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Generation scheduling of wind thermal integrated power system using grey wolf optimization

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Abstract: *Integrating wind power with any other energy source in power system has many operational and scheduling complications because of its inconsistent nature in the process of wind forecasting. In this paper, a new meta-heuristic optimization method named Grey Wolf Optimization algorithm is involved for solving the problem of generation scheduling (GS) to obtain best possible solution in power systems taking into account the load balance, reserve requirement, wind power availability constraints, inequality and equality constraints. The proposed GWO method is applied to a test system involves 26 conventional units and 2 wind farms. The system performance of GWO algorithm is established by evaluating the results obtained for different number of trails and various iterations for five different populations. Calculation of the solution for different populations in the system discloses that the best optimal schedule achieved by Grey Wolf Optimization algorithm.*

Keywords: *Generation scheduling, Grey wolf optimization, Total generation cost reduction, Wind power availability.*

I. Introduction

Electricity becomes the primary need for all in the world with rapid emerging technologies. Electricity demand is increasing day by day. Thus, non-conventional energy sources are needed for the generation of electricity to meet consumers overall demand effectively. Wind energy is judged to be the most reliable and promising source of electric power production in near future for the following advantages. It is clean and has no greenhouse and net carbon emissions and it is cheap and economically effective in general.

The generation scheduling problem aims to lessen the production cost of electric power under different operational constraints and physical limitations on the components of the power system. Proper scheduling of unit improves the economic benefits of a power system and it is must to select the best solution method. Since large economic benefits could be achieved from unit scheduling improvement, a considerable attention has been devoted to development of related solution methods. Various mathematical programming and heuristic. Various approaches include mathematical programming and heuristic approaches such as dynamic programming [19], neural networks [20], simulated annealing [21-23], evolutionary programming [24-26] constraint logic programming [27], genetic algorithm [28-30], Lagrangian relaxation [31-33], branch and bound [34], tabu search [35,36], particle swarm optimization [37-40] approaches have been devoted to solve the UC problem.This paper considers the generation scheduling problem which includes wind power generation along with thermal generating stations. In this problem, by increasing the reserve requirements, the impacts of wind power generation are modeled when specifying the reserve inequality for this problem. The irregular nature of wind power generation in each period is replaced by wind energy speed of each period and power related to this speed. The 26 conventional units and 2 wind farms in test system is solved by the proposed GWO optimization algorithm and the results are compared among different populations and with conventional PSO method[39] to prove that GWO has better computational efficiency.

II. Problem Formulation

The objective function of the GS problem is to minimize the total production cost including fuel cost, operating and maintenance cost of the generating units for the specified period under the operating constraints. The time horizon for study of this problem is one year with monthly intervals for major changes in the schedules. Due to the longer time intervals in the scheduling than the time interval of change in any generating unit, the ramp rate and minimum up/down constraints on output of the generating units are all ignored. The equation of objective function is given by,

minJ $=\sum_{t=1}^{T}\sum_{g=1}^{N_G}\{F(P_{GD}(g,t)).n(t)\}.U(g,t)+$
*t=1Tg=1NGPGDg,t+PGRg,t.OMVCTg.nt.Ug,t+t=1Tg=1NGPGg.*max*g.OMFCTg.nt8760+ t=1Tg=1NWPWw,t.OMVCWw.nt.Vw,t+t=1Tw=1NWPW,*max*w.OMFCWw.nt8760* (1)

where,

$$F(P_{GD}(g,t)) = a_g + b_g.P_{GD}(g,t) + c_g.(P_{GD}(g,t))^2$$

The equation of this objective function is subject to the number of systems and its unit constraints. The following equation should be satisfied to meet the load demand.,

$$Pd(t) = \sum_{g=1}^{N_G} P_{GD}(g,t).U(g,t) + \sum_{W=1}^{N_W} P_W(w,t).V(w,t)$$

t=1, 2, 3… T (2)

The reserve requirement should also be satisfied. The reserve in a system is needed to provide for any feasible unpredicted generation shortage. The accuracy of the load and wind power forecasts will have a significant bearing on the system reserve levels. Increasing amounts of wind capacity causes a greater increase in the required reserve. In this paper, there are two parts in operating reserve requirement .1) Percentage of the total system load (eg., 5% of system load) 2) Surplus/Excess reserve is chosen to balance the inequality among the predicted wind electric power production and its actual value. The percentage of total wind power availability (RESW) is used in this paper to find the second part of the operating reserve. The error due to wind power forecasting is compensated using the factor (RESW). It is assumed to be 10% of the total wind power availability in each wind farm. The conventional units (26 units) in the system are responsible for both the parts of the operating reserve requirement.

