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Mixed integer programming of security-constrained daily hydrothermal generation scheduling (SCDHGS)

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Dynamic ramp rate;
Prohibited operating zones;
Tighter approximated MILP formulation.

Abstract. This paper presents the application of Mixed-Integer Programming (MIP) approach for solving Daily Hydrothermal Generation Scheduling (DHGS). In restructured power systems, Independent System Operators (ISOs) execute Security-Constrained Unit Commitment (SCUC) program to plan a secure and economical hourly generation schedule for daily/weekly-ahead market. DHGS is a highly dimensional mixed-integer optimization problem, which might be very difficult to solve when applied for realistic power system; therefore, we use MIP. This approach allows precise modeling of hydro and thermal systems that are represented in high detail. It includes valve point loadings, Prohibited Operating Zones (POZs), dynamic ramp rate limits, non-linear start-up cost functions of thermal units, variable fuel cost, operating services, fuel and emission limits of thermal units and variable head water-to-power conversion function of hydro plants. To assess the approach, a study case based on an IEEE 118 bus system is performed. The effectiveness of the proposed model is shown on different test systems.

1. Introduction

Daily Hydrothermal Generation Scheduling (DHGS) is an important issue in economical operation of power systems. Short-term hydrothermal coordination consists of determining the optimal usage of available hydro and thermal resources during a scheduling period of time (1 day-1week), in order to satisfy a forecasted energy demand at minimum total cost [1]. The Main objective is focused on the optimal use of water resources for minimizing the production cost of thermal plants, considering the practical constraints related to thermal plants, hydroelectric system and electrical power system (satisfying power demand constraint). Therefore, DHGS is a large-scale non-linear and complicated constrained power system optimization problem that can be solved using different optimization techniques as, for example, Lagrangian Relaxation (LR) [2], Dynamic Programming (DP) [3], Mixed Integer Programming (MIP) [4], Benders Decomposition (BD) [5] and various intelligent techniques [6-8].

In competitive markets, the main objective of a generation company (GENCO)'s generation scheduling is to maximize its profit. A GENCO's profit is the difference between its revenue and expenses (i.e., capital and operating costs). In contrast to GENCOs' objective, ISO, as the key market entity, has the authority and responsibility to commit and dispatch system resources and curtail loads for maintaining the system security (i.e., balancing load demands and satisfying fuel, environmental, and network security requirements) [9,10]. Market operators in various

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ISOs apply the Standard Market Design (SMD) for scheduling a secure and economically viable power generation for the day-ahead market. One of the key components of SMD is Security-Constrained Unit Commitment (SCUC), which utilizes the detailed market information submitted by participants, such as the characteristics of generating units, availability of transmission capacity, generation offers and demand bids, scheduled transactions, curtailment contracts, and so on [9,11]. Therefore, it is very important for GENCOs and ISOs to consider a rigorous and comprehensive model of both hydro and thermal units in daily hydrothermal generation scheduling in a competitive environment [12,13].

Recent papers [12-15] propose the 0/1 mixed-integer linear programming approach that allows precise but separate modelling of hydro and thermal subsystems, and don't consider network security requirements. This paper combines both thermal and hydro subsystems from the ISO point of view.

Almost all of the aforementioned works have modelled the DHGS problem without considering the dynamic constraints of hydro units (e.g. minimum up time and down time) and hydro plant ramp rate constraints. As a result, the solution may contain some unsatisfactory behavior such as frequent switching of hydro units. Frequent cycling of hydro units in daily operations is usually not allowed because of the resulting mechanical stress. Minimizing hydro unit cycling with minimum up time, minimum down time and plant ramp rate constraints may also help to decrease wear and tear costs and other start-up costs of hydro units which can depend on the frequency of cycling constraint violations.

In addition, none of those papers solved UC with unit's prohibited zone limit. The Prohibited Operating Zones (POZs) in the input-output curve of generator are due to steam valve operation or vibration in a shaft bearing. Since it is difficult to determine the actual prohibited zone by actual performance testing or operating records, normally the best economy is achieved by avoiding operation in areas that are in actual operation. In practical operation, adjustment of the generation output of a unit must avoid operation in the prohibited zones. Hence we can say that not considering POZs in DHGS problem could fail to provide feasible solutions, because the optimal solution may require generating units to operate in their respective prohibited zones.

Furthermore, precise modelling for both hydro and thermal units operating characteristics usually result in higher nonlinear, non-smooth and non-convex functions. Valve point loading is an example of such type of cost function. Power plants commonly have multiple valves that are used to control the power output of the unit. When steam admission valves in thermal units are first opened, a sudden increase in losses is registered, which results in ripples in the cost function; then there is a need for use of non-differentiable and non-convex functions [1]. Detailed modeling of start-up costs requires using exponential functions [1]. Furthermore, taking into account ramp limitations, a precise modeling of contribution of the unit to the spinning reserve of the system requires the use of complex restrictions, usually formulated as nonlinear constraints [16,17]. Minimum up and down time constraints also require the enforcement of conditions usually expressed as nonlinear constraints [16]. Modelling of hydro system considers variable head water-to-power conversion function of hydro units, canals between reservoirs, inflows, topology of river-catchments, water rights, dependence of the hydro units characteristics with the head of upstream and downstream reservoirs, reservoirs volume, etc. This makes the model non-linear and non-concave [14].

The method used in this paper is based on MIP approach because Security Constrained Daily Hydrothermal Generation Scheduling (SCDHGS) is a mixed-integer optimization problem with a large number of 0-1 variables, continuous and discrete control variables, and a series of prevailing equality and inequality constraints. MIP method could obtain a better solution than LR method, which would result in wider applications of MIP method in power markets. In addition, it is easier to add constraints to MIP model, and nonlinearities of the problem can be accurately incorporated by using piecewise linear approximation, and no significant effort is needed to change the algorithm, which will speed up the development of a program and facilitate its applications to large-scale power systems [18,19].

In this paper, MIP approach is proposed for solving Security Constrained Daily Hydrothermal Generation Scheduling (SCDHGS) problem, which considers more practical constraints and rigorous modeling of thermal and hydro units than previous works in the area to the best of our knowledge. The main contributions of this paper can be summarized as:

(a) Presentation of linear formulation for valve point loading;

(b) Using dynamic ramp rate limit instead of fix ramp rate limit;

(c) Using flexible method for considering multi POZs for thermal units and multi-head for hydro units.

This paper is organized as follows: In Section 2, the optimal Daily Hydrothermal Generation Scheduling model is formulated as a 0/1 mixed-integer linear programming problem. Section 3 presents the case studies, and provides results with detailed discussion. Finally, conclusions are stated in Section 4.

