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Research Article

Robust stochastic optimal short-term generation scheduling of hydrothermal systems in deregulated environment

Morteza Nazari-Heris
Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran, m.nazari@ieee.org
ORCID: 0000-0001-9275-2856
Behnam Mohammadi-Ivatloo
Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran, mohammadi@ieee.org
ORCID: 0000-0002-0255-8353
Somayeh Asadi
Department of Architectural Engineering, Pennsylvania State University, Pennsylvania, USA,
asadi@engr.psu.edu
ORCID: 0000-0002-7118-1772

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Abstract: Hydrothermal systems play a significant role in electric energy systems as important power generation units, which have been studied in previous researches considering remarkable efforts. The optimal short-term hydrothermal scheduling (STHS) aims to attain optimal production scheduling of thermal and hydro plants for determining minimum operation cost of providing demand in the determined time interval. Different constraints should be studied in the solution of such issue containing limitations associated with water discharge, water storage, power production of plants, power balance of the system and water balance of hydro plants. In addition, valve impacts of thermal plants and complex hydraulic coupling of hydro plants are the other operational and technical constraints. In this study, the robust stochastic STHS is studied considering market price and demand uncertainties. Accordingly, robust optimization method is employed in this study to model price uncertainties. In addition, the uncertainties of load demand are handled using scenario-based modeling procedure. The scheduling problem of hydrothermal system is studied in a deregulated environment, where the hydrothermal system belongs to the private company and is capable to sell the surplus generated power to the market. Accordingly, the company aims to obtain maximum profit by selling power to market in addition to supplying power demand of the company. The introduced scheme for stochastic robust STHS is simulated and the provided solutions are investigated to verify the effectiveness of the scheme.

Keywords: *Electric energy systems, Hydrothermal systems, Deregulated environment, Robust optimization method, Short-term scheduling,*

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1. INTRODUCTION

Hydropower is a renewable energy source considered as practical procedure of producing large quantities of electrical energy. Hydropower production has been introduced as an effective concept in improving the power system stability, which supports application of renewable energy sources including wind turbines or photovoltaic systems [1]. The statistics reported in the area of hydropower generation proves that the hydropower plants allocate 16% of total electrical energy production of the world [2]. Thermal power generation units require high operational costs; however, the initial development costs of such plants are lower. Moreover, the operation cost of hydropower units is ignorable; however, such units need high construction cost. Accordingly, the integration of thermal and hydro units is defined as a practical solution for supplying power demand due to economic and technical viewpoints [3].

The optimal production scheduling of power systems is an essential issue in electrical energy systems, which has attracted researcher's attention in previous publications. STHS obtains simultaneous production scheduling of both thermal and hydro units for minimizing cost of hydrothermal systems providing electrical load demand [4]. The most important challenges of this problem contain valve impact of the thermal plants and complex hydraulic coupling of hydro units. In addition, a series of constraints should be handled in obtaining optimal STHS consisting of limitations of water discharge, water storage, power generation of hydro and thermal plants, power system demand and water balance of the hydro plants [5].

Various remarkable efforts have been made in studying the STHS problem. Research studies in this area can be divided two major classifications, where in the first one, researchers introduced new optimization techniques to solve the optimal STHS problem, and in the second category, new frameworks are introduced for the problem with various aims and constraints. In the first category, the authors have proposed mathematical optimization methods and heuristic concepts to the solution of the issue. Mathematical models applied to study the STHS include non-linear programming [5], decomposition method [6], Lagrange multiplier [7], Opt Quest/NLP (OQNLP) concept [8], and dynamic programming (DP) [9]. The heuristic approaches are applied to study STHS including genetic algorithm [10], particle swarm optimization [11], differential evolution [12], Cuckoo search method [13], group search optimization [14], artificial bee colony [15], and teaching learning based optimization [16]. The authors have proposed a real coded genetic algorithm approach based on new mutation process to provide the optimal solution of hydrothermal systems in [17]. Harmony search concept is proposed in [18] for dealing with optimal STHS, where the introduced new scheme for obtaining optimal solution of optimization process of the harmony search method. Moreover, the new models have been introduced for STHS. The multi-objective economic emission dispatch of hydrothermal systems has been studied in [19], where two conflicting objectives are considered to minimize the cost and reduce emission of pollutant gases. Self-scheduling of hydro-thermal systems has been investigated in [20]. Information gap decision theory is employed to the hydrothermal scheduling for the load uncertainty issue in [21]. Long-term planning of hydrothermal systems has been studied in [22] considering risk-averse policies. Pumped storage unit are considered in [23] for investigating hydrothermal systems. The capability of participation of hydrothermal generation companies (GENCOs) in power market has been analyzed in [24]. The stochastic STHS and stochastic midterm financial risk constrained are investigated in [25] and [26], respectively.