$$\sum_{g=1}^{N_G} P_{GR}(g,t).U(g,t) \geq P_{R(t)} + RESW \times \sum_{w=1}^{N_W} P_W(w,t).V(w,t)$$

t=1, 2, 3… T (3)

The generating unit constraints should also be satisfied. Therefore the equation satisfies the wind power availability is given by,

$$P_W(w,t) \leq W_{av}(w,t) \quad (4)$$

t =1, 2, 3… T

The equation showing the maximum and minimum generation in the generating units is as follows.,

$$P_{Gg,min} \leq P_{GD}(g,t) + P_{GR}(g,t) \leq P_{Gg,max} \quad (5)$$

III. Wind Generation Model

It is necessary to accurately evaluate the electricity generated by a wind unit, located at a specific site, throughout the generation scheduling. Wind speed from 5m/s to about 25m/s is treated to be most suitable nearly for all wind turbines. With respect to the wind speed, there is some variation in the power produced.

LOW SPEED REGION(ZERO TO CUT-IN(V_{ci})SPEED): In this region, the turbine is kept in braked position till minimum wind speed(about 5m/s), known as cut-in speed becomes available. Below this speed, the operation of the turbine is not efficient.

MAXIMUM POWER-COEFFICIENT REGION: In this region, rotor speed is varied with wind speed so as to operate it at constant tip-speed ratio, corresponding to maximum power coefficient, C_{PMAX}. In this range, the nature of characteristics is close to that of maximum power available in the wind and is given by,

$$\frac{P_o}{A} = \frac{1}{2}\rho {u_o}^3 \quad (6)$$

The turbine is operated at maximum-power-output point using pitch control.

CONSTANT POWER REGION (CONSTANT-TURBINE-SPEED REGION): During high-speed winds (above 12m/s), the rotor speed is limited to an upper permissible value based on the design limits of system components. In this region, the power coefficient is lower than C_{PMAX}.

FURLING SPEED REGION(CUT-OUT(V_{co}) SPEED AND ABOVE): Beyond a certain maximum value of wind speed (around 25m/s), the rotor is shut down and power generation is stopped to protect the blades, generator and other components of the system. The power generated P_i is given by,

$$P_i = \begin{cases} 0 \\ P_r \times \left(A + B \times SW_i + C \times SW_i^{\,2}\right) \\ P_r \\ 0 \end{cases} \qquad (7)$$

$$\begin{gathered} 0 \leq SW_i < V_{ci} \\ V_{ci} \leq SW_i < V_r \\ V_r \leq SW_i \leq V_{co} \\ SW_i > V_{co} \end{gathered}$$

Where A, B & C are constants and are given by,

$$A = \frac{1}{(V_{ci} - V_r)^2}\left\{V_{ci}\,(V_{ci} + V_r) - 4V_{ci}V_r\left[\frac{Vci + Vr}{2Vr}\right]^3\right\} \qquad (8)$$

$$B = \frac{1}{(V_{ci} - V_r)^2}\left\{4(V_{ci} + V_r)\left[\frac{Vci + Vr}{2Vr}\right]^3 - (3V_{ci} + V_r)\right\} \qquad (9)$$

$$C = \frac{1}{(V_{ci} - V_r)^2}\left\{2 - 4\left[\frac{Vci + Vr}{2Vr}\right]\right\} \qquad (10)$$

The model for wind power production is used to make a wind turbine rated 2MW, with rated, cut-in, and cutout wind speeds of 14m/s, 2.5m/s and 25 m/s respectively. However for the formulation of equation for P_i and parameters of the wind power curve, the wind speed of less than 4.3 m/s must be expelled to avoid a wind power output of less than zero.

IV. Overview Of GWO Method

The GWO is a new meta-heuristic and swarm intelligence based algorithm and it imitates the headship hierarchy and hunting method of grey wolves in nature proposed by Syed Ali Mirjalili, Syed Mohammad Mirjalili and Andrew Lewis. Grey Wolf Optimizer(GWO) algorithm find its application in various optimization problems such as Economic dispatch problems, Training multi-layer perceptron neural network, Optimal control of DC motor, Blackout risk prevention in a smart grid and Feature subset selection.