2. SCDHGS formulation based on MIP

The objective of SCDHGS is to determine an optimum schedule of generating units for minimizing the cost of supplying energy and ancillary services with considering network security constraints. In this paper network, security constraints include both transmission flow and bus voltage constraints. In the case of a hydro company, the production costs are negligible. As it is reported in [14], the start-up costs have real impact on the short-term scheduling of hydro generation. Start-up costs are mainly caused by the increased maintenance of windings and mechanical equipment and by malfunctions of the control equipment. Therefore, we consider modeling of start-up costs of hydro plants to avoid unnecessary start-ups. Thus, the objective function is formulated as follows:

$$\min \sum_{t\in T}\left\{\sum_{i\in I}[F(i,t)+A_iZ(i,t)+B(i,t)+C(i,t)] + \sum_{j\in J}A_jY(j,t)\right\}, \tag{1}$$

where the first term represents thermal operating cost including fuel, shutdown, start-up costs and valve point loadings cost; the second term represents the start-up cost of hydro units over the given period. The list of symbols is presented in the Nomenclature section. As mentioned earlier, in practice, with considering valve point loading effects on hydrothermal scheduling, the non-linear function of fuel cost thermal has non-differentiable points, and there is a need for use of non-differentiable and non-convex function [1]. Next section provides an alternative linear formulation of this problem that allows us to tighter the approximated MILP formulations for unit commitment problems in Security Constrained Daily Hydrothermal Generation Scheduling. In addition, nonlinear constraints such as start-up costs, minimum up and down time constraints and maximum and minimum power output constraints are converted into linear constraints.

2.1. Thermal units' model

2.1.1. Piecewise linear approximation of nonlinear fuel cost function considering POZ

Practical generating thermal units have prohibited operating zones due to some faults in the machines or their accessories such as pumps, boilers, etc. [20]. A unit with prohibited operating zones has discontinuous input-output characteristics (Figure 1). As shown in Figure 1, the quadratic production cost function

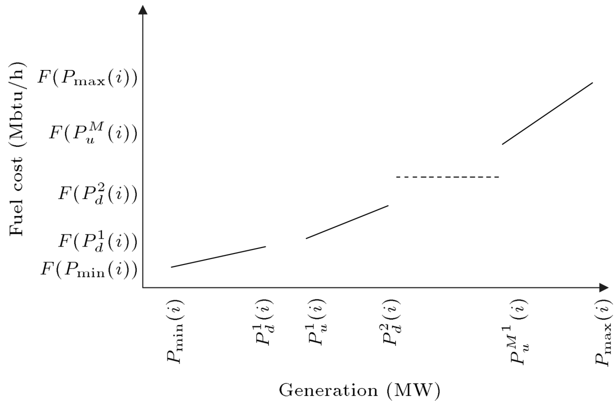

Figure 1. Piecewise linear fuel cost curve with M prohibited zones.

can be accurately approximated by a set of piecewise blocks [21]. The analytic representation of this linear approximation with M POZs is:

$$F(i,t)=\sum_{n=1}^{M+1}\left[\beta_n(i,t)F(p_{n-1}^u(i))+b_n(i)\delta_n(i,t)\right] \quad \forall i\in I, \quad \forall t\in T, \tag{2}$$

$$P(i,t)=\sum_{n=1}^{M+1}[p_{n-1}^u(i)\beta_n(i,t)+\delta_n(i,t)] \quad \forall i\in I, \quad \forall t\in T, \tag{3}$$

$$\delta_n(i,t)\geq 0 \quad n=1,2,\cdots,M+1, \quad \forall i\in I, \quad \forall t\in T, \tag{4}$$

$$\delta_n(i,t)\leq[p_n^d(i)-p_{n-1}^u(i)]\beta_n(i,t) \quad n=1,2,...,M+1, \quad \forall i\in I, \quad \forall t\in T, \tag{5}$$

$$\sum_{n=1}^{M+1}\beta_n(i,t)=I(i,t) \quad \forall i\in I, \quad \forall t\in T, \tag{6}$$

$$\beta_n(i,t)\in\{0,1\} \quad n=1,2,\cdots,M+1, \quad \forall i\in I, \quad \forall t\in T, \tag{7}$$

where:

$$p_0^u(i)=p_{\min}(i) \quad \text{and} \quad p_{M+1}^d(i)=p_{\max(i)}.$$

2.1.2. Valve point loadings cost

For more practical and accurate modeling of SCDHGS problem, the nonlinear fuel cost function needs to be modified due to the consideration of valve-point effects, which is referred to as a sharp increase in fuel loss, which is added to the fuel cost curve due to the wire

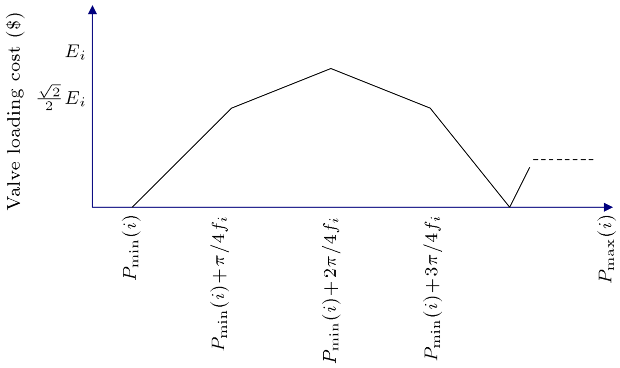

Figure 2. Linear approximation of absolute sinus function of valve point loading cost.

drawing effects, when steam admission valve starts to open [22]. Previous works [23-25] implement absolute sinus function of power generated by thermal units, considering valve point loadings, but this function is very non-smooth and non-convex, and can be an obstacle in MIP model. To overcome this obstacle, we proposed this linear formulation to cope with valve point loadings (Figure 2).

$$C(i,t)=\frac{2f_i e_i}{\pi}\left\{\begin{array}{l}\sqrt{2}\sum_{n=0}^{k_i}[\psi_{4n+1}(i,t)-\psi_{4n+4}(i,t)]\\ +\left(2-\sqrt{2}\right)\sum_{n=0}^{k_i}[\psi_{4n+2}(i,t)-\psi_{4n+3}(i,t)]\end{array}\right\}$$

$$\forall i\in I,\qquad \forall t\in T, \tag{8}$$

where f_i and e_i are coefficients of valve point effects for ith thermal unit, and $\psi_n(i,t)$ is power generated by nth block.