This study presents a novel robust stochastic modeling of STHS in the deregulated environment. In the proposed model, the private company owning the hydrothermal system aims to obtain a maximum profit of selling the generated power in the market in addition to satisfying the load demand of company. The proposed model in this study models the uncertainty of market price employing the robust optimization (RO) method, and the uncertainty of load demand using scenario-based modeling approach. The proposed robust STHS is employed on a system including three hydro units and one thermal plant to evaluate the performance of the model. The studied system is responsible to satisfy daily load demand of the company and is capable to sell the electrical energy in power market. The obtained results are analyzed, which shows the high performance of the model.

The rest of this paper is as: Section 2 provides the formulation of the proposed robust STHS. The case study is prepared in Section 3. The results of the introduced model on the case study are provided in Section 4. Finally, the conclusion of the paper is done in Section 5.

2. PROBLEM FORMULATIONS

The objective of robust stochastic STHS is maximizing the profit of selling electrical energy to the market in addition to satisfying the company daily load demand. The market price and demand uncertainties are handled by using RO and scenario-based modeling methods. This section aims to study the objective function, operational and technical constraints of the issue. In this study, the uncertainty of load demand is modeled by a scenario-based method [27]. Five scenarios are studied for load demand in this research. The load demand uncertainty states s_1 to s_5 are 0.92, 0.96, 1, 1.04, and 1.08.

2.1. Operation cost and Constraints of Thermal Plants

The operation cost of thermal plants, which is considered in the objective function of the problem, is formulated as a quadratic function of power generated by such plants [4]:

$$F_{i,s}^{t}(P_{i,s}^{t}) = a_i (P_{i,s}^{t})^2 + b_i P_{i,s}^{t} + c_i \tag{1}$$

where, $F_{i,s}^{t}$ and $P_{i,s}^{t}$ are used to indicate operation cost and generated power of i^{th} thermal unit at t^{th} time interval in s^{th} scenario. The cost coefficient of i^{th} thermal plant is sown by a_i, b_i, and c_i.

The impact of valve in thermal units should be considered due to existence of several steam admitting valves in thermal units. This issue is normally added as a sinusoidal term to the quadratic cost function of thermal units complicating the issue. So the precious cost function of thermal plants has been considered in the introduced robust stochastic STHS [4]:

$$F_{i,s}^{t}(P_i^{t}) = a_i (P_{i,s}^{t})^2 + b_i P_{i,s}^{t} + c_i + \left| e_i \sin(f_i (P_i^{\min} - P_{i,s}^{t}) \right| \tag{2}$$

where, e_i and f_i indicate coefficients of vale-point effect of i^{th} thermal plant, and the minimum power production of i^{th} thermal plant is defined by $P_i^{\min}$.

The power production of thermal units are limited to the lower and upper bounds in STHS as follows [4]:

$$P_i^{\min} \le P_{i,s}^{t} \le P_i^{\max} \tag{3}$$

where, the maximum power production of i^{th} thermal plant is defined by $P_i^{\max}$.

2.2. Generation Formulation and Constraints of Hydropower Plants

As mentioned before, generated power by hydro and thermal plants should satisfy the company daily demand, and the extra generated power can be sold in the power market. The power production of hydro plants is a function of released water and reservoir volume in each time interval of the scheduling time horizon, which can be stated as [28]:

$$P_{j,s}^{t} = c_{1j}(V_{j,s}^{t})^{2} + c_{2j}(Q_{j,s}^{t})^{2} + c_{3j}(V_{j,s}^{t}Q_{j,s}^{t}) + c_{4j}(V_{j,s}^{t}) + c_{5j}(Q_{j,s}^{t}) + c_{6j} \tag{4}$$

where, $P_{j,s}^{t}$ indicates generated power of j^{th} hydro unit at t^{th} time interval in s^{th} scenario. $V_{j,s}^{t}$ and $Q_{j,s}^{t}$ are the respective indicators of volume and the discharge of j^{th} hydro plant at t^{th} time interval in s^{th} scenario. The power production coefficients of j^{th} hydro unit are defined by c_{1j}, c_{2j}, c_{3j}, c_{4j}, c_{5j}, and c_{6j}.

