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RESEARCH

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Optimum generation scheduling incorporating wind energy using HHO–IGWO algorithm

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Abstract

Recently, renewable energy participation is gaining importance in the existing power system. However, the large penetration of these renewable energy sources into the existing power system network may cause an imbalance in supply and demand response. Unit commitment is the decision-making process in which generating units are turned ON and OFF at the hourly interval as per the load demand under certain constraints to provide economic scheduling. Thus, an advanced intelligent approach is needed to cope with this combined unit commitment problem with a large penetration of intermittent sources. This paper offers the solution to optimal scheduling by implementing the hybrid Harris Hawks optimizer algorithm (HHO–IGWO). Standard IEEE systems with 10-, 19-, 20-, and 40 units are simulated. Further, to test the feasibility and effectiveness of the proposed method, a comparative analysis for a 10-, 20-, and 40-unit system has also been performed with penetration. The comparative analysis reveals that proposed is more efficient in tackling unit commitment problem in the presence of wind as renewable energy source.

Keywords: Generation scheduling (GS), Harris Hawks optimizer (HHO), Improved gray wolf optimizer (IGWO), Renewable energy, Economic dispatch

Introduction

Electric power plays a vital role in the development, modernization, and progress of upgraded technology. Conventional energy sources such as coal, oil, and gas are rapidly exhausting. The systematic management of the generation schedule within the constraints comes under the category of unit commitment. Unit commitment problem is a complex problem where the generation schedule is planned well in advance with sufficient spinning reserve to satisfy sudden increase in demand [1]. Sustainable power sources such as wind and solar are gaining more significance as these sources are inexhaustible and provide economic operation. Wind energy is getting more attention in the power sector, as wind power helps to reduce the burden on conventional fuels and also decreases environmental pollutants. But, due to the stochastic nature of wind energy, constant power is not available at all times, which results in even more complexity. As the manual calculations require large amounts of computation time to solve unit commitment problems involving wind power, a computer-based system used to solve UC problems not only enhances the computational capability but also improves solution efficiency and reliability with a proper logical approach.

Optimization is the process in which a particular objective function is solved by applying a defined algorithm to get the optimal solution. Over a few decades, several heuristics and metaheuristics have been built by researchers to handle various optimization problems using globally accepted algorithms, such as binary bat algorithm [2], salp swarm algorithm [3], ant colony optimization [4], shuffled frog leaping algorithm [5], biogeography-based optimization [6], gravitational search algorithm [7], differential evolution algorithm [8], particle swarm optimization [9]. Baldwin et al. [10] were the first who published a paper in the field of unit commitment in the year 1959. Priority method, dynamic programming, Lagrange relaxation, and branch & bound methods are the foremost methods to solve the unit commitment problem. Afterward, new optimization methods such as genetic algorithm, simulated annealing, analytical hierarchy process, and particle swarm optimization were implemented by researchers to solve the unit commitment problem more precisely. Recently, due to the introduction of renewable energy sources such as wind and solar, the load demand on conventional sources has reduced to a large extend. Some technical findings related to thermal-wind commitment are discussed as follows:

Dieu et al.[11] have presented a primary generating schedule excluding start-up and shunt down constraints that is updated by IPL and ALH to resolve ramp rate constraint commitment. The hybrid algorithm is found to be effective in providing increased spinning reserve. Yuan et al. [12] proposed the IBPSO method in which unit characteristics are enhanced by using BPSO for tackling unit commitment problem and heuristic lambda-iteration method for economic load dispatch problem. Tan et al. presented a solution for optimal allocation and sizing of renewable DG sources in various distribution networks by the ant lion optimization algorithm (ALOA) [13]. Entezariharsini et al. elaborated impacts of increased wind power in terms of the level of penetration. Stochastic programming including wind power uncertainty is presented to minimize the annual operational cost of generators [14]. Bhadoria et al. utilized the inherent property of moths to converge toward the light to solve the economic load dispatch problem with due consideration of renewable energy sources [15]. Anand et al. have combined the exploration capability of particle swarm optimizer (PSO) and exploitation competency of sine–cosine algorithm (SCA) to form hybrid civilized swarm optimization algorithm. Reddy et al. [16] have presented sigmoid and tangent hyperbolic transfer functions and applied three binary gray wolf optimizer (BGWO) models to solve the profit-based self-scheduling problem of generation. Suresh et al. have modeled a hybrid system consisting of wind and solar by implementing probability distribution methods using diverse probability.

These optimization methods are found to be efficient in solving complicated generation scheduling issues. But, one of the major issues with these techniques is their inefficiency in finding local optimal points during the search process. Eventually, the No-Free-Lunch theorem permits the design of new algorithms as no single algorithm is efficient enough to solve all optimization issues. This motivates us to solve the combinational unit commitment problem using a hybrid variant of Harris Hawks optimizer

(HHO) and an improved gray wolf optimizer (IGWO).This paper offers the solution to the unit commitment problem incorporating wind by using the proposed HHO–IGWO algorithm. Standard IEEE systems consisting of small, medium, and large systems, which include 10-, 19-, 20-, and 40 units, are simulated in MATLAB software using a hybrid HHO–IGWO algorithm with and without wind penetration. The unit commitment problem formulation with wind penetration is discussed in the subsequent section.

Construction of unit commitment problem

Unit commitment problem is an optimization problem in which, the generated power is systematically distributed for a forecasted load to minimize the overall cost of power generation while satisfying all equality and inequality constraints. The major objective of unit commitment problem is selecting a proper generating schedule to minimize the total power generation cost. The total fuel cost F_{T} is determined using Eq. (1) by summing up the generation cost of each unit for a defined time interval [17].

$$F_T = \sum_{h=1}^{H} \left(\sum_{i=1}^{N} \left[\left(a_i P_{i,h}^2 + b_i P_{i,h} + c_i \right) U_{i,h} + \mathrm{STC}_i (1 - U_{i(h-1)}) U_{i,h} \right] \$/\mathrm{hr} \right) \quad (1)$$

where a_i, b_i and c_i are the fuel cost function expressed in \$/h, \$/MWh, and \$/MWh^2 respectively.

Mathematically, start-up cost STC_i [18] is expressed as the sum of Hot start-up cost $\left(\mathrm{HSc}_{i,h}\right)$ and $\left(\mathrm{CSc}_{i,h}\right)$ ith unit respectively.

$$\mathrm{STC}_i = \begin{cases} \mathrm{HSc}_{i,h};\ \mathrm{MD}t_i \le T_{i,h}^{\mathrm{OFF}} \le (\mathrm{MD}t_i + \mathrm{CSh}_i) & (i = N; h = 1, 2, 3, \ldots, H) \\ \mathrm{CSc}_{i,h};\ T_{i,h}^{\mathrm{OFF}} > (\mathrm{MDt}_i + \mathrm{CSh}_i) \end{cases} \quad (2)$$

The power balance is achieved when overall generation meets the allocated load as expressed in Eq. (3) [19],

$$\sum_{i=1}^{N} \mathrm{PG}_i \cdot U_{i,h} + P_g^w = D_L \quad (i = 1, 2, \ldots, N;\ h = 1, 2, 3...., H) \quad (3)$$

For arbitrary free unit power outputs, within minimum and maximum power limit, $\mathrm{PG}_i^{\min} \le \mathrm{PG} \le \mathrm{PG}_i^{\max}$ $(i = 1, 2, \ldots, N\ ;\ h = 1, 2, \ldots, H)$, it is assumed that the Rth reference unit power output is constrained by the power balance Eq. (4) [19].