$$p(i,t)=p_{\min}(i)I(i,t)+\sum_{n=0}^{k_i}\left[\begin{array}{l}\psi_{4n+1}(i,t)+\psi_{4n+2}(i,t)\\+\psi_{4n+3}(i,t)+\psi_{4n+4}(i,t)\end{array}\right]$$

$$\forall i\in I,\qquad \forall t\in T, \tag{9}$$

$$\frac{\pi}{4f_i}\chi_1(i,t)\leq\psi_1(i,t)\leq\frac{\pi}{4f_i}I(i,t)$$

$$\forall i\in I,\qquad \forall t\in T, \tag{10}$$

$$\frac{\pi}{4f_i}\chi_n(i,t)\leq\psi_n(i,t)\leq\frac{\pi}{4f_i}\chi_{n-1}(i,t)$$

$$\forall i\in I,\qquad \forall t\in T,\qquad n=2,3,\cdots,x_i, \tag{11}$$

$$\chi_n(i,t)\in\{0,1\}\qquad \forall i\in I,\qquad \forall t\in T,$$

$$n=1,2,\cdots,x_i, \tag{12}$$

where:

$$k_i=\text{floor}[f_i\frac{p_{\max}(i)-p_{\min}(i)}{\pi}],$$

and:

$$x_i=\text{floor}[4f_i\frac{p_{\max}(i)-p_{\min}(i)}{\pi}].$$

Constraint (9) states that the power output of unit i at hour t is the sum of minimum power output, if the unit is on, plus the power generated in each block. Constraint (10) limits the power generated in first block; this power should be greater than zero and smaller than or equal to $\pi/4f_i$, that is "power length" of each block. In this constraint, $I(i,t)$ is used ensuring that power generated of first block is equal to zero, if unit i is off at hour t. To limit the generated power in each block, $\chi_n(i,t)$ is introduced in Constraints (10) to (12). This binary variable equals one, if the generated power of unit i at hour t has exceeded block n.

2.1.3. Dynamic ramping up/down limit

Ramp rate limit restricts the power output between two successive operating periods. The generators respond to hourly system load fluctuations by increasing or decreasing the produced power. In this section, we use dynamic ramp rate with M POZs, and ramp rate is the function of power generation (Figure 3).

$$\text{RUL}(p(i,t))=\sum_{n=1}^{M+1}\text{RUL}_n(i)\beta_n(i,t)$$

$$\forall i\in I,\qquad \forall t\in T, \tag{13}$$

$$\text{RDL}(p(i,t))=\sum_{n=1}^{M+1}\text{RDL}_n(i)\beta_n(i,t)$$

$$\forall i\in I,\qquad \forall t\in T. \tag{14}$$

Constraints (13) and (14) indicate dynamic ramp limit with M POZs. The binary variables are used to indicate which operating zone has been selected. Another formulation for dynamic ramp rate is proposed in [26].

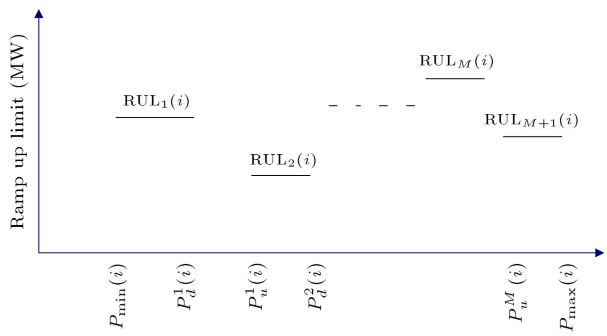

Figure 3. Ramping up limit as a stepwise linear function of generation with M POZs.

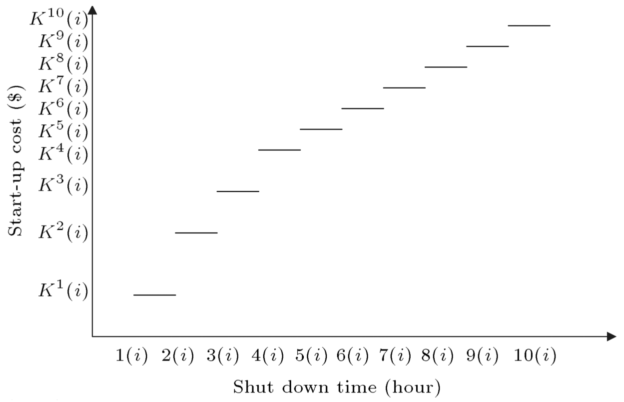

Figure 4. Piecewise linear start-up cost.

2.1.4. Stair-wise formulation of the time-dependent start-up cost function

The start-up cost is modeled as a nonlinear (exponential) function of the number of hours a unit has been off. Two different formulations for linear formulation of time-dependent start-up cost function are proposed in [27,28]. In [27,28], the start-up cost is modeled as a linear function of the number of hours a unit has been off (Figure 4). In this paper, the formulation of [27] is implemented, and by using large enough number of NL, start-up cost approximates the original exponential model.

$$B(i,t)=\sum_{\lambda=1}^{\mathrm{NL}} K^{\lambda}(i)w^{\lambda}(i,t) \qquad \forall i\in I, \qquad \forall t\in T. \tag{15}$$

The above equation represents the time varying start-up cost linear function, and $K^{\lambda}(i)$ is the cost of the λth discrete interval of the start-up cost of unit i. $w^{\lambda}(i,t)$ is the binary variable and equals 1, if unit i is started-up at the beginning of hour t, and it has been off for λ hours.

$$\sum_{\lambda=1}^{\mathrm{NL}} w^{\lambda}(i,t)=y(i,t) \qquad \forall t\in T, \tag{16}$$

$$s(i,t-1)=\sum_{\lambda=1}^{\mathrm{NL}-1}\lambda w^{\lambda}(i,t)+\gamma(i,t)$$

$$\forall i\in I, \qquad \forall t\in T, \tag{17}$$

$$\mathrm{NL}w^{\mathrm{NL}}(i,t)\le\gamma_i(t)\le\overline{s}_i\left\{w^{\mathrm{NL}}(i,t)-y(i,t)+1\right\}$$

$$\forall i\in I, \qquad \forall t\in T, \tag{18}$$

$$w^{\lambda}(i,t)\in\{0,1\} \qquad \forall i\in I, \qquad \forall\lambda\in\Lambda, \qquad \forall t\in T. \tag{19}$$

Constraint (16) forces only one of the binary variables to be equal to 1, if unit i is started up. Eq. (17) relates the variables to the time counter through a dummy variable $\gamma(i,t)$. A Dummy variable is used when unit i is started up at hour t, which has been off for NL hours or longer, or is used when unit i is off at hour t.

