

Hydrothermal Scheduling Using an Improved Particle Swarm Optimization Technique Considering Prohibited Operating Zones

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Abstract: This study presents a solution procedure using particle swarm optimization to solve the Hydrothermal coordination problem for power generation considering Prohibited Operating Zones (POZ). Prohibited Operating Zones (POZ) induce nonlinear characteristics into the problem, dividing the operating region into various non-convex sub regions. This non convexity affects the performance of any algorithm to perform well. PSO is used as base algorithm to search for a better solution. The PSO algorithm is enhanced by the introduction of Crazyness function to effectively search for a better quality solution. In addition power balance, water discharge, reservoir volume and ramp limits are considered.

Key words: Hydrothermal coordination, prohibited operating zones, particle swarm optimization, crazyness function

INTRODUCTION

The energy efficient generation scheduling is well considered in power sector in order to reduce the production cost and also to improve the system stability and maximizing the power quality. The Hydro Thermal Coordination (HTC) is to determine the optimal generation schedule of the hydro and thermal units to minimize the total production cost over a scheduling horizon. The hydrothermal coordination problem is the one which deals with how to run all the generation units during the particular period of time to meet the forecasted demand and other operating constraints, especially how the hydro units can be utilized at the maximum level to reduce the total generation fuel cost by minimizing the thermal generator operation.

This study presents a HTC problem comprising of generating units modeled with POZ. The non linear characteristic of a generator include discontinuous prohibited zones, Ramp rate limits which are non- smooth and non-convex. Various literatures discussed about the non convexity in fuel cost function of the generating units considering with valve point effect (Lee and Breipohl, 1993; Gaing, 2003; Albert and Ebenezer, 2004; 2005). This valve point effect is modeled in two forms one is in the form of prohibited operating zones and the other is by including a rectified sinusoidal component in the fuel cost function (Albert and Ebenezer, 2005). This study proposes a HTC problem comprising of generating units modeled with POZ. In general, sufficient literature on HTC

problems proved the successful application of the global optimization technique such as genetic algorithm. Some of the computational complexities experienced by the above technique are overcome by Particle Swarm Optimization (PSO) introduced by Kennedy and Eberhart as one of the advanced heuristic algorithm (Kennedy and Eberhart, 1995). This study introduces a new algorithm based on particle swarm optimization to solve the HTC problem with POZ. The premature convergence of other heuristic techniques degrades their performance and reduces their search capability. Whereas the PSO technique can generate high quality solution within shorter duration compare to other stochastic methods, by having control over the inertia weight. In this study, the HTC problem is solved by considering the non linear constraints such as power balance constraints, total water discharge constraints and reservoir volume constraints, ramp rate limit and prohibited operating zones with respect to cost function in hydrothermal coordination problem.

Mathematical formulation of HTC: The Hydrothermal coordination problem can be formulated as a mathematical optimization problem as follows.

Min

$$C = \{u_{it} \cdot C_i(P_{it}) + SUP_{it} + SDN_{it}\} \quad (1)$$

Where

$$C_i(P_{it}) = \sum_{i=1}^N \alpha_i + \beta_i P_{it} + \gamma_i P_{it}^2 \quad 1, 2, \dots, N, \\ t = 1, 2, \dots, T$$

Subject to

System-wide (coupling) constraints $\forall t \in [1, T]$

$$\sum_{i=1}^N P_{i,t} + \sum_{j=1}^M P_{j,t} \geq D_t \text{ (Power Balance)} \quad (2)$$

$$\sum_{i=1}^N R_{s,i,t} + \sum_{j=1}^M R_{s,j,t} \geq R_t \text{ (Reserve Requirements)} \quad (3)$$

Thermal unit Constraints $\forall t \in [1, T], \forall i \in [1, N]$

$$P_i \leq P_{i,t} \leq P_i \text{ (Operating limits)} \quad (4)$$

$$P_{i,t} - P_{i,(t-1)} \leq UR_i \text{ and } P_{i,(t-1)} - P_{i,t} \leq DR_i \text{ (Ramp rates)} \quad (5)$$