$$P_{\mathrm{hR}} = D_L - \sum_{\substack{i=1 \\ i \ne R}}^{\mathrm{NG}} (P_{g(i)} U_{i,h} + P_g^w) \quad (h = 1, 2, \ldots, H) \quad (4)$$

In order to mitigate unpredictable disturbances such as sudden load demand or unexpected tripping of lines or generators, some additional generation capacity must be readily available. This additional generation capacity is referred to as spinning reserve. Due to wind penetration, some additional power is accessible from this renewable energy source. This additional power contributed by wind energy results in reducing the liability on thermal units. Equation (6) signifies that the total available generation should always be equal to or greater than sum of load demand and spinning reserve [19].

$$\sum_{i=1}^{N} P_{g\ \max(i)} U_{i,h} + P_{g(h)}^{W} \geq D_{L(h)} + \mathrm{SR}_{(h)} \quad (h = 1, 2, \ldots H) \tag{5}$$

Generators cannot be turn-on and turn-off instantly. Minimum up time (MUT) is the time to set a generating unit online after it has already been shut down [19].

$$T_{i,h}^{\mathrm{ON}} \geq \mathrm{MUT} \tag{6}$$

Similarly, the minimum down time (MDN) is the amount of time for which a particular unit should be kept in off condition before putting it online [19].

$$T_{i,h}^{\mathrm{OFF}} \geq \mathrm{MDN} \tag{7}$$

Mathematical modeling of uncertainties of wind power

Wind power can be evaluated by probability distribution function which is mathematically represented as,

$$\mathrm{pdk}(\nu, k, \lambda) = \frac{k}{\lambda}\left(\frac{\nu}{\lambda}\right)^{k-1} \exp\left[-\left(\frac{\nu}{k}\right)^{k}\right] \tag{8}$$

As the power generated by wind is an uncertain due to the randomness of wind speed, which is mathematically described as [15],

$$Pw = \begin{cases} 0 & (\nu^h \leq \nu_{\mathrm{in}}\ or\ \nu^h \geq \nu_{\mathrm{out}}) \\ P_{wr} & (\nu_r \leq \nu^h \geq \nu_{\mathrm{out}}) \\ \frac{(\nu - \nu_{\mathrm{in}})}{\nu_r - \nu_{\mathrm{in}}} & (\nu_{\mathrm{in}} \leq \nu^h \geq \nu_r) \end{cases} \tag{9}$$

From Eq. (9), when wind speed ν^h is less than or equal to minimum rated velocity, wind power is zero. The probability of wind power being 0, p_{wr} be calculated as per Eqs. (10) and (11) respectively [20].

$$P_r(P_w = 0) = \mathrm{cdf}(\nu_{\mathrm{in}}) + [1 - \mathrm{cdf}(\nu_{\mathrm{out}})] \tag{10}$$

$$\text{For } P_w = 0, \Pr\left[1 - \exp\left[-\left(\frac{\nu_{\mathrm{in}}}{\lambda}\right)^{k}\right] + \exp\left[-\left(\frac{\nu_{\mathrm{out}}}{\lambda}\right)^{k}\right]\right. \tag{11}$$

The probability density function (pdf) in Eq. (12) [20] depends upon ν_{in} and ν_r due to randomness in wind speed.

$$\mathrm{pdf}(P_W) = \frac{\mathrm{KL}\nu_{in}}{(P_{\mathrm{wr}})^{\lambda}}\left[\frac{1 + \left(\mathrm{LP}_{w}/P_{\mathrm{WR}}\right)\nu_{\mathrm{in}}}{\lambda}\right] \times \exp\left[-\left(\frac{1 + \left(\mathrm{LP}_{W}/P_{\mathrm{WR}}\right)\nu_{\mathrm{in}}}{\lambda}\right)^{k}\right] \tag{12}$$

Since output power delivered by wind generator is never remains constant and continuously fluctuates over an entire period, exact wind power extrapolation is not possible. The subsequent section presents mathematical formulation of HHO–IGWO.

Mathematical formulation of hybrid HHO–IGWO algorithm

HHO has inherent proficiency of proper balance between intensification and diversification. Studies revealed that slow convergence gives rise to reduced computational efficiency. The HHO algorithm does not need initial values for the judgment variables and exploit a stochastic indiscriminate search instead of using gradient search [21]. In Eq. (13a), when $q \geq 0.5$ or perch on randomly on tall trees and modeled as in Eq. (13b) for $q < 0.5$ [22].

$$X(\text{itn} + 1) = \{X_{\text{rand}}(\text{itn}) - r_1 \times \text{abs}(X_{\text{rand}}(\text{itn}) - 2 \times r_2 \times X(\text{itn}))\,; \; q \geq 0.5 \tag{13a}$$

$$X(\text{itn} + 1) = \{(X_{\text{prey}}(\text{itn}) - X_m(\text{itn})) - r_3 \times (L\text{b} + r_4 \times (\text{Ub} - \text{Lb}));\quad q < 0.5 \tag{13b}$$

where $X(\text{itn} + 1)$ is the Hawks position in ensuing iteration (itn), $X_{\text{rand}}(\text{itn})$ is randomly selected Hawks, corresponding to the vectors r_1, r_2, r_3, r_4, and q are random values in between (0, 1) and these are modified in each iteration between upper bound (Ub) and lower bound (Lb). $X_{\text{prey}}(\text{itn})$ denotes the position of prey.$X_m(\text{itn})$ epitomizes the mean position of Hawks which is determined using Eq. (14) [23].

$$X_m(\text{itn}) = \frac{1}{N}\left(\sum_{i=1}^{N} X_i(\text{itn})\right) \tag{14}$$

Changeover from exploration to exploitation phase depends upon the fugitive energy of the target, assessed using Eqn. (15) [23].

$$E_A = 2 \times E_0 \times \left(1 - \frac{\text{itn}}{\text{itn}_{\max}}\right) \tag{15}$$

where E_A is evading energy of the prey, E_0 is the initial energy of the prey changing randomly between $(-1, 1)$ and $\text{itn}_{\max}$ is maximum iterations. Equation (16) is used to determine the upgraded position of Hawks. The successful capture relies on attacking strategies of Hawks and escaping nature of prey depending upon change of escape (r). Hawks perform a soft besiege for $r \geq 0.5 \& |E| \geq 0.5$ [24].

$$X(\text{itn} + 1) = \Delta X(\text{itn}) - E_A \times \text{abs}(J \times X_{\text{prey}}(\text{itn}) - X(\text{itn})) \tag{16}$$

$$\Delta X(\text{itn}) = \left(X_{\text{prey}}(\text{itn}) - X(\text{itn})\right) \tag{17}$$

where $\Delta X(\text{itn})$ is the variance between current location of prey and locality of Hawks at iteration itn. $J = 2(1 - r)$ is the Jump energy which modifies randomly in every iteration. r_5 is the random numeral in the range (0, 1). The tired target fails to escape and Hawks perform hard besiege as modeled in Eq. (18). Hawks perform a hard besiege for $r \geq 0.5 \& |E| < 0.5$ [24].

$$X(itn+1) = X_{\text{prey}}(itn) - E_A \times abs(\Delta X(itn)) \quad (18)$$

$$Y = X_{\text{prey}}(\text{itn}) - E \times \text{abs}(JX_{\text{prey}}(\text{itn}) - X(\text{itn})) \quad (19)$$

$$Z = Y + S \times L_F(D) \quad (20)$$

where Y and Z are the positions based on soft besiege.

