Short Term Optimal Hydro-Thermal Scheduling of the Transmission System Equipped with Pumped Storage in the Competitive Environment

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ABSTRACT:
The considerable development of the electricity market subjects in recent years has provided a complex and more competitive environment for the participants. Each participant in this environment adopts a special strategy to maximize its profit or minimize its energy costs considering the significant constraints. In this paper, a short term optimal scheduling of thermal units, hydropower units, wind turbines, and pumped storage units has been proposed based on the energy market guidelines. The main objective of this research is to minimize the thermal energy production costs considering the uncertainty parameters along with the maximum utilization of clean energy production in the system. In order to evaluate the research goals, IEEE 5-bus standard test system is selected as the case study, which is equipped with both conventional and clean energy resources. In addition, probabilistic behaviors related to energy demand and wind production have been considered. Results proved the effectiveness of this model in minimizing the energy cost of thermal units.

KEYWORDS: Short Term Optimal Scheduling, Wind-Hydro-Thermal Power Plants, Clean Energy Production, Competitive Energy Market, Transmission System, Uncertainty Modeling

1. INTRODUCTION

Nowadays, Renewable Energy Sources (RESs) have been ever-increasingly used in all over the worldwide due to tendencies towards the use of clean energies [1]. The building of new conventional power plants is declined with ascending slope for covering the load growth because of the environmental and economic aspects. On the other hands, the conventional power plants with large fuel costs and environmental problems have been restricted with the advent of RERs. Therefore, the power system structure has been influenced by the presence of new energy resources and the special analysis of the system is required to facilitate the participation of significant technologies with various advantages.

Clean energy resources such as wind turbines, solar panels, and hydropower plants have significant penetration in producing the consumer's energy in the integrated Wind-Hydro-Thermal power systems (WHT). Since the energy production of thermal power plants is costlier for the system, the wind farms along with hydropower plants can be more suitable choice for freely generation of the energy with less environmental problems [2]. Because of fluctuations in the output of wind turbines due to the wind speed volatility, the use of energy storage systems would be necessary to store the surplus production of wind turbines when their energy production is greater than the energy consumption in the system. In this respect, pumped storage power plants is one of the large capacity storage systems that not only can consume the surplus energy in the low consumption hours, but also it can generate energy when the energy production is less than its consumption in the turbine mode [3]. In the regard of the WHT units integrated with pumped storage systems, many studies have been done with various research goals, which some of the most important ones are investigated here.

In this regard, multi-objective optimization approach is effectively employed for solving the short-term optimal scheduling of the WHT system with various objectives. For example, the multi objective optimal scheduling of WHT systems has been conducted in [4] with the aim of minimizing the operation cost of system, net power loss in system, and greenhouse gas emissions related to the thermal units. In another work [5], multi-objective formulation combined with Particle Swarm Optimization (PSO) algorithm is used for coordination scheduling of the hydro-thermal-wind system integrated with large scale electric vehicles for effective usage of wind power production in the system. In [6], multi-objective optimization is integrated with crisscross search PSO algorithm for the economic emission scheduling of the WHT system and pumped storage to analyze the impacts of integration of RESs with conventional power plants over the power system scheduling. Moreover, a new short-term multi-objective complementary scheduling model is presented in [7] for the WHT system considering the economic and environmental objectives. Besides the usage of multi-objective optimization method in short-term optimal scheduling of WHT system, other optimization strategies are also applied for this aim in recent literature. For example, the authors in [8] improved the optimization strategy of the WHT system integrated with pumped storage and minimized the operation cost of the system. Moreover, the fluctuations in the outputs of wind turbines had been modeled. In this research, the impact of various optimization algorithms for the different areas was also investigated to illustrate the proposed model effectiveness. A logarithmic size mix integer linear programming formulation is investigated in [9] with the aim of tackling highly non-differentiable characteristics and non-convexity in the short-term hydrothermal scheduling using the piecewise linear function. In addition, a new model is presented in [10] for optimizing the operation of hydropower plant considering the impacts of demand response program in minimizing the energy cost of system.