2.1.5. Minimum Up Time (MUT) and Minimum Down Time (MDT)

Linear expressions of minimum up time and minimum down time are stated as follows:

$$\sum_{t=1}^{B(i)}[1-I(i,t)]=0 \qquad \forall i\in I,l, \tag{20}$$

$$\sum_{\tau=t}^{T_1} I(i,\tau)\ge UT(i)y(i,t)$$

$$\forall i\in I, \qquad T_1=t+UT(i)-1,$$

$$\forall t=B(i)+1,\cdots,\Theta-UT(i)+1, \tag{21}$$

$$\sum_{\tau=t}^{\Theta}[I(i,\tau)-y(i,t)]\ge 0$$

$$\forall i\in I, \qquad \forall t=\Theta-UT_i+2,\cdots,\Theta, \tag{22}$$

$$\sum_{t=1}^{C(i)} I(i,t)=0 \qquad \forall i\in I, \tag{23}$$

$$\sum_{\tau=t}^{T_2}[1-I(i,\tau)]\ge\mathrm{DT}(i)Z_i(t)$$

$$\forall i\in I, \qquad T_2=t+\mathrm{DT}(i)-1,$$

$$\forall t=C(i)+1,\cdots,\Theta-DT(i)+1, \tag{24}$$

$$\sum_{\tau=t}^{\Theta}[1-I(i,\tau)-z(i,t)]\ge 0$$

$$\forall i\in I, \qquad \forall t=\Theta-DT(i)+2,\cdots,\Theta, \tag{25}$$

where:

$$B(i)=\min\{\Theta,(UT(i)-U^0(i))I^0(i)\},$$

and:

$$C(i)=\min\{\Theta,[DT(i)-s^0(i)][1-I^0(i)]\}.$$

Once a unit is committed, it should not be turned off for a minimum number of hours. Eq. (20) is related to the initial status of the units if $B(i)$ is less than $UT(i)$, and this equation forced the unit to be on. Eq. (21) satisfy MUT limit for consecutive periods, and Eq. (22) satisfy MUT limit for the last hours. Once a unit decommitted, it should not be turned on for a minimum number of hours, and Constraints (23)-(25) enforce the MDT limit.

2.1.6. Power output limits

These constraints ensure that the power generated from each unit is constrained by the practical capacity limits of the thermal unit. Ramp-up rate limit, and the start-up and shut-down ramp rates limits are considered; therefore, they are more practical constraints and allows us to have rigorous modeling of thermal and hydro units in SCDHGS problem.

$$p_{\min}(i)I(i,t) \le p(i,t) \le \overline{p}(i,t) \qquad \forall i \in I, \qquad \forall t \in T, \tag{26}$$

$$\overline{p}(i,t) \le p_{\max}(i)\left\{I(i,t) - z(i,t+1)\right\} + \mathrm{SD}(i)Z(i,t+1) \qquad \forall i \in I, \qquad \forall t \in T, \tag{27}$$

$$p(i,t+1) - p(i,t) \le \mathrm{SU}(i)y(i,t+1) + \mathrm{RUL}(p(i,t)) \qquad \forall i \in I, \qquad \forall t \in T, \tag{28}$$

$$p(i,t-1) - p(i,t) \le \mathrm{SD}(i)Z(i,t) + \mathrm{RDL}(p(i,t)) \qquad \forall i \in I, \qquad \forall t \in T. \tag{29}$$

Constraint (26) indicates that generation output limits and power output of each unit for each period is greater than minimum power output if unit is on and less than the upper limit of unit. The next constraint show the upper limit of real power generation of unit i at time study. Constraint (28) indicates the start-up ramp rate and Ramp-Up Limit (RUL), and Constraint (29) refers to the shut-down ramp rate and Ramp-Down Limit (RDL). In a majority of published papers, RUL and RDL were assumed fixed, but in this paper, we use dynamic ramp rate to give a more accurate model.

The other thermal generation units constraints considered are: system spinning and operating reserve requirements [29], shut-down time counter [27] and logical status of commitment [30]. Beside the previously described thermal generation unit constraints, this paper also considers additional system-wide constraints such as fuel constraints and emission limits [28,31-33] in this formulation for representing the interactions among electricity market, fuel market and environment. For the sake of brevity, the formulation of these constraints is not included in this paper. However, the interested reader is referred to mentioned references, where a precise formulation for these constraints is provided.

2.2. Cascaded-hydro units' model

This section considers not only the nonlinear dependence between power generation, water discharge and head, but also the variable head of the associated reservoir (Figure 5), in order to obtain more realistic and feasible results. In most papers, the effect of the variation of head has been neglected and head is assumed fixed. For example, Ref. [30] presented a homogenous Interior Point (IP) method to solve the STHTC problem. Many constraints were considered in the model and effectiveness of the proposed model has been reported for medium-size and large-size case studies, but the effect of the variation of head has been neglected and head is assumed fixed to avoid nonlinearities, which allows using a single unit performance curve. Since this simplification may lead to inaccuracies, in our paper, the effect of the variation of head is considered, and the proposed MILP model takes into account the accurate representation of the variation of performance curves with the reservoir head. Therefore, relationships between water discharge, generated power and multi-head of reservoir are presented in the set of curves instead of single unit performance curve. Moreover, to prevent unnecessary commitments and loss of water during maintenance and start-up period, the start-up cost of hydro plants are considered in the model. The proposed model takes into account head-dependent reservoirs with MIP formulations, as well as hydro plants, connected both in parallel and series (Figure 6). The number of heads for power plants is considered to be L in the following formulations (Figure 5).

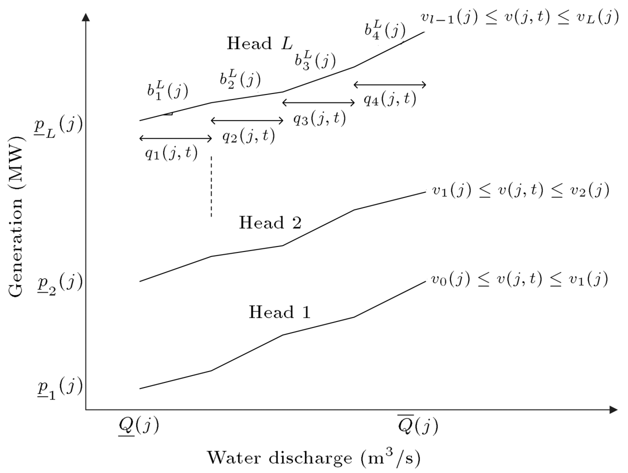

Figure 5. Three-dimensional piecewise linear non-concave unit performance curve for hydro plant j at hour t.

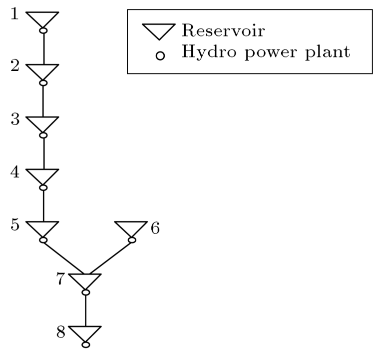

Figure 6. Hydraulic topology of the river basin.

2.2.1. Volume and head

In this part, the general formulations of hydro power plants with L heads are presented:

$$v(j,t) \geq v_0(j) \qquad \forall j \in J, \qquad \forall t \in T, \tag{30}$$

$$v(j,t) \leq v_L(j)\beta_{L-1}(j,t) + \sum_{n=2}^{L} v_{n-1}(j)[\beta_{n-2}(j,t) - \beta_{n-1}(j,t)] \qquad \forall j \in J, \qquad \forall t \in T, \tag{31}$$

$$v(j,t) \geq v_{L-1}(j)\beta_{L-1}(j,t) + \sum_{n=3}^{L} v_{n-2}(j)[\beta_{n-2}(j,t) - \beta_{n-1}(j,t)] \qquad \forall j \in J, \qquad \forall t \in T, \tag{32}$$

$$\beta_1(j,t) \geq \beta_2(j,t) \geq \cdots \geq \beta_{L-1}(j,t) \qquad \forall j \in J, \qquad \forall t \in T, \tag{33}$$

where $\beta_0(j,t) = 1$.

