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Stochastic Short-Term Hydro-Thermal Scheduling Based on Mixed Integer Programming with Volatile Wind Power Generation

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Abstract- *This study addresses a stochastic structure for generation companies (GenCo's) that participate in hydro-thermal self-scheduling with a wind power plant on short-term scheduling for simultaneous reserve energy and energy market. In stochastic scheduling of HTSS with a wind power plant, in addition to various types of uncertainties such as energy price, spinning /non-spinning reserve prices, uncertainties of RESs, such as output power of the wind power plant are also taken into account. In the proposed framework, mixed-integer non-linear programming of the HTSS problem is converted into a MIP. Since the objective of the study is to show how GenCos' aim to achieve maximum profit, mixed-integer programming is used here. Therefore, to formulate the MIP for the problem of HTSS with a wind power plant in the real-time modeling, some parameters like the impact of valve loading cost (VLC) that are accompanied by linear modeling, are considered. Furthermore, in thermal units, parameters such as prohibited operating zones (POZs) and different uncertainties like the energy price and wind power are included to formulate the problem more suitably. The point that is worth noting is the use of dynamic ramp rate (DRR). Also, the application of multi-functional curves (L) of hydro plants is considered when studying inter-unit scheduling. Finally, the required tests are conducted on a modified IEEE 118-bus system to verify the accuracy and methodology of the proposed method.*

Keyword: Hydro-thermal self-scheduling (HTSS), Mixed-integer programming (MIP), Price uncertainty, Stochastic programming, Wind uncertainty.

NOMENCLATURE

Indices

i	Thermal unit index
h	Hydro unit index
t	Time interval (hour) index
s	Scenario index
w	Wind unit index

Constants

π_t^b	Bilateral contract price ($/MWh)
Θ	Number of periods for the planning horizon
SDC_i	Shut-down cost of unit i ($)
SUC_h	Start-up cost of unit h ($)
b_i^n	Slope of block n in the fuel cost curve of unit i ($/MWh)
b_h^n	Slope of the volume block n of the reservoir associated with unit h (m^3/s/Hm^3)
b_{hk}^n	Slope of block n in the performance curve k of unit h (MW/m^3/s)
e_i, f_i	Valve loading cost coefficients
$F(p_{n-1i}^u)$	Cost of generation of n-1^{th} upper limit in fuel cost curve of unit i ($/h)
$Rain_{hts}$	Forecasted natural water inflow of the reservoir associated with unit h (Hm^3/h)
L	Number of performance curves
Np_i	Number of prohibited operating zones
N_l^{bP}	Number of blocks in piecewise linearization of start-up fuel function
Np	Number of price levels
Ns	Number of scenarios after scenario reduction
p_t^b	Power capacity of bilateral contract (MW)
p_s	Probability of scenario s
p_s^{nr}	Normalized probability of scenario s
$p_i^{\max}$, $p_i^{\min}$	Maximum and Minimum power output of unit i (MW)
$p_{hn}^{\min}$	Minimum power output of unit h for performance curve n (MW)
p_h^c	Capacity of unit h (MW)
p_{ni}^d	Lower limit of the n^{th} prohibited operating zone of unit i (MW)
p_{n-1i}^u	Upper limit of the $(n-1)^{th}$ prohibited operating zone of unit i (MW)
$\overline{Qout}_h$	Maximum water discharge of unit h (m^3/s)
$\underline{Qout}_h$	Minimum water discharge of unit h (m^3/s)
RDL_i^n	Ramp down limits for block n (MW)
RUL_i^n	Ramp up limits for block n (MW)

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SUE_i	Start-up emissions generated by unit *i* (lbs)
SDE_i	shut-down emissions generated by unit *i* (lbs)
$SUR_i(i_i)$	Start-up and shut-down ramp rate limits of unit *i* (MW/h)
$SDR_i(i_i)$	Start-up and shut-down ramp rate limits of unit *i* (MW/h)
$RDL(p_{its})$	Ramping down limits of unit *i* (MW)
$RUL(p_{its})$	ramping up limits of unit *i* (MW)
vol_{hn}^{max}	Maximum volume of the reservoir *h* associated to the n^{th} performance curve (Hm^3)
vol_h^{min}	Minimum volume of the reservoir associated to unit *h* (Hm^3)
V	Wind speed (m/s)
p_r	Rated out power (KW)
v_{in}	Cut-in speed (m/s)
v_{out}	Cut-out speed (m/s)
v_r	Rated output speed (m/s)
p	Wind power generation (KW)
p_w	Total wind power (KW)

Variables

G_{its}^n	Generation of block *n* in the fuel cost curve of unit *i* (MW)
ψ_{its}^n	Generation of block *n* of unit *i* of valve loading effects curve (MW)
π_{ts}^{sp}	Market price for energy (\$/MWh)
π_{ts}^{sr}	Market price for spinning reserve(\$/MWh)
π_{ts}^{ns}	Market price for non-spinning reserve (\$/MWh)
SUC_{its}	Start-up cost of unit *i* (\$)
VLC_{its}	Valve loading effects cost of unit *i* (\$)
F_{its}	Fuel cost of unit *i* (\$)
N_{its}^d	Non-spinning reserve of unit *i* in the spot market when unit is off , respectively (MW)
N_{its}^u	Non-spinning reserve of unit *i* in the spot market when unit is on, respectively (MW)
N_{hts}^d	Non-spinning reserve of a unit *h* in the spot market when unit is off , respectively (MW)
N_{hts}^u	Non-spinning reserve of a unit *h* in the spot market when unit is on, respectively (MW)
$pout_{its}$	Power output of unit *i* (MW)
$pout_{its}^{max}$	Maximum power output of unit *i* (MW)
$pout_{hts}$	Power output of unit *h* (MW)
$pout_{wts}$	Power output of wind unit *w* (MW)
p_{ts}^{sp}	Power for bidding in the spot market (MW)
$profit_s$	Profit of scenario *s*
Qd_{hts}^n	Water discharge of unit *h* and block *n* (m^3/s)
SR_{its}	Spinning reserve of thermal unit *i* in the spot market (MW)
SR_{hts}	Spinning reserve of hydro unit *h* in the spot market (MW)
vol_{hts}	Water volume of the reservoir associated with unit *h* (Hm^3)

Binary variables

$I_{its} = 1$	if unit *i* is online
$I_{hts} = 1$	if unit *h* is online
$I_{its}^d = 1$	if unit *i* provides non-spinning reserve when the unit is off
$\delta_{its}^n = 1$	if block *n* in fuel cost curve of unit *i* is selected
$\delta_{hts}^n = 1$	if the volume of reservoir water is greater than v_n (h)
$\chi_{its}^n = 1$	if the power output of unit *i* exceeds block *n* of the valve loading effects curve
$Z_{its} = 1$	if thermal unit *i* is started-up
$I_{hts} = 1$	if hydro unit *h* is started-up
$Y_{its} = 1$	if unit *i* is shut-down

Sets

I	Thermal units
H	Hydro units
W	Wind units
N	Set of indices for blocks of piecewise linearization in the hydro unit performance curve (*L*)
NEM	Blocks of piecewise linearization in the thermal units emission curve
T	Periods of market time horizon $T=\{1, 2, ..., NT\}$
S	Scenario

List of abbreviations

HTSS	Hydro-thermal self-scheduling
SHTS	Short-term hydro-thermal scheduling
WP	Wind Power
GenCo’s	generation companies
MIP	Mixed-integer programming
MILP	Mixed-integer linear programming
MCS	Monte-Carlo simulation
VLC	Valve loading cost
POZs	Prohibited operating zones
PDF	Probability distribution function
LMCS	Lattice Monte-Carlo simulation
RWM	Roulette Wheel mechanism
ARIMA	Autoregressive integrated moving average
ARMA	Autoregressive moving average
RDL	Ramp- down limit
RUL	Ramp- up limit
DRR	Dynamic ramp rate
RESs	Renewable energy sources
UC	Unit commitment