Economic dispatch and unit commitment issues are other topics, which are considered in modeling the WHT systems in recent literatures. For example, in [11], an economic dispatch model is presented for the WHT system to minimize the energy cost of thermal units along with proper usage of the wind and hydropower generations. In [12], a unit commitment model is proposed to coordinate the operation of hydrothermal power plants for supporting the required reserve in the presence of high penetration of wind power. In another study, the authors in [13] have used an improved hybrid PSO algorithm for solving the day-ahead multi objective model related to the WHT system integrated with pumped storage. Minimizing the total cost of the system along with greenhouse gas emissions were the main objectives of this research. The PSO technique integrated with lambda-gamma iteration is applied for modeling the short term unit commitment of the WHT system in [14] with the aim of establishing proper coordination between the participated elements. In [3], the authors proposed the chance constrained programming technique to model the uncertainties of solar radiation and wind speed in the optimal dispatch of the WHT system combined with solar panel and pumped storage. The minimizing fuel cost of thermal units along with maximizing the utilization of the RERs are posed as the two main goals of this research. The CO_2 reservoir model is presented in [15] for the hydrothermal scheduling problem considering the CO_2 constraints. The proposed model in this research allows the solving of problem via different stochastic dynamic programming approaches.

In all of the mentioned references, the optimal scheduling of the WHT system integrated with pumped storage is conducted using the simplistic models for the participant elements while some of the important aspects of the production units should be considered in the scheduling horizon. In addition, the uncertain behaviors of the energy consumers along with fluctuations of wind power are not modeled simultaneously through considering the proper scenarios. Therefore, this paper is structured to model the wind-thermal-hydropower-pumped storage system considering the complete constraints of each unit in the scheduling time horizon. Moreover, energy load and wind turbine production are considered as the uncertainty parameters and Latin Hyperbolic Sampling (LHS) method is used for generating the scenarios for them. Since the large number of generated scenarios is not accepted for the practical problems due to the high computational burden, the Fast Forward Selection (FFS) approach is also employed to reduce the number of generated scenarios to the logical number of them. Since the proposed system is targeted for incorporation of high penetration of wind turbines, the reserve market is also considered along with energy market for covering the volatility of wind turbine's output.

The reminder of this paper is organized as follows: Uncertainty quantification is explained in Section 2. Section 3 presents the problem formulation of this paper. The simulation results are evaluated in Section 4. Finally, Section 5 describes the conclusion of this paper.

This paper is the extended version of the conference paper that is presented in the 5th international conference on technology and energy management with the approach of energy, water, and environment.

2. UNCERTAINTY QUANTIFICATION

2.1. Latin Hyperbolic Sampling Method

Stochastic programming is one of the effective analysis regarding the uncertainty modeling of the stochastic behaviors of energy production units and volatility of the energy market prices as well as energy demand. In this approach, various states of uncertain parameter's occurrence are considered along with their occurrence probability in stochastic modeling of the systems with high share of RESs. Each of these states are called scenario and several scenario generation methods are proposed for this aim yet. One of the effective of them is the LHS method that can be applied for scenario generation process in the stochastic programming models. In the LHS approach, the scale of cumulative probability (0-1.0) is divided into the intervals according to the number of generated scenarios [16]. In the next step, the midpoint of the mentioned intervals is selected for extracting the related scenarios with their probability. In this research, the LHS technique is employed to generate appropriate scenarios for the wind speed and energy demand as the uncertain parameters. More information about the LHS method can be fully found in [17].