This GWO algorithm replicates the intelligent search strategy employed by the grey wolves to find the exact prey and to attack it successfully by coordinating with each other during the hunting process. Alpha, Beta, Delta and Omega are the four types of grey wolves employed for simulate the leadership hierarchy. Encircling prey, hunting, searching for prey, and attacking prey are the four important steps that are implemented to perform optimization.

1 Social hierarchy

The grey wolves in general have a strict social hierarchy to mutually help out each other in hunting process and to maintain stability. The position of Alpha wolf is based on its potential and attacking capability. In this Generation Scheduling problem, the first and best fittest solution is finalized as alpha (α) , the second and third best solutions are named beta (β), and delta (δ) respectively. The other remaining solutions are assumed to be omega (ω).α, β and δ are used to guide the hunting (Optimization) in GWO algorithm. The ω solutions follow these three solutions namelyα, β and δ throughout the optimization process.

2 Mathematical models

Mathematical model of hunting technique and the social hierarchy of grey wolves are needed to design and perform GWO algorithm.

2.1 *Encompassing prey:* The prey is encircled by the grey wolves during the hunting process. Mathematical model of encircling action is as follows:

$$\vec{E} = \left|\vec{C}.\vec{X}_P(k) - \vec{X}(k)\right| \qquad (11)$$

$$\vec{X}_{(k+1)} = \vec{X}_p(k) - \vec{A}.\vec{E} \qquad (12)$$

Where $\vec{A}$ and $\vec{C}$ are coefficient vectors and are given by:

$$\vec{A} = 2.\vec{a}.\vec{r_1}.\vec{a} \qquad (13)$$

$$\vec{C} = 2.\vec{r_2} \qquad (14)$$

$\vec{X}$is the position vector of grey wolves and $\overrightarrow{X_P}$ is the vector representing the position vector of the prey.

r_1 andr_2 are random vectors between the interval [0,1] and values of $\vec{a}$ linearly varies from 2 to 0 during the iteration process.

2.2 *Hunting Mechanism:* The location of prey is found by the grey wolves generally in an efficient manner and they surround it. The hunt is headed by the alpha followed by beta and delta. Remaining search agents must update their positions with respect to the position of best search agent and is mathematically formulated as,

$$\vec{E}_\alpha = \left|\overrightarrow{C_1}.\vec{X}_\alpha - \vec{X}\right| \quad (15)$$

$$\vec{E}_\beta = \left|\overrightarrow{C_2}.\vec{X}_\beta - \vec{X}\right| \quad (16)$$

$$\vec{E}_\delta = \left|\overrightarrow{C_3}.\vec{X}_\delta - \vec{X}\right| \quad (17)$$

$$\vec{X}_1 = \vec{X}_\alpha(k) - \vec{A}_1.(\vec{E}_\alpha) \quad (18)$$

$$\vec{X}_2 = \vec{X}_\beta(k) - \vec{A}_2(\vec{E}_\beta) \quad (19)$$

$$\vec{X}_3 = \vec{X}_\delta(k) - \vec{A}_3.(\vec{E}_\delta) \quad (20)$$

Each omega wolf will update its position using the following equation.

$$\vec{X}(k+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{x_3}}{3} \quad (21)$$

Where k indicates the current iteration, $X_\alpha(k), X_\beta(k) and\ X_\delta(k)$ are the positions of the grey wolves α, β and δ at k^{th} iteration respectively.

2.3 *Seek for prey and hitting the prey:* Exploration and Exploitation are the two different abilities of the grey wolves. Seeking for the prey is the exploration ability and harassing the prey is the exploitation ability. Here an arbitrary value 'A' in between the interval [-2a,2a] is considered. If the value of A>1, the omega wolves should deviate its way to find the fittest prey. If the value of A<1, the omega wolves will attack the estimated prey by the dominant wolves.

3 GWO algorithm

Step 1: Initialize the population (n) of the grey wolves.

Step 2: Initialize the value of parameter 'a' and the value of the co-efficient vectors A and C and the current iteration value 'k'.

Step 3: Initialize the maximum number of iterations along with the total number of generating units.

Step 4: Calculate the fitness of each search agent $\vec{X}_\alpha$, $\vec{X}_\beta$ and $\vec{X}_\delta$.

- α will be the best search agent
- β is the second best search agent
- δ is the third best search agent

Step 5: Check k<maximum no. of iteration.

Step 6: If yes, Update the position of the current search agent for each search agent $\vec{X}_\alpha$, $\vec{X}_\beta$ and $\vec{X}_\delta$ using the equation no. 8, 9, 10 & 11.

