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Fixed Head Hydrothermal Scheduling with Wind Farms

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ABSTRACT:- *The price of fossil fuels, and the incentives offered by governments in many countries have driven the development and evolution of renewable energy sources such as wind energy. The optimal allocation of generations of short-term hydrothermal scheduling (SHTS) needs to be revised taking into account the impact of wind farms. This paper presents an analytical method for eliminating the two iterative loops of the classical* $\lambda - \gamma$ *iteration method for SHTS with wind farms in order to enhance the computational efficiency. It includes the simulation results of four test cases with a view to highlight its computational efficiency, irrespective of the problem size.*

NOMENCLATURE

PM	proposed method
SHTS	short term hydrothermal scheduling
NET	normalized execution time
a_i b_i c_i	fuel cost coefficients of the i^{th} thermal generating plant
B	loss coefficients
d_i e_i f_i	water discharge rate coefficients of the i^{th} hydro plant
$F_i(P_{Gi})$	fuel cost function of the i^{th} generating plant in $\$/h$
$F_{ik}(P_{T\,ik})$	fuel cost function of the i^{th} thermal plant at k^{th} interval, $\$/h$
ng	number of generating plants
nt	number of thermal plants
nh	number of hydro plants
$nInt$	number of intervals
P_{Dk}	total power demand at k^{th} interval, MW
$P_{Dk}^{\Re}$	net demand to be supplied by all the generators in the set $\Re$ at k^{th} interval
P_{Gi}	generation at the i^{th} generating plant
${P_{G_i}}^{\min}$ & ${P_{G_i}}^{\max}$	minimum and maximum of P_{Gi} respectively
P_{Lk}	system losses at k^{th} interval
$P_{T\,ik}$	generation at the i^{th} thermal plant in the k^{th} interval, MW
$P_{H\,ik}$	generation at the i^{th} hydro plant in the k^{th} interval, MW
$P_{Gk}^{\Re}$	net power to be generated by all the generators in the set $\Re$ at k^{th} interval
${P_{T_i}}^{\min}$ & ${P_{T_i}}^{\max}$	minimum and maximum power limits of the i^{th} thermal plant respectively, MW
${P_{H_i}}^{\min}$ & ${P_{H_i}}^{\max}$	minimum and maximum power limits of the i^{th} hydro plant respectively, MW
P_W	output of the wind turbine

P_W^{rate}	rating of the wind turbine
P_{Wt}	output of the wind turbine at interval-*t*
t_k	duration of k^{th} interval
V_i^{avl}	available water for the i^{th} hydro plant over the scheduling period, M cubic ft
V	wind speed (m/s)
V_{ci}	cut-in speed (m/s)
V_{co}	cut-out speed (m/s)
V_{ci}	rated speed (m/s)
$Y_{ik}(P_{Hik})$	water discharge rate of the i^{th} hydro plant in the k^{th} interval, M cubic ft/h
λ	incremental cost of received power
λ_k	incremental cost of received power at k^{th} interval
Φ	objective function to be minimized
Φ_T	augmented objective function to be minimized
$\Re$	a set of generator numbers
α, β, γ	wind generator coefficients

I. INTRODUCTION

Climate changes, global warming in particular, have required environmental issues to be seriously considered in power systems operation. As an alternative to traditional fossil fuels, renewable wind generation is rapidly deployed, which is plentiful, widely distributed, and environmentally friendly. The penetration of wind energy has increased substantially in recent years and is expected to continue growing in the future. Wind power is generally regarded as problematic for power system operation due to its limited predictability and variability. In particular, optimal allocation of generations to various generating plants needs to be revised.

Short range hydrothermal scheduling (SHTS) determines the hourly scheduling of available hydro and thermal generating units over the planning horizon, usually one day or one week. The recent penetration of wind farms, which are plentiful, widely distributed and environmentally friendly, need to be included in the SHTS problems. Due to insignificant operating cost of wind plants similar to hydro plants, the total fuel cost of thermal units is considered as the objective function besides including the various hydraulic and electric system constraints such as generation limits, available water and the energy balance equivalence over a scheduling horizon. It is a large-scale, dynamic, non-linear, and complicated constrained optimization problem [1].