2.2. Fast Forward Selection Method

Generating the numerous scenarios are typically done in the stochastic based problems with the aim of considering the more occurrence states of the uncertain parameters. However, a large number of scenarios has created some basic challenges for modeling the systems in the practical problems. In such problems, large number of generated scenarios not only has increased the computational burden, but also the complexity of the system is also increased in the presence of the numerous scenarios. Due to this, scenario reduction methods are introduced for reducing the number of scenarios to the suitable amount for the practical problems. In this regard, FFS approach is proposed for selecting the appropriate scenarios among the generated scenarios with the aim of reducing the computational burden and complexity of the problems. In this method, the distance of each scenario is computed from other scenarios and the scenarios with minimum distance with other scenarios are selected as the candidate scenarios for stochastic modeling of the system. Therefore, FFS approach is applied in this work for selecting scenarios with high probability of occurrence to effectively model the stochastic behaviors of wind speed and energy consumption. More details about the FFS method can be reached from [18, 19].

3. PROBLEM FORMULATION

In this paper, we consider the wind-thermal-hydropower-pumped storage system for maximizing the utilization of clean energy resources in the system along with minimizing the energy cost of thermal units. For this aim, standard IEEE 5-bus test system is selected and integrated with two wind farms and thermal units, and one hydropower and pumped storage system. The schematic of the mentioned system with location of production units is demonstrated in Fig. 1.

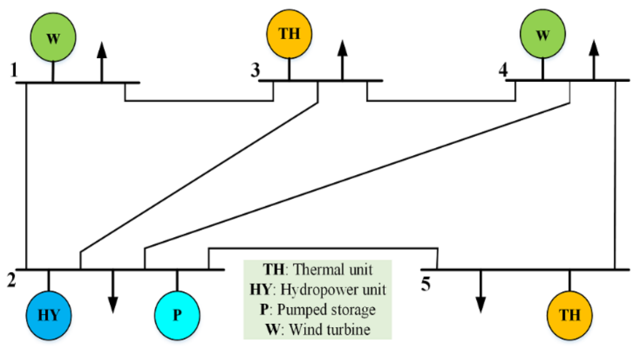

Fig. 1. The schematic of the IEEE 5-bus test system.

As seen in Fig. 1, the transmission lines between the system buses have provided the possibility of energy transmitting between all buses which brings more flexibility in providing the energy demand of the system. In addition, the production of clean energy resources can be transmitted to the other buses for decreasing the thermal unit's power generation. In this study, both energy and reserve markets are considered to manage intermittency of wind power and energy demand. Therefore, the objective function of this problem consists of the energy and reserve dispatch parts, which is formulated as follows:

$$\begin{aligned} f = & \sum_{G}\sum_{t=1}^{T}\sum_{s=1}^{5}\Pr_s^L.\Pr_s^W.[(\alpha_{1G}^{TH}.(P_{G,s,t}^{TH})^2+\alpha_{2G}^{TH}.P_{G,s,t}^{TH}+\alpha_{3G}^{TH}).X_{G,t}^{TH} \\ & +SUC_{G,t}^{TH}.X_{G,t}^{TH,SU}+SDC_{G,t}^{TH}.X_{G,t}^{TH,SD}+CRU_G.Ru_{G,s,t}+ \\ & CRD_G.Rd_{G,s,t}]+\sum_{h}\sum_{t=1}^{T}\sum_{s=1}^{5}\Pr_s^L.\Pr_s^W.(5.RHYu_{h,s,t}+4.RHYd_{h,s,t}) \end{aligned} \quad (1)$$

Where, $\Pr_s^L$ and $\Pr_s^W$ are the probability of scenarios related to the energy load and wind turbine production. The coefficients of α_G^{TH} are used for modeling the energy production cost of thermal units. $X_{G,t}^{TH}$ denotes the ON/OFF status of the thermal units. $SUC_{G,t}^{TH}$ and

$SDC_{G,t}^{TH}$ are the startup and shut down costs of thermal units. CRU_G and CRD_G are the proposed up and down reserve costs of thermal units. $Ru_{G,s,t}$ and $Rd_{G,s,t}$ present the amount of up and down reserve capacity for thermal unit *G* at time *t* and scenario *s*. $P_{G,s,t}^{TH}$ denotes the amount of power production of thermal units. $RHYu_{h,s,t}$ and $RHYd_{h,s,t}$ are the up and down reserve capacities determined for the hydropower unit *h* at time *t* and scenario *s*.