1. INTRODUCTION

The aim of restructured power systems is to reduce various types of operating costs and / or increase the GenCo’s profit. This profit increment is known as hydro-thermal self-scheduling. To maximize the GenCo’s profit, a structure is proposed in this paper for the mixed-integer programming problem, where a stochastic process is used for hydro-thermal self-scheduling with volatile wind power generation. In references [1, 2], point out one of the most important subjects of power systems known as short-term hydro-thermal scheduling. In Ref. [3], a stochastic structure of GenCo’s that participate in hydro-thermal self-scheduling on short-term scheduling for simultaneous reserve energy and energy market is presented. In Ref. [4], hourly-based daily/weekly scheduling of hydro-thermal units is addressed. A new optimization study that makes use of mixed-integer linear programming for the problem of hydro-thermal self-scheduling was implemented in joint energy and reserve electricity with day-ahead method in Ref. [5]. In Ref. [6], studies the use of mixed-integer programming in the day-ahead market to solve the hydro-thermal self-scheduling problem. For methods that include special conditions such as nonlinearity, inequality, etc. suitable solutions have been proposed in the literature; for instance the following studies: Lagrangian relaxation (LR) in Ref. [7], mixed-integer programmin in Ref. [8], Benders decomposition (BD) in Ref. [9]. Also, different intelligent methods are introduced in Ref. [10], such as branch and boundary (B&B), nonlinear programming (NLP), and Lagrangian relaxation (LR) methods in Ref. [11]. The solution proposed for solving this problem is a deterministic MIP scheduling model for scheduling power plants, where the effects of upstream hydro-plant with three performance curves (*L*) are considered as piecewise linear using approximation in Refs. [12, 13]. Regarding the uncertainty of hydro plants modeling, a solution associated with the multi-functionality is introduced for the hydro-thermal problem of the day-ahead market in Ref. [14, 15]. In Ref. [16], The authors focus on population growth during recent years. In addition, they address the utilized amounts of fuels (oil, charcoal, gas) in percentage for generating electricity all over the globe. In Ref. [17], the application of renewable energies is still increasing during the last years thanks to their suitable features such as being clean, inexpensive and environmentally-friendly. One of the fastest technologies in association with renewable energies, which is advancing today, is the use of wind energy technology. In Ref. [18], reliable tools and methods such as pumped storage were introduced for energy reserve objectives. Balancing of lacks is mentioned as a new field of research regarding the cooperation and scheduling of hydro-wind units in Ref. [19]. In Refs. [20-22], solutions for environmental problems of a power system in the future and integrity of hydro-thermal-wind power plants are provided. In Ref. [23], presents conditions such as uncertainty of energy price in the electricity market environment, where a stochastic formulation and specific conditions of wind energy are needed for trading wind energy. Modern activities through uncertainty are introduced considering energy price scenarios in electricity market price in Ref. [24]. Moreover, energy, fuel, and ancillary services for price-based unit commitment in a stochastic structure were presented taking into account random hourly generation of prices in Ref. [25]. Also, this reference makes use of theMonte-Carlo simulation(MCS). In Ref. [26], having this in mind that GenCos' are looking for maximizing their profit, a stochastic midterm scheduling algorithm is suggested for hydro-thermal (conventional) power plants considering risk constraints. Noting the stochastic nature of electricity price, hydro-thermal self-scheduling with a multi-stage structure was presented in Ref. [27]. Moreover, solving the hydro-thermal self-scheduling problem for power plant units that employ a deterministic method for mixed-integer programming (MIP) scheduling is proposed in Ref. [28]. A stochastic structure of mixed-integer programming is introduced for scheduling a power system comprised of hydro-wind units in Ref. [29]. In Ref. [30], Furthermore, the autoregressive integrated moving average model was used as a tool in the hydro-thermal self-scheduling (HTSS) problem. Using a fuzzy distance method for stochastic scheduling regarding the uncertainty of trade relating to CO_2 pollution and its two-stage nature is proposed in Ref. [31]. In addition, parameters such as valve loading cost are excluded. In Ref. [32], a structure is introduced for linearization considering the valve loading cost effect. It is notable that valve loading cost has a nonlinear sinusoidal function form. A hydro-thermal self-scheduling structure related to dynamic ramp rate is proposed in Ref. [33]. A linearization formula is employed in Refs. [34,35] for presenting hydro-thermal-wind self-scheduling. In Ref. [36], an optimal randomized model is proposed for solving the power system planning problem with regard to the capacity of water, wind and photovoltaic units (PVs), and it is used to solve the problem using the MILP method and then the two-step. In Ref. [37], a multi-stage optimal solution approach is suggested with regard to dynamic programming for GenCo's whose power is based on wind power. From random planning for energy and reserves markets, GenCo's use a combination of compressed air energy storage, wind, and heat to maximize the profit in Ref. [38]. In Ref. [39], An approach has been proposed using optimal planning for coordination between wind farms, solar parks, and fossil fuel thermal units. It is necessary to conclude that the ultimate goal is to consider profit and environmental debate. In Ref. [40], From the perspective of the use of wind energy in the power generation from energy and reserves markets, the United States reviews the cost and reserve prices of large-scale power systems. The presented formula of this paper consists of different terms including valve loading cost, fuel cost, pollution function, and other constraints of generation units. It should be said that GenCo's can use this method to find the necessary results of daily scheduling introduced for next days of unit commitment (UC). The contribution of this study is to propose a multi-stage structure for the problem of hydro-thermal self-scheduling with a wind power plant, where in addition to various uncertainties of energy price, special attention has been paid to wind power uncertainty caused by wind power plants, which can affect the daily decisions (short-term) of the power system scheduling. Regarding this, one of the notable features of this research is that a stochastic structure is proposed for short-term scheduling of hydro-thermal self-scheduling with a wind power plant. The aim of the presented model by taking into account the efficient optimization following mixed-integer programming scheduling problem is to achieve the maximum profit for GenCo's. Furthermore, to include the effect of price uncertainty along with other uncertainties, probability distribution function, is also employed (for predicting price errors) which is of significant importance in error prediction field. Moreover, as an efficient and applicable method is required for power generation in the fields of energy price, spinning reserve price, non-spinning reserve price, and wind power of wind power plants, Lattice Monte-Carlo simulation (LMCS) and Roulette Wheel mechanism(RWM) are utilized for this purpose. With regard to the structure of the proposed study, the linearization process transform is used in the model to consider the impact of valve loading cost. Noting that this effect is nonlinear, a sinusoidal function in a nonlinear form is taken into account. Finally, a general equation is presented for hydro units considering multi-functional curves (L). Therefore, in the cases such as depletion-power curves for multi-functional hydro units, a general linear equation is proposed for fuel cost, the effects of valve loading cost, etc in their self-scheduling.

The remaining of the paper is organized as follows. Section 2 describes the formulation of the stochastic model considering different uncertainties of the system in the problem of HTSS with a wind power plant. Section 3 explains the application of the stochastic method in HTSS with a wind power plant, and then presents a formulation for scheduling of MIP. Section 4 discusses two studies to stochastic the importance and key role of the proposed scheme. Additionally, this research uses an IEEE 118-bus test system to examine understudy cases to verify their validity. Section 5 compares the results of the current study and a number of other works available in the literature and finally, some notable results obtained by investigating understudy cases are reported and discussed in Section 6 along with a summarized conclusion.