The power production of hydro plants similar to thermal plants in STHS should be limited as follows [28]:

$$P_{j}^{\min} \le P_{j,s}^{t} \le P_{j}^{\max} \tag{5}$$

where, the minimum and maximum power production of j^{th} hydro plant are defined by $P_{j}^{\min}$ and $P_{j}^{\max}$, respectively.

The water discharge and reservoir volumes of the hydro plants are restricted to lower and upper bounds in the STHS as [28]:

$$Q_{j}^{\min} \le Q_{j,s}^{t} \le Q_{j}^{\max} \tag{6}$$

$$V_{j}^{\min} \le V_{j,s}^{t} \le V_{j}^{\max} \tag{7}$$

where, the minimum and maximum values of water discharge of j^{th} hydro unit are defined by $Q_{j}^{\min}$ and $Q_{j}^{\max}$, respectively. The minimum and maximum volumes of reservoir of j^{th} hydro plant are $V_{j}^{\min}$ and $V_{j}^{\max}$, respectively.

The other important constraint, which should be handled in the STHS, is dynamic water balance in reservoirs, which is demonstrated in Fig. 1. The dynamic water balance of the hydropower units, which is studied in STHS, can be stated as [28]:

$$V_{j,s}^{t} = V_{j,s}^{t-1} + I_{j,s}^{t} - Q_{j,s}^{t} - S_{j,s}^{t} + \sum_{k \in R_{up}^{j}} (Q_{j,s}^{t-Td_{k}} + S_{j,s}^{t-Td_{k}}) \tag{8}$$

where, the inflow rate of j^{th} hydro unit at t^{th} time in s^{th} scenario is defined by $I_{j,s}^{t}$.

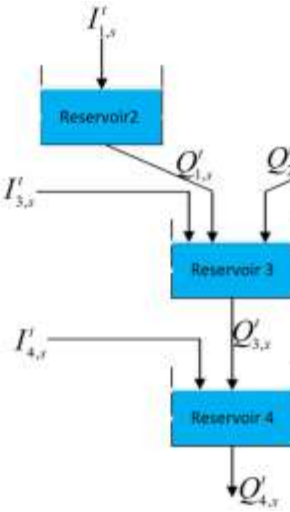

Fig. 1. Dynamic water balance of hydropower unit

The initial and final volumes of reservoirs are considered to be known in STHS, the following constrains can be stated [28]:

$$V_j^0 = V_j^{initial} \tag{9}$$

$$V_j^0 = V_j^{final} \tag{10}$$

where, $V_j^{initial}$ and V_j^{final} are the initial and final reservoir storage of j^{th} hydro plant.

2.3. Power Balance

The sum of power produced by hydro and thermal units should satisfy demand and power sold to the power market in the proposed robust stochastic STHS to ensure that the power balance is attained.

$$P^t_{Load,s} + P^t_{Sell} = \sum_{l=1}^{N_T} P^t_{j,s} + \sum_{m=1}^{N_H} P^t_{i,s} \tag{11}$$

where, P^t_{Load} is the company load at t^{th} time interval in s^{th} scenario. P^t_{Sell} is the sold power to the power market at t^{th} time interval.

2.4. The Proposed Robust Stochastic Scheduling of Hydrothermal Systems

The RO concept is recently introduced as an impactful tool for studying uncertainties associated with power system parameters. The RO method takes advantages of studying the uncertainties parameters without having the parameters probability distribution functions [20]. This uncertainty of power market price, which has effect in a profit of power sold to the market, is studied using the polyhedral uncertainty sets in RO concept [29].