All of the generation units considered in this research should work based on some operational constraints. Therefore, the complete constraints of them along with the energy and reserve market constraints are posed in the solving of problem and formulated as follows:

$$\sum_h P_{h,t}^{HY} + \sum_G P_{G,t}^{TH} + \sum_w P_{w,t}^{Wind} + \sum_p P_{p,t}^{T} = \sum_i P_{i,t}^{L} + \sum_p P_{p,t}^{P} \quad \forall t \tag{2}$$

$$P_{w,t}^{Wind} \le P_{Max,w}^{Wind} \tag{3}$$

$$P_{i,t}^{Gen} = P_{i,t}^{Trans} + \sum_i P_{i,t}^{L} \quad \forall t,\ \forall i \tag{4}$$

$$P_{i,t}^{Trans} = \beta_{ij}.(\theta_{i,t} - \theta_{j,t}) \tag{5}$$

$$-\pi \le \theta_{i,t}, \theta_{j,t} \le \pi \tag{6}$$

$$\underline{P}_{ij}^{Trans} \le P_{i,t}^{Trans} \le \bar{P}_{ij}^{Trans} \tag{7}$$

$$\sum_G (Ru_{G,t} + Rd_{G,t}) + \sum_h (RHYu_{h,t} + RHYd_{h,t}) = 0.1\sum_i P_{i,t}^{L} \quad \forall t \tag{8}$$

$$P_{G,t}^{TH} + Ru_{G,t} \le \bar{P}_G^{TH} \quad \forall t,\ \forall \mathrm{G} \tag{9}$$

$$P_{G,t}^{TH} - Rd_{G,t} \ge \underline{P}_G^{TH} \quad \forall t,\ \forall \mathrm{G} \tag{10}$$

$$P_{h,t}^{HY} + RHYu_{h,t} \le \bar{P}_h^{HY} \quad \forall t,\ \forall \mathrm{h} \tag{11}$$

$$P_{h,t}^{HY} - RHYd_{h,t} \ge \underline{P}_h^{HY} \quad \forall t,\ \forall \mathrm{h} \tag{12}$$

$$X_{G,t}^{TH}.\underline{P}_G^{TH} \le P_{G,t}^{TH} \le X_{G,t}^{TH}.\bar{P}_G^{TH} \quad \forall G \in \{3,5\},\ \forall t \in 1{:}T \tag{13}$$

$$P_{G,t}^{TH} - P_{G,t-1}^{TH} \le Ramp_G^{TH,Up} \tag{14}$$

$$P_{G,t-1}^{TH} - P_{G,t}^{TH} \le Ramp_G^{TH,Down} \tag{15}$$

$$X_{G,t}^{TH} - X_{G,t-1}^{TH} \le X_{G,t+THU(G,y)}^{TH} \tag{16}$$

$$X_{G,t-1}^{TH} - X_{G,t}^{TH} + X_{G,t+THD(G,y)}^{TH} \le 1 \tag{17}$$

$$THU(G,y) = \begin{cases} \mathrm{y} & y \le MUT_G \\ 0 & y > MUT_G \end{cases} \quad \forall\ G \tag{18}$$

$$THD(G,y) = \begin{cases} \mathrm{y} & y \le MDT_G \\ 0 & y > MDT_G \end{cases} \quad \forall\ G \tag{19}$$

$$X_{G,t}^{TH} - X_{G,t-1}^{TH} \le X_{G,t}^{TH,SU} \tag{20}$$

$$X_{G,t-1}^{TH} - X_{G,t}^{TH} \le X_{G,t}^{TH,SD} \tag{21}$$

$$X_{G,t}^{TH} - X_{G,t-1}^{TH} \le X_{G,t}^{TH,SU} - X_{G,t}^{TH,SD} \tag{22}$$

$$\begin{aligned} P_{h,t}^{HY} &= a_1^h.(\upsilon_{h,t}^{HY})^2 + a_2^h.(\varpi_{h,t}^{HY})^2 + \\ & a_3^h.(\upsilon_{h,t}^{HY}.\varpi_{h,t}^{HY})^2 + a_4^h.(\upsilon_{h,t}^{HY}) + a_5^h.(\varpi_{h,t}^{HY}) + a_6^h \end{aligned} \tag{23}$$