2. STOCHASTIC MODELING OF UNCERTAINTIES

Among various available methods, the LMCS method can be used for the outage of different types of power plants. Also, taking into account the price prediction error, other types of uncertainties that are rather related to the price can be employed. Hence, Lattice law is introduced in Ref. [41]. In Ref. [41], Lattice law, as given in Eq. (1), includes n points of order r with a dimension (dimensions) of d:

$$\sum_{l=1}^{r}\frac{k_l}{n_l}.v_l \bmod 1 \quad k_l = 0,1,\ldots,n_l-1 \;\; l=1,\ldots,r \tag{1}$$

It is obvious from (1) that $v_1, v_2, \ldots, v_r$ are generated randomly, and vector d is independent of integers and is in a linear form. Using criterion d, which is used for extracting scenarios, the number of random values is achieved. Moreover, the required range of changes of k_l for order l is denoted in the given equation. Thereby, the pattern of all points is presented by two methods : the first one is the conventional MCS, given in Fig. 1(A), and the second one is a first-order lattice law, illustrated in Fig. 1(B).

The use of LMCS uniformly distributes numerous formed points over the whole space of the considered points. In this method, according to its structure, the entire desired space is utilized and it can include all of the points. Fig. 2 shows the PDF of the discretized price with a prediction error.

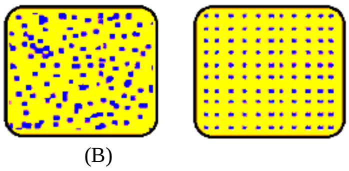

Fig. 1. Demonstration of points obtained using (A) the conventional MCS, and (B) a first-order lattice law.

Fig. 2. The PDF of the discretized price with a prediction error.

The horizontal axis in Fig. 2 denotes the price prediction error, while the vertical axis shows the probability values. The former axis has a zero average value for all seven intervals located at the center. In addition, each interval posses a level with an assigned number. In Refs. [42,43], there is a standard deviation for each interval with a price prediction error (σ). Regarding different price prediction levels and the obtained probabilities from PDF, RWM is used in Refs. [43, 44] to form price scenarios for each hour. As seen in Fig. 3, it includes the range of [0 1] and the use of desired probabilities along with the normalization process. As a result, considering the probability range [0 1] for extracting random numbers beside the normalization of price predictions, RWM can be used. Finally, using the available method, in addition to maintaining the uncertainty behavior of the system with an appropriate approximation, the number of scenarios will be reduced.

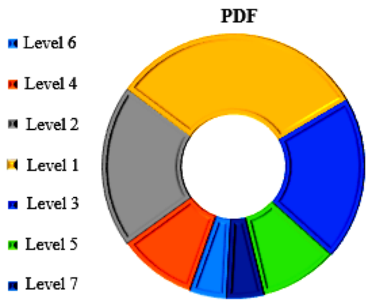

Fig. 3. Different levels of price prediction using RWM along with considering the normalization probability.

In [42,43], scenario reduction process (*Ns* number of scenarios) is used, where weak scenarios or scenarios with low probability are eliminated. Therefore, scenarios with high probability are preserved to participate in the stochastic multi-objective HTSS(MO-HTSS) problem with a wind power plant. Fig. 4 illustrates a scenario based on stochastic modeling considering different uncertainties.

3. MIP FORMULATION FOR STOCHASTIC HTSS

3.1. Maximization of Expected Profit

The first objective function of the stochastic HTSS with a wind power plant (conventional type) is the maximization of expected profit (E_G^P) of GenCo's and is expressed as in Eq. (2) and Eq. (3):

$$f_1 : \max E_G^P = \pi_t^b p_t^b + \sum_{s \in N_s} p_s^{nr}\, profit_s \tag{2}$$

$$profit_s = \sum_{t \in T} \left\{ \begin{array}{l} \pi_t^{sp} p_{ts}^{sp} + \\ \sum_{i \in I} \left\{ SR_{its}\pi_{ts}^{sr} + \left(N_{its}^u + N_{its}^d \right)\pi_{ts}^{ns} \right\} \\ + \sum_{h \in H} \left\{ SR_{hts}\pi_{ts}^{sr} + \left(N_{hts}^u + N_{hts}^d \right)\pi_{ts}^{ns} \right\} \\ - \sum_{i \in I} \left\{ \begin{array}{l} F_{its} + SDC_i Y_{its} + SUC_{its} + \\ VLC_{its} \end{array} \right\} \\ - \sum_{h \in H} SUC_h I_{hts} \end{array} \right\} \tag{3}$$

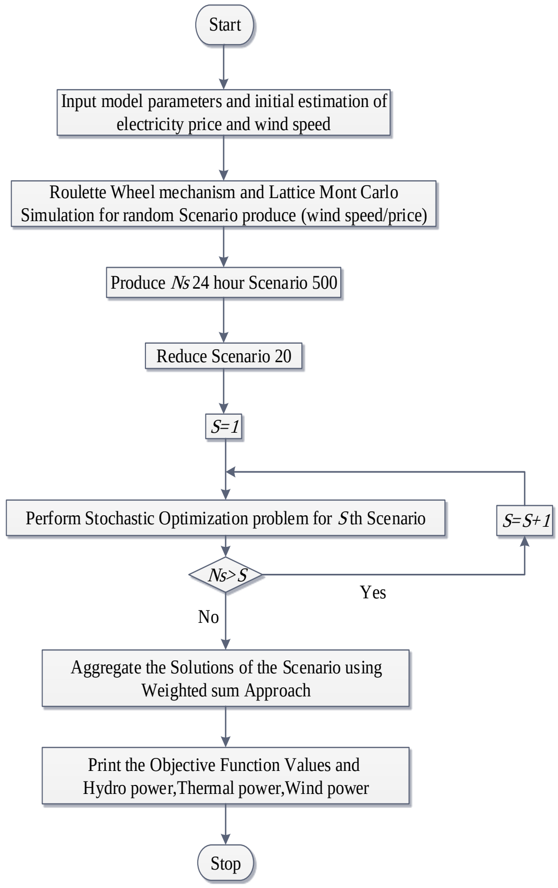

Fig. 4. Flowchart of the modeling presented for considering different uncertainties based on a stochastic scenario.

Here we tend to discuss the first objective function attempting to maximize the expected profit (E_G^P). Hence, in the section equation, the first objective function consists of two parts : the first part equals the bilateral contract for extracting fixed revenue, and the second part is equal to the sum of the times of each scenario multiplied by the corresponding revenue. In Ref. [45], the start-up cost of hydro units (conventional) is obtained from Eq. (3). The proposed stochastic HTSS with a wind power plant is comprised of various equality and inequality constraints and different uncertainties. One of the important constraints is the sum of power generated by hydro-thermal (conventional) and wind units (unconventional), which are equal to the sum of power traded in the spot market plus the bilateral contract. This is given in Eq. (4):

$$\forall t \in T, \forall s \in S$$

$$\sum_{i \in I} pout_{its} + \sum_{h \in H} pout_{hts} + \sum_{w \in W} pout_{wts} = p_t^b + p_{ts}^{sp} \tag{4}$$

In Section 3.2 of the paper, other constraints of the thermal units are described. To provide a relationship between hydro and wind units it is necessary to introduce a model for hydro units. Therefore, by studying Sections 3.3 and 3.4, this issue is addressed.

3.2. Model of Thermal Units

It should be noted that as the equations of thermal units have nonlinear structures they must be transformed into linear equations. As a result, the equations presented in Sections 3.2.1, 3.2.2, 3.2.3, 3.2.4 and 3.2.5 for these units are linearized because of the necessity of solving the considered problem.