Constraint (30) states that the volume of each hydro plant at each period should be greater than the minimum content of that hydro plant. Constraints (31) and (32) appoint right head corresponding to volume. It should be noted that Constraints (33) avoid the combination 0-1 for variables $\beta_n(j,t)$. Note that $\beta_n(j,t)$ is equal to 1 when $(n+1)$th head is used.

2.2.2. Piecewise linearization of variable head water-to-power conversion function

The power output of a hydro unit is, in general, a nonlinear function of the turbine discharge rate and the net head or, equivalently, the volume of the stored water in the reservoir. Due to the reservoirs small storage capacity and fluctuations of water discharge and power output, which affects the plant head, a multi head reservoir is included in the proposed general MIP formulations. The linear relationship between generated powers, discharged water and variable head can be described by Constraints (34) and (35) as follow:

$$p(j,t) - \underline{p}_k(j)I(j,t) - \sum_{n\in N} q_n(j,t)b_n^k(j) - \overline{p}(j)\left[(k-1) - \sum_{n=1}^{k-1}\beta_n(j,t) + \sum_{n=k}^{L-1}\beta_n(j,t)\right] \leq 0 \qquad \forall j \in J, \qquad \forall t \in T, \qquad 1 \leq k \leq L, \tag{34}$$

$$p(j,t) - \underline{p}_k(j)I(j,t) - \sum_{n\in N} q_n(j,t)b_n^k(j) + \overline{p}(j)\left[(k-1) - \sum_{n=1}^{k-1}\beta_n(j,t) + \sum_{n=k}^{L-1}\beta_n(j,t)\right] \geq 0 \qquad \forall j \in J, \qquad \forall t \in T, \qquad 1 \leq k \leq L. \tag{35}$$

The definition of the parameters and variables can be found in the Nomenclature Section.

2.2.3. Water discharge limits

$$Q(j,t) = \underline{Q}(j)I(j,t) + \sum_{n\in N} q_n(j,t) \qquad \forall j \in J, \qquad \forall t \in T. \tag{36}$$

In the above constraint, $Q(j,t)$ is water discharge of hydro plant j at hour t, and $\underline{Q}(j)$ is minimum water discharge of hydro plant j if it is on. For flooding prevention and irrigation requirements, the following constraint is needed.

$$\underline{\theta}(j,t) \leq Q(j,t) + s(j,t) \leq \overline{\theta}(j,t) \qquad \forall j \in J, \qquad \forall t \in T. \tag{37}$$

$\underline{\theta}(j,t)$ and $\overline{\theta}(j,t)$ are minimum and maximum water discharge of hydro plant j at hour t, respectively. Also, $s(j,t)$ is the spillage of hydro plant j at hour t. Here, we use two blocks for linearization of the spillage-volume curve [14], which can be incorporated into the MIP problem.

$$q_1(j,t) \leq \overline{Q}_1(j)I(i,t) \qquad \forall j \in J, \qquad \forall t \in T, \tag{38}$$

$$q_1(j,t) \geq \overline{Q}_1(j)h_1(j,t) \qquad \forall j \in J, \qquad \forall t \in T, \tag{39}$$

$$q_n(j,t) \leq \overline{Q}_n(j)h_{n-1}(i,t) \qquad \forall j \in J, \qquad \forall t \in T, \qquad \forall n \in N, \tag{40}$$

$$q_n(j,t) \geq \overline{Q}_n(j)h_n(j,t) \qquad \forall j \in J, \qquad \forall t \in T, \qquad \forall n \in N. \tag{41}$$

Constraints (38) and (39) restrict the first block of water discharge, and Constraints (40) and (41) restrict other blocks of water discharge. $\overline{Q}_n(j)$ is maximum water discharge of the nth block of hydro plant j. $h_n(j,k)$ is the binary variable and equal to one, if the water discharge of hydro plant j at hour t exceeds the nth block.

2.2.4. Logical status of commitment

Constraint (42) is related to logical relationships between three binary variables, i.e. start-up status, shut-down status and status of unit at each time. Besides, Constraint (43) is used for avoiding the simultaneous commitment and decommitment of each unit.

$$y(j,t) - z(j,t) = I(j,t) - I(j,t-1)$$

$$\forall j \in J, \qquad t \in T, \tag{42}$$

$$y(j,t) + z(j,t) \leq 1 \qquad \forall j \in J, \qquad t \in T. \tag{43}$$

2.2.5. Security constraints

In this paper, the transmission constraints will be formulated as linear constraints, based on a DC power flow model. DC power flow network model is more accurate than the linear power flow model. The physical flow in a transmission network is governed by Kirchoff's Current Law (KCL) and Kirchoff's Voltage Law (KVL), which are taken care in DC model. In contrast, the linear power flow model considers only KCL [34]. With DC power flow model, transmission constraints are formulated as linear constraints, and the practical constraints related to thermal plants, hydroelectric systems are represented by piecewise linear approximation; therefore, SCDHTG is a Mixed Integer Linear Programming (MILP) problem.

DC power flow equation in steady state:

$$\sum_{i=1}^{\mathrm{NG}_b} P_{it} - P_{bt}^D = \sum_{l=1}^{L_b} P_{lt} \qquad \forall b, \qquad \forall t \in T, \tag{44}$$

$$F_{lt} = \frac{1}{X_l}(\delta_{ls} - \delta_{lr}) \qquad \forall b, \qquad \forall t \in T. \tag{45}$$

Transmission flow limits in the base case:

$$-F_{lt}^{\max} \leq F_{lt} \leq F_{lt}^{\max} \qquad \forall l, \qquad \forall t \in T. \tag{46}$$

The other hydro generation unit constraints can be consideredas: Initial and final volume [14], water balance [30] and operating services [31]. Precise formulation for these constraints is formally defined in the mentioned references.

3. Case studies

We apply 3 case studies, consisting of a modified IEEE 118-bus system, to illustrate the impact of two important kinds of nonlinear behavior, which includes prohibited operating zone and valve point loading effects on SCDHGS. A modified IEEE 118-bus system is the largest SCUC test case with publicly available data that we could find in literature, and has 54 thermal generating units (33 coal-fired units, 11 gas-fired units and 10 oil-fired units) and 8 hydro plants.

Table 1. Hourly load distribution over 24-hour period.