$$\underline{P}_h^{HY} \le P_{h,t}^{HY} \le \bar{P}_h^{HY} \tag{24}$$

$$\underline{\upsilon}_h^{HY} \le \upsilon_{h,t}^{HY} \le \bar{\upsilon}_h^{HY} \tag{25}$$

$$\underline{\varpi}_h^{HY} \le \varpi_{h,t}^{HY} \le \bar{\varpi}_h^{HY} \tag{26}$$

$$\begin{aligned} \upsilon_{h,t}^{HY} &= \upsilon_{h,t-1}^{HY} + O_{h,t}^{HY} - \varpi_{h,t}^{HY} - S_{h,t}^{HY} \\ &+ \sum_{R \in K_h^{UP}} (\varpi_{R,t-T_R}^{HY} + S_{R,t-T_R}^{HY}) \end{aligned} \tag{27}$$

$$\upsilon_{h,0}^{HY} = \upsilon_h^{Initial} \tag{28}$$

$$\upsilon_{h,24}^{HY} = \upsilon_h^{End} \tag{29}$$

$$P_{p,t}^{T} = \tau_p^{T}.Q_{p,t}^{T} \quad \forall p,\ \forall t \tag{30}$$

$$P_{p,t}^{P} = \tau_p^{P}.Q_{p,t}^{P} \quad \forall p,\ \forall t \tag{31}$$

$$V_{p,t+1}^{Ur} = V_{p,t}^{Ur} + Q_{p,t}^{P} - Q_{p,t}^{T} \quad \forall p,\ \forall t \tag{32}$$

$$V_{p,t+1}^{Lr} = V_{p,t}^{Lr} + Q_{p,t}^{T} - Q_{p,t}^{P} \quad \forall p,\ \forall t \tag{33}$$

$$\underline{V}_P^{Ur} \le V_{p,t}^{Ur} \le \bar{V}_p^{Ur} \quad \forall p,\ \forall t \tag{34}$$

$$\underline{V}_P^{Lr} \le V_{p,t}^{Lr} \le \bar{V}_p^{Lr} \quad \forall p,\ \forall t \tag{35}$$

$$V_p^{Ur,Ini} \le V_{p,t}^{Ur} \quad \forall p,\ t = T \tag{36}$$

$$V_p^{Lr,Ini} \le V_{p,t}^{Lr} \quad \forall p,\ t = T \tag{37}$$

$$0 \le Q_{p,t}^{T} \le \bar{Q}_p^{T} \quad \forall p,\ \forall t \tag{38}$$

$$0 \le Q_{p,t}^{P} \le \bar{Q}_p^{P} \quad \forall p,\ \forall t \tag{39}$$

$$P_{h,t}^{HY},\ P_{G,t}^{TH}, P_{w,t}^{Wind},\ P_{p,t}^{T},\ P_{p,t}^{P},\ P_{i,t}^{Gen},\ \upsilon_{h,t}^{HY},\ \varpi_{h,t}^{HY} \ge 0 \tag{40}$$