3.2.1. Fuel cost function considering POZs

In thermal units, a quadratic function is assigned to calculate the fuel cost. Noticing that these units have special operating conditions, mechanical limitations such as shaft ball bearing vibration hinder the operation of such units in some areas that must be separated from other areas. Fig. 5 shows the linearized form of the fuel cost function of thermal units, which linear and piecewise and has *M* POZs. For this, from a mathematical point of view, equations (5) and (6) are ruling for

$\forall i \in I, \forall t \in T, \forall s \in S$

$$F_{its} = \sum_{n=1}^{M+1}\left[F(p^u_{n-1i})\delta^n_{its} + b^n_i G^n_{its}\right] \tag{5}$$

$$pout_{its} = \sum_{n=1}^{M+1}[(p^u_{n-1i})\delta^n_{its} + G^n_{its}] \tag{6}$$

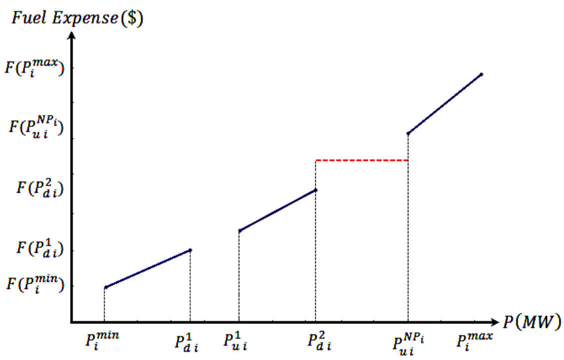

Fig. 5. Linearization of the fuel cost function along with *M* POZs in a piecewise linear form.

Furthermore, considering that the fuel cost function of thermal units has variable 0 or 1, only when this function of power block *n* and for the *i*-th thermal unit will be 1 that the mentioned function is considered in a piecewise and linear form. The result is that the output power of the thermal unit is obtained from Eq. (6). In the rest of the discussion, the fuel cost function of units can be transformed from a nonlinear to linear form Ref. [46]. The necessary constraints are given in Eqs. (7-9). For accurate examination, the maximum $p^d_{M+1\,i} = p^{max}_i$ and minimum $p^u_{o\,i} = p^{min}_i$ output power of this plant as the upper and lower limits are given in Eq. (8). However, considering constraint (9), the unit which is definitely operating in the allowed areas is taken into account.

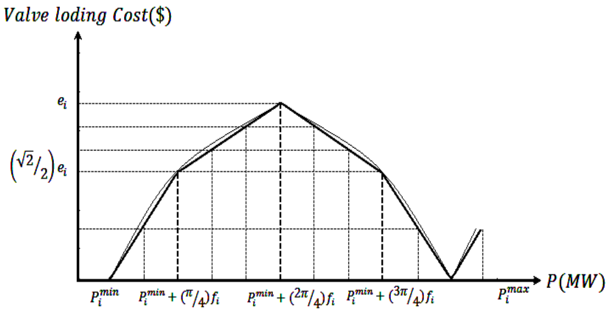

Fig. 6. Effect of VLC as a pure sinusoidal function which is transformed into a linear form

$$G^n_{its} \ge 0;\ n = 1,2,...,M+1 \quad \forall i \in I, \forall t \in T, \forall s \in S \tag{7}$$

$$\delta^n_{its}[p^d_{ni} - p^u_{n-1i}] \ge G^n_{its} \quad n = 1,2,...,M+1 \tag{8}$$

$$I_{its} = \sum_{n=1}^{M+1}\delta^n_{hts} \quad \forall i \in I, \forall t \in T, \forall s \in S \tag{9}$$

3.2.2. Valve loading cost effects

In references [32], [47] and [48], a general case of valve loading cost function for thermal units is presented, which is in a completely nonlinear or nonconvex form. According to Fig. 6 and considering the presented discussion, it is the effects of Eqs. (10)-(13) on investigating the effects of VLC are obviously noted. It is crystal clear that one of the features of function *foam* (.) in Eq. (13) is that it rounds its argument to its closest upper integer value. Take *foam* (3.1) for example, where it outputs 4. It is construed from Eq. (11) that when the necessary power is obtained from each block of the thermal unit, and the considered unit with its minimum power participates in cooperation and scheduling of other units, this power will be equal to the power produced by $pout_{its}$.

$\forall i \in I, \forall t \in T, \forall s \in S$

$$VLC_{its} = \left(\frac{2}{\pi}\right)(e_i f_i)\left\{\begin{array}{l}(\sqrt{2})\sum_{n=0}^{k_i}[\psi^{4n+1}_{its} - \psi^{4n+4}_{its}] \\ +(2-\sqrt{2})\sum_{n=0}^{k_i}\left[\psi^{4n+2}_{its} - \psi^{4n+3}_{its}\right]\end{array}\right\} \tag{10}$$

$\forall i \in I, \forall t \in T, \forall s \in S$

$$pout_{its} = p^{\min}_i I_{its} + \sum_{n=0}^{k_i}\left[\psi^{4n+1}_{its} + \psi^{4n+2}_{its} + \psi^{4n+3}_{its} + \psi^{4n+4}_{its}\right] \tag{11}$$

$\forall i \in I, \forall t \in T, \forall s \in S$

$$I_{its}\left(\frac{\pi}{4f_i}\right) \ge \psi^1_{its} \ge \chi^1_{its}\left(\frac{\pi}{4f_i}\right) \tag{12}$$

$\forall i \in I, \forall t \in T, n = 2,3,...,x_i, \forall s \in S$

$$\chi^{n-1}_{its}\left(\frac{\pi}{4f_i}\right) \ge \psi^n_{its} \ge \chi^n_{its}\left(\frac{\pi}{4f_i}\right) \tag{13}$$

$$k_i = foam\left[f_i\left(\frac{p^{\max}_i - p^{\min}_i}{\pi}\right)\right]$$

$$x_i = foam\left[4f_i\left(\frac{p^{\max}_i - p^{\min}_i}{\pi}\right)\right] \tag{13.1}$$

The role of the first block given in constraint (12) states that the output power of the thermal unit is determined by this block. In fact, a value equal to or greater than ($\pi/4f_i$), which corresponds to the first block, shows the output of thermal units. Now, according to Eq. (12), it is obvious that when the i-th thermal unit is trying to generate power, the binary variable $I_{i\,t\,s}$ is used to prevent the operation of that unit. Referring to Eq. (12) and Eq. (13), one may notice that the reason behind using a binary variable $\chi^n_{i\,t\,s}$ is to take into account the necessary limitation resulting from the generated power of each block. In other words, the binary variable will be 1 when $pout_{i\,t\,s}$ with respect to block n, has a higher upper limit. If $pout_{i\,t\,s}$ is greater than $(n\pi/4f_i) + p^{min}_{i\,t\,s}$, the binary variable $\chi^n_{i\,t\,s}$ will be equal to 1.

3.2.3. Generation capacity limits of the thermal unit

Constraints of the thermal power plant have one lower and one upper limit. Hence, the mathematical relationships related to RDL and RUL of the thermal power plant constraints can be written as Eqs. (14-17).

$$p_i^{\min} I_{its} \le pout_{its} \le pout_{its}^{\max} \tag{14}$$

$$p_i^{\max}\{I_{its} - Y_{i\,t+1\,s}\} + Y_{i\,t+1\,s} SDR_i(i_i) \ge pout_{its}^{\max} \tag{15}$$

$$RDL(p_{its}) + SDR_i(i_i) Y_{its} \ge pout_{i\,t-1\,s} - pout_{its} \tag{16}$$

$$SUR_i(i_i) Z_{i\,t+1\,s} + RUL(p_{its}) \ge pout_{i\,t+1\,s} - pout_{its} \tag{17}$$

3.2.4. Dynamic RDL and RUL

In this section, according to the conducted study in Ref. [33], it should be said that a function with a DRR is obtained for power plants. According to condition $\forall i\epsilon I, \forall t\epsilon T, \forall s\epsilon S$, equations (18) and (19) are introduced to determine RDL and RUL.

$$RDL(p_{its}) = \sum_{n=1}^{M+1} \delta^n_{its} RDL^n_i \tag{18}$$

$$RUL(p_{its}) = \sum_{n=1}^{M+1} \delta^n_{its} RUL^n_i \tag{19}$$

The generated power by thermal units is among those cases that should be noted and considered in the calculations shown in Fig.7. It seems that despite the presence of , thermal units have succeeded to be associated with DRR through . In addition, the ruling relationships in these cases are written in Eqs. (18-19).