The $L_F(D)$-based designs which follow the certain rule [25]. At this stage, the prey has enough energy and besiege during this phase depends on levy flight (LF) concept as modeled in Eq. (21) [25]. Hawks perform a soft besiege through rapid dives for $|E| \geq 0.5$ &$r < 0.5$.

$$X(\text{itn}+1) = \begin{cases} Y\,;\ \text{if } F(Y) < F(X(\text{itn})) \\ Z\,;\ \text{if } F(Z) < F(X(\text{itn})) \end{cases} \quad (21)$$

$$Y = X_{\text{prey}}(\text{itn}) - E \times \text{abs}(JX_{\text{prey}}(\text{itn}) - X_m(\text{itn})) \quad (22)$$

$$Z = Y + S \times L_F(D) \quad (23)$$

where Y and Z are the positions based on hard besiege.

The Hawks are very close to prey and perform hard besiege as modeled in Eq. (24). Hawks perform hard besiege through rapid dives for $|E| < 0.5$ &$r < 0.5$.

$$X(\text{itn}+1) = \begin{cases} Y'\,;\ \text{if } F(Y') < F(X(\text{itn})) \\ Z'\,;\ \text{if } F(Z') < F(X(\text{itn})) \end{cases} \quad (24)$$

where Y' and Z' are the positions based on hard besiege.

Updating $X(\text{iter}+1)$ by improved gray wolf optimizer (IGWO)

At this stage, a weighted average of alpha, beta, and delta wolfs is evaluated and then best individual is assigned a weight, obtained by multiplying its corresponding vectors 'A' and 'C'. The best fitness value of gray wolves depends upon the fitness value evaluated as 'a' shown in eqn. (25). Mathematically, $(\overrightarrow{G_w})$&$\overrightarrow{W}_{G(\text{itn}+1)}$ vectors are defined through Eqn. (27) to (28) [25].

$$a = 2 - t \times \left(\frac{2}{\text{itn}_{max}}\right) \quad (25)$$

$$\overrightarrow{G_W} = \left|C \times W_{\text{prey}}(\text{itn}) - W_G(\text{itn})\right| \quad (26)$$

$$W_G(\text{itn}+1) = W_{\text{Prey}}(\text{itn}) - \overrightarrow{A} \times G_W \quad (27)$$

The extreme search process takes place and various fitness values for $(\overrightarrow{W_\alpha})$, $(\overrightarrow{W_\beta})$ and $(\overrightarrow{W_\delta})$ are updated using Eqs. (31), (33) and (35).The final position for capturing the prey is evaluated by Eq. (36).

$$G_{\alpha} = \text{abs}\left(\overrightarrow{C_1} \cdot \overrightarrow{W}_{\alpha} - \overrightarrow{W_G}\right) \tag{28}$$

$$\overrightarrow{W_1} = \overrightarrow{W_{\alpha}} - \overrightarrow{A_1} \cdot \overrightarrow{G_{\alpha}} \tag{29}$$

$$G_{\beta} = \text{abs}\left(\overrightarrow{C_2} \cdot \overrightarrow{W}_{\beta} - \overrightarrow{W_G}\right) \tag{30}$$

$$\overrightarrow{W_2} = \overrightarrow{W_{\beta}} - \overrightarrow{A_1} \cdot \overrightarrow{G_{\beta}} \tag{31}$$

$$G_{\delta} = \text{abs}\left(\overrightarrow{C_3} \cdot \overrightarrow{W}_{\delta} - \overrightarrow{W_G}\right) \tag{32}$$

$$\overrightarrow{W_3} = \overrightarrow{W_{\delta}} - \overrightarrow{A_3} \cdot \overrightarrow{G_{\delta}} \tag{33}$$

$$\overrightarrow{W}_{(itn)} = \left(\frac{\overrightarrow{W}_1 + \overrightarrow{W}_2 + \overrightarrow{W_3}}{3}\right) \tag{34}$$

The pseudocode of the proposed metaheuristic algorithm has been depicted in the flowchart as shown in Fig. 1. In this study, sequential hybridization is utilized for initializing gray wolf position, and thereafter, updated gray wolf positions are more intensively explored by the search agents.

Implementation of proposed HHO–IGWO algorithm for unit commitment problem

The HHO–IGWO method is a metaheuristic algorithm that has an excellent ability of exploration and exploitation and effectively utilized to solve the unit commitment problem [26].

Pseudocode to repair spinning reserve, MDT, MUT, constraints

Once a unit is started, it should not be turned off immediately before reaching MUT. This is required to satisfy economic, mechanical, and design limitations. Similarly, any unit which is once de-committed should not put online immediately. The HHO–IGWO algorithm may sometimes perform unenviably to satisfy the spinning reserve constraint. However, some repair in minimum up/down constraint, excessive spinning reserve is needed. The flowchart for spinning reserve repairing is illustrated in Fig. 2.

De-committing of excess of units

During the repair process of MDT/MUT and spinning reserve, some of the units may get unnecessarily ON. To avoid this situation that could result in an excessive cost for running those units, some of the units need to be shut down. Figure 3 shows the flowchart for de-committing excessive spinning reserve. Figure 4 shows the flowchart of entire process of commitment using HHO–IGWO.