Over the years, numerous mathematical methods with various degrees of near-optimality, efficiency, ability to handle difficult constraints and heuristics are suggested in the literature for solving the SHTS problems, such as gradient search technique [1], $\lambda-\gamma$ iteration method, dynamic programming [1], Lagrange relaxation [2], decomposition and coordination method [3], mixed integer programming [4], Newton's method [5]. Linear programming [6], network flow programming [7,8], non-linear programming [9] etc. Dynamic programming among these approaches has been found to tackle the complex constraints directly but suffers from the curse of dimensionality. The other methods have necessitated simplifications in order to easily solve the original model, which may lead to sub-optimal solutions with a great loss of revenue. Generally, these classical methods can be efficiently applicable for the SHTS problems with differentiable fuel cost function and constraints.

Recently artificial intelligence based methods, simulated annealing approach [10], evolutionary programming [11], genetic algorithm [12], artificial immune system [13], tabu search [14], ant colony optimization [15], particle swarm optimization [16], differential evolution [17], quantum-inspired evolutionary algorithm [18] and artificial bee colony [19] are suggested for SHTS. These methods are able to provide good solution and deal with complicated nonlinear constraints more simply and effectively. Moreover, these algorithms do not depend on the first and second differentials of the objective function. However, the above mentioned methods require a large amount of computation time especially for large-scale SHTS problems. This paper presents an efficient analytical method for solving fixed-head SHTS problem with wind farms. The proposed algorithm is tested on three SHTS problems with wind farms and the results are presented.

II. PROBLEM FORMULATION

The main objective of SHTS problem with wind farms is to determine the optimal schedule of hydro and thermal plants of a power system in order to minimize the total system operating cost, represented by the fuel cost required for the system's thermal generation. It is intended to meet the forecasted load demand over the scheduling period, while satisfying various system and unit constraints. The SHTS problem is formulated as

$$\text{Minimize} \quad \Phi = \sum_{k=1}^{nInt} \sum_{i=1}^{nt} t_k \cdot F_{ik}(P_{T\,ik}) \tag{1}$$

Subject to the power balance constraint

$$\sum_{i=1}^{nt} P_{T\,ik} + \sum_{j=1}^{nh} P_{H\,jk} - P_{Dk} - P_{Wt} - P_{Lk} = 0 \quad ; \quad k = 1, 2, \cdots, nInt \tag{2}$$

and to the water availability constraint

$$\sum_{k=1}^{nInt} t_k \cdot Y_{ik}(P_{H\,ik}) = V_i^{avl} \quad ; \quad i = 1, 2, \cdots, nh \tag{3}$$

with

$$P_{T\,i}^{\min} \le P_{T\,ik} \le P_{T\,i}^{\max} \quad ; \quad i = 1, 2, \cdots, nt$$

$$P_{H\,i}^{\min} \le P_{H\,ik} \le P_{H\,i}^{\max} \quad ; \quad i = 1, 2, \cdots, nh \tag{4}$$

$$\text{Where} \quad F_{ik}(P_{T\,ik}) = a_i \cdot P_{T\,ik}^{\;2} + b_i \cdot P_{T\,ik} + c_i \quad \$/h \tag{5}$$

$$Y_{ik}(P_{H\,ik}) = d_i \cdot P_{H\,ik}^{\;2} + e_i \cdot P_{H\,ik} + f_i \quad m^3/h \tag{6}$$

$$P_{Lk} = \sum_{i=1}^{ng} \sum_{j=1}^{ng} P_{G\,ik} B_{ij} P_{G\,jk} \tag{7}$$

$$P_G = \{P_{T1}, P_{T2}, \cdots, P_{Tnt}, P_{H1}, P_{H2}, \cdots, P_{Hnh}\} \tag{8}$$

2.1 Classical $\lambda - \gamma$ iteration method [1]

The augmented Lagrangian function for the SHTS problem is written as

$$\Phi_T = \sum_{k=1}^{nInt} \left[\begin{array}{l} \sum_{i=1}^{nt} t_k \; F_{ik}(P_{T\,ik}) - \lambda_k \\ \left(\sum_{i=1}^{nt} P_{T\,ik} + \sum_{j=1}^{nh} P_{H\,jk} - P_{Dk} - P_{Wt} - P_{Lk} \right) \end{array} \right] + \sum_{i=1}^{nh} \gamma_i \left[\sum_{k=1}^{nInt} t_k \; Y_{ik}(P_{H\,ik}) - V_i^{avl} \right] \tag{9}$$

