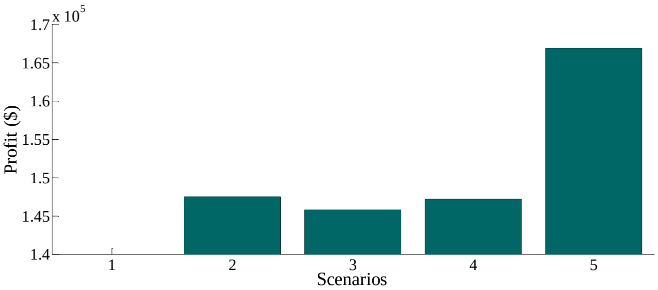

Fig. 10. Profit of wind units

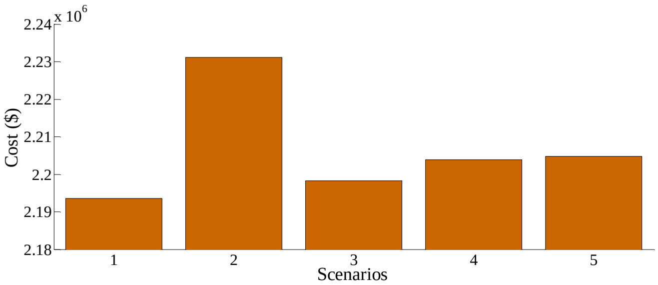

Fig. 11. Total system operation costs

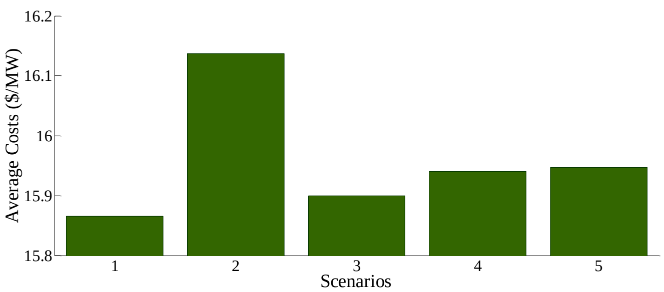

Fig. 12. Average costs

5. Conclusion

The utilization of pumped-storage units not only covers the curtailment of wind units made by uncertainty, while clearing day-ahead market, and increases the profit of wind units' owners, but also diminishes the total operation cost of the power system. The reduction of market clearing price has advantages for both consumers and system. Moreover, the units with uncertainty do not accept the risk of participation in the wholesale market. In this respect, ISO penalizes the units that are not able to meet their pledged generation. The storage units mitigate the risk of participation of uncertain units and supply them to be able to take part in trading of day-ahead power procedure. The results of simulation indicate that coordinated operation increases the profit of both uncertain wind resource and pumped-storage power plant. In addition, the coordinated operation has provided economic advantages for system and consumers.

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