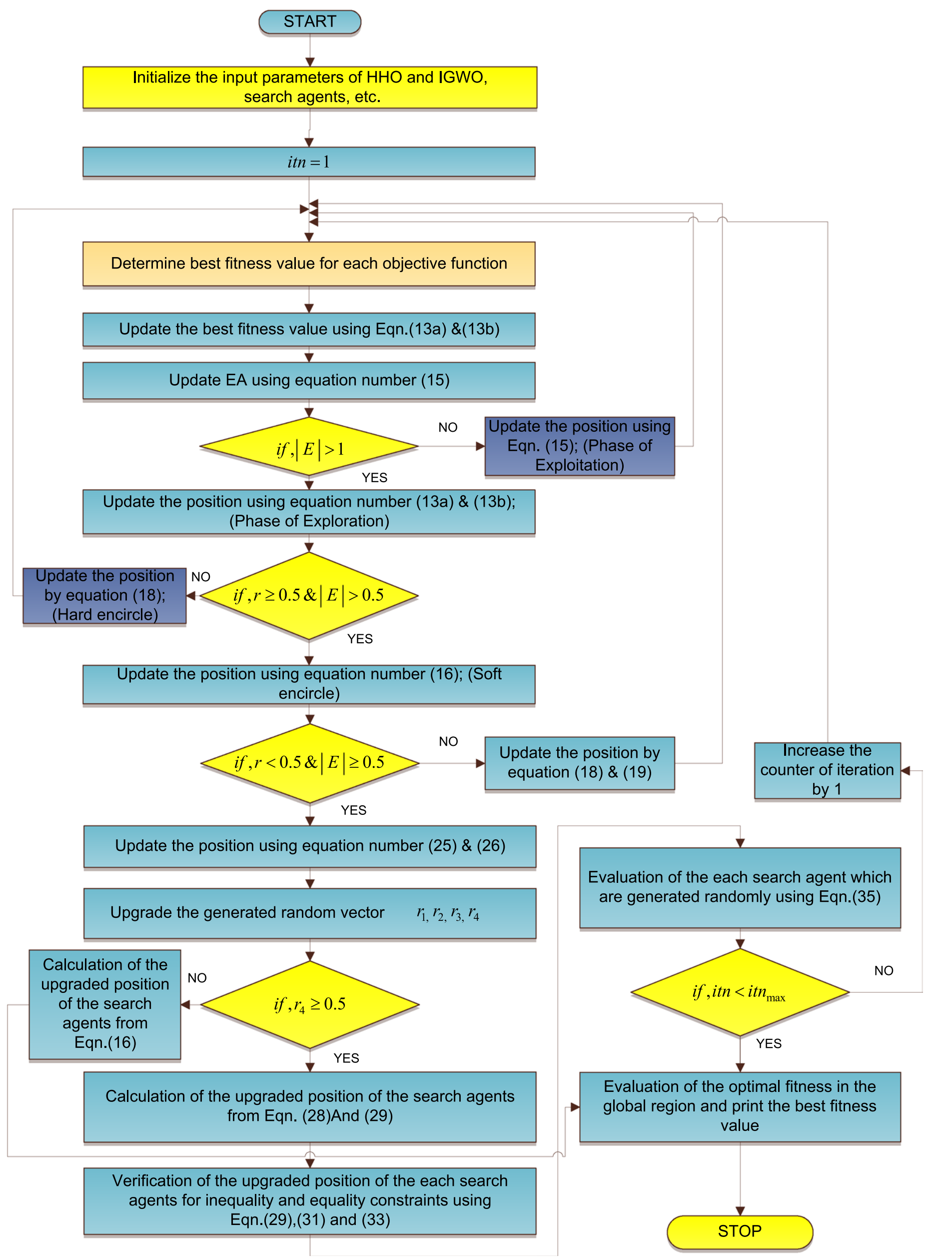

Fig. 1 Flowchart for HHO–IGWO algorithm

Results and discussion

In this section, the test results of standard IEEE with 10, 19, 20 and 40 thermal units along with wind penetration are analyzed. The test systems are simulated in MATLAB 2018a Windows 10, CPU@2.10Ghz-4 GB RAM Core i5. To check the performance of the HHO–IGWO method for solving the optimal scheduling, the standard test system of IEEE is taken into consideration. Table 1 illustrates generation scheduling for 10 generating units, and Table 2 shows generation scheduling for 10 generating units with wind penetration. From Tables 1 and 2, it can be seen that the cost of generation

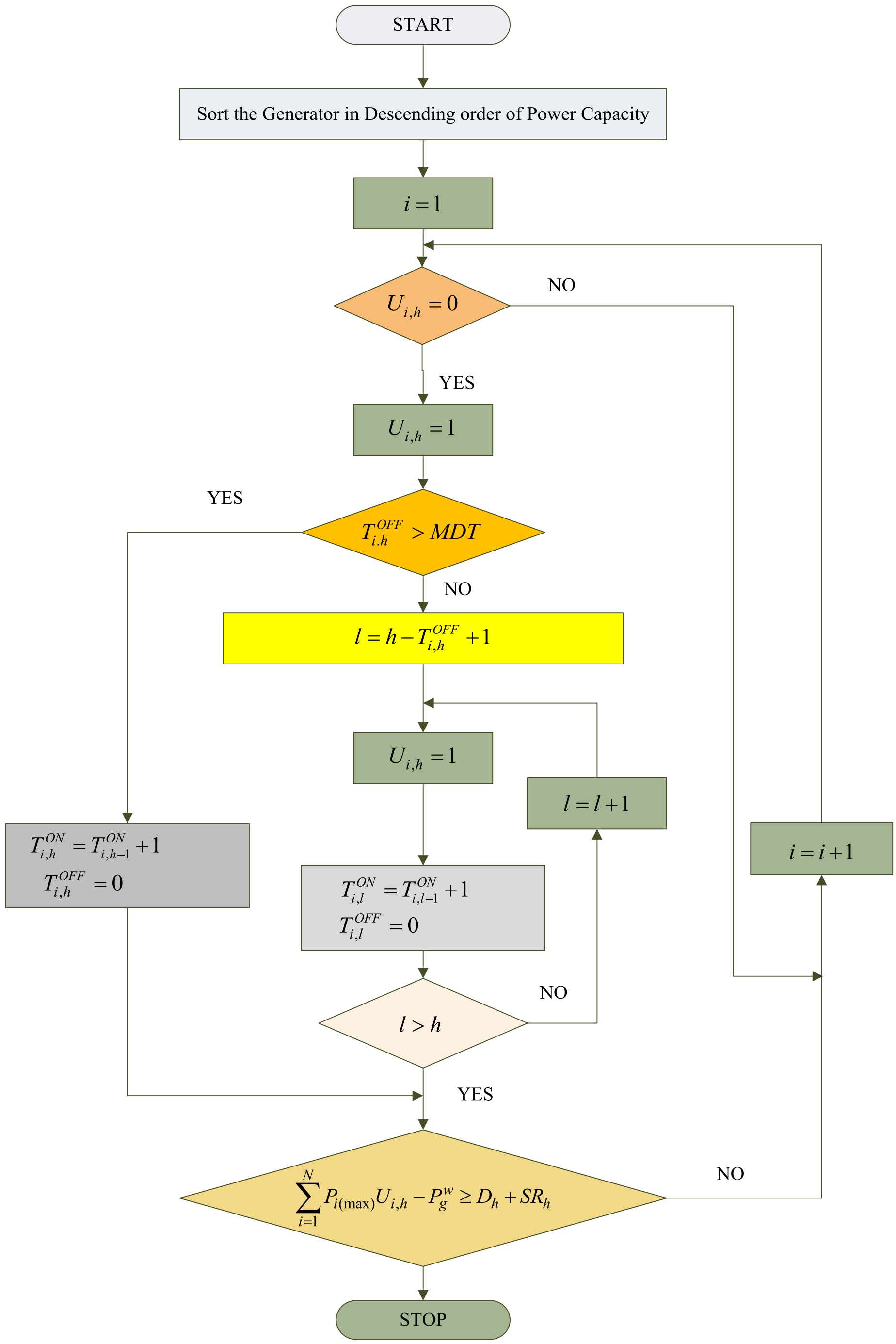

Fig. 2 Flowchart for spinning reserve repairing

with thermal units is 563435.9964 $ per hour, and the cost of generation for the same number of units with wind penetration is 492400.2699 $ per hour. This suggests that there is a cost-saving of 71,035.7265($/hr) and for 8760 h per year the total saving in cost is 622272964.14($/year).