Hydro system constraints $\forall t \in [1, T], \forall j \in [1, M]$

$$Q_j \leq Q_{j,t} \leq \bar{Q}_j \text{ (Hydro discharge limits)} \quad (6)$$

$$V_j \leq V_{j,t} \leq \bar{V}_j \text{ (Reservoir operating limits)} \quad (7)$$

$$V_{j,t} = V_{j,t-1} - Q_{j,t} - S_{j,t} + I_{j,t} + \sum_{k=1}^{M_1} (Q_{k,t-d_k} + S_{k,t-d_k}) \text{ (Water balance)} \quad (8)$$

$$V_{j0} = V_{j,ini} \text{ (Reservoir initial volume)} \quad (9)$$

$$V_{j,t} = V_{j,fin} \text{ (Reservoir target volume)} \quad (10)$$

Prohibited operating zone: The literature (Lee and Breipohl, 1993; Su and Chiou, 1997) have shown the input-output characteristics of thermal unit considering POZ as inequality constraints. The feasible operating zones of unit i can be described as follows:

$$\begin{aligned} & \underline{P}_i \leq P_i \leq P_{i,1}^l \\ & P_{i,z-1}^u \leq P_i \leq P_{i,z}^l, z = 2, 3, \dots, Z_i \\ & P_{i,n_i}^u \leq P_i \leq \bar{P}_i \end{aligned} \quad (11)$$

where z is the number of prohibited zones of unit i . Adjusting the generating units output P_i must avoid unit operation in the prohibited zones.

MATERIALS AND METHODS

The following formulation is used for solving the short term hydrothermal scheduling problem through PSO technique to be discussed in the next section. Arbitrarily select a time interval 'd' in the schedule horizon. Let the unknown thermal generation in the dth time interval be the dependent generation.

The P_{id} can be calculated by assuming that the thermal generations of the independent intervals, i.e., P_{it} for $t = 1, 2, \dots, d-1, d+1, \dots, T$ are known. In order to obtain the P_{id} the hydro generation in the P_{id} dependent interval, is required to be calculated.

Solution of P_{id} and P_{it} : Substituting the equations as given in (Hota *et al.*, 1993), we get the expression as

$$K(P_{jt})^2 - P_{jt} + (D_t - P_{it}) = 0 \quad (12)$$

The water discharge rate in any interval then becomes a function Q' ($D_t - P_{it}$) and the total water discharge is expressed as

$$Q_{total} = \sum_{t=1}^Z n_t Q'(D_t - P_{it}) \quad (13)$$

Given the quantity of total water discharge Q_{total} and the load pattern, i.e., D_t for $t = 1, 2, \dots, Z$, the water discharge rate in the dependent interval is obtained as

$$Q'(D_d - P_{id}) = \left[Q_{total} - \sum_{t=1, t \neq d}^Z n_t Q'(P_{jt}) \right] / n_d \quad (14)$$

where n_d is the dependent time interval.

After obtaining the discharge rate in the dependent interval, the hydro generation in this interval, P_{jd} , is obtained from the function of the discharge rate as in (Hota *et al.*, 1993), by simple algebraic method. The thermal generation in the dependent interval can be calculated as:

$$P_{id} = D_d + K(P_{jd})^2 - P_{jd} \quad (15)$$

The hydrogeneration in the non dependent intervals are then obtained by solving the following Equation.

$$K(P_{jt})^2 + D_t - P_{jt} - P_{it} = 0 \text{ for } t = 1, 2, \dots, (d-1), (d+1), \dots, T. \quad (16)$$

The volume of water in the reservoir at the end of each interval is then calculated using Equation as given in (Hota *et al.*, 1993). All generation level and water volumes must be checked against their limiting values as per the Equations given in (Hota *et al.*, 1993). In determining optimal solution for the hydrothermal coordination according to the above mentioned problem

solving formulation, the main objective is to determine thermal generation in the non-dependent interval. In this paper particle swarm optimization based algorithm has been applied to determine the non-dependent thermal generations and hence, the global optimum hydrothermal coordination is achieved.