$$U_\lambda = \left\{ \begin{array}{l} \lambda_{Sell}^{t,u} \in R^{+} :\ \underline{\Gamma_\lambda} \le \dfrac{\sum \lambda_{Sell}^{t,u}}{\sum \lambda_{Sell}^{t}} \le \overline{\Gamma_\lambda} \quad \forall t, \\ \lambda_{Sell}^{t,u} \in \left[\underline{\lambda_{Sell}^{t}}, \overline{\lambda_{Sell}^{t}} \right] \qquad \forall t \end{array} \right\} \tag{12}$$

where, the minimum and maximum selling power to the market is defined by $\left[\underline{\lambda_{Sell}^{t}}, \overline{\lambda_{Sell}^{t}} \right]$. RO method employs uncertainty budgets for imposing the lower and upper restrictions of power market price, which are defined by $\underline{\Gamma_\lambda}$ and $\overline{\Gamma_\lambda}$. In this study, the robust stochastic STHS is studied, where the price uncertainty is modeled utilizing RO concept and the load demand uncertainty is studied using scenario-based modeling method. The system in the proposed STHS model is responsible to satisfy the daily load demand and is capable to sell the surplus generated power to the market. The system operation cost includes fuel cost of thermal units considering ignorable operation cost of hydropower units. Accordingly, the objective function of the introduced framework can be stated as [30]:

$$\begin{array}{l} \max \ \sum\limits_{t=1}^{24} \{ -\sum\limits_{i=1}^{N_i} a_i (P_{i,s}^{t})^2 + b_i P_{i,s}^{t} + c_i + \left| e_i \sin(f_i (P_i^{\min} - P_{i,s}^{t}) \right| \\ + \max \ \min(\lambda_{Sell,R}^{t} \times P_{Sell}^{t}) \} \end{array} \tag{13}$$

where, the uncertain power market price at t^{th} time interval is defined by $\lambda_{Sell,R}^{t}$, and the power sold to the market at t^{th} time interval is indicated by $P_{G,Sell}^{t}$. The inner problem can be reformulated to an equivalent formulation as follows [30]:

$$\begin{array}{ll} \min & \lambda_{Sell,R}^{t} \times P_{Sell}^{t} \\ \text{s.t.} & z_{Sell}^{t} \le 1 \ :\ \xi_1^{t}, \ \forall t, \\ & \sum\limits_{t=1}^{T} (z_{Sell}^{t}) \le \Gamma \ :\ \beta, \\ & z_{Sell}^{t} \ge 0 \end{array} \tag{14}$$

where, ξ_1^{t} and β are dual variables. Accordingly, the robust formulation of the problem is obtained using the Karush–Kuhn–Tucker (KKT) condition, which is provided as follows [30]:

$$\begin{array}{ll} \max & \sum\limits_{t=1}^{24} \{ \lambda_{Sell,R}^{t} \times P_{Sell,s}^{t} - \xi_1^{t} - \Gamma \beta - \\ & \sum\limits_{i=1}^{N_i} a_i (P_{i,s}^{t})^2 + b_i P_{i,s}^{t} + c_i + \left| e_i \sin(f_i (P_i^{\min} - P_{i,s}^{t}) \right| \\ s.t. & (1) - (11) \\ & \xi_1^{t} + \beta \ge \hat{\lambda}_h P_{Sell}^{t} \\ & \xi_1^{t} \ge 0 \\ & \beta \ge 0 \end{array} \tag{15}$$

3. CASE STUDY

The proposed framework for robust stochastic STHS is studied on a test system to assess performance of the model. The studied case study contains four cascade hydro plants and one equivalent thermal unit. The characteristics of hydropower and thermal plants, and demand of the studied system are adopted from [31]. Table 1 provides the characteristics of four hydro units, which include limitation of reservoir volume (10^4 m^3), limitations of water release (10^4 m^3), and limitations of power generation capacity (MW). The cost coefficients of hydropower plants are prepared in Table 2. In addition, Table 3 provides the coefficients of cost and vale-point loading effect of thermal plant. As mentioned before, valve effects of thermal units increase the complexity level of the issue, which is studied in this research.

Table 1. Characteristics of hydropower plants

Hydro plant j	$V_j^{\min}$	$V_j^{\max}$	$V_j^{initial}$	V_j^{final}	$Q_j^{\min}$	$Q_j^{\max}$	$P_j^{\min}$	$P_j^{\max}$
1	80	150	100	120	5	15	0	500
2	60	120	80	70	6	15	0	500
3	100	240	170	170	10	30	0	500
4	70	160	120	140	13	25	0	500

Table 2. Power production coefficients of hydro units

Hydro plant j	c_{1j}	c_{2j}	c_{3j}	c_{4j}	c_{5j}	c_{6j}
1	-0.0042	-0.42	0.030	0.90	10.0	-50
2	-0.0040	-0.30	0.015	1.14	9.5	-70
3	-0.0016	-0.30	0.014	0.55	5.5	-40
4	-0.0030	-0.31	0.027	1.44	14.0	-90

Table 3. Characteristics of thermal Plants

Thermal plant i	a_{1i}	b_{1i}	c_{1i}	d_{1i}	e_{1i}	$P_j^{\min}$	$P_j^{\max}$
1	0.002	19.2	5000	700	0.085	500	2500

The system load demand is shown in Fig. 2. Considering this figure, the minimum and maximum values of load demand are 1290 and 2320 MW, respectively. The company is responsible to provide daily load demand and sell the surplus power to the market.

