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Optimal generation scheduling and dispatch of thermal generating units considering impact of wind penetration using hGWO-RES algorithm

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Abstract

In order to achieve paramount economy, hybrid renewable energy sources are gaining importance, as renewable sources are costless. Over the past few years wind energy incorporation drew more consideration in the electricity market, as wind power took an affirmative role in energy saving as well as sinking emission pollutants. Recently developed Grey wolf optimizer (GWO) algorithm has conspicuous behavior for verdicting global optima, without getting ensnared in premature convergence. In the proposed research the exploitation phase of the grey wolf optimizer has been further improved using random exploratory search algorithm, which uses perturbed solutions vectors along with previously generated solution vectors. The paper presents a hybrid version of Grey Wolf Optimizer algorithm combined with random exploratory search algorithm (hGWO-RES) for the solution of combinatorial scheduling and dispatch problem of electric power systems. To validate the feasibility of the algorithm, the proposed algorithm has been tested on 23 benchmark problems. To verify the feasibility and efficacy of operation of proposed algorithm on generation scheduling and dispatch of electric power systems, small and medium scale power systems consisting of 7-, 10-, 19-, 20- and 40-generating units systems taken into consideration. Commitment and scheduling pattern has been evaluated with and without wind integration and it has been experimentally founded that proposed hybrid algorithm provides superior solution as compared to other recently reported meta-heuristics search algorithms.

Keywords Generation scheduling and dispatch (GSD) · Grey wolf optimizer · Unit commitment problem

1 Introduction

Hybrid renewable energy sources are getting importance, as renewable sources are costless. Over the past few years, wind energy incorporation drew more consideration in electricity generation market, as wind power acting as an affirmative role in energy saving as well as sinking emission pollutants. Also, multidisciplinary design *optimization* and multidisciplinary system *design optimization are emerging area for the solution of design* and optimization problems incorporating a number of disciplines. Scientific revolution has affected every aspect of contemporary life. In recent years, with the advancement in computer technology, new era of problem-solving methods has been emerged making use of computers. These methods are becoming more suitable for solving complex problems. These problem-solving methods with direct human involvement are sluggish. So, computer-aided design are widely adopted emphasizing on use of computer for engineering design problems. The computer-aided design not only emphasis on simulating a system but also helps to find the optimal design with high accuracy, low cost, high speed and reliability. Optimization techniques are considered to be one of the best tools for solving the engineering problems and to find the optimal results for the problem. The optimization process initialize with random set for specified problem and then improving them over predefined steps. The engineering problems to be tackled consist of various difficulties such as unconstrained, constrained, uncertainties, local solution, global solution, multiple objectives, etc. Optimization technique must be able to discourse these issues. In the recent years, various meta-heuristics search algorithms has been implemented such as Biogeography based Optimizer [1], Grey Wolf Optimizer [2], Ant Lion Optimizer [3], Moth Flame Optimizer [4], Multi Verse Optimizer [5], Dragon Fly Algorithm [6], Sine Cosine Algorithm [7], Lightning

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Search Algorithm [8], Seeker Optimization Algorithm [9],Virus Colony Search Algorithm [10], Whale Optimization Algorithm [11], Wind Driven Optimization [12], Water Cycle Algorithm [13], Salp Swarm Algorithm [14], Symbiotic Organism Search [15], Search Group Algorithm [16], Stochastic Fractal Search Algorithm [17], The Runner Root Algorithm [18], Ant Colony Optimization [19], Shuffled Frog Leaping Algorithm [20], Flower Pollination Algorithm [21], Optics Inspired Optimization [22], Cultural Evolution Algorithm [23], Grasshopper Optimization Algorithm [24], Interior Search Algorithm [25], Colliding Bodies Optimization [26], Krill Herd Algorithm [27], Competition over Resources [28], Binary Bat Algorithm [29], Mine Blast Algorithm [30], Biogeography Based Optimization [31], Adaptive Cuckoo Search Algorithm [32], Bat Algorithm [33], Animal Migration Optimization [34], Gravitational Search Algorithm [35], Branch and Bound Method [36], Expert System Algorithm [37], Genetic Algorithm [38], Binary Gravitational Search Algorithm [39], Collective Animal Behavior Algorithm [40], Bird Swarm Algorithm [41], Cognitive Behavior Optimization [42], Electromagnetic Field Optimization [43], Firework Algorithm [44], Water Wave Optimization [45], Earthworm Optimization Algorithm [46], Forest Optimization Algorithm [47], Mean Variance Optimization Algorithm [48], League Championship Algorithm [49], Chaotic Krill Herd Algorithm [50], Elephant Herding Optimization [51], Differential Evolution Algorithm [52], Imperialistic competition algorithm [53], Invasive weed optimization [54], Particle swarm optimization algorithm [55], Crow Search Algorithm [56], Self-Adaptive Bat Algorithm [57]. The brief review of these algorithms is depicted in Table 1. A large portion of these calculation depends on straight and nonlinear programming systems that require broad slope data and for the most part attempt to locate an enhanced arrangement in the region of a beginning stage. These numerical improvement calculations give a valuable technique the worldwide ideal in basic and perfect models [3]. However, some certifiable designing and logical improvement issues are exceptionally intricate and hard to settle, utilizing these techniques. On the off chance that there are more than one neighborhood minima in the problem, the outcome may rely upon the choice of an underlying point, and the acquired minima may not really be the global minima. Also, The No-Free-Lunch theorem for optimization allow developers to develop a new algorithm or to improve the existing algorithm because, it logically proves that there is no such optimization algorithm which can solve all the optimization problems with equal efficiency for all. Some algorithms work best for a few problems and worst for the rest of the problems. So, there is always a scope or improvement to develop the algorithm which could work well for most of the problems. In the proposed research, hybrid variant of grey wolf optimizer has been implemented to solve combinatorial optimizations problems of multidisciplinary system design.