Step 7: Update the values of a, A, C and calculate the fitness of all search agents with the updated value of a, A, C. If No, Return the alpha value.

Step 8: Using the newly calculated fitness value, update the position of each search agent $\vec{X}_\alpha$, $\vec{X}_\beta$ and $\vec{X}_\delta$.

Step 9: Now again check whether k<maximum number of iterations. If yes, increment the iteration number by 1 and go to step 6.

Step 10: If k>maximum number of iterations, then stop the process and return the alpha value.

4 GWO initialization procedures

The values of W_{max}, W_{min} and maxiter are taken as 1.0, 0.1 and 100 respectively.[values taken based on the other papers mentioned in reference [16, 17, 18].

V. Result of Test System

The proposed GWO optimization algorithm is applied to a model system. By using two approaches its effectiveness was verified. The two methods are one is initialization and another one is simulation parts. Initially, this optimization approach is applied to the test system 1. And the test results are compared with the other methods to verify the feasibility solution of GS problem while using the proposed GWO optimization method.

1. GWO INITIALIZATION PROCEDURE

Test system 1: The test system one has 28 generating units which include 26 thermal units and 2 wind units . The input data for test system 1 is taken from the reference papers [10, 12]. Table 1 denotes the wind power availability with respect to the wind speed. The percentage of annual peak load is calculated. The wind data is mentioned for 12 months. The percentage of annual peak load is calculated by using the reserve requirements and wind speed. The reference values are taken from [12].

TABLE 1. Load pattern, reserve requirement and wind farm output

Period(month)	Percentage of annual peak load (%)	Reserve requirements (MW)	Wind speed		Wind power availability (MW)	
			unit 26	Unit 27	Unit 26	Unit 27
1	87.8	120.5483	5.788	8.284	3.576	16.607
2	88	120.5905	5.358	8.149	2.23	15.675
3	75	104.1935	5.829	9.446	3.717	25.718
4	83.7	116.2843	7.193	9.134	9.817	23.076
5	90	124.6211	7.989	8.284	14.604	16.607
6	89.6	123.1303	7.559	7.19	11.905	9.798
7	88	120.6043	7.25	6.826	10.13	7.913
8	80	109.9162	7.063	9.836	9.122	29.202
9	78	108.0626	7.591	8.127	12.097	15.529
10	88.1	121.0406	6.165	8.213	4.937	16.119
11	94	129.6722	6.414	8.966	6.007	21.715
12	100	139.1649	7.035	10.202	8.973	32.676

TABLE 2. The Simulation Results for Different Population Sizes of GWO for 100 Iterations and 100 Trails in Test System (26C + 2W)

Method	Pop	Total cost(M$)		Standard Deviation	Accuracy
		Minimum cost	Average cost		
GWO	10	292.065	295.524	1.3034	50.01585
	20	293.162	295.707	1.0484	42.52871
	30	292.795	296.786	1.1568	49.243
	40	293.185	297.904	1.2082	53.697
	50	292.108	297.94	1.7087	53.538

Test system 2: It includes table 2 . In table 2 the total cost and accuracy are calculated for various populations using the proposed GWO method. It's only for 26 conventional and 2 wind units. The total cost which includes minimum cost, average cost and standard deviation represented in M$.
Test system 3: it includes table 3. In table 3 the load in month wise data (12 months) is calculated for conventional and wind units (26+2). By using the month load values we can calculate the annual load. In table 4 the comparison is given between the conventional with wind (26C+2W) and conventional with wind. Proposed GWO performances are compared with the PSO method. The PSO approach values are taken from [12]. In annexure 1 the table 4 and 5 is mentioned.

TABLE 3. Optimal Solution Result for Suppying Load (Result) Contribution (MW) for Test System(26C+2W)