The co-ordination equation from the above function can be obtained as

$$t_k \frac{\partial F_{ik}(P_{T\,ik})}{\partial P_{T\,ik}} + \lambda_k \frac{\partial P_{Lk}}{\partial P_{T\,ik}} = \lambda_k \tag{10}$$

$$\gamma_i \; t_k \frac{\partial Y_{ik}(P_{H\,ik})}{\partial P_{H\,ik}} + \lambda_k \frac{\partial P_{Lk}}{\partial P_{H\,ik}} = \lambda_k \tag{11}$$

The above co-ordination equations along with constraint Eqs. 2, 3 and 4 are iteratively solved to obtain optimal SHTS.

2.2 Wind Farm Model

The generated power that varies with the wind speed, of a wind turbine can be determined from its power curve, which is a plot of output power against wind speed. The typical characteristic of wind turbine relating wind speed and generator power output indicating the cut-in speed, the rated wind speed and cut-out speed is shown in Fig. 1.The wind turbine starts generating power, when the wind speed is at cut-in wind speed (V_{ci}) and shut down for safety reasons at cut-out wind speed (V_{co}). It generates the rated power, P_W^{rate}, when the wind speed is in-between the rated wind speed (V_r), and the cut-out wind speed. The power output of a wind turbine for a given wind speed can be calculated from the following mathematical model.

$$P_W = \begin{cases} 0 & 0 \le V < V_{ci} \\ P_W^{rate} \times \left(\alpha V^2 + \beta V + \gamma\right) & V_{ci} \le V < V_r \\ P_W^{rate} & V_r \le V < V_{co} \\ 0 & V \ge V_{co} \end{cases} \tag{12}$$

In the proposed formulation, it is assumed that the wind speed is uniform at the entire wind farm and all the wind turbines in the wind farm possess the same characteristics. The wind farm is therefore treated as a wind turbine, possessing the rating of the entire wind farm.

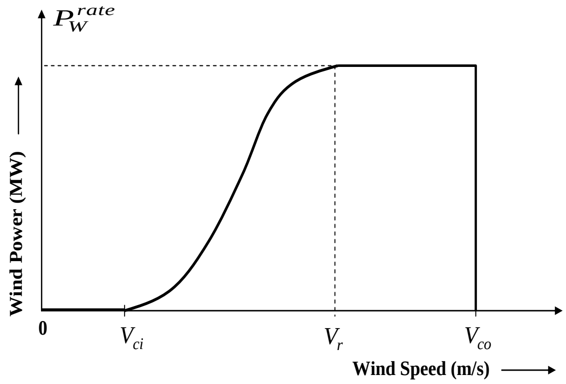

Fig.1 Typical Characteristic of a Wind Turbine

III. PROPOSED METHODOLOGY

The solution process of the $\lambda - \gamma$ iteration method involves time-consuming three iterative loops, in which the λ -iterations itself accounts for two iterative loops in each γ -iteration. The computational speed can be enhanced, if λ -iterations are eliminated, thereby avoiding two iterative loops. An analytical non-iterative approach is developed instead of λ -iterations in the proposed approach.

The co-ordination equation of the conventional $\lambda - \gamma$ iteration method, neglecting the losses can be written as,

$$t_k . \frac{\partial F_{ik}(P_{G\,ik})}{\partial P_{G\,ik}} = t_k (2.a_i P_{Gik} + b_i) = \lambda_k \quad ; \quad i = 1,2 ... nt \tag{13}$$

$$t_k . \frac{\partial Y_{ik}(P_{G\,ik})}{\partial P_{G\,ik}} = t_k (2.\gamma_i d_i P_{Gik} + \gamma_i e_i) = \lambda_k \quad ; \quad i = nt+1, nt+2 ... ng \tag{14}$$