Hour	Load (MW)	Hour	Load (MW)
1	2730	13	3120
2	2574	14	2964
3	2262	15	3432
4	1560	16	3510
5	1950	17	3315
6	2340	18	3471
7	2730	19	3666
8	3042	20	3822
9	3198	21	3900
10	3432	22	3510
11	3471	23	3393
12	3276	24	3198

The peak load of 3900 MW occurs at hour 21. The IEEE test system used in [35] is also used here to test the performance of the proposed MIP optimization problem of SCDHGS. We use the same data for thermal units and constraint settings as described in [35]. The valve loading coefficients and POZ data are given in [36], and the hourly load distribution over the 24-h horizon is given in Table 1. For hydro plants we use 3 performance curves and each performance curve is modeled through 4 blocks, as shown in Figure 5. The other detailed hydro generating unit data are taken from [14]. All cases in this section are calculated using a Pentium IV, 3 GHz personal computer with 1GB RAM. The models were implemented in GAMS, using CPLEX solver [37]. In each case, we run SCDHGS and DHGS solution by excluding transmission and voltage constraints, and then compare the results for finding the effect of security constraints on each case.

3.1. Case 1: SCDHGS problem, considering valve loading cost and not considering POZs

In this section, we focus on Valve Loading Cost (VLC) of thermal units and ignore POZs. Thermal units 5, 10, 11, 28, 36, 43, 44 and 45 have valve loading cost. The commitment schedule is shown in Table 2, in which 1 and 0 represent ON/OFF states of units at different hours, and hour 0 represents the initial condition. The daily operating cost is $782347.41. In this system, economical units (such as 4-5, 11, 44 and 45) are used as base units, and expensive units (such as 1-3, 6-9 and 46-51) are not committed at all, but when valve loading cost effect is considered, expensive thermal unit 52 should be committed in order to satisfy the load at peak hour. The remaining units are committed accordingly to satisfy hourly load demands, and the total generated power by thermal and hydro units in the period of study is equal to

Table 2. Case 1: With VLC and without POZ.

Daily cost = $782347.412	
Hours (0-24)	
1-3	1000000000000000000000000
4-5	1111111111111111111111111
6-10	1000000000000000000000000
11	1111111111111111111111111
12-18	0000000000000000000000000
19	1111111111111111111111100
20-21	1111111111111111111111111
22-23	1000000000000000000000000
24-25	1111111111111111111111111
26	1000000000000000000000000
27-29	1111111111111111111111111
30-38	1000000000000000000000000
39	1111111111100000000000000
40	1111111111111111111111111
41-43	1000000000000000000000000
44-45	1111111111111111111111111
46-51	1000000000000000000000000
52	1111111111111111111111111
53-54	1000000000000000000000000
Hydro1	1111111111111111111111110
Hydro2	1111111111111111111111110
Hydro3	1111111111111111111111110
Hydro4	1111111111111111111000000
Hydro5	1111111111111111111111111
Hydro6	1100000000000011111111110
Hydro7	1111111111111111111110000
Hydro8	1111111111111111111111111

Table 3. Case 2: Without VLC and with POZ.

Daily cost = $788796.974	
Hours (0-24)	
1-3	1000000000000000000000000
4-5	1111111111111111111111111
6-10	1000000000000000000000000
11	1111111111111111111111111
12-18	0000000000000000000000000
19	1111111111111111111111110
20-21	1111111111111111111111111
22-23	1000000000000000000000000
24-25	1111111111111111111111111
26	1000000000000000000000000
27-29	1111111111111111111111111
30-38	1000000000000000000000000
39	1111110000000011111111111
40	1000000000000000000000000
41-43	1000000000000000000000000
44-45	1111111111111111111111111
46-51	1000000000000000000000000
52	1111111111111111111111111
53-54	1000000000000000000000000
Hydro1	1111111111111111111111110
Hydro2	1111111111111111111111000
Hydro3	1111111111111111111111110
Hydro4	1111111111111111100000000
Hydro5	1000000011111111111111111
Hydro6	1000000000000000001111110
Hydro7	1111111111111111100000000
Hydro8	1111111111111111111111111

58631.12 MW and 15234.88 MW, respectively. For finding the effect of security constraints on this case, we calculate DHGS solution by excluding transmission and voltage constraints; transmission flow violations will occur on lines 41,126,136-139 at hours 19-23. The daily operating cost is $756321.518, which is cheaper than those considered security constraints. Compared with earlier situation, unit 4, 44 and expensive thermal unit 52 are decommitted at hours 1-24. Correspondingly, inexpensive thermal unit 10, 39 and hydro 4 are committed at certain hours (e.g., 1-24, 11-24 and 19-23) to compensate the reduced supply and to satisfy the physical constraints.

3.2. *Case 2: SCDHGS problem, considering POZs and not considering valve loading cost*

In this section, we ignore valve loading cost. Thermal units 7, 10, 30, 34, 35 and 47 have POZs limitations. SCDHGS has a daily operating cost of $788796.97, as shown in Table 3. Compared with Case 1, thermal units 19 and 39 are committed at certain hours (e.g., 23, 14-24), and thermal unit 40 that was off in all 24 hours has been on. If we compare the daily operating cost of this case with respect to Case 1, it can be seen that the daily operating cost, considering prohibited operating zones, is higher than that of Case 1. Also, the total generated power of thermal and hydro units at the scheduling period is equal to 58360.49 MW and 15505.51 MW, respectively. Consequently, the total generated power of thermal units has been decreased in comparison with Case 1, but generated power of hydro units has been increased. When we calculate DHGS solution by excluding transmission and voltage constraints, transmission flow violations occur on the same line in Case 1, but at different hours. The daily operating cost is $748329.91, which is cheaper than what those security constraints are considered. Compared with earlier situation, unit 4, 19, 44 and expensive thermal unit 52 are decommitted at hours 1-24. Correspondingly, inexpensive thermal unit 10, 40 and hydro 4, 5, 7 are committed at certain hours (e.g., 1-24, 11-24 and 17-23, 1-6, 17-22) to compensate the reduced supply and to satisfy physical constraints.

3.3. Case 3: SCDHGS problem with valve loading cost and POZs

In this part, we consider the effects of valve loading cost and POZs on the optimal solution. The commitment schedule is shown in Table 4. The daily operating cost with considering valve loading cost and POZs is 789203.7343. For a better description, total generated power by thermal and hydro units for all case studies, over a 24-h period, is shown in Figure 7(a) and (b), respectively. Compared with Case 1, thermal units 19 and 39 are committed at certain hours (e.g., 23-24, 12-21) and thermal unit 40 that was on in all 24 hours has been off and hydro units 6, 7 and are commited at more hours to compensate the reduced supply for decommitting of thermal unit 40, and to satisfy physical constraints. If we compare the daily operating cost of this case with respect to Cases 1 and 2, it can be seen that the daily operating cost, with considering the prohibited operating zones, is higher. Also, the total generated power of thermal and hydro units at the scheduling period is equal to 58993.96MW, 14872.04 MW, respectively. Consequently, the total generated power of thermal units has been increased in comparison with Case 1, but generated power of hydro units has been decreased, because of the additional practical constraint such as valve loading cost and POZs. For quick reference, the three case tests are briefly described in Table 5.

Table 4. Case 3: With VLC and with POZ.