units	**m1**	**m2**	**m3**	**m4**	**m5**	**m6**	**m7**	**m8**	**m9**	**m10**	**m11**	**m12**
1	11.26	11.26	5.23	3.85	8.265	5.68	5.68	3.85	6.35	8.68	9.365	10.35
2	5.58	8.58	10.23	8.69	11.68	11.684	11.684	8.69	9.65	9.25	11.265	11.35
3	10.59	10.59	11.65	11.243	10.68	11.356	11.356	11.243	10.68	11.35	10.35	9.36
4	3.89	5.89	9.25	10.265	8.94	10.68	10.68	10.265	11.95	5.32	8.69	11.894
5	9.54	11.54	8.25	6.25	3.298	8.69	8.69	6.25	5.68	10.65	3.25	10.358
6	18.68	18.68	6.18	8.265	19.268	17.268	17.268	8.265	19.368	9.35	19.865	19.25
7	5.265	13.265	12.35	6.842	15.36	19.684	19.684	6.842	5.98	19.65	9.23	18.59
8	9.584	9.584	18.25	13.268	18.95	14.865	14.865	13.268	4.97	12.35	15.365	15.26
9	15.84	19.84	19.025	17.268	15.69	12.987	12.987	17.268	16.98	5.39	18.35	9.68
10	25.68	25.68	16.028	29.487	75.268	74.856	74.856	29.487	75.98	16.25	17.36	75.68
11	75.356	75.356	57.86	53.598	69.68	19.684	59.684	53.598	59.687	72.65	74.25	72.68
12	56.298	56.298	66.87	67.268	74.68	39.258	69.258	67.268	69.68	32.68	75.98	74.258
13	71.021	75.021	75.016	75.169	69.268	48.587	74.587	75.169	74.95	55.62	69.32	69.25
14	90.265	96.265	99.016	99.04	96.268	93.102	93.102	99.04	98.674	59.32	99.35	96.58
15	98.265	98.265	75.013	91.468	98.674	92.125	92.125	91.468	32.957	78.96	89.25	78.265
16	92.154	92.154	88	97.468	92.157	88.145	98.145	97.468	31.57	96.35	59.35	89.36
17	55.265	59.684	115.13	147.54	149.59	151.98	151.98	146.54	145.98	145.3	145.37	154.35
18	59.357	57.684	55.025	154.27	154.27	145.7	154.7	134.27	96.25	132.7	125.35	148.96
19	125.33	96.358	56.021	149.89	153.27	55.025	55.013	128.89	100.65	55.36	108.69	56.258
20	110.6	102.66	57.036	55.032	55.024	59.025	59.025	55.203	86.32	121.4	119.35	146.4
21	198.25	198.25	68.648	77.059	69.035	68.068	69.235	56.098	119.7	152.4	186.35	196.38
22	178.86	161.88	75.321	78.365	190.27	196.03	116.73	129.26	109.68	71.68	142.37	123.35
23	179.66	187.21	178.27	189.92	196.28	169.36	144.19	70.251	169.61	107.1	99.35	120.35
24	240.21	340.21	286.6	248.86	256.22	245.87	345.87	248.86	298.32	320.2	348.65	310.35
25	303.27	283.27	280.25	168.46	252.68	321.35	285.35	337.65	151	320.7	190.35	350.38
26	220.27	160.27	190.35	312.51	166.62	328.35	189.35	150.99	254.35	368.3	366.25	320.35
27	75.26	75.26	65.26	65.878	19.68	20.53	40.65	36.298	12.68	12.65	78.36	25.36
28	25.015	25.015	19.26	**12.68**	78.94	89.26	89.26	66.258	26.35	67.35	36.98	75.35
Total Cost(M$/yr)	**341.9**	**342.7**	**292**	**325.9**	**350.4**	**348.9**	**342.7**	**311.5**	**303.7**	**343**	**366**	**389.4**

TABLE 4. Results in Different Test Systems of GWO along with PSO for 100 trails in different Test Cases

Test system	Methods	Pop Size	Total cost(M$)			Accuracy
			Min	Avg.	Std.dev	
26 C+ 2W	PSO	10	293.6009	297.9482	2.0575	46.177
26C+2W	Proposed GWO	10	292.065	295.1544	1.202046	50.01585

2. Simulation Result of GWO

The simulation procedure is based on the acceleration values (appropriate values). The minimum, average and standard deviation of the objective function of GS was obtained by those acceleration values. Table 2 & 3 denotes the best result of this GS problem employing 100 iterations and 100 trails. Table shows the best result of this GS problem employing 100 iterations and 100 trails. However, by comparison of proposed GWO approaches, it can be concluded that the proposed GWO with 2 wind + 26 conventional units which has a total cost which is less than the cost related to the proposed GWO with 26 conventional + 2 wind units.

Figure 1 shows the 100 trails values for wind and thermal unit with 5 populations 10, 20, 30, 40 and respectively.