3.2.5. Other constraints of thermal units

System operators need auxiliary services to provide safety against events. Reserve services are categorized into three groups: spinning reserves, non-spinning reserves in Ref. [48], and alternative or backup reserves. It should be noted that the reserves are important for active and reactive powers. In the following, other constraints given in Refs. [6 and 49] for thermal units are introduced, which include: startup cost function, minimum up time (MUT), the minimum down time (MDT), etc. Moreover, binary variables for scheduling and cooperation of power plants associated with fuel limitations are required.

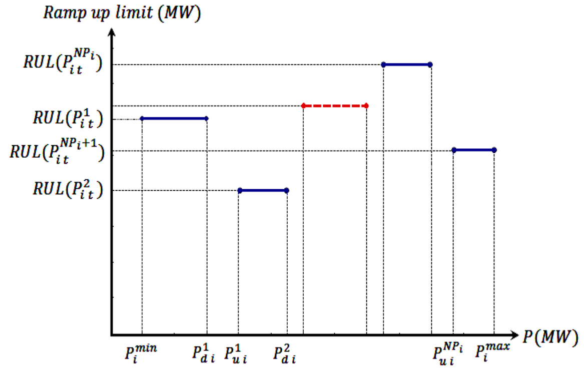

Fig. 7. Generated power in the form of a stepwise function with *M* POZs accompanied by limiting the power increment.

3.3. Model of hydro units

Based on Fig.8, a relationship between water depletion, produced power by hydro units and dam reservoirs of the upstream units that are in multiple forms, is established. In general, a model is proposed for hydro units. Nevertheless, it is worth mentioning that these units can have a relationship with upstream unit's reservoirs through MIP formulations. To better describe the mentioned notes, it is concluded from Fig. 8 that hydro unit's are established in parallel, are hydraulically coupled structures and are related to reservoirs of upstream hydro units. It is worth sharing that in the formulation of MIP scheduling problem for hydro units model, some parameters including power plant dam reservoirs with small storage volumes, water depletion oscillations, the output power of the plant, etc are also presented. Accordingly, the performance curve (L) of hydro units, given in the formulations, and a number of upstream units should be accurately considered. Thereby, the other constraints concerning the hydro units, which will be mentioned in the following, are worth noting.

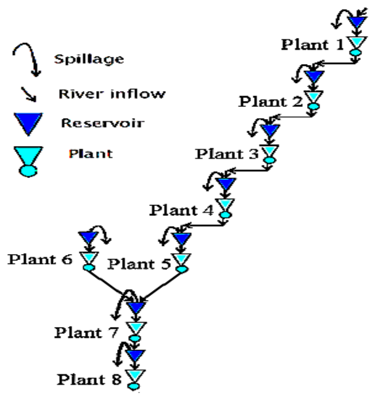

Fig. 8. Hydraulic configuration of the river pool corresponding to hydro units.

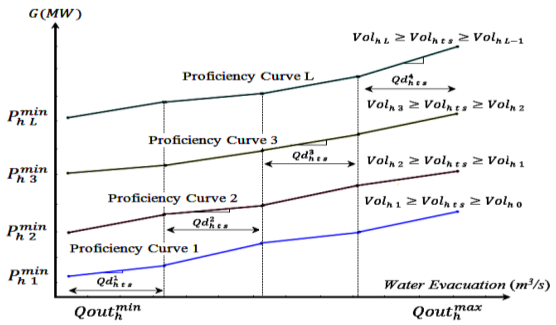

Fig. 9. Performance curves of hydro unit *h* at time *t* using piecewise approximation in a linear form.

3.3.1. Linear formulations for volume and multi-performance curves

This section of the hydro unit model, as shown in Fig. 9, includes linear relationships along with performance curves (L) of hydro units. Equations of this section are written in Eqs. (20-21).

$$vol_{hts} \ge vol_h^{\min} \qquad \forall h \in H \tag{20}$$

$$vol_{hL}^{\max}\delta_{hts}^{L-1} + \sum_{n=2}^{L} vol_{hn-1}^{\max}[\delta_{hts}^{n-2} - \delta_{hts}^{n-1}] \ge vol_{hts} \tag{21}$$

Performance curves δ_{hts}^{n} are determined according to water volume available in dam reservoirs of hydro units. For this, Eqs. (22-23) can be used.

$$vol_{hL-1}^{\max}\delta_{hts}^{L-1} + \sum_{n=3}^{L}[\delta_{hts}^{n-2} - \delta_{hts}^{n-1}]\, vol_{hn-2}^{\max} \le vol_{hts} \tag{22}$$

$$\delta_{hts}^{1} \ge \delta_{hts}^{2} \ge .... \ge \delta_{hts}^{L-1} \tag{23}$$

3.3.2. Linear power discharge performance curves

As mentioned previously, this section discusses the linearized equations, water depletion of dam reservoirs, hydro power, and their performance curves (L). Hence, these equations are given according to Eqs. (24-25).

$$pout_{hts} - p_{hk}^{\min} I_{hts} - \sum_{n\in N} Qd_{hts}^{n} b_{hk}^{n} - p_h^c[(k-1) - \sum_{n=1}^{k-1}\delta_{hts}^{n} + \sum_{n=k}^{L-1}\delta_{hts}^{n}] \le 0 \;,\; 1 \le k \le L \tag{24}$$

$$pout_{hts} - p_{hk}^{\min} I_{hts} - \sum_{n\in N} Qd_{hts}^{n} b_{hk}^{n} + p_h^c[(k-1) - \sum_{n=1}^{k-1}\delta_{hts}^{n} + \sum_{n=k}^{L-1}\delta_{hts}^{n}] \ge 0 \;,\; 1 \le k \le L \tag{25}$$

3.3.3. Other constraints of hydro units

In summary, we can mention cases like (1) water overflow from dam reservoirs of hydro units [6], (2) water balance and the initial volume of water in dam reservoir of hydro units [6,12], and operation related services [48].

3.4. Model of wind farms

Wind energy is conceived of as one of the most important renewable energies. Some benefits of wind energy include lack of pollution during energy generation, no need for fuel, low investment cost, to name but a few. It should be noted that wind sources change in accordance to their installation site, weather conditions, and some other parameters. In addition, wind power plants (unconventional units) have uncertainties, hence the produced energy by these units is not highly reliable. To further describe wind turbines, it is recommended to notice the power produced by such plants. Fig. 10 shows the use of the power equation for depicting the curve of output electrical power (kW) of a wind plant in terms of wind speed (m/s). This is performed using a simple and usual system which has succeeded to convert wind energy into electrical energy. The system is known as wind to electrical converter system (WECS).

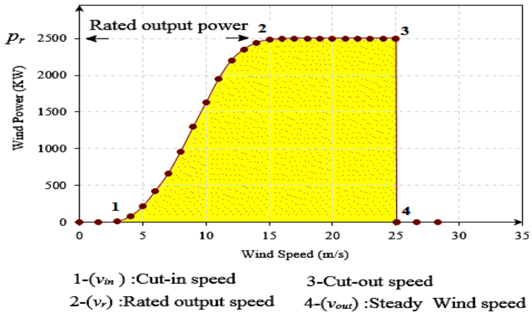

Fig. 10. A simple power-speed curve of a turbine in a wind power plant.