1.1 Novely and contribution

The main contributions of the proposed research study are as follows:

- A novel hybrid grey wolf inspired optimizer algorithm has been proposed by improving exploitation phase of existing GWO algorithm using random exploratory search algorithm.
- In the proposed research, two algorithms are combined recursively to improve the local search capability of existing GWO algorithm and proposed algorithm has been tested for 23-benchmark problems including unimodal, multimodal and fixed dimension optimization.
- Performance analysis of the proposed algorithm has been investigated for standard Numerical Optimization Problem.
- For validation, the proposed algorithm has been tested on combinatorial optimization problem (i.e. Unit Commitment and dispatch Problem) of electric power system for small and medium scale power systems consisting of 7-, 10-, 19-, 20- and 40-generaing units.
- The performance of the proposed algorithm has been investigated by comparing it with various recently developed meta-heuristics search algorithm.

2 Unit commitment problem formulation

Unit Commitment of power system units is a multidimensional optimization task for preparation and maneuver of participated units. Contemporary power system network has diverse generating resources, which can be broadly grouped together into two categories i.e. conventional and non-conventional generation sources. Unfortunately, load demand is never steady and it has the tendency to change at every instant of time, a great difficulty arises for the generation that tends to cope with this variable load. Thus, it is required to make a judgment on which generating unit to turn on and which unit to turnoff and at what time it is desirable in the power system network. This complex process of obtaining on-off pattern of generating units, which should satisfy the load demand and spinning reserve parameter is known as unit commitment problem [1]. Unit commitment problem is a part of system planning schedule of 8-h to 24 h planning is done before-hand this duration is quite moderate, however it can to lead

Table 1 Brief review of various heuristics and meta-heuristics search algorithms

Author's name	Algorithm	Year	Type of problem solved	Nu. of benchmark functions	Ref.
Li X.	Animal migration optimization	2013	N/A	23	[34]
Mirjalili S.	Adaptive gbest-guided gravitational search algorithm	2014	Engineering optimization	25	[58]
Mirjalili S.	Ant Lion optimizer	2015	Engineering optimization	19	[3]
Simon D.	Biogeography-based optimization	2008	Real world problem	14	[1]
Rashedi E.	Binary gravitational search algorithm	2009	N/A	23	[39]
Mirjalili S.	Binary PSO-GSA	2014	N/A	22	[59]
Meng Bing Z.	Bird swarm algorithm	2015	N/A	18	[41]
Mirjalili S.	BBO train multilayer perceptron	2014	Bio-medical optimization	6	[60]
Kuo H.C.	Cultural evolution algorithm	2013	Reliability engineering problems	7	[23]
Wang G.	Chaotic Krill Herd algorithm	2014	N/A	14	[50]
Mohseni S.	Competition over resources	2014	N/A	8	[28]
Mudong L.	Cognitive behaviour optimization	2015	Engineering optimization	20	[42]
Mirjalili S.	Dragonfly algorithm	2015	Propeller design	19	[6]
Ghorbani N.	Exchange market algorithm	2014	N/A	12	[61]
Beheshti Z.	Electromagnetic field optimization	2015	N/A	30	[43]
Wang G.	Elephant herding optimization	2015	N/A	15	[51]
Tan Ying	Firework algorithm	2010	N/A	9	[44]
Ghaemi M.	Forest optimization algorithm	2014	Feature weighting	4	[47]
Rashedi E.	Gravitational search algorithm	2009	N/A	23	[35]
Saremi S.	Grasshopper optimization algorithm	2017	Engineering optimization	19	[24]
Mirjalili S.	Grey Wolf optimizer	2014	Engineering optimization	29	[2]
Singh N.	GWO-SCA	2017	Bio-medical optimization	22	[62]
Dai C.	Human group optimizer	2011	N/A	14	[63]
Gandomi A.	Interior search algorithm	2014	Engineering optimization	14	[25]
Gandomi A.	Krill Herd	2012	N/A	20	[27]
Shareef H.	Lightning search algorithm	2015	N/A	24	[8]
Sadollah A.	Mine blast algorithm	2012	Engineering optimization	16	[30]
Mirjalili S.	Moth-flame optimization algorithm	2015	Engineering optimization	29	[4]
Mirjalili S.	Multi-verse optimizer	2015	Engineering optimization	19	[5]
Salimi H.	Stochastic fractal search	2014	Engineering optimization	23	[17]
Cheng M.	Symbiotic organism search	2014	Engineering optimization	26	[15]
Mirjalili S.	Sine cosine algorithm	2016	Aircraft wing design	19	[7]
Mirjalili S.	Salp swarm algorithm	2017	Engineering optimization	19	[14]
Li Dond M.	Virus colony search	2016	Engineering optimization	30	[10]
Eskandar H.	Water cycle algorithm	2012	Engineering optimization	19	[13]
Mirjalili S.	Whale optimization algorithm	2016	Engineering optimization	29	[11]