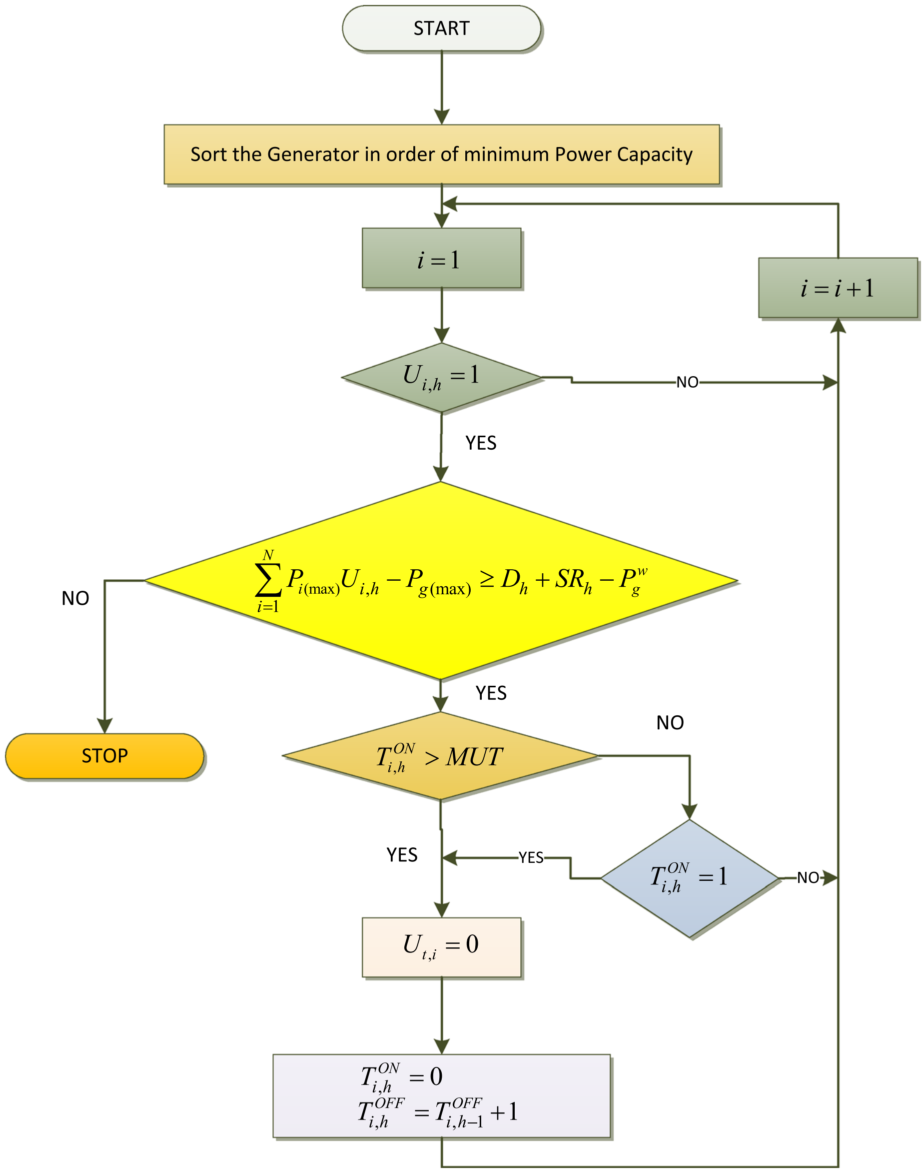

Fig. 3 Flowchart for the de-commitment of excessive generating units

Table 3 illustrates generation scheduling for 19 generating units with 10% SR for thermal-wind system. The cost of generation with thermal units is 207001.8242 $ per hour, and the cost of generation for the same number of units with wind penetration is 196723.619 $ per hour. This suggests that there is a cost-saving of 10,278.2052($/hr) and for 8760 h per year the total saving in cost is 90037077.552($/year).

Table 4 illustrates generation schedule for 20 generating units with wind penetration. The cost of generation with thermal units is 1127513.692$ per hour, and the cost of generation for the same number of units with wind penetration is 1052906.5262 $ per hour. This suggests that there is a cost-saving of 71,954.1638($/hr) and for 8760 h per year the total saving in cost is 630318474.888($/year).

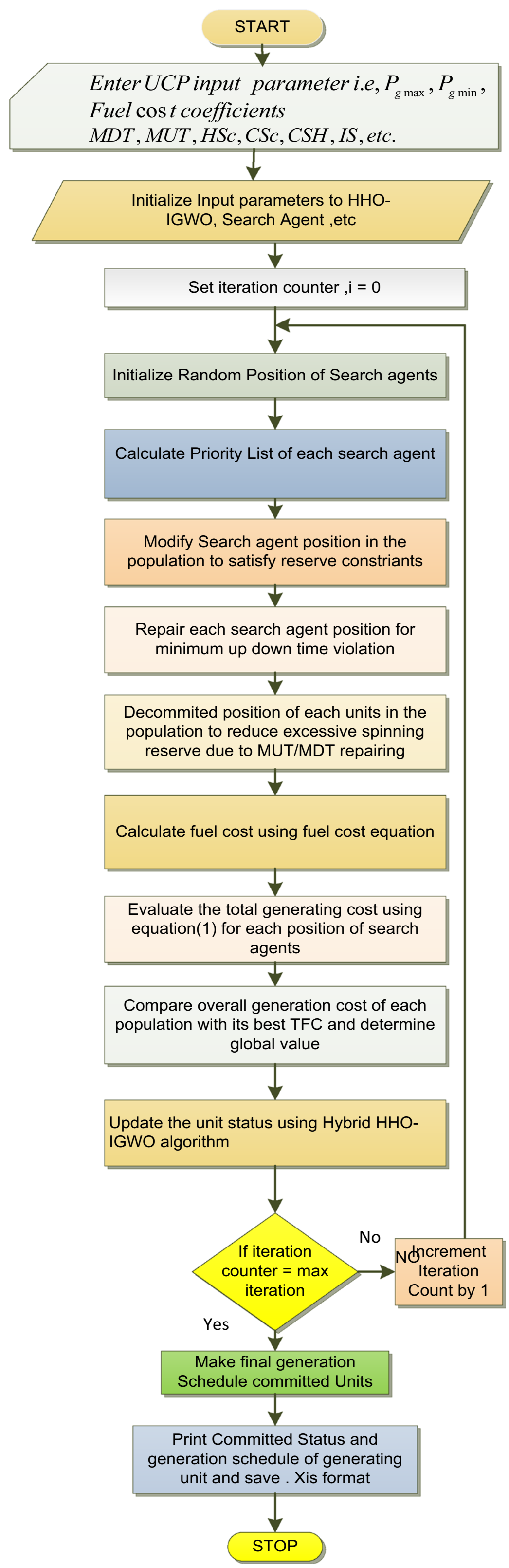

Fig. 4 Flowchart of entire process of commitment using HHO–IGWO

Table 1 Power scheduling for 10-unit test system with (10% SR) using hHHO–IGWO

Time (h)	Generation scheduling										Power (MW)	Start-up cost	Hourly fuel cost
	GN^1	GN^2	GN^3	GN^4	GN^5	GN^6	GN^7	GN^8	GN^9	GN^{10}			
1	455	245	0	0	0	0	0	0	0	0	700	1020	13,683
2	455	295	0	0	0	0	0	0	0	0	750	550	14,554
3	455	370	0	0	25	0	0	0	0	0	850	900	16,809
4	455	455	0	0	40	0	0	0	0	0	950	0	18,598
5	455	390	0	130	25	0	0	0	0	0	1000	0	20,020
6	455	360	130	130	25	0	0	0	0	0	1100	0	22,387
7	455	410	130	130	25	0	0	0	0	0	1150	0	23,262
8	455	455	130	130	30	0	0	0	0	0	1200	0	24,150
9	455	455	130	130	85	20	25	0	0	0	1300	430	27,251
10	455	455	130	130	162	33	25	0	10	0	1400	60	30,076
11	455	455	130	130	162	73	25	10	10	0	1450	60	31,916
12	455	455	130	130	162	80	25	43	10	10	1500	60	33,890
13	455	455	130	130	162	33	25	10	0	0	1400	0	30,058
14	455	455	130	130	85	20	25	0	0	0	1300	0	27,251
15	455	455	130	130	30	0	0	0	0	0	1200	0	24,150
16	455	310	130	130	25	0	0	0	0	0	1050	0	21,514
17	455	260	130	130	25	0	0	0	0	0	1000	0	20,642
18	455	360	130	130	25	0	0	0	0	0	1100	0	22,387
19	455	455	130	130	30	0	0	0	0	0	1200	0	24,150
20	455	455	130	130	162	33	25	10	0	0	1400	490	30,058
21	455	455	130	130	85	20	25	0	0	0	1300	0	27,251
22	455	455	0	0	145	20	25	0	0	0	1100	0	22,736
23	455	425	0	0	0	20	0	0	0	0	900	0	17,645
24	455	345	0	0	0	0	0	0	0	0	800	0	15,427