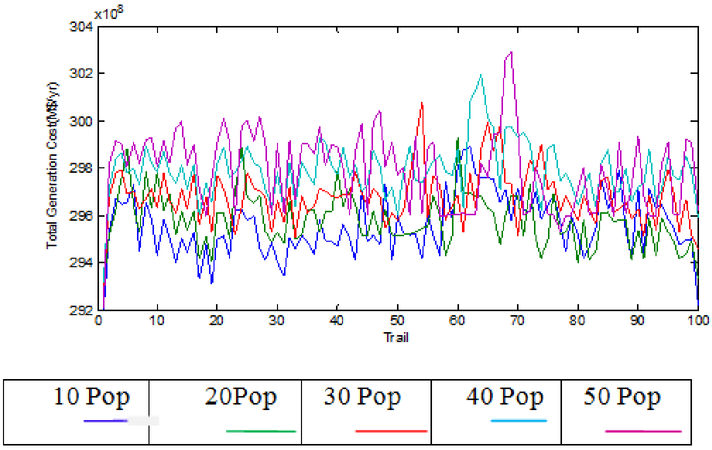

Fig.1. sensitivity analysis of parameter's selection for proposed GWO (2W+26C)

Figure 2 shows the 100 iteration values for 2 wind + 26 conventional units which indicates the total generation cost with respect to the iterations.

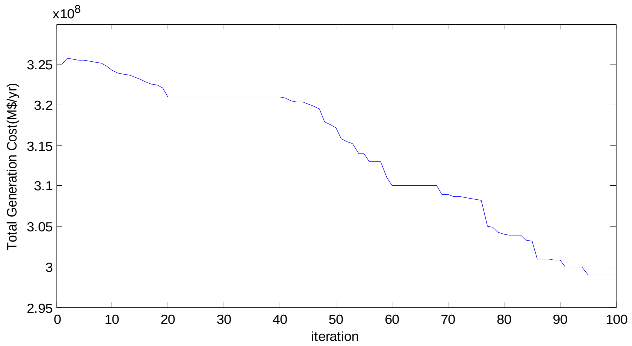

Fig. 2. Convergence characteristics of proposed GWO with 100 iterations (26 conventional + 2 wind units)

VI. Conclusion

This paper presents a new optimization method for solving the generation scheduling (GS) problem based on the GWO algorithm. A new position update tactic that is integrated in the GWO method is employed to satisfy the constraints by the solutions of this problem. The output of GWO method in test system(26C+2W)is compared with the results of five different pollutions say 10, 20, 30, 40 & 50. The above simulation results show that the proposed meta-heuristic and swarm intelligence based GWO algorithm has better computational efficiency and it is shown that the Grey wolf Optimizer (GWO) algorithm obtains near optimal solution for GS problems**.** Future research work will focus on some other approach with better improvement to incorporate security constraints.

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Appendix

a_g, b_g, c_g The coefficients of generating unit g
c_1, c_2, c_3 Weighting factors called acceleration constants
D dimension of the particle
g index for thermal generator unit
n(t) number of hours in time t
N_G Number of thermal generator units
N_W Number of wind units
OMFCT(g) operation and maintenance fixed cost of thermal unit g ($/MWyr)
OMFCW(w) operation and maintenance fixed cost of wind unit w ($/MWyr)
OMVCW(w) operation and maintenance variable cost of wind unit w ($/MWyr)
$P_d(t)$ System demand at time t (MW)
$P_{GD}(g,t)$ Load contribution of thermal unit g at time t (MW)
$P_{GR}(g,t)$ Reserve contribution of thermal unit g at time t (MW)
$P_R(t)$ A fraction of total system load for system reserve requirements (first part) at time t (MW)
$P_W(w,t)$ Generation of wind unit w at time t (MW)
RESW a fraction of total wind power employed to compensate wind power prediction errors (%)
T number of periods under study (12 months)
T index for time
W index for wind unit
$U(g,t)$ Commitment state of unit g at time t (on = 1, off=0)
$V(w,t)$ Commitment state of wind unit w at time t (on = 1, off=0)
$W_{av}(w,t)$ Maximum available wind power of wind unit w at time t (MW)
$Ah_k(t)$ Water inflow to the reservoir k during hour
$Ph_k(t)$ Generation of k^{th} hydro unit at hour t
$Kh_k(t)$ Spilled outflow to the reservoir k during hour t
$Qh_k(t)$ Turbine outflow for reservoir k during hour t
${Qh_k}^{max}$ Max turbine outflow for reservoir k during hour t
${Qh_k}^{min}$ Min turbine outflow for reservoir k during hour t
$Vh_{.k}(t)$ Volume of water for reservoir k during hour t
${Vh_k}^{max}$ Max volume of water for reservoir k
${Vh_k}^{min}$ Min volume of water for reservoir k
pk Input / output characteristics of k^{th} hydro unit