short-term planning (next hour) to very long-term planning (one week to few weeks). Basically, unit commitment problem is a hierarchical problem as it does not end with the achievement of bare on-off patterns of units but economic factors are deeply incorporated with it. Next level of problem is allocation of real power in units that participated in load. So this problem can be subdivided into two sub problem Viz. optimum allocation (commitment) of generators at each stations for various load levels and "allocation of generation" to each station. The first problem in power system dialect is called the unit commitment problem (UCP) and second is called load scheduling or dispatch problem (EDP). Since this problem has both binary (UC) as well as continuous (ED) variable, it is known as the link optimization problem. In recent years, due to tremendous increase in load demand, large interconnections of hybrid electric networks are taken into consideration, which basically

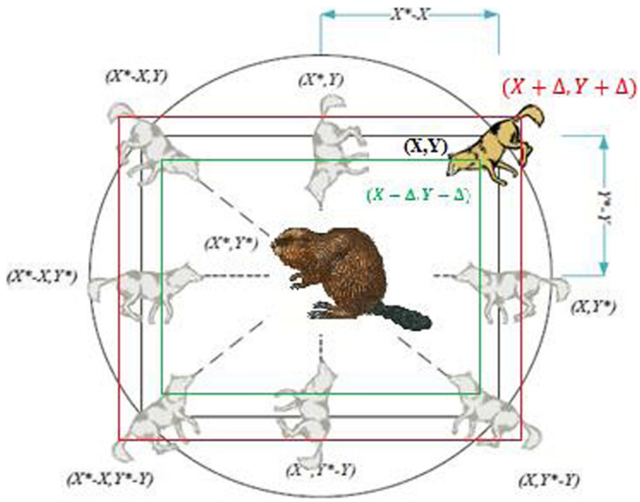


Fig. 1 2-D view of position vectors along with perturbed position vectors $\left(\overrightarrow{\mathrm{X}}_i+\Delta_i\right)$, $\left(\overrightarrow{\mathrm{X}}_i-\Delta_i\right)$ and possible next location w.r.t. Prey

consist of an integration of thermal unit with one renewable energy source as a wind system, acknowledged as hybrid renewable energy system (HRES) [64–66]. The vagueness in Wind Power crafts difficulties for obtaining UC Patterns. Wind integrated thermal power systems are analyzed on the basis of various simulation techniques such as Weibull probability distribution function [67], diverse Probability distribution function [68], adaptable Probability distribution function [69], incomplete Gama function [70], artificial neural networks [71], adaptive neuro-fuzzy approach [71], Gaussian PDF [72], copula theory [73], Levy alpha-stable distribution function [74], P-SCOPF [75], Differential evolution [76], Genetic algorithm [77], hPSO-SQP [78, 79], Upgraded Inertia Wight (PSO-IIW) [80], Fuzzy approach [81], neural network with MIPSO algorithm [82] and Teaching learning based