Overall Generation cost = 563,435.9964 ($)

Table 2 Power scheduling for 10-unit system with wind penetration using hHHO–IGWO

Time (h)	Generation scheduling										Generated power (MW)	Start-up cost	Hourly fuel cost
	GN^1	GN^2	GN^3	GN^4	GN^5	GN^6	GN^7	GN^8	GN^9	GN^{10}			
1	373	150	0	0	0	0	0	0	0	0	523	550	10,672
2	429	150	0	0	0	0	0	0	0	0	579	260	11,600
3	455	237	0	0	0	0	0	0	0	0	692	560	13,544
4	455	350	0	0	0	0	0	0	0	0	805	400	15,515
5	455	378	0	0	25	0	0	0	0	0	858	900	16,949
6	455	455	0	0	53	0	0	0	0	0	963	0	18,859
7	455	420	130	0	25	0	0	0	0	0	1030	0	20,576
8	455	455	130	0	51	0	0	0	0	0	1091	0	21,710
9	455	444	130	130	25	0	0	0	0	0	1184	0	23,858
10	455	455	130	130	89	0	25	0	0	0	1284	260	26,515
11	455	455	130	130	118	20	25	0	0	0	1333	170	27,928
12	455	455	130	130	160	20	25	10	0	0	1385	60	29,721
13	455	455	130	130	71	20	25	0	0	0	1286	60	26,967
14	455	451	130	130	25	0	0	0	0	0	1191	90	23,981
15	455	353	130	130	25	0	0	0	0	0	1093	0	22,265
16	455	199	130	130	25	0	0	0	0	0	939	0	19,580
17	455	157	130	130	25	0	0	0	0	0	897	0	18,851
18	455	250	130	130	25	20	0	0	0	0	1010	0	21,277
19	455	340	130	130	25	20	0	0	0	0	1100	60	22,863
20	455	455	130	130	90	20	0	0	0	0	1280	340	26,179
21	455	433	130	130	25	0	0	0	0	0	1173	0	23,665
22	455	455	0	0	53	0	0	0	0	0	963	0	18,859
23	455	285	0	0	0	0	0	0	0	0	740	0	14,380
24	455	170	0	0	0	0	0	0	0	0	625	0	12,379
Cost of generation = 492,400.2699 ($)													

Table 3 Power scheduling of 19-unit system with wind penetration using hHHO–IGWO

Hour	GN^1	GN^2	GN^3	GN^4	GN^5	GN^6	GN^7	GN^8	GN^9	GN^{10}	GN^{11}	GN^{12}	GN^{13}	GN^{14}	GN^{15}	GN^{16}	GN^{17}	GN^{18}	GN^{19}
1	425	0	0	195	0	0	0	0	0	0	328	0	878	475	0	691	0	0	0
2	431	0	0	199	0	0	0	0	0	0	333	0	886	481	0	698	0	0	0
3	444	0	0	209	0	0	0	0	0	0	345	0	900	495	0	700	0	0	0
4	403	0	0	178	0	0	0	0	0	0	308	309	844	451	0	662	0	0	0
5	425	0	0	194	0	0	0	0	0	0	328	329	877	475	0	690	0	0	0
6	458	0	0	219	0	0	0	0	0	0	357	359	900	510	0	700	0	0	0
7	459	0	56	220	0	0	0	0	0	0	359	360	900	512	0	700	0	0	0
8	453	0	52	215	0	0	0	0	0	0	353	354	900	504	0	700	0	0	0
9	500	0	94	269	0	0	0	0	0	0	400	0	900	581	0	700	0	0	0
10	426	0	0	195	0	0	0	0	0	0	328	330	878	476	0	692	0	0	0
11	455	0	0	217	0	0	0	0	0	0	0	356	900	506	0	700	0	0	0
12	442	0	0	207	0	0	0	0	0	0	0	344	900	493	0	700	0	0	0
13	437	0	0	203	0	0	0	0	0	0	338	0	895	487	0	700	0	0	0
14	446	0	0	210	0	0	0	0	0	0	347	0	900	498	0	700	0	0	0
15	491	0	0	244	0	0	45	0	0	0	387	0	900	545	0	700	0	0	0
16	453	0	0	215	0	0	30	0	0	0	353	354	900	504	0	700	0	0	0
17	461	0	0	221	0	0	0	0	0	0	360	361	900	513	0	700	0	0	0
18	455	0	0	217	0	0	0	0	0	0	355	356	900	507	0	700	0	0	0
19	431	0	0	199	0	0	0	0	0	0	333	334	886	481	0	698	0	0	0
20	459	0	0	220	0	0	0	0	0	0	359	0	900	512	0	700	0	0	0
21	441	0	0	207	0	0	0	0	0	0	343	0	900	492	0	700	0	0	0
22	429	0	0	197	0	0	0	0	0	0	331	0	883	479	0	696	0	0	0
23	380	0	0	161	0	0	0	0	0	0	287	289	810	428	0	633	0	0	0
24	445	0	0	0	0	0	0	0	0	0	0	347	900	496	0	700	103	0	0