Focusing on Fig. 10, one may notice that it consists of different parts : p (kW) is equal to the output power of the wind plant, p_r (kW) is the rated power of the wind plant. However, other characteristics of the curve in Fig. 10 consist of three velocities : v_{ci} , v_r , and v_{co} , all in (m/s). Generally, in this part of the study, a random value model is used to estimate time series ARMA (n, n-1), the random velocity of wind to identify the model and estimate the data [54], we can use equation (26) where y_t is the amount of time series per hour (t).

$$y_t = \sum_{i=1}^{n}\phi_i y_{(t-i)} + \alpha_t - \sum_{j=1}^{n-1}\theta_j \alpha_{(t-j)} \tag{26}$$

This equation includes n autoregressive parameters, n-1 moving average parameters, α_t is the white noise or the same prediction error, normal distribution with mean zero and σ which represents the standard deviation. In evaluating the model, coefficients θ_j and ϕ_i are calculated and future scenarios are obtained in equation (26) based on past wind speed data. In the following, wind speed is calculated using equation (27), where μ_t represents the mean value.

$$WS_t = \mu_t + \sigma_t y_t \tag{27}$$

Figs. 11 and 12 show the simulated wind speed and wind power for 20 scenarios in a 24-hour period obtained by the ARMA model, respectively.

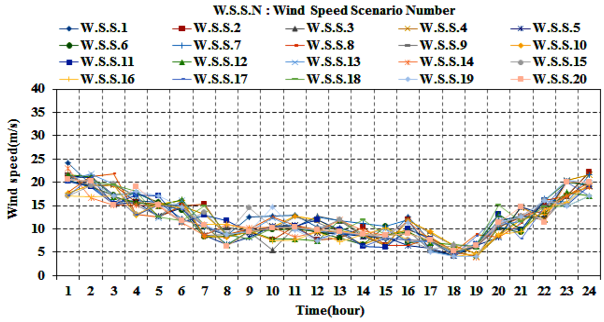

Fig. 11. Wind speed simulated by the ARMA model

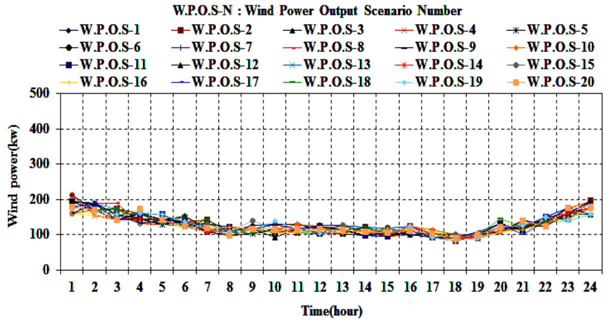

Fig. 12. Wind power simulated by the ARMA model

It should be noted that for performing ARMA time series calculations MINITAB software was used to reduce the visual scenario of VISUAL STUDIO programming. Nordex-N80 is a wind turbine model that has the characteristics of this type of turbines, such as startup speed, nominal speed, output speed and turbine capacity, wind -power curve-wind speed, as shown in Fig. 10. The output power of a wind unit is given in Eq. (28). In different literature regarding wind turbines, such as in Refs. [20, 21, 22, 29 and 50], a simple characteristic is employed to show the relationship between the input power (the speed caused by wind) and the output (electrical) power. Scrutinizing Fig. 10 makes it clear that the generated power of a wind plant is obtained by Eq. (28).

$$\begin{Bmatrix} P=0 & v_{in}>V \text{ or } v_{out}<V \\ P=aV+b & v_r \geq V \geq v_{in} \\ P=p_r & v_{out} \geq V \geq v_r \end{Bmatrix} \quad (28)$$

$$a=(\frac{1}{v_r-v_{in}})p_r \;,\; b=-(\frac{v_{in}}{v_r-v_{in}})p_r$$

Eq. (28) represents the output power of a wind plant in different speeds. It is obvious that the wind speed can be a limiting factor for the output power of the plant. If the sum of generated power from wind energy at places with a great number of wind units located close to each other (wind farms) is required, the real generated power of such units is found from Eq. (29).

$$p_t^{WG}=p_W.A_W.\eta.N_{WG} \quad (29)$$

Where, A_W represents the whole area covered by wind units, η is the efficiency of the generator and wind turbine inverter, and N_{WG} denotes the number of important generators corresponding to wind turbines.

4. CASE STUDIES

The IEEE 118-bus test system shown in Fig.13 is used to study the problem of stochastic HTSS with a wind power plant along with testing the proposed case studies and approving their validity. The test system includes 54 thermal units with different fuels. Among these units, there are 10 units with cruel oil fuel, 11 units with gas fuel, and 33 units with charcoal fuel. In addition, the data of 8 hydro power plants are extracted from Ref. [12]. Fig. 14 shows a schematic of a simple scheme for three different power plants in power systems. This simple scheme illustrates locations of conventional (hydro-thermal) and unconventional (wind) power plants.

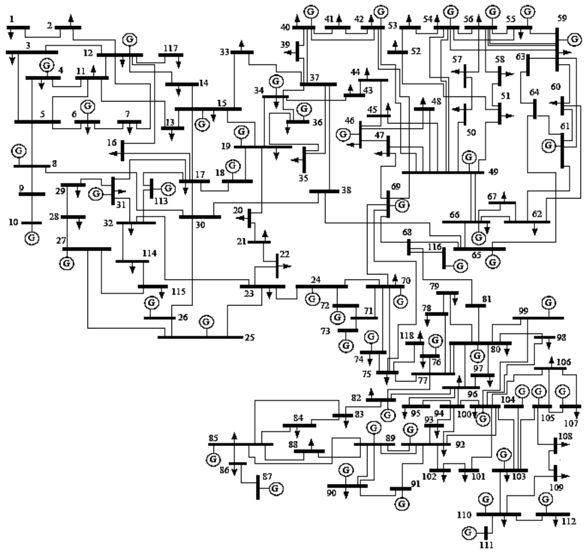

Fig. 13. The utilized IEEE 118-bus test system for study and tests of the proposed scheme.

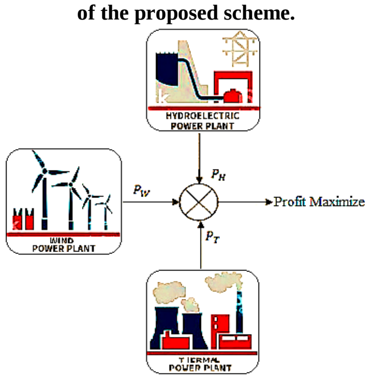

Fig. 14. A schematic of a simple design related to the location of conventional and unconventional power plants in a power system.

GAMS software was used in Ref. [50] to solve stochastic HTSS problem accompanied by MIP scheduling and optimization. It is worth noting that in this study the assumed time for short-term scheduling is 24 hours (one day) and the number of scenarios after reduction is 20. Also, a personal computer with Intel (R) core (TM) i3-2370 M CPU @ 2.40 GHz - RAM 4.00 GB, and CPLEX solver from GAMS software are utilized for simulation purposes. Necessary assumptions and data for case studies of the research are reported in this section: (1) It should be said that due to the availability of required data of ramp rate these data are assumed as constant values in this study, (2) During scheduling and cooperation process among units, some of thermal units, such as 33, 41, 46, and 49 are not employed because they impose high costs on the system, (3) In bilateral contract of electricity pricing, it is necessary to determine the amount and price of energy for each hour. Therefore, these two values are assumed to be 1000 MWh and 45 $/MWh, respectively. (4) A part of hydro unit modeling is comprised of the relationship between three parameters: the head of water in the dam reservoir, depleted water from the dam reservoir, and the generated power. This relationship is of great importance. Fig. 9 shows that hydro units have a number of performance curves (L) where each curve includes a number of blocks, the number of which is 3 and 4. (5) In [51], it is concluded that the amount of fuel consumption and costs of hydro units will be equal to the used energy at the startup time. (6) The required data for scheduling wind units by other generating units is drawn from [52]. (7) All data of thermal units like POZs and coefficients of VLC are extracted from [54]. (8) For scheduling and cooperation of hydro and thermal units, the required data given in [12, 52] are used. Following is described the two cases that were utilized for investigations.