Overview of PSO algorithm: PSO is one of the modern heuristics algorithms. In 1995, Kennedy and Eberhart first introduced the PSO technique (Kennedy and Eberhart, 1995), motivated by social behavior of organism such as fish schooling and bird flocking. So, as a heuristic optimization tool, provides a population-based search procedure in which individuals called particles change their position (states) with time. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience and the neighboring experiences of particles, making use of the best position encountered by itself and its neighbors.

Let x and v denote a particle position and its corresponding velocity in a search space respectively. The modified velocity and position of each particle can be calculated using the current velocity and the distance from pbest to gbest as shown in the following expressions:

$$V_{id}^{(t+1)} = \omega \cdot V_{id}^{(t)} + c_1 \cdot \text{rand}_1 \cdot (pbest_{id} - x_{id}^{(t)}) + c_2 \cdot \text{rand}_2 \cdot (gbest_d - x_{id}^{(t)}) \quad (17)$$

where,

- $V_i^{(t)}$: velocity of particle I at iteration t.
- ω : Inertia weight factor
- c_1, c_2 : Acceleration constant
- $\text{rand}_1, \text{rand}_2$: random number between 0 and 1.
- $X_i^{(t)}$: Current position of particle I at iteration t.
- $Pbest_{id}$: best of particle i.
- $gbest_d$: gbest of the group.

Similar to other evolutionary algorithms, PSO must also have a fitness function that takes the particle's position and assigns to it a fitness value. For consistency, the fitness function is the same as for the other algorithms. The position with minimum fitness value in the entire run is called the global best (gbest). Also each particle keep tracking its minimum fitness value, called as local best (l best or pbest). Each particle is initialized with a random position and velocity. The velocity v_j^t of the jth particle, each of n dimensions, accelerated towards the global best and its own personal best.

PSO has a well balanced mechanism to enhance both global and local exploration abilities. This is

realized by inertia weight w and is calculated by the following expression:

$$\omega = \omega_{max} - \left(\frac{\omega_{max} - \omega_{min}}{\text{iter}_{max}} \right) \times \text{iter} \quad (18)$$

where, ω_{max} ω_{min} is the initial and final weight, iter_{max} is the maximum iteration count and iter is the current iteration number. From the above equation certain velocity can be calculated, which gradually gets close to pbest and gbest. The current position (searching point in the solution space) can be modified by the following expression:

$$X_{id}^{(t+1)} = X_{id}^{(t)} + V_{id}^{(t+1)}, i = 1, 2, 3, \dots, n \text{ and } d = 1, 2, 3, \dots, m \quad (19)$$

Craziness function: The main draw backs of the PSO are its premature convergence, especially while handling problems with more local optima and heavily constrained. To solve this, the concept of craziness (Kennedy and Eberhart, 1995), with the particles having a predetermined probability of craziness, is incorporated, while in general increases the probability of finding a better solution in the complex domain.

Thus, "crazy" agents are initiated, when they find a premature convergence of the procedure. In this study, the probability of craziness ρ_{cr} (identification of particles and randomizing its velocity) is expressed as a function of inertia weight, to ensure the control of inertia weight during the search

$$\rho_{cr} = \omega_{min} - \exp\left(-\frac{\omega^t}{\omega_{max}}\right) \quad (20)$$

Thus

$$v_j^t = \begin{cases} \text{rand}(0, v_{max}), & \text{if } \rho_{cr} \geq \text{rand}(0, 1) \\ v_j^t, & \text{Otherwise} \end{cases} \quad (21)$$

where

ω^t is the inertia weight at the tth iteration of the run and $\text{rand}(0, 1)$ is the random number between 0 and 1. It is obvious that, if the PSO procedure gets stuck in the beginning of the run, a high value of ρ_{cr} will be used to generate "crazy" particles. While the run progresses, a comparatively low value of ρ_{cr} will be used to generate "Crazy" particles. Thus the significance of control of inertia weight in the PSO algorithm is also retained.