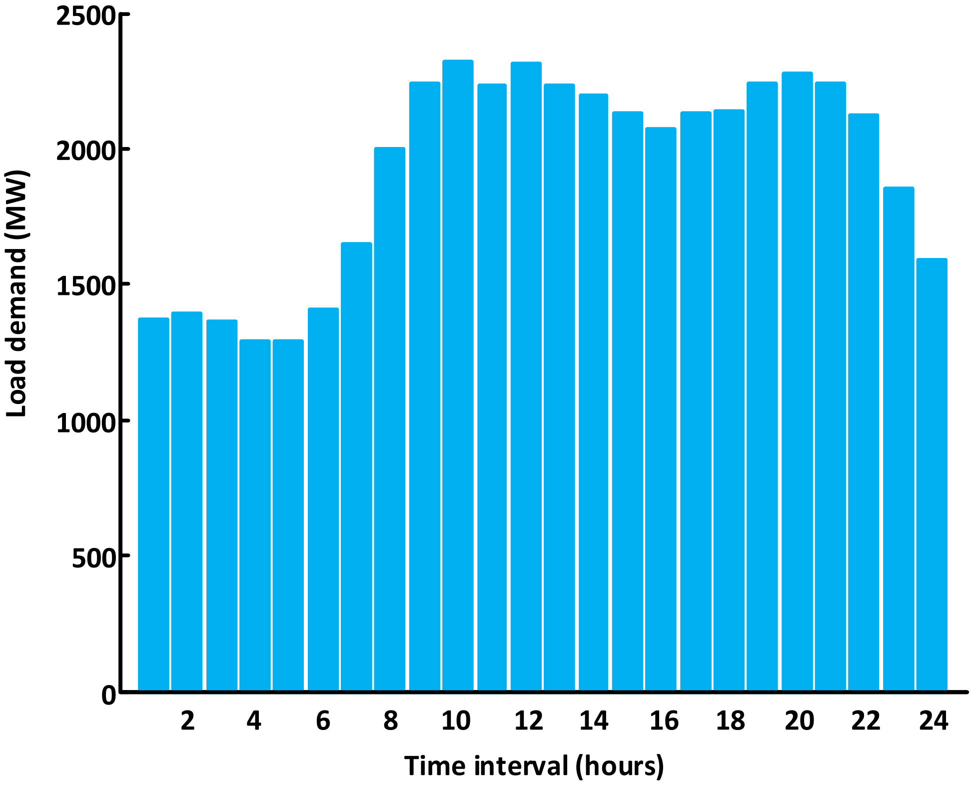

Fig. 2. Daily load demand of the hydrothermal system

The market price forecasted is shown in Fig. 3, which are adopted from [32]. Considering this figure, power market price in variant in the time interval, where the minimum value of price is related to *t=2-7*, where the power market price is equal to 25 \$/MWh. In addition, the maximum value of price is related to *t=21-22*, where the forecasted power market price is equal to 65 \$/MWh.