Case 1 addresses the stochastic solution of the HTSS problem to maximize the profit of GenCo's. Hence, this study aims at investigating the effects of VLC, POZs, uncertainties of energy price, spinning and non-spinning reserve prices, without considering the effect of wind power uncertainty on maximizing the overall profit expected from hydro-thermal units in the absence of wind units. It could be expected that the effect of VLC causes additional costs on thermal plants, changes the produced power, and reduces the profit of GenCo's. In Case 2, the same conditions of Case 1 are assumed, but the effect of wind power uncertainty on maximizing the overall profit expected from hydro-thermal units in the presence of wind units. It could be expected that the effect of neglecting the effects of VLC and POZs results in the increase of profit and limitation of the problem solving space.

4.1. Case 1: Stochastic HTSS problem considering VLC and POZs

According to Table 1, the overall profit expected from a stochastic solution of the HTSS problem in the absence of wind units will be 5419857.42 $. Table 1 (shown in Appendix A) shows scenario number, probability, total power, overall spinning reserve, and overall profit of 20 selected scenarios, separately.

As per Table 1 (shown in Appendix A), the highest scenario probability is 40.6%. On the other hand, in the proposed stochastic solution, the participation of each scenario is accepted only if it is equal to all 20 selected scenarios with the overall probability of 54.16% and if it covers an equal proportion of uncertainty spectrum of the power system. Therefore, the proposed stochastic solution with a probability of 33% will cover more stochastic areas of the probability spectrum. One can observe from Fig. 15 That there is a connection between the changes of the energy price and the overall generated power by the plants. Once the energy price is increased in the spot market, most of the thermal units tend to continue their participation in generating power along with the other units. However, it should be noted that thermal units 7, 10, 30, 34, 35, and 45 have limitations on POZs. Overall, the thermal and hydro units produce 165835.76 MW and 15763.62 MW electrical power, respectively.

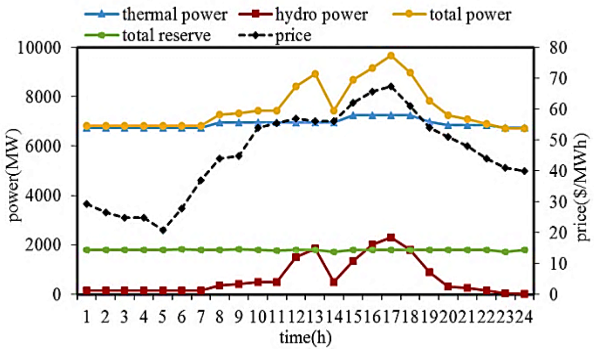

Fig. 15. Scheduling results of total power and price for 20 scenarios.

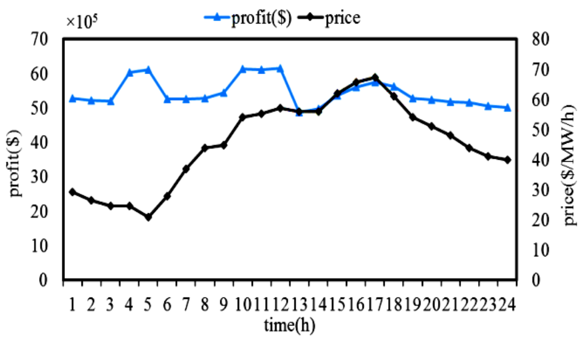

Fig. 16. Curves of 20 selected scenarios including the hourly profit and energy price of GenCo's.

Having this in mind, Fig.16 illustrates how energy price oscillations can affect 20 selected scenarios related to the profit of GenCo's. Consequently, during hours 13:00 - 21:00, when the energy price increases, GenCo's try to produce much more power and achieve a considerable amount of profit. Nevertheless, between hours 1:00 - 13:00 and 21:00 - 24:00 the situation is completely different. Table 2 (shown in Appendix B) lists the number of equations, variables, discrete variables, solution time, and the number of iterations.

4.2. Case 2: Stochastic HTSS problem considering WP and neglecting VLC and POZs

According to Table 3 (shown in Appendix C), the overall profit expected from the stochastic solution of the HTSS problem in the presence of wind units will be 5841292.48 $. Table 3 (shown in Appendix C),shows scenario number, probability, total power, overall spinning reserve, and overall profit of 20 selected scenarios, separately.

Referring to Table 3(shown in Appendix C), the highest scenario probability is 43.2% . It should be noted, however, that in the proposed stochastic solution, the participation of each scenario is accepted only if it is equal to all 20 selected scenarios with the overall probability of 56.17% and if it covers an equal proportion of the power system uncertainty spectrum. Therefore, the proposed stochastic solution with a probability of 43.2% will cover more stochastic areas of the power system probability spectrum. In the framework of the proposed model for solving the HTSS problem in the absence of a wind plant, among 500 scenarios generated by LMCS and RWM, only 20 scenarios will remain. Scheduling results of the hydro-thermal units and the costs related to 20 scenarios are given in Fig. 17. One can observe from Fig. 17 that there is a connection between the changes in energy price and overall generated power of plants. Once the energy price increases in the spot market, most of the thermal units tend to continue participation in generating power along with other units. As a result, thermal units 3, 33, 46 and 49 that a great amount of generation cost must be turned off during the scheduling period. Overall, thermal units produce 166260.17 MW and the average generation power is 6927.51 MW. The minimum generated power by thermal units at hour 00:00 is 6855 MW/h. Yet, the maximum generated power during 16-18 is 7253 MW/h. Variations in the generated power of thermal units are very small, i.e. 3.6%, and this is because of the range of power changes of the thermal units. For this reason, thermal units follow the energy price changes very slowly. On the other hand , hydro units, during the whole period, produce 15854.6 MW, where the average power generation is 656.8 MW/h. The minimum generated power of hydro units at the hour 24:00 is 23.95 MW and the maximum generated power at hour 17:00 is 2300 MW. Since the variations in the generated power of hydro units are very great 73.39%, they can follow energy price changes in the spot market. At the first hours of scheduling, water is stored in reservoirs because energy price is low. However, at middle hours due to the increase in energy price, the generated power by hydro units increases as well. Finally, at last hours and with the decrease in energy price, the produced power also decreases and water is stored in reservoirs to meet the constraint of the final volume of the reservoir water. During the whole scheduling time (24 hours) of scenario 15, the wind unit produces 3089.49 kW, where its average is 128.72 kW/h. Since the accurate prediction of wind speed is impossible, the changes in the produced power by wind unit are very small 0.28% . The reason for these small variations is the range of power changes in the wind unit. Hence, the wind unit can follow the energy price changes up to a point. However, Fig. 18 shows how energy price oscillations can affect 20 selected scenarios related to the profit of GenCo's.

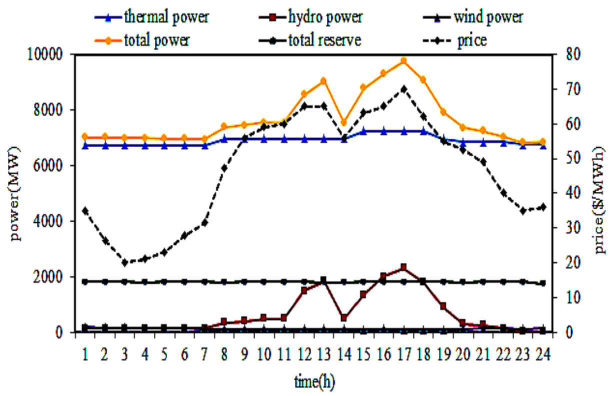

Fig .17. Scheduling results of total power and price for 20 scenarios.