Let the fuel cost and hydel discharge coefficient are redefined for the available (known) values of γ

$$\left.\begin{aligned} a_i' &= a_i \\ b_i' &= b_i \\ c_i' &= c \end{aligned}\right\} \text{for all thermal plants } i = 1, 2, \cdots, nt \tag{15}$$

$$\left.\begin{aligned} a_i' &= \gamma_i\, d_i \\ b_i' &= \gamma_i\, e_i \\ c_i' &= \gamma_i\, f_i \end{aligned}\right\} \text{for all hydel plants } i = nt+1, nt+2, \cdots, ng \tag{16}$$

Eqs. 13 and 14 can be written using the newly defined coefficients of Eqs. 15 and 16 as

$$t_k(2a_i'P_{Gik} + b_i') = \lambda_k \quad ; \quad i \in \Re \tag{17}$$

Where $\Re$ is a set of generators, initially it contains all the generators as

$$\Re = \{1, 2, \cdots, nt, nt+1, nt+2, \cdots, ng\} \tag{18}$$

Rearranging Eq. (17) for optimal generation at interval-k as

$$P_{Gik} = \frac{\lambda_k - b_i'}{2a_i'} \quad ; \quad i \in \Re \tag{19}$$

The above equation can be written in terms of $P_{Dk}^{\Re}$ as

$$P_{Gik} = \frac{P_{Dk}^{\Re} - \rho - b_i'\sigma}{2a_i'\sigma} \quad ; \quad i \in \Re \tag{20}$$

Where

$$\rho = \sum_{i \in \Re} \frac{b_i'}{2a_i'} \quad ; \quad \sigma = \sum_{i \in \Re} \frac{1}{2a_i'} \tag{21}$$

$P_{Dk}^{\Re}$ is the power demand to be supplied by all the generators in the set of $\Re$. Initially it equals P_{Dk} .

Eq. (20) provides optimal generations for the available values of γ and minimizes the following cost function that involves the fuel cost of the thermal plants and the fictitious cost of the hydel plants.

$$Min \quad \varphi_k = \sum_{i \in \Re} a_i' P_{Gik}^2 + b_i' P_{Gik} + c_i' \tag{22}$$

Substituting Eq. (20) in Eq. (22) and rearranging

$$Min \quad \varphi_k = A_k P_{Dk}^2 + B_k P_{Dk} + C_k \tag{23}$$

$$\text{Where} \quad \left. \begin{aligned} A &= \sum_{i \in \Re} \frac{1}{4a_i'\sigma^2} \\ B &= \sum_{i \in \Re} \frac{\rho}{2a_i'\sigma^2} \\ C &= \sum_{i \in \Re} \left(\frac{1}{4a_i'}\right)\left(\frac{\rho^2}{\sigma^2} - b_i'^2\right) + C_i' \end{aligned} \right\} \tag{24}$$

Eq. (23) does not include the transmission loss. It can be included by altering the equation as

$$\varphi_k = A_k P_{Gk}^{\Re\,2} + B_k P_{Gk}^{\Re} + C_k \tag{25}$$

where

$$P_{Gk}^{\Re} = \sum_{i \in \Re} P_{Gik} = P_{Dk}^{\Re} + P_{Lk} \tag{26}$$

The P_{Lk} can be calculated by Eq.(7) through substituting the generations obtained by Eq.(20) for the set of generators in $\Re$ and the generations of limit violated generators.

Differentiating and equating Eq. (25) to zero yields the optimal λ that minimizes φ_k

$$\lambda^o = \frac{\partial \varphi_k}{\partial P_{Gk}^{\Re}} = 2A_k P_{Gk}^{\Re} + B_k \quad \$/MWh \tag{27}$$

The individual unit generation can be obtained by

$$P_{Gik} = \frac{\lambda^o - b_i'}{2a_i'} \quad \text{MW} \quad ; \quad i \in \Re \tag{28}$$

Though Eq. (28) provides the optimal generation P_{Gik} at interval-k for the available γ values, it may not satisfy the water availability constraint of Eq. (3). The SHTS problem may be solved iteratively for optimal γ values that satisfy the water availability constraint. The algorithm is obtained below:

Read the system data

Choose initial γ -values for all hydel plants.