Where, $P_{G,t}^{TH}$ and $P_{w,t}^{Wind}$ are the power production of hydropower plant and wind turbine, respectively. $P_{p,t}^{P}$ and $P_{p,t}^{T}$ are the respective indicators of the power consumption and production of the pumped storage. The amount of energy transmitted between line i-j is indicated with $P_{i,t}^{Trans}$. $\theta_{i,t}$ and β_{ij} are the voltage angle and susceptance of feeder i-j in DC power flow. $\upsilon_{h,t}^{HY}$ and $\varpi_{h,t}^{HY}$ are the volume and discharging amount of water in the reservoir of hydropower plant h^{th} at time t^{th}. The power production coefficients related to the hydropower plant are indicated by $a_{1,..,6}^{h}$. $Q_{p,t}^{T}$ / $Q_{p,t}^{P}$ are the maximum amount of pumping/turbining flow of water in the pumped storage. τ_p^{P} (τ_p^{T}) is the conversion factor power (water-flow) to water-flow (power). $V_{p,t}^{Ur}$ and $V_{p,t}^{Lr}$ are the respective indicators of volume of water in the upper and lower reservoirs of the pumped storage. Equations (2) and (4) state the electrical energy balance constraint. The constraints related to the power transmission between line i-j are considered in equations (5) – (7). Equations (8) – (12) present the constraints related to the reserve market. Ramp up and down limitations of thermal units are enforced by constraints (14) and (15). Equations (16) – (19) impose the minimum up and down time limitations for the thermal units. Equation (23) presents the power production of hydropower plant, which is a function of discharging water and volume of water in the reservoir. Constraints (24) – (26) express the limitations of hydropower production, volume of water in the reservoir, and discharging amount of water. Equation (27) states the dynamic water balance of the hydropower plant. Initial and final amount of water in the reservoir should be kept based on the constraints (28) and (29). The amount of power production and consumption in the pumped storage are described by the equations (30) and (31). The dynamic water balance related to the available water in the upper and lower reservoirs are modeled using the equations (32) and (33). The reminder constraints present the bounds of volume of water in the upper and lower reservoirs along with discharging water.

4. SIMULATION RESULTS

In this paper, standard IEEE 5-bus test system is considered for analyzing the wind-thermal-hydropower-pumped storage system in the transmission level [20]. The pumped storage is used in this study to increase the system reliability and effective usage of wind turbine production. All required data about the pumped storage can be accessed in [21]. Two wind farms located at buses 1 and 4 are considered with 75 and 35 MW capacity, which each of them consists of 2.5 MW wind turbines. All parameters in wind power modeling along with wind speed data are available in [16]. All characteristics of the thermal units along with hydropower plant can be found in [22]. Because of the existence of nonlinear equations along with the integer variables related to the ON/OFF status of thermal units, optimal short term scheduling problem is converted to a Mixed Integer Non-Linear (MINLP) problem, which is solved using the SBB [23] and DICOPT [24] solvers in the General Algebraic Modeling System (GAMS) [25]. The same simulation results are reached for two mentioned solvers that indicate the proper level of optimality for the extracted results.

In order to capture the uncertainties associated with wind turbine's output and electricity demand, we have employed the LHS method for generating 1000 scenario for the mentioned uncertain parameters and then FFS technique is applied for reducing the number of them to 5. After solving the MINLP problem, the expected amount of objective function is computed considering the occurrence probability of each generated scenario and its amount became \$5156.549. In addition, based on the short term scheduling of production units, the amount of their outputs are illustrated in Fig. 2 over the scheduling time horizon.

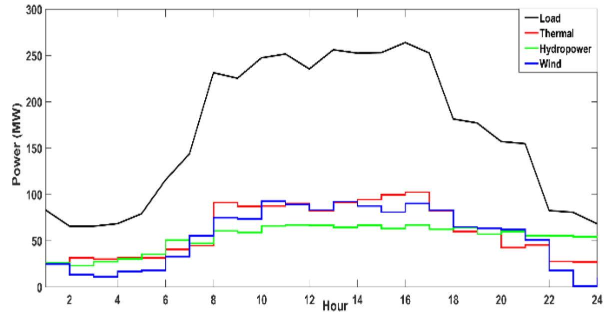

Fig. 2. The outputs of production units in 24 hours.