Overall operating cost 196,723.619 $

Table 4 Power scheduling of 20-unit system with wind penetration using hHHO–IGWO

Power scheduling for 20-unit system with wind penetration																				
Hour	GN^1	GN^2	GN^3	GN^4	GN^5	GN^6	GN^7	GN^8	GN^9	GN^{10}	GN^{11}	GN^{12}	GN^{13}	GN^{14}	GN^{15}	GN^{16}	GN^{17}	GN^{18}	GN^{19}	GN^{20}
1	455	156.5	0	0	0	0	0	0	0	0	455	156.5	0	0	0	0	0	0	0	0
2	455	209.5	0	0	0	0	0	0	0	0	455	209.5	0	0	0	0	0	0	0	0
3	455	316	0	0	0	0	0	0	0	0	455	316	0	0	0	0	0	0	0	0
4	455	410	0	0	25	0	0	0	0	0	455	410	0	0	0	0	0	0	0	0
5	455	396.5	0	0	25	0	0	0	0	0	455	396.5	0	130	0	0	0	0	0	0
6	455	429	0	0	25	0	0	0	10	0	455	429	130	130	0	0	0	0	0	0
7	455	455	0	0	50	0	0	0	0	0	455	455	130	130	50	0	0	0	0	0
8	455	455	130	0	40.5	0	0	0	0	0	455	455	130	130	40.5	0	0	0	0	0
9	455	455	130	130	59.5	0	25	0	0	0	455	455	130	130	59.5	0	0	0	0	0
10	455	455	130	130	127	20	25	0	0	0	455	455	130	130	127	20	25	0	0	0
11	455	455	130	130	162	24.5	25	0	0	10	455	455	130	130	162	24.5	25	0	10	0
12	455	455	130	130	162	65.5	25	10	10	10	455	455	130	130	162	65.5	25	0	10	0
13	455	455	130	130	128	20	25	0	0	0	455	455	130	130	128	20	25	0	0	0
14	455	455	130	130	65.5	0	0	0	0	0	455	455	130	130	65.5	20	0	0	0	0
15	455	455	130	130	41.5	0	0	0	0	0	455	455	130	0	41.5	0	0	0	0	0
16	455	319.5	130	130	25	0	0	0	0	0	455	319.5	130	0	25	0	0	0	0	0
17	455	273.5	130	130	25	0	0	0	0	0	455	273.5	130	0	25	0	0	0	0	0
18	455	367.25	130	130	25	0	25	0	0	0	455	367.25	130	0	25	0	0	0	0	0
19	455	455	130	130	32.7	0	25	0	0	0	455	455	130	0	32.7	0	0	0	0	0
20	455	455	130	130	130	0	25	0	0	0	455	455	130	130	130	20	25	10	0	0
21	455	455	130	130	104	0	0	0	0	0	455	455	0	130	104	20	25	0	10	0
22	455	455	0	0	68	0	0	0	0	0	455	455	0	130	0	20	25	0	0	0
23	455	300	0	0	0	0	0	0	0	0	455	300	0	130	0	0	0	0	0	0
24	455	360	0	0	0	0	25	0	0	0	455	0	0	130	0	0	0	0	0	0
Cost of generation = 1,052,906.5262 $																				

Table 5 Power scheduling for 1–20 units with wind using hHHO–IGWO

Power scheduling for 1–20 units with wind penetration

Hour	GN^1	GN^2	GN^3	GN^4	GN^5	GN^6	GN^7	GN^8	GN^9	GN^{10}	GN^{11}	GN^{12}	GN^{13}	GN^{14}	GN^{15}	GN^{16}	GN^{17}	GN^{18}	GN^{19}	GN^{20}
1	455	194.5	0	0	0	0	0	0	0	0	455	194.5	0	0	25	0	0	0	0	0
2	455	246	0	0	0	0	0	0	0	0	455	246	0	0	25	0	0	0	0	0
3	455	349.2	0	0	0	0	0	0	0	0	455	349.2	0	0	25	0	0	0	0	0
4	455	440	0	0	25	0	0	0	0	0	455	440	0	0	25	0	0	0	0	0
5	455	455	0	0	54.5	0	0	0	0	0	455	455	0	0	54.5	0	0	0	0	0
6	455	455	130	0	107	0	25	0	0	0	455	455	0	0	107	0	0	0	0	10
7	455	455	130	130	68.7	0	25	0	0	0	455	455	130	130	68.7	0	0	0	0	0
8	455	455	130	130	84	0	25	0	0	0	455	455	130	130	84	20	0	0	0	0
9	455	455	130	130	72.2	0	25	0	0	0	455	455	130	130	72.2	20	25	0	0	0
10	455	455	130	130	153	20	25	0	0	0	455	455	130	130	153	20	25	0	0	0
11	455	455	130	130	162	51.2	25	10	10	10	455	455	130	130	162	51.2	25	10	10	0
12	455	455	130	130	162	80	25	25.66	10	10	455	455	130	130	162	80	25	25.66	10	10
13	455	455	130	130	154	20	25	10	0	0	455	455	130	130	154	20	25	0	0	0
14	455	455	130	130	79	0	25	0	0	0	455	455	130	130	79	20	25	0	0	0
15	455	433.2	130	130	25	0	0	0	0	0	455	433.2	130	130	25	0	0	0	0	0
16	455	282.2	130	130	25	0	0	0	0	0	455	282.2	130	130	25	0	0	0	0	0
17	455	234.25	130	130	25	0	0	0	0	0	455	234.25	130	130	25	0	0	0	0	0
18	455	337.3	130	130	25	0	0	0	0	0	455	337.3	130	130	25	0	0	0	0	0
19	455	435.1	130	130	25	0	0	0	0	0	455	435.1	130	130	25	0	0	0	0	0
20	455	455	130	130	152	20	25	0	0	0	455	455	130	130	152	20	25	0	0	0
21	455	455	130	130	150	20	25	0	0	0	455	455	130	130	150	20	25	0	0	0
22	455	455	0	0	162	52.7	25	0	10	0	455	455	0	0	0	52.7	25	0	10	0
23	455	398.7	0	0	25	0	0	0	0	0	455	398.7	0	0	0	0	0	0	0	0
24	455	301.2	0	0	0	0	0	0	0	0	455	301.2	0	0	0	0	0	0	0	0

Table 6 Power scheduling for 21–40 units with wind using hHHO–IGWO

Power scheduling for 21–40 units with wind penetration																				
Hour	**GN**^{21}	**GN**^{22}	**GN**^{23}	**GN**^{24}	**GN**^{25}	**GN**^{26}	**GN**^{27}	**GN**^{28}	**GN**^{29}	**GN**^{30}	**GN**^{31}	**GN**^{32}	**GN**^{33}	**GN**^{34}	**GN**^{35}	**GN**^{36}	**GN**^{37}	**GN**^{38}	**GN**^{39}	**GN**^{40}
1	455	194.5	0	0	0	0	0	0	0	0	455	194.5	0	0	0	0	0	0	0	0
2	455	246	0	0	0	0	0	0	0	0	455	246	0	0	0	0	0	0	0	0
3	455	349.25	0	0	0	0	0	0	0	0	455	349.2	0	0	0	0	0	0	0	0
4	455	440	0	0	25	0	0	0	0	0	455	440	0	0	0	0	0	0	0	0
5	455	455	0	0	54.5	0	0	0	0	0	455	455	0	0	54.5	0	0	0	0	0
6	455	455	0	0	107	20	0	0	0	0	455	455	0	0	107	0	0	0	0	10
7	455	455	0	0	68.75	20	0	0	0	0	455	455	0	0	68.75	0	0	0	0	0
8	455	455	130	0	84	20	0	0	0	0	455	455	0	0	84	0	0	0	0	0
9	455	455	130	130	72.25	20	25	0	0	0	455	455	130	130	72.25	0	0	0	0	0
10	455	455	130	130	153.5	20	25	0	0	0	455	455	130	130	153.5	20	25	0	0	10
11	455	455	130	130	162	51.2	25	0	0	0	455	455	130	130	162	51.2	25	0	0	0
12	455	455	130	130	162	80	25	25.6	10	10	455	455	130	130	162	80	25	0	0	0
13	455	455	130	130	154	20	25	0	0	0	455	455	130	130	154	20	25	0	0	0
14	455	455	130	130	79	0	25	0	0	0	455	455	130	130	79	0	0	0	0	0
15	455	433.25	130	130	25	0	0	0	0	0	455	433.2	130	130	25	0	0	0	0	0
16	455	282.25	130	130	25	0	0	0	0	0	455	282.2	130	130	25	0	0	0	0	0
17	455	234.25	130	130	25	0	0	0	0	0	455	234.2	130	130	25	0	0	0	0	0
18	455	337.37	130	130	25	0	0	0	0	0	455	337.375	130	130	25	0	0	0	0	0
19	455	435.1	130	130	25	0	0	0	0	0	455	435.1	130	130	25	0	0	0	0	0
20	455	455	130	130	152.5	20	25	0	10	0	455	455	130	130	152.5	20	25	0	0	0
21	455	455	130	0	150.75	20	25	0	0	0	455	455	0	0	150.75	20	25	0	0	0
22	455	455	130	0	0	52.75	25	0	0	0	455	455	0	0	0	52.75	25	0	0	0
23	455	398.75	0	0	0	0	0	0	0	0	455	398.75	0	0	0	0	0	0	0	0
24	455	301.25	0	0	0	0	0	0	0	0	455	301.25	0	0	0	0	0	0	0	0
Cost of generation = 21,723,661.1608 $																				