Set the interval $k = 1$

Evaluate P_{Wt} and set $P_{Dk}^{\Re} = P_{Dk} - P_{Wt}$ and $\Re = \{1, 2, \cdots, nt, nt+1, nt+2, \cdots, ng\}$

Evaluate the constants ρ, σ, A, B and C for the generator in the set $\Re$

Compute the generation P_{Gik} using Eq. (20) and then calculate P_{Lk} and $P_{Gk}^{\Re}$ by Eqs. 7 and 26 respectively.

Evaluate λ^{o} using Eq. (27) and then solve Eq. (28) for all the generators in the set $\Re$.

Check for limit violation of generators. If any of the generation violates, then set the respective limit as the generation by $P_{Gik} = P_{Gi}^{\min} or \quad P_{Gi}^{\max}$, eliminate the violated generator from the set $\Re$, reduce the power demand as $P_{Dk}^{\Re} = P_{Dk}^{\Re} - P_{Gik}$ and go to step (5).

Repeat steps 4-8 for all the intervals in the scheduling period.

Check for convergence through water availability constraints. If the algorithm converges, go to step 10; else, project new values for γ and go to step 3 optimal solutions is obtained. Print the optimal generations and their cost stop

IV. NUMERICAL RESULTS

The proposed method (PM) is tested on four SHTS problems with farms. The data comprising the cost characteristics of thermal plants, the discharge characteristics of hydel plants, their loss coefficients and water storage for each hydel plant are available in [20]. The first system under study comprises of one thermal and one hydel plant, the second unit has one thermal and two hydel plants, the third is made up of two thermal and two hydel plants and the last one contains of one thermal and one hydel plant. A wind farm is included in all the four SHTS problems, whose data are given in Table-1. The wind speed data is given in Table 2.

As the PM is an enhanced version of the classical $\lambda - \gamma$ iteration method, the results are compared with that of classical $\lambda - \gamma$ iteration method in order to exhibit the computational efficiency of the developed algorithm. The fuel costs obtained by the PM for all the test problems are presented in Table 3, which also includes the fuel costs of the $\lambda - \gamma$ iteration method. It is very clear from the results that the PM gives the same result of the $\lambda - \gamma$ iteration method, thereby indicating that the PM is as reliable as $\lambda - \gamma$ iteration method. The normalized execution time (NET) of the PM is compared with that of the $\lambda - \gamma$ iteration method for all the test problems in Table 4. This table clearly indicates that the PM is much faster than that of the $\lambda - \gamma$ iteration method, thereby illustrating that the PM is computationally efficient. The optimal generations obtained by the PM for all the test problems are graphically presented in Fig.2.

Table 1 Wind Farm data

		Problem-1	Problem-2	Problem-3	Problem-4
Wind Farm rating	P_W^{rate}	75 MW	6 MW	150 MW	135 MW
Wind Farm Coefficients	α	0.0031			
	β	0.0474			
	γ	-0.1401			

Table 2 Wind Speed data for 24 hours

Interval	Wind Speed m/s	Interval	Wind Speed m/s	Interval	Wind Speed m/s
1	10.4065	9	8.0714	17	11.9306
2	11.3105	10	7.8417	18	13.0000
3	10.8640	11	9.3849	19	11.4987
4	10.8640	12	8.9586	20	12.1733

5	11.9306	13	8.0714	21	12.2935
6	11.0567	14	11.8082	22	11.4987
7	11.3734	15	8.6682	23	10.0725
8	9.5246	16	8.8141	24	7.0500

Table 3 Comparison of Fuel cost

Test Problem	$\lambda-\gamma$ **iteration method** $(\$/day)$	**PM** $(\$/day)$
1	81966.42	81966.42
2	541.58	541.58
3	42572.82	42572.82
4	139426.98	139426.98

Table 4 Comparison of NET

Test Problem	$\lambda-\gamma$ **iteration method (s)**	**PM (s)**
1	0.68	0.35
2	0.88	0.53
3	0.93	0.59
4	0.62	0.34