Daily cost = $789203.734	
	Hours (0-24)
1-3	1000000000000000000000000
4-5	1111111111111111111111111
6-10	1000000000000000000000000
11	1111111111111111111111111
12-18	0000000000000000000000000
19	1111111111111111111111111
20-21	1111111111111111111111111
22-23	1000000000000000000000000
24-25	1111111111111111111111111
26	1000000000000000000000000
27-29	1111111111111111111111111
30-38	1000000000000000000000000
39	1111111111111111111111000
40	1000000000000000000000000
41-43	1000000000000000000000000
44-45	1111111111111111111111111
46-51	1000000000000000000000000
52	1111111111111111111111111
53-54	1000000000000000000000000
Hydro1	1111111111111111111111110
Hydro2	1111111111111111111111000
Hydro3	1111111111111111111111110
Hydro4	1111111111111111111000000
Hydro5	1111111111111111111111111
Hydro6	1111111111111111111111000
Hydro7	1111111111111111111111110
Hydro8	1111111111111111111111111

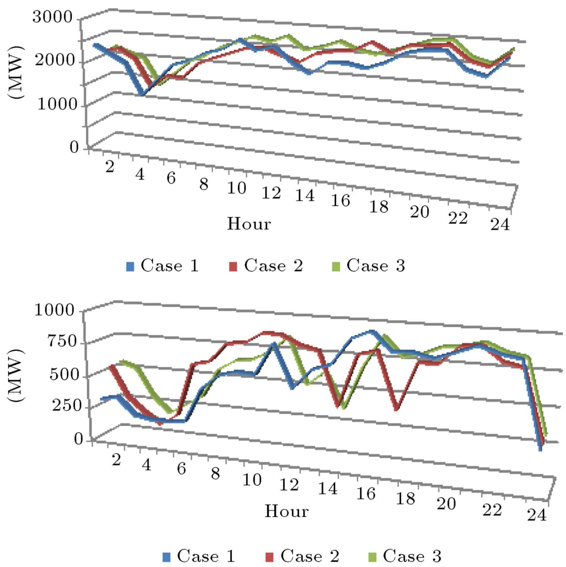

Figure 7. Total generated power by thermal and hydro units in 3 case studies.

When we calculate DHGS solution by excluding transmission and voltage constraints, transmission flow violations occur on the same line in Case 1, but at different hours, beside the lines 140 and 143. Tables 6-8 show all the transmission flow violations on congested lines, for three case studies, without considering the security constraints in which 1 and 0 represent congested/uncongested status of lines at different hours, and hour 0 represents the initial condition. The daily operating cost is $747226.2916, which is cheaper than those considered with the security constraints. Compared with earlier situations, unit 4, 19, 43, 44 and expensive thermal unit 52 are decommitted at hours 1-24, and hydro 6, 7 are decommitted at certain hours (e.g., 1-18, 17-23). Correspondingly, inexpensive thermal units 10 and 40 are committed at certain hours (e.g., 1-24) to compensate the reduced supply and to satisfy the physical constraints. For more explanation,

Table 5. Daily operating cost in 3 cases.

	With security constraints	Without security constraints
	Daily operating cost ($)	**Daily operating cost ($)**
Case 1	782347.412	756321.518
Case 2	788796.974	748329.915
Case 3	789203.7343	747226.2916

Table 6. Congested/uncongested status of violated lines in Case 1 (with VLC and without POZ).

	Hours (0-24)
L37	0000000000000000000111000
L41	0000000000000000000111110
L123	0000000000100001001111110
L124	0000000000000000001111110
L125	0000000000000000000000000
L126	0000000000000000000111110
L134	0000000000000000001111110
L136	0000000000000000001111110
L137	0000000000000000000111110
L138	0000000000000000000111110
L139	0000000000000000000111110
L140	0000000000000000000000000
L142	0000000000111000000000000
L143	0000000000000000000000000

Table 7. Congested/uncongested status of violated lines in Case 2 (without VLC and with POZ).

	Hours (0-24)
L37	0000000000000000000111000
L41	0011001000000000000111000
L123	0000000001000000111111100
L124	0000000001001000100111100
L125	0000000000000000000000000
L126	0000000001000000100000100
L134	0000000001001000100111100
L136	0000000001001000100111100
L137	0000000000000000100000100
L138	0000000000000000100000100
L139	0000000000000000000000100
L140	0000000000000000000000000
L142	0000000000000000011111000
L143	0000000000000000000000000

Table 8. Congested/uncongested status of violated lines in Case 3 (with VLC and POZ).

	Hours (0-24)
L37	0000000000000000000011000
L41	0001000000010000100111000
L123	0000000000111001100111110
L124	0000000000111001100000000
L125	0000000000010001100000000
L126	0000000000111001100000000
L134	0000000000111001100000000
L136	0000000000111001100000000
L137	0000000000111001100000000
L138	0000000000111001100000000
L139	0000000000111001100000000
L140	0000000000010001100000000
L142	0000000000000000000111110
L143	0000000000011001100000000

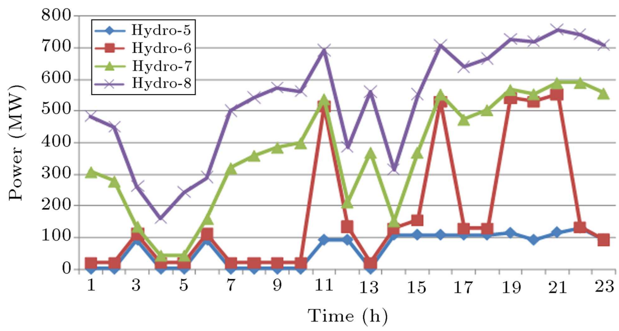

Figure 8. Hydro units hourly load dispatch for Case 3.

it can be seen from Tables 2-4 that POZ and VLC constraints cause changes in the amount of power generated by thermal and hydro units that have these constraints, and no changes in the condition of their unit commitment schedule. Figure 8 represents the hydro generation scheduling for Case 3, called hydro unit hourly load dispatch.

4. Conclusions

In this paper, the thorough and comprehensive MIP formulations for solving SCDHGS problem are proposed. The objective is to minimize the total cost while providing the total demand. The proposed framework consists of many practical constraints such as prohibited operating zones, valve point loadings, dynamic ramp rate, and fuel and emission limitations for thermal units. Furthermore, for hydro plants, the multi performance curve with spillage and time delay between the reservoirs are considered. The main feature of the proposed framework refers to the linear nature of the formulations, which is very important for application of the model in large scale and real size power system. Therefore, the proposed scheme is practical to generate the appropriate information for ISOs, to decide how much power is generated by each generator. The results of implementing the proposed model show that the solution time of the problem is rationale. The research work under way is to present a stochastic model for SCDHGS.