Particles velocities on each dimension are clamped to maximum allowable velocity v_{max} if the sum of accelerations exceeds the limit (Eberhart and Shi, 2001). V_{max} is an important parameter that determines the resolution with which regions between the present position and the target position are searched. If v_{max} is too high, agents may fly past good regions. If it is low, agents may not explore sufficiently beyond locally good regions. To enhance the performance of the PSO, v_{max} is set to the value of the dynamic range of each control variable in the problem.

Evaluation of each particle: Each Particle is evaluated using the fitness function of the problem to minimize the fuel cost function given by Lee and Breipohl (1993). The best fitness value of each particle up to the current iteration is set to that if the local best of that particle.

Modification of each searching point: Using the global best and the local best of each particle up to the current iteration, the searching point of each agent has to be modified according to the following expression:

$$\begin{aligned}
 p_j(t) &= v_j(t) + p_j(t-1) \\
 v_j(t) &= \omega(t)v_j(t-1) + c_1 \text{rand}_1 (P_{Lbest,j} - P_j(t-1)) \\
 &\quad + c_2 \text{rand}_2 (P_{Gbest} - P_j(t-1))
 \end{aligned}$$

where rand_1 and rand_2 are random numbers between 0 and 1 and C_1, C_2 are acceleration factors. Similar to inertia weight, acceleration factors also controls the exploration of the PSO (Kennedy and Eberhart, 1995). These are the stochastic acceleration terms that pull each particle towards P_{best} and G_{best} positions. Thus improved performance of PSO can be obtained carefully selecting suitable values for inertia weight C_1 and C_2 . Thus, new searching points were explored for the next iteration to further exploit the search. The elements of the new searching point matrix $P_j(t)$ should be forced to satisfy the real power generation limits given in (Far and Mcdonald, 1994). Once the new searching points were determined, inertia weight had to be modified using (18).

Modification of the global and the local bests: Each particle should be evaluated using the fitness function of the dynamic economic dispatch, as was done in point (1) in this section. P_{Gbest} and $P_{Lbest,j}$ have to be modified according to the present fitness function values evaluated using the new searching points of the particle. If the best fitness value of all the fitness function values is better than the $O_{j,best}(t-1)$, then change P_{Gbest} to this value of the searching point of the corresponding particle contribute for this best fitness value. Similarly, the local best of other particle in the population should be

changed accordingly if the present fitness function value is better than the previous one.

Termination criteria: Repeat from (1) until the maximum number of iterations is reached.

Implementation of HTC problem using PSO (C) algorithm: To apply a PSO algorithm to an optimization problem, some essential components need to be designed. The implementation of these PSO components for solving the hydrothermal coordination problem as described below.

Representation of trial solution vector: According to the problem solution methodology, a dependent thermal generation is randomly selected. The non-dependent thermal generation for P_{it} for $t = 1, 2, \dots, Z, t \neq d$, are together taken as $(Z - 1)$ dimensional trail vector.

Let $P_i = [P_{i1}, P_{i2}, \dots, P_{i(d-1)}, P_{i(d+1)}, \dots, P_{iz}]$ be the trial vector of the i th component of a particle.

Initialization of particle of trial vectors: Let the particle size be N_p . Each initial parent particle trail vector, $P_i = 1, 2, \dots, N_p$, is selected randomly from a feasible range in each dimension. This done by setting the t th components of each parent particle as

$$\begin{aligned}
 P_{it} &= \text{rand} [P_i, \bar{P}_i], \text{ for } t = 1, 2, \dots, \\
 &\quad (d-1), (d+1), \dots, Z
 \end{aligned} \tag{22}$$

where, $[P_i, \bar{P}_i]$ denotes a uniform random variable ranging over $[P_i, \bar{P}_i]$.