As seen in Fig. 2, the outputs of wind, thermal, and hydropower units are at the lowest level in the early morning, not only to meet the low amount of energy demand in these hours, but also to store the surplus of production using the pumped storage for utilizing it in the high energy demand times later. In the peak times (8 am to 17 pm) with the highest energy consumption, all of the mentioned production units have increased their outputs to supply an adequate amount of energy for the consumers without any load shedding in the system. However, at the end of the night, the production of thermal units is reduced in order to avoid costly energy generation and the output of wind turbines is limited due to the wind speed drop at the mentioned times, so the system is organized to use the hydropower plant capacity to meet the energy demand during the end hours of night. To exact evaluation of thermal unit's production, the cost of their energy generation is shown in Fig. 3 for scenarios 3 and 4 during a day.

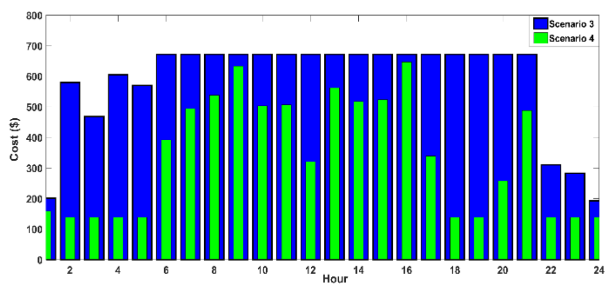

Fig. 3. The energy generation cost of thermal units in 24 hours.

It is obvious from the Fig. 3 that all of thermal units located at bus 3 and 5 have produced the low amount of energy during the early morning hours and at night, so the energy cost of them at mentioned times is lower than the peak times. In the aforementioned time intervals, the ability of wind turbines and hydropower plant had been sufficient for meeting the load of these times. However, each of the thermal units relatively has the maximum operation at peak times to help satisfying the high energy demand of these times. In this respect, the pumped storage is also worked on the pumped mode in the early morning hours and at the end of the night to store the surplus energy production in the system and it is discharged at peak times for meeting a portion of demand. Moreover, an effective potential of the hydropower unit is also used during a day for supplying clean energy to the consumers. In the hydropower unit, the volume of the water in the reservoir is key for supporting the system to provide energy demand in various conditions of the power grid. Therefore, the variations in the volume of water along with the behaviors of the discharging water in the hydropower unit are illustrated in Fig. 4.

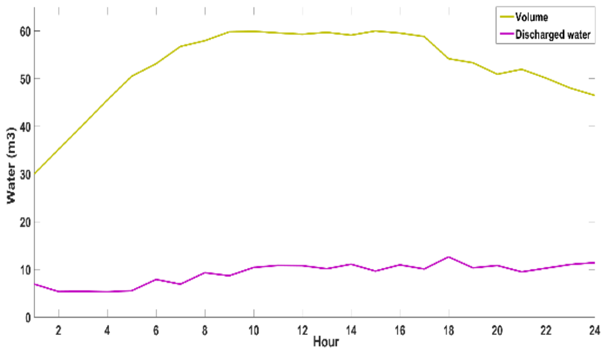

Fig. 4. Variations in the volume of water and discharging water in the reservoir of the hydropower unit.

As seen in Fig. 4, hydropower unit is discharged at the lower amount in the early morning hours (1-8 am) due to the lower energy demand during this period. This is led to lower amount of water discharging in the reservoir of the hydropower unit in mentioned times. Thereby, the amount of volume of water is increased in the early morning hours due to higher amount of water entering to the reservoir in comparison with water outlet it. However, this trend is stopped by increasing the energy demand in the morning from 8 am to 17 pm that has led to the increment of the hydropower unit's output for assisting the system in establishing dynamic energy balance. Moreover, the increasing volume of water in the reservoir has also been stopped at peak times due to increment of the discharging water in these times. On the other hand, decreasing the input water to the reservoir at night along with a relative increase in discharging water has led to a reduction in the volume of water in mentioned hours. In addition to the hydropower unit role in clean energy production and stabling the system, pumped storage as another effective system is considered with the aim of effective usage of stochastic producer's outputs during a day. The behavior of the pumped storage in charging and discharging modes over the scheduling horizon is demonstrated in Fig. 5.