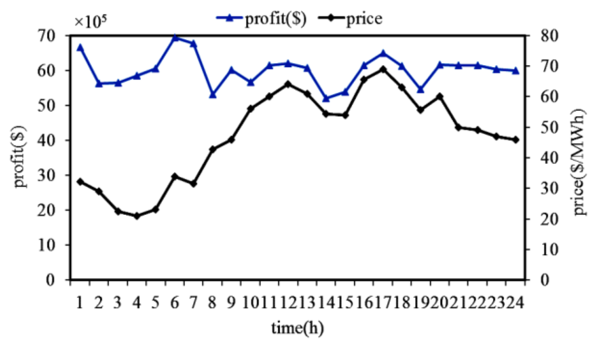

Fig. 18. Curves of 20 selected scenarios that include hourly profit and energy price of GenCos'.

According to 20 selected scenarios, during hours 13:00 - 21:00 the total generated power by hydro-thermal units in the presence of wind units will change with a change in the energy price. Consequently, during this time interval when the energy price is the maximum, GenCo's try to produce more power to obtain more profit. Nevertheless, between hours 1:00 - 13:00 and 21:00 - 24:00 , the situation is completely different. Although the calculation procedure of the proposed method may be time consuming, it seems that it can be considered a fully reasonable method for daily decision making.Table 4 (shown in Appendix D) lists the number of equations, variables, discrete variables, solution time, and the number of iterations. In this section, the overall profit expected from solving the HTSS problem in the presence of wind unit neglecting VLC and POZs has increased 421435.06 $ compared to Case 1.

5. COMPARATIVE ANALYSIS

In this section, we review references [3, 13, 14 and 15] by comparing them. Mixed-integer programming (MIP) for solving the HSS problem only refers to the profit objective function of GenCo's. This article focuses on three studies, the result of which is the second study, which is based on the stochastic variable with a profit value of 938340.178 $ [3].

In Ref. [13], mixed-integer programming for solving the SCHTC problem refers only to the cost objective function of independent system operators (ISO). At the same time, the discussion on profit is not included in this article.

In Ref. [14], the single-objective profit function is used to solve the HTSS problem of GenCo's, which is associated with mixed-integer programming. This article also has three case studies. The profit value of the third case is 5980401.18 $. Mixed-integer programming was used to solve the HTSS problem in Ref. [15]. In addition, the function is multi-objective, which includes profit and pollution.

However, in our research, using mixed-integer programming to solve the HTSS and wind power problem based on the stochastic variable, only one objective function is used to maximize the profit. The profit values of the first and second case studies are 5419857.42 $ and 5841292.48 $, respectively. It should be noted that there are some issues in this study such as taking into account various types of constraints and lack of certainties of wind power, energy prices, etc. which can be used in the discussion on profit, how to plan and participate effectively in GenCo's.

6. CONCLUSIONS

A structure is proposed for the MIP problem in this study to maximize the GenCo's profit, where a stochastic process is used for the HTSS. Among the given criteria, considering or neglecting of which may impact on the study, are fuel limitation, VLC, POZs, where a linearization method is used to model them. Furthermore, various uncertainties are assumed for energy price and wind power.

To achieve a more realistic structure of the considered HTSS with a wind power plant problem and obtain more accurate results, one main parameter known as performance curves (L) of hydro units should be taken into account. Moreover, in this stochastic HTSS with a wind power plant problem, different uncertainties with essential predictions are employed that can be very effective on maximizing GenCo's profit.

Hence, in general, the objective of this study is to utilize the HTSS with a wind power plant in short-term (24 hours) scheduling and a stochastic model is presented that includes different operating constraints considering/neglecting some other criteria. In addition, uncertainties associated with energy price prediction, spinning/non-spinning reserves, and renewable energy resources like windpower are employed. It was previously mentioned that the main strategy of GenCo's decision making in simultaneous participation of conventional (hydro-thermal) and unconventional (renewable sources like a wind power plant) units and the use of various scheduling and optimization methods is to achieve the maximum expected profit.

As a result, the methodology to reach the maximum expected profit of GenCo's is proposed in this paper and acceptable results are obtained. With regard to the proposed framework, only 20 out of 500 scenarios remain indicating a 25% filtering ratio. As a result of this scenario filtering, more areas are covered by uncertainties. The advantage of the proposed method is the increased accuracy and its disadvantage is to select the filtering ratio.

Then the process and computations times will increase. The result is that the amount of profit from the first case, which refers to the stochastic hydro-thermal self-scheduling (HTSS) regarding VLC, POZs is 5419857.42 $. Profit of the second study i.e. the stochastic hydro-thermal self-scheduling (HTSS) without VLC, POZs is 5841292.48 $. The final point is that GenCo's can maximize their profit in the short-term while generating greater power and providing better services.

Appendix

Table A. 1. Results of stochastic solving of scenarios in case study 1 based on HTSS problem

Number	Scenario number	Probability	Normalized probability	Total power (MW)	Total reserve (MW)	Profit ($)
1	5	0.4063068	0.573	6830	1814	5272942.7
2	15	0.0004821	0.028	6830	1811	5213649.1
3	50	0.0007234	0.033	6830	1811	5199421.8
4	61	0.0060395	0.020	6830	1793	6023951.2
5	100	0.0017311	0.007	6830	1814	6108186.1
6	131	0.0206119	0.008	6830	1796	5258321.6
7	155	0.0045621	0.035	6830	1814	5252624.6
8	178	0.0076238	0.014	7278	1774	5272942.7
9	206	0.0003581	0.008	7338	1814	5452952.6
10	261	0.0403841	0.084	7428	1808	6138442.1
11	274	0.0036746	0.023	7427	1811	6108186.1
12	290	0.0054987	0.025	8427	1795	6158952.1
13	311	0.0035498	0.004	8927	1777	4871240.5
14	350	0.0183591	0.006	7427	1792	4974193.5
15	357	0.0003714	0.035	8675	1814	5361612.8
16	400	0.0000855	0.011	9175	1809	5468491.6
17	419	0.0070981	0.021	9657	1813	5445152.3
18	444	0.0048820	0.003	8975	1813	5433257.7
19	451	0.0019921	0.055	7827	1812	5433257.7
20	472	0.0136728	0.007	7250	1791	5286042.7

Table A. 2. Statistics of optimization results obtained from solving stochastic HTSS problem. The solver continuously repeats the iterations to achieve the most appropriate solution obtained from the final convergence.

HTSS framwork	Number of single equation	Number of single variables	Number of discrete variables	Number of discrete iterations*	Solution time(Sec)
Stochastic (case 1)	1345701	1087021	602040	36825	1740
Stochastic (case 2)	852719	803005	185601	68139	1369

*Number of iterations means the number of iterations that a solver converges to find the solution.

Table A. 3. Results of stochastic solving scenarios of case study 2 based on HTSS problem

Number	Scenario number	Probability	Normalized probability	Total power (MW)	Total reserve (MW)	Profit ($)
1	2	0.0082613	0.573	6830	1814	5272942.7
2	33	0.0046231	0.028	6830	1811	5213649.1
3	45	0.0001602	0.033	6830	1811	5199421.8
4	59	0.0060510	0.020	6830	1793	6023951.2
5	62	0.0018352	0.007	6830	1814	6108186.1
6	67	0.0066505	0.008	6830	1796	5258321.6
7	84	0.0036497	0.035	6830	1814	5252624.6
8	90	0.0022006	0.014	7278	1774	5272942.7
9	103	0.0036084	0.008	7338	1814	5452952.6
10	116	0.0019720	0.084	7428	1808	6138442.1
11	230	0.0005223	0.023	7683	4009	6140559.5
12	241	0.0045762	0.025	8670	3974	6191594.5
13	283	0.0007503	0.004	9169	3933	6073792.4
14	340	0.0073501	0.006	7664	3967	5191563.7
15	385	0.4320186	0.035	8742	4016	5390029.3
16	392	0.0006214	0.011	9358	4005	6140559.5
17	417	0.0003985	0.021	9638	4013	5393587.6
18	451	0.0184900	0.003	8926	4013	6114807.3
19	480	0.0012030	0.055	7900	4011	5462054.0
20	500	0.0573180	0.007	7520	3965	6163720.9

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