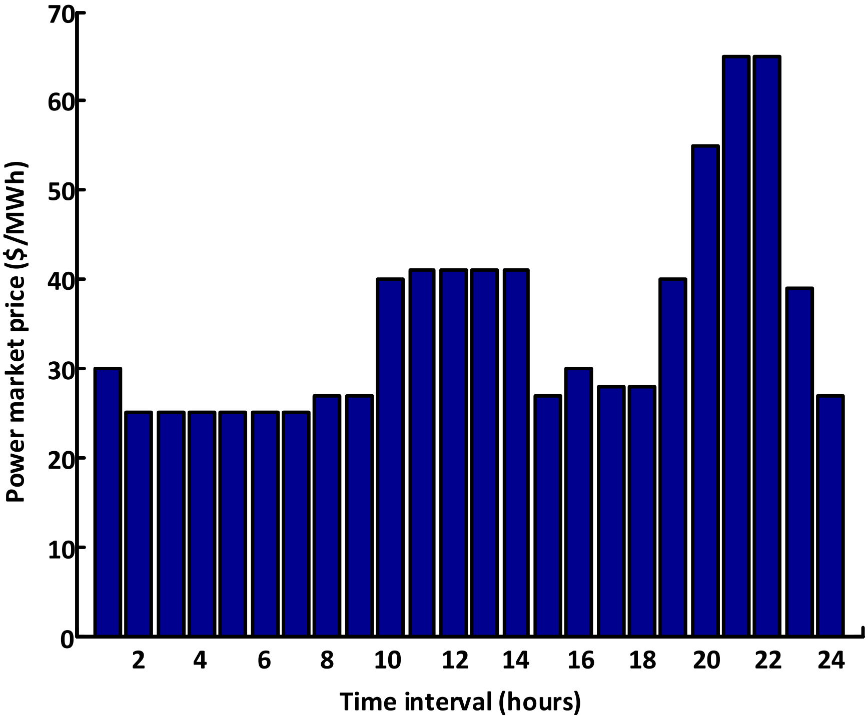

Fig. 3. Daily forecasted power market price

4. SIMULATION RESULTS

The introduced model for the robust stochastic STHS is investigated for the studied system, and the simulation results are reported and investigated in this section. The proposed framework for the robust stochastic STHS is solved employing SBB solver [33] under General Algebraic Modeling System (GAMS) [34].

The optimal solution of the studied system is reported for the budget of 6 and deviation percentage of the power price 15%. Table 4 provides the optimal production scheduling of hydropower units and thermal plant. As seen in this table, the generated power by four hydro units and the equivalent thermal plant is more than demand, which are sold to the market in order to attain profits to the system owner. In addition, the thermal plant has participated in power generation in some time intervals with the maximum generation capacity, which is due to high price value of the market. Power generation of the thermal unit is more than sum of the generated power utilizing hydro units in all scheduling time horizons. Daily production of the hydro plants is depicted in Fig. 4. The analysis of this figure shows that the hydro unit *1* generate the maximum power during the day. The amount of power generated by hydro units are varied during the time interval due to the operational constraints of the hydro units. The obtained profit for the selected robust budget and price deviation percentage is equal to $743,158.69.

Table 4. Simulation results for scheduling of hydropower and thermal units

Hour	Hydro unit *4*	Hydro unit *3*	Hydro unit *2*	Hydro unit *1*	Thermal unit
1	82.70	50.16	39.25	129.03	2500
2	76.12	51.30	32.96	125.74	1450
3	75.40	52.93	34.58	121.63	1450
4	74.27	54.50	36.59	115.82	1450
5	72.80	55.50	39.43	129.40	1450
6	72.03	55.99	42.44	142.46	1450
7	71.58	55.99	44.21	176.70	1450
8	75.13	57.18	43.51	220.91	1950
9	75.27	58.95	41.81	242.90	1950
10	80.17	68.31	40.97	273.21	2500
11	81.89	71.50	42.02	284.10	2500
12	81.62	72.38	38.91	284.76	2500
13	81.69	73.49	40.12	286.69	2500
14	82.22	74.67	39.63	286.74	2500
15	74.67	68.56	35.70	282.21	1950
16	79.53	75.85	32.61	289.60	2500
17	74.02	72.69	37.53	289.27	2200
18	72.13	71.91	44.95	291.85	2200
19	73.93	75.06	49.82	299.63	2500
20	87.51	85.76	51.36	305.62	2500
21	91.45	88.68	52.72	303.94	2500
22	91.11	88.40	54.84	299.82	2500
23	89.13	87.34	52.47	289.67	2500
24	84.65	81.87	49.45	284.65	2500