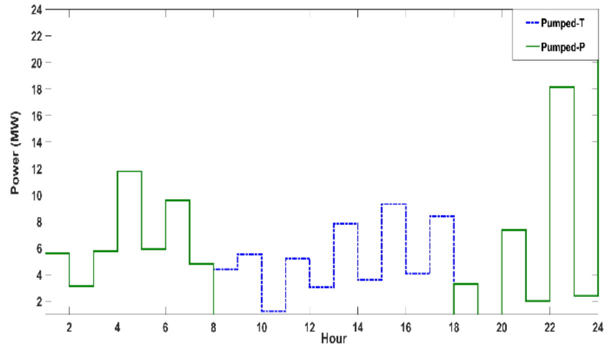

Fig. 5. The behavior of the pumped storage in charging and discharging modes over the scheduling horizon.

According to this Figure, pumped storage is worked in the pump mode (Pumped-P) in the early morning hours (1-8 am) when the outputs of production units is greater than energy demand. However, by increasing the energy demand from 8 am to 18 pm, the effective potential of pumped storage is used by switching from pump mode to the turbine mode (Pumped-T) for covering the energy required to establish dynamic energy balance at peak times. In addition, reducing the energy demand at night has led to a re-switching of pumped storage to the pump mode with the aim of consuming the surplus of energy generation in the system for transmitting the water in the down reservoir to the up reservoir for using its potential in producing energy, when energy demand is greater that the outputs of generation units.

In addition to the energy market dispatch, which is analyzed in the previous paragraphs, the reserve market dispatching is also investigated effectively in this study. We clear both energy and reserve markets simultaneously and after running the problem by GAMS, the results related to reserve market are demonstrated in Fig. 6.

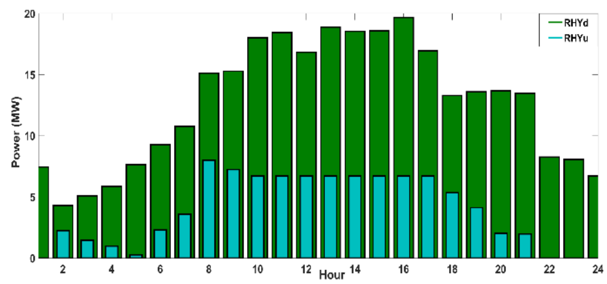

Fig. 6. The reserve market dispatch variables during a day.

Since the thermal units have proposed high prices for up and down reserves, they are not designated as marginal producers in the reserve market. Therefore, the amount of up and down reserve capacity for them has been became zero. However, the hydropower plant is determined as the marginal producer through proposing the lower reserve prices in comparison with thermal units. The amounts of up and down reserve production of hydropower plant are illustrated in Fig. 6. As seen in this Figure, because of the high amount of energy consumption at peak times, the magnitude of reserve dispatch at these hours has been higher than at other times. Since the amount of energy production of thermal units is very low in early morning and at the end of the day due to lower energy demand, so the up reserve required at these hours relatively has become zero. In addition, the amount of down reserve dispatch is greater than up reserve at mentioned times due to lower energy consumption.

5. CONCLUSION

In this paper, the optimal short term scheduling of wind-thermal-hydropower-pumped storage systems has been investigated with the aim of minimizing the energy generation costs and effective utilization of clean energy resources at the transmission level. For this aim, all of the generation units have been modeled considering the complete constraints of them for achieving more accurate results. The wind turbine outputs along with electricity demand are posed as the uncertainty parameters and LHS method is applied for scenario generation while the FFS approach is used for scenario reduction. To provide safe and reliable energy delivering for the consumers in the presence of stochastic producers such as wind turbines, reserve market is cleared simultaneously with energy market to determine the 10 percentages of energy load as the reserve capacity for the thermal and hydropower units. For an assessment of this work, the standard IEEE 5-bus test system is chosen and integrated with wind-thermal-hydropower-pumped storage systems. After solving the problem, obtained results show the effectiveness of the proposed method in minimizing the total energy production costs through optimal dispatch of renewable energy generation units.

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