Nomenclature

Indices

i	Thermal unit index
j	Hydro unit index
t	Time interval (hour) index

Constants

η	Conversion factor equal to $3.6 \times 10^{-3}(\mathrm{Hm^3 s/m^3 h})$
Θ	Number of periods of the planning horizon
$\underline{\theta}(j,t)$	Minimum water discharge of unit j at hour t ($\mathrm{m^3/s}$)
$\overline{\theta}(j,t)$	Maximum water discharge of unit j at hour t ($\mathrm{m^3/s}$)
τ_{ij}	Time delay between reservoir of plant i and reservoir of plant j (h)
A_i	Shut down cost of unit i (\$)
A_j	Start-up cost of unit j (\$)
$b_n(i)$	Slope of block n of fuel cost curve of unit i (\$/MWh)
$b_n(j)$	Slope of the volume block n of the reservoir associated to unit j ($\mathrm{m^3/s/Hm^3}$) (1 $\mathrm{Hm^3}$=10^6 $\mathrm{m^3}$)
$b_n^k(j)$	Slope of the block n of the performance curve of k unit j ($\mathrm{MW/m^3/s}$)
$be_n(i)$	Slope of segment n in emission curve of unit i
$DT(i)$	Minimum down time of unit i (h)
e_i	Valve loading coefficient
f_i	Valve loading coefficient
$F(p_{n-1}^u(i))$	Cost of generation of $(n-1)$th upper limit in fuel cost of unit i
$F(j,t)$	Forecasted natural water inflow of the reservoir associated to plant j in period t ($\mathrm{Hm^3/h}$)
$K^\lambda(i)$	Cost of the λth discrete interval of the start-up cost of unit i (\$/h)
$I^0(i)$	Initial status of unit i (0/1)
L	Number of variable head
M	Number of prohibited operation zones
$\mathrm{MSR}(i)$	Maximum sustained ramp rate (MW/Min)
MU	Maximum number of the units that can be on at the same time
NL	Number of blocks of the piecewise linearization of the variable cost function
$p_{\min}(i)$	Minimum power output of unit i (MW)
$p_{\max}(i)$	Maximum power output of unit i (MW)
$\underline{p}_n(j)$	Minimum power output of plant j for performance curve n (MW)
$\overline{p}(j)$	Capacity of plant j (MW)
$p_n^d(i)$	Lower limit of nth prohibited zone of unit i (MW)
$p_{n-1}^u(i)$	Upper limit of $(n-1)$th prohibited zone of unit i (MW)
$\underline{Q}(j)$	Minimum water discharge of hydro plant j if is on ($\mathrm{m^3/s}$)
$\overline{Q}_n(j)$	Maximum water discharge of block n of plant j ($\mathrm{Hm^3}$)
$\mathrm{RDL}_n(i)$	Ramp down limit for block n (MW)
$\mathrm{RUL}_n(i)$	Ramp up limit for block n (MW)
$s^0(i)$	Time periods of unit i has been shut-down at the beginning of the planning horizon (h)
$\overline{s}(j)$	Maximum spillage of unit j ($\mathrm{m^3}$)
$s_{\max}(i)$	Maximum hour unit i can be off (h)
$\mathrm{SD}(i)$	Shut-down ramp rate limit of unit i (MW/h)
$\mathrm{SU}(i)$	Start-up ramp rate limit of unit i (MW/h)
$UT(i)$	Minimum up time of unit i (h)
$U^0(i)$	Time periods of unit i has been on-line at the beginning of the planning horizon (h)
$v_0(j)$	Minimum content of the reservoir associated to plant j ($\mathrm{Hm^3}$)
$v^0(j)$	Reservoir content at the beginning of the study time ($\mathrm{Hm^3}$)
$V^\Theta(j)$	Reservoir content at the end of the study time ($\mathrm{Hm^3}$)
$v_n(j)$	Maximum content of the reservoir j associated to nth variable head ($\mathrm{Hm^3}$)

Variables

$\beta_n(i,t)$	Binary variable equal to 1, if block n of fuel cost curve of unit i at hour t has been selected
$\beta_n(j,t)$	Binary variable equal to 1, if variable head $n+1$ of unit j at hour t has been selected
$\chi_n(i,t)$	Binary variable equal to 1, if power output of unit i at hour t has exceeded block n
$\delta_n(i,t)$	Generation of block n of fuel cost curve of unit i at hour t
$\gamma(i,t)$	Dummy variable (h)
$\psi_n(i,t)$	Generation of block n of unit i at hour t of valve point loadings curve
$\psi_n(j,t)$	Volume block n for the reservoir of hydro plant j at hour t (MW)
$B(i,t)$	Start-up cost of unit i at hour t ($)
$b_n(i)$	Slope of power block n of fuel cost curve of unit i ($/MWh)
$b_n^l(j)$	Slope of the block n of the performance curve l of hydro plant j (MW/m^3/s)
$c(i,t)$	Valve point loadings cost of unit i at hour t ($)
$F(i,t)$	Fuel cost of unit i at hour t ($)
$h_n(j,t)$	Binary variable equal to 1 if the water discharge of unit j at hour t has exceeded block n
$I(i,t)$	Binary variable equal to 1, if unit i is on-line at hour t
$I(j,t)$	Binary variable equal to 1, if hydro plant j is on-line at hour t
$Iu_n(i,t)$	Binary variable equal to 1, if block n of ramping up limit curve of unit i at hour t has been selected
$p(i,t)$	Power for bid on spot market at hour t (MW)
$\overline{p}(j,t)$	Maximum power output of unit i at hour t (MW)
$p(j,t)$	Maximum power output of unit j at hour t (MW)
$Q(j,t)$	Water discharge of unit j at hour t (m^3/s)
$q_n(j,t)$	Water discharge of block n of unit j at hour t (m^3/s)
$\mathrm{RDL}(p(i,t))$	Ramping down limit of unit i at hour t (MW)
$\mathrm{RUL}(p(i,t))$	Ramping up limit of unit i at hour t (MW)
$s(i,t)$	Time periods in which unit i has been shut-down at hour t (h)
$s(j,t)$	Spillage of the reservoir associated to unit j at hour t (m^3/s)
$v(j,t)$	Water content of the reservoir associated to plant unit j at hour t (Hm^3)
$w^\lambda(i,t)$	Binary variable equal to 1, if unit i is started up at the beginning of hour t and it has been offline for λ hours
$y(i,t)$	Binary variable equal to 1, if unit i is started up at the beginning of hour t
$y(j,t)$	Binary variable equal to 1, if unit j is started up at the beginning of hour t
$z(i,t)$	Binary variable equal to 1, if unit i is shut-down at the beginning of hour t
$z(j,t)$	Binary variable equal to 1, if unit j is shut-down at the beginning of hour t

Sets

I	Set of thermal units
J	Set of hydro units
N	Set of indices of the blocks of the piecewise linearization of the unit performance curve
T	Set of indices of the periods of the market time horizon
Λ	Set of the discrete intervals of the start-up cost function for thermal units
Ω_j	Set of upstream reservoirs of plant j

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