The above procedure is delineated in the flowchart shown in Fig. 1.

RESULTS AND DISCUSSION

The performance of the proposed PSO algorithm is tested on a standard test system is taken from (Wood and Wollen berg, 1984). It comprises a hydro and an equivalent thermal plant. The schedule horizon is 3 days and there are six 12-hr intervals. This unit has got the prohibited operating zones as follows,

$$\begin{aligned}
 \text{Zone 1: } & [870 \ 910], \text{ Zone 2: } [790 \ 810], \\
 \text{Zone 3: } & [750 \ 775], \text{ Zone 4: } [1200 \ 1230]
 \end{aligned}$$

To validate the feasibility of the proposed algorithm, the test system was also solved using the gradient search algorithm (Hota *et al.*, 1999) and the PSO algorithm

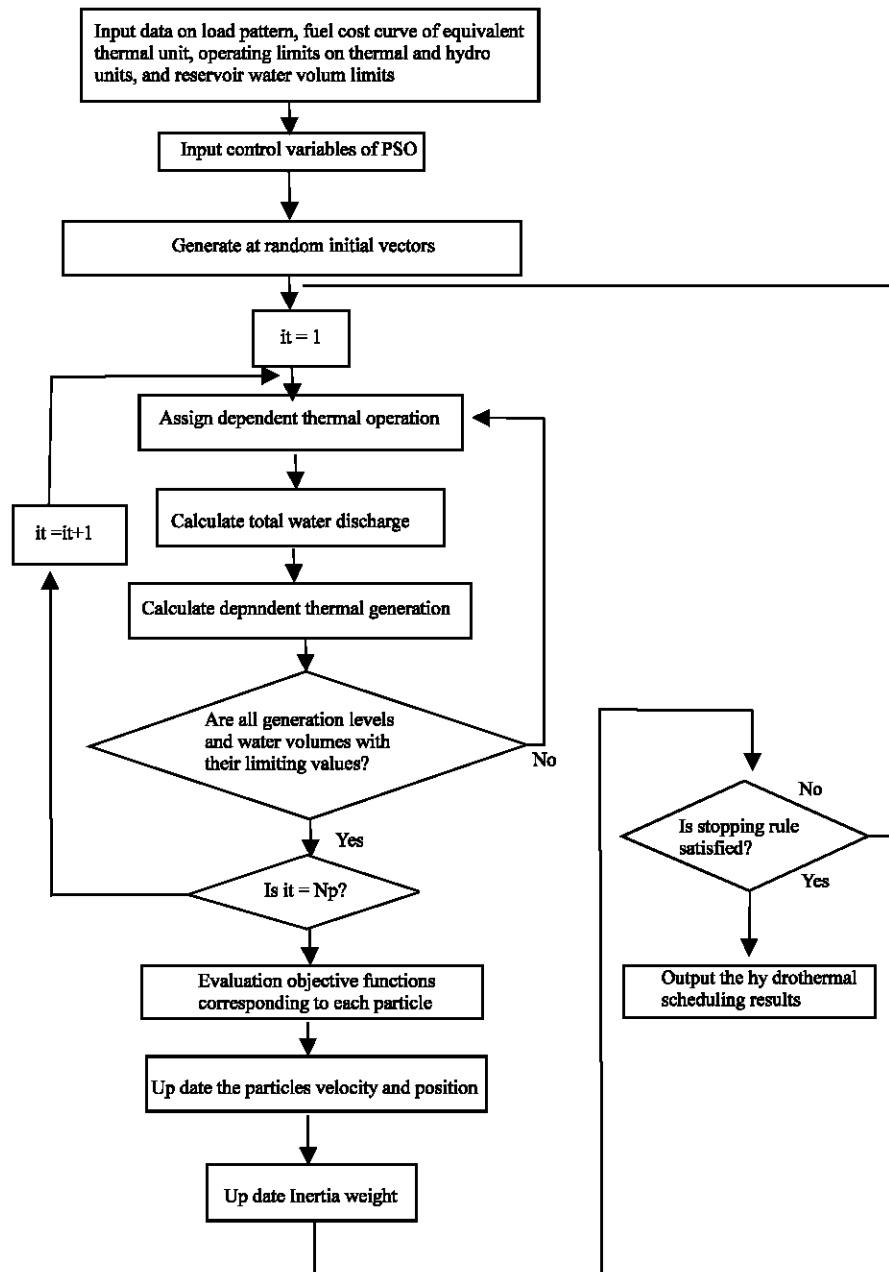


Fig. 1: Flowchart for the HTC problem by PSO (C) technique

without including the crazy function. The algorithm was coded using MATLAB software and the gradient based search algorithm was adopted from the optimization toolbox. The simulation was conducted on a Pentium 4 PC for 100 trial runs to study the robustness of the developed PSO based HTC algorithm.

The following simulation parameters are selected for both the PSO algorithms to solve the HTC problem. The selection procedure has been adopted from (Albert and Ebenezer, 2004). These

simulation parameters are found to be most suitable for the test case adopted to demonstrate the feasibility of the proposed algorithms. Particle size = 100, Maximum inertia weight = 1.3, Minimum inertia weight = 0.7, $C1 = C2 = 2$, maximum velocity = , $k_{max} = 30$. For both the methods penalty parameters are taken as 10000. Termination of the PSO algorithms is done when there is no improvement in the solution for a pre-specified number of iterations.