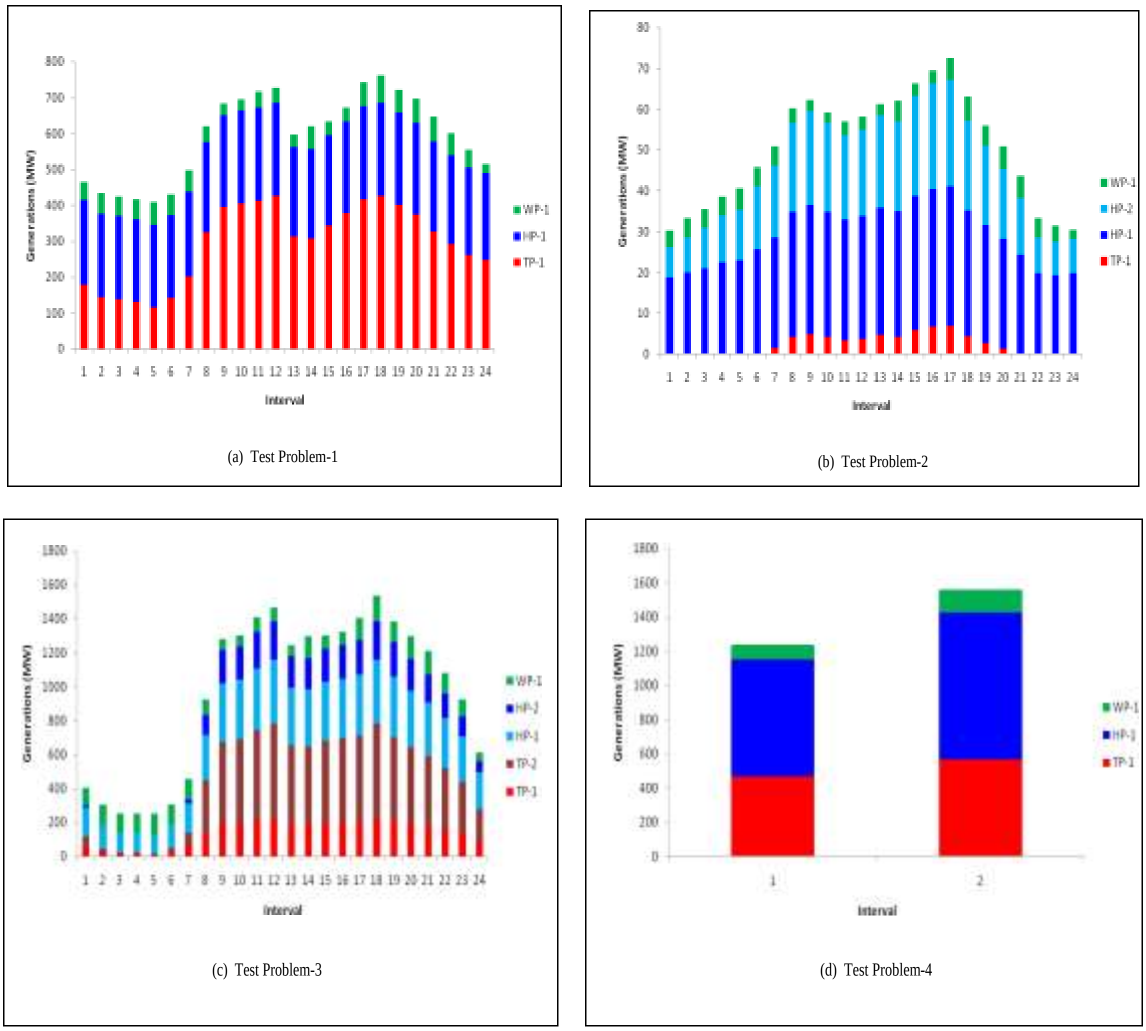

Fig.2 Optimal Generation obtained by the PM

V. CONCLUSION

SHTS is one of the most important issues in the economic operation of power system. The objective of SHTS is to determine the optimal amount of water discharges of hydro plants and power generations of thermal plants over a scheduling horizon so as to minimize the total fuel cost of thermal plants while satisfying various hydraulic and electric system constraints. The SHTS has been modified to include the wind farms. An analytical method for eliminating the two iterative loops of the classical $\lambda - \gamma$ iteration method for SHTS with wind farms with a view of enhancing the computational efficiency has been presented. The simulation results of four test cases clearly illustrated its computational efficiency.

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