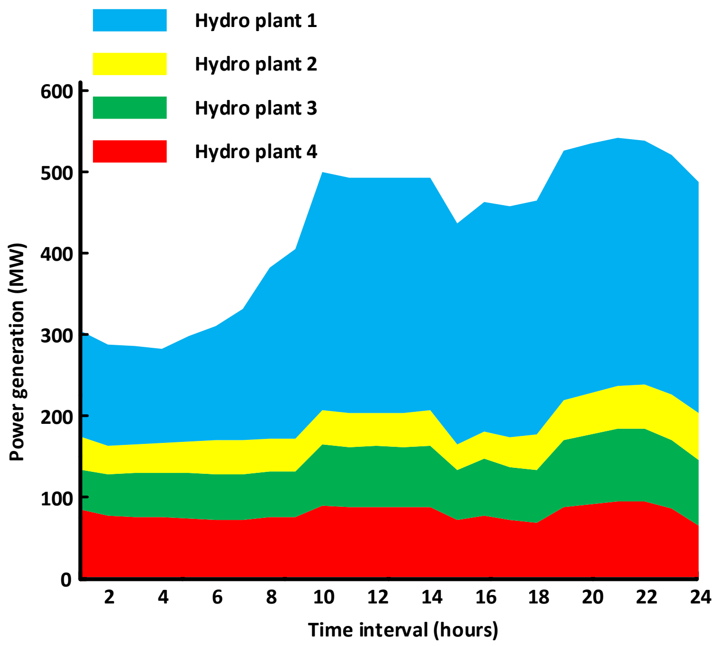

Fig. 4. Daily power production of the hydro plants

The proposed model is employed on the studied hydrothermal system considering the robust budget of 1-10 and deviation percentage of the power market price 5%-25%. The obtained results for the profit of the company is provided for the above-mentioned values and are shown in Fig. 5. As seen in this figure, the obtained solution for the profit of the company is the maximum value for uncertainty budget of 1 and price deviation of 5%, which is obtained as $872866.55. On the other hand, the obtained profit of the company is the minimum value for uncertainty budget of 10 and price deviation of 25%, where the profit is equal to $530363.87. It can be found that by increasing the price deviation percentage from the forecasted value with the constant robust budget, the profit is deceased. On the other hand, the profit is reduced by increasing the robust budget for a constant value of price deviation percentage form forecasted value. In other words, the profit of the system is decreased considering the high level of robustness.

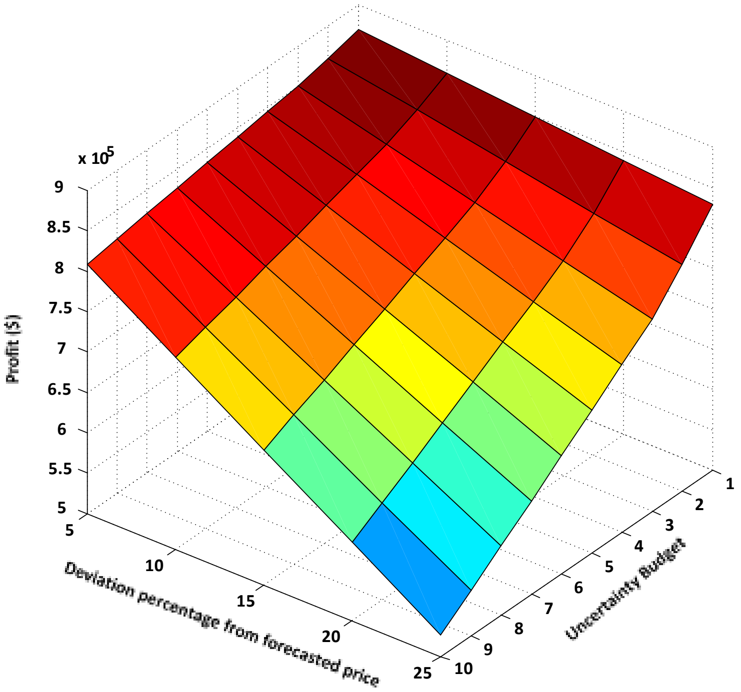

Fig. 5. Total profit of the company for uncertainty budgets and deviation percentages

5. CONCLUSION

This study proposed a new robust stochastic modeling of optimal scheduling of hydrothermal systems in deregulated environments. The studied hydrothermal system belongs to a company, which is capable to sell the surplus generated power to the system after supplying daily load demand. The proposed framework for the robust stochastic hydrothermal scheduling aims to maximize the profit of company considering the power price and demand uncertainties. Accordingly, the uncertainty associated with daily forecasted price is studied employing RO concept and the uncertainty of daily load demand is studied employing a scenario-based modeling approach. The proposed model is implemented on a test system including four cascaded hydropower units and one equivalent thermal unit. The profit of the company is obtained for various ranges of budgets and various deviation percentages of price from the forecasted values. The results are reported and investigated, which proves that the profit of the company is grown by lowering the robustness level.

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