Best result obtained using the proposed, PSO and the gradient search algorithms are shown in Table 1. This

Table 1: Best Hydrothermal Schedules obtained by all the three techniques

Technique	Interval	Thermal generation (MW)	Hydro generation (MW)	Volume (acre - ft)	Discharge (acre-ft h ⁻¹)	Cost (Rs)
PSO (C)	1 st day 0:00-12:00	968.212	231.78	106216.2	1771.3	710002.4
	12:00-0:00	870	630	88683	3461.1	
	2 nd day 0:00-12:00	870	230	95005.8	1473.1	
	12:00-0:00	870	930	59580.6	4952.1	
	3 rd day 0:00-12:00	810	140	71271	1025.8	
	12:00-0:00	775	525	60000	2939.25	
Gradient search	1 st day 0:00-12:00	1013.21	186.787	108900	1258.33	710422.76
	12:00-0:00	870	630	91366.8	3461.1	
	2 nd day 0:00-12:00	870	230	97689.6	1473.1	
	12:00-0:00	870	930	62264.4	4952.1	
	3 rd day 0:00-12:00	790	160	72762	1125.2	
	12:00-0:00	750	550	60000	3063.5	
PSO	1 st day 0:00-12:00	890.23	309.77	101565	1869.55	710169.73
	12:00-0:00	910	590	86417.4	3262.3	
	2 nd day 0:00-12:00	870	230	92740.2	1473.1	
	12:00-0:00	910	890	59580.6	4753.3	
	3 rd day 0:00-12:00	810	140	71271	1025.8	
	12:00-0:00	775	525	60000	2939.25	

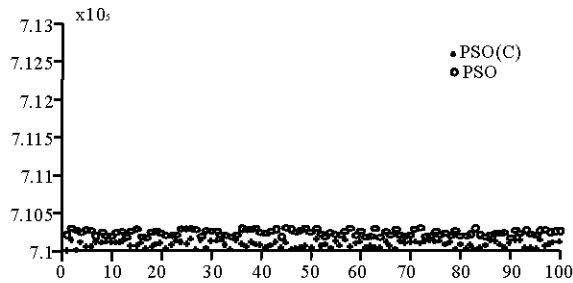


Fig. 2: Best solution obtained for 100 trail runs

result was obtained for 71 trial runs. The average cost obtained the proposed PSO based HTC algorithm is Rs. 710052.7 and even this cost is comparatively less than the best cost obtained using the gradient search algorithm and the PSO algorithm without the crazy agents. During the simulation the crazy agents are generated at an average of 12 times when the inertia weight reduces below an average of 0.83. The best solution obtained by the PSO(C) and PSO for 100 trail runs is plotted in Fig. 2.