Table 7 Percentage cost-saving for 10-, 19-, 20-, and 40 units using hHHO–IGWO

Test system	Thermal system cost	Wind-thermal system cost	Cost-saving (%)
10 units	563,435.9964$	492,400.2699 $	12%
19 units	207,001.8242$	196,723.619 $	4.9%
20 units	1,127,513.692$	1,052,906.5262 $	6.5%
40 units	2,253,542.984$	2,172,364.16$	3.2%

Table 8 Comparison of 10-unit wind–thermal system with other algorithms

Method	Best cost	Worst cost	Mean	CPU time (in seconds)
Operational cycle-based algorithm [19]	563,937.70	–	564,227	19.4
GA [27]	563,977	565,606	564,275	221
EACO [19]	563,938	565,869	564,831	–
DBDE [28]	563,977	564,241	564,028	3.6
PSO [27]	564,212	565,783	565,103	120
Clustering method [19]	563,938	563,976	563,945	39.6
QBGSA [19]	515,339.6	517,156.8	516,425.4	49
BPSO [19]	516,778.5	519,963.0	518,304.5	61
BGSA [19]	517,736.6	520,577.2	519,254.8	61
EP [29]	564,551	566,231	565,352	100
HPSO [19]	563,942	565,785	564,772	–
BF [30]	564,842	565,872	NA	110
SGA [27]	565,943	570,121	569,042	–
hGWO-RES [19]	511,680	511,687	511,683	80.3
hHHO–IGWO[Proposed Method]	492,856.29	492,862.73	492,888.48	3.48

In Tables 5 and 6 illustrates generation schedule for 40 generating units with wind penetration. The cost of generation with thermal units is 2249657.3623 $ per hour. From Table 6, it can be seen that the cost of generation for the same number of units with wind penetration is 2172361.1608 $ per hour. This suggests that there is a cost-saving of 77,296.2015($/hr) and for 8760 h per year the total saving in cost is 67714725.14($/year).

Table 7 illustrates percentage cost-saving for 10-, 19-, 20-, and 40- units with wind using hHHO–IGWO. It shows with 10-unit system, there is % cost-saving of 12%. For 19 units, there is a % cost-saving of 4.90%. For 20 units, there is a % cost-saving of 6.5% while in case of 40 units, 3.2% cost-saving is noted. It is observed that proposed algorithm is efficient in solving unit commitment problem with more precision and accuracy.

Table 8 shows a cost comparison of 10 units (10% SR) for power generation with wind penetration. In Table 8, best, worst, and mean values for various methods are presented. Results illustrated in Table 8 reveal that the proposed method is more effective in solving unit commitment problem as compared to other known techniques.

Table 9 shows a cost comparison of 20 units (10% SR) for power generation with wind penetration. In Table 9, best, worst, and mean values for various methods are presented. Results illustrated in Table 8 show that HHO–IGWO gives total generation cost wind

Table 9 Comparison of 20-unit wind–thermal system with other algorithms

Method	Best cost	Worst cost	Mean	CPU time (in seconds)
BMFO-SIG [20]	1,114,700 $	–	–	–
hGWO-RES [19]	1,071,700 $	–	–	–
GWO [31]	106,611.77$	–	–	1.25
hHHO–IGWO[Proposed Method]	1,052,906.52 $	1,055,303.13$	1,058,600.38$	1.19

Table 10 Comparison of 40-unit wind–thermal system with other algorithms

Method	Best cost	Worst cost	Mean	CPU time (in seconds)
BMFO-SIG [20]	2,266,500$	–	–	–
hGWO-RES [19]	2,198,400$	–	–	–
hHHO–IGWO[Proposed Method]	2,172,364.16$	2,178,985.50$	2,181,325.28$	1.48

penetration as 1,052,906.52$ which is less than BMFO-SIG, hGWO-RES, and GWO methods. The comparative analysis reveals that proposed method is efficient in resolving unit commitment problem with large wind penetration.

Similarly, Table 10 illustrates a cost comparison of 40 units (10% SR) for power generation with wind penetration. Results illustrated in Table 8 show that HHO–IGWO gives total generation cost wind penetration as 1,052,906.52$ which is less than BMFO-SIG and hGWO-RES methods. This suggests that that the proposed method is more effective in solving unit commitment problem when compared to other competent methods.

Conclusion

In this research work, a novel hybrid optimization technique based on the integration of HHO and IGWO has been utilized effectively to solve the UC problem. Four standard IEEE test systems are simulated with due effect of wind power penetration into the existing conventional thermal system consisting of 10-, 19-, 20-, and 40 units. The analysis shows that the proposed hybrid metaheuristic algorithm is efficient to provide a cost effective solution for handling the unit commitment problem. Further, to investigate the validity of the proposed algorithm, a comparative analysis for a 10-, 20-, and 40-unit system with wind penetration is also been performed. The comparative study reveals that the proposed algorithm is a promising technique to solve the UC problem with renewable energy penetration.

List of symbols

a_i, b_i and c_i Fuel cost coefficients

CS(h)	Cold starting hour of the ith unit
$CSc_{i,h}$	Cold start-up cost
D_L	Demand at 'h' hour
F_T	Total fuel cost
itn_{max}	Maximum iterations
N	Number of generators

MUT	Minimum up time
MDT	Minimum down time
$P_{g\max(i)}$	Maximum generation by *i*th unit
$P_{g\min(i)}$	Minimum generation by *i*th unit
$P_{g(i)}$	Minimum generation by *i*th unit
P_g^w	Power contributed by renewable energy
$P_{R(h)}$	Output power available at *R*th unit at '*h*' hours
STC_i	Start-up cost of *i*th generating unit
SDC_i	Shut-down cost of *i*th generating unit
$SR_{(h)}$	Spinning reserve at '*h*' hour
$T_{i,h}^{ON}$	Time for which *i*th unit is continuously ON
$T_{i,h}^{OFF}$	Time for which *i*th unit is continuously OFF
$U_{i,h}$	Status of *i*th unit

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Author contributions
DD analyzed and interpreted the data regarding the scheduling of each power generating units for 24 h duration and also drafted the work or substantively revised it and act as major contributor in writing the manuscript. VK has made substantial contribution in research design and developed the entire MATLAB software for the HHO-IGWO to solve the commitment and generation scheduling and dispatch problem of electric power system. PA contributed in renewables data analysis and overall reformation of the work. All authors have read and approved the manuscript, and the content of the manuscript has not been published or submitted for publication elsewhere.

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Availability of data and materials
The data sets used and/or analyzed during current research study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that they have no competing interests.

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