CONCLUSION

An improved PSO based algorithm to solve the HTC problem is proposed. In this problem the prohibited operating zones as inequality constraints are included in the thermal generating units. All the thermal generating units are represented are modeled as single equivalent thermal plant. The POZ complicates the solution domain and makes the solution algorithm to easily trap into a local minimum. To solve this heavily constrained HTC problem, the PSO algorithm is improved by including the craziness function. The efficiency of this newly proposed algorithm

is illustrated using a standard test system. Numerical results demonstrate that the proposed PSO based technique provides a cheaper schedule compared with the gradient search technique in terms of quality and reliability. Although it requires more simulation time than the traditional approaches in obtaining the optimal solution, the results are so greatly improved that it makes the sacrifice worthwhile. The simulation time can be significantly reduced by implementing the proposed algorithm in parallel processing machines.

NOMENCLATURE

- D_t : Load demand forecasted at time 't' (in MW)
- t : Time Interval(hr) index
- T : Total number of time intervals (scheduling horizon)
- R_t : Spinning reserve requirements (in MW).
- C : Total thermal production cost in Rs
- N : Number of available thermal units.
- u_{it} : Commitment state of ith thermal; unit $u_{it} = 1$ if committed or $u_{it} = 0$ if reserved
- P_{it} : Power output of ith thermal unit (in MW).
- i : Index of the thermal unit.
- C_i : (P_{it}) Fuel cost function of ith thermal units in Rs/hr;a function of p_{it} .
- $R_{s,it}$: Spinning reserve contribution of ith thermal units(in MW).
- Maximum power output of ith thermal unit(in MW).
- Minimum power output of ith thermal units(in MW).
- $R_{s,i}$: Maximum spinning reserve contribution of ith thermal unit(in MW).
- Up-ramp limit of the ith thermal unit(in MW/Hr).
- Down-ramp limit of the ith thermal unit(in MW/Hr).
- $T_{up,i}$: Minimum-up time of the ith thermal unit(in h).

$T_{dn,i}$: Minimum downtime of the i th thermal unit(in h).
 SUP_i : Start-up cost of the i th thermal unit in Rs.
 SDN_i : Shut-down cost of the i th thermal unit in Rs.
 M : Number of hydro units.
 P_{jt} : Power output of j th hydroplant.(in MW).
 j : Index of the hydro units.
 $R_{s,jt}$: Spinning reserve contribution of j th hydroplant(in MW)
 Q_{jt} : Discharge rate of j th hydroplant in $m^3 h^{-1}$ (positive for generating/negative pumping).¹
 S_{jt} : Spillage rate over j th reservoir (in $m^3 h^{-1}$).
 I_{jt} : Water inflow rate in j th reservoir in $m^3 h^{-1}$.
 V_{jt} : Volume of water stored in j th reservoir at the end of time interval t (in m^3).
 Maximum water discharge if j th hydroplant ($m^3 h^{-1}$).
 Minimum water discharge if j th hydroplant ($m^3 h^{-1}$).
 Upper bound of volume variation of j th reservoir (in m^3).
 Lower bound of volume variation of j th reservoir (in m^3).
 $V_{j,ini}$: Initial storage volume of j th reservoir at the beginning of scheduling horizon (in m^3).
 $V_{j,fin}$: Target storage volume of j th reservoir at the end of scheduling horizon (in m^3).
 Number of hours in the j^{th} interval.
 k : Constant.
 P_{Lj} : total electric loss between the hydro plant and the load in the j^{th} interval.
 Q : (.)water discharge rate function.
 Z_i : Number of prohibited operating zones of unit i

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