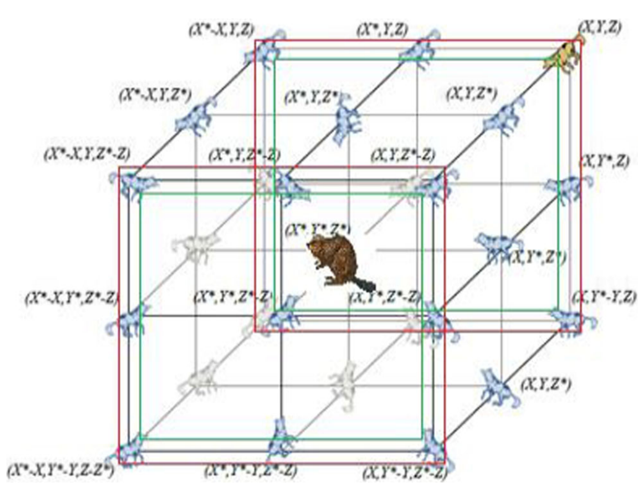


Fig. 2 3-D view of position vectors along with perturbed position vectors $\left(\overrightarrow{\mathrm{X}}_i+\Delta_i\right)$, $\left(\overrightarrow{\mathrm{X}}_i-\Delta_i\right)$ and possible next location w.r.t. Prey

optimizer [83]. No free lunch theorem has logically demonstrated that there exists no method suitable to all optimization problems [84]. Hence, the hybrid variant of grey wolf optimizer combined with random exploratory search algorithm has been proposed to evaluate the generation scheduling and dispatch of thermal power system combined with renewable energy system. The objective function for thermal power system with consideration of wind power can be mathematically described as per Eq.(1), as wind turbine do not consume fossil fuel and does not include any fuel cost.

$$FC_T=\sum_{h=1}^{H}\sum_{n=1}^{NOU}FC_n\left(P_n^h\right)U_n^h+U_n^h\left(1-U_n^{h-1}\right)SUC_{n,h}+U_n^{h-1}\left(1-U_n^h\right)SDC_n \tag{1}$$

where, $FC_n\left(P_n^h\right)$ describe the fuel cost of n-th generating units at h-th hours and $SUC_{n,\ h}$ represents the startup cost of n-th generating units for h-th hours and these costs may be mathematically described as:

$$FC_n\left(P_n^h\right)=a_n\left(P_n^h\right)^2+b_n\left(P_n^h\right)+c_n \tag{2}$$

$$SUC_{n,h}=\left\{\begin{array}{lll}HSC_n & if & T_{n,down}\le T_{n,off}^h\le T_{n,down}+T_{n,cold}\\ CSC_n & if & T_{n,off}^h\ge T_{n,down}+T_{n,cold}\end{array}\right\} \tag{3}$$

Where, HSC_n hot start is cost, and CSC_n is cold start cost, $T_{n,\ down}$ is minimum down time of n-th unit, $T_{n,off}^h$ is consecutive off time of n-th unit and term $T_{n,\ cold}$ represents the cold start hour of the n-th units.

The aforementioned unit commitment problem is subjected to various equality and non-equality constraints and which are mathematically described below:

a) Power Operational constraints:

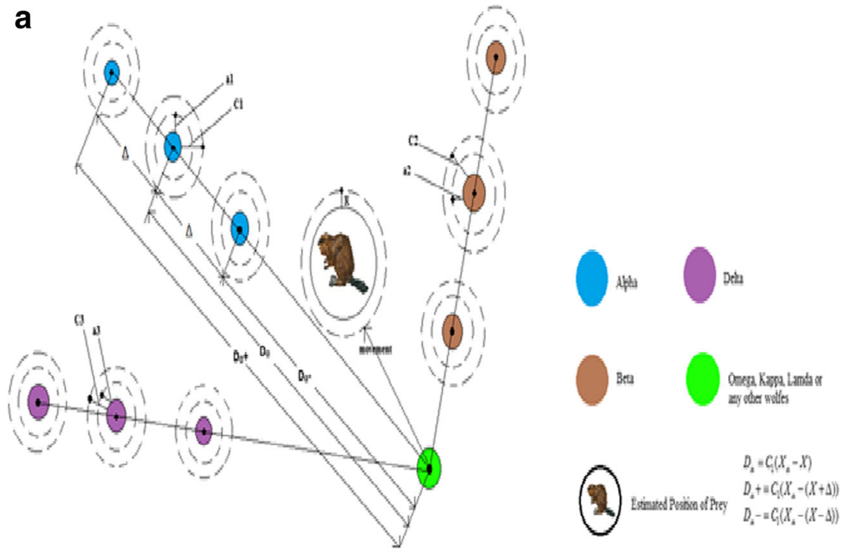
$$\sum_{i=1}^{N}P_{i,t}+P_{W,t}-P_{D,t}=0 \tag{4}$$

b) Spinning Reserve Constraint

$$SR_{j,u}^h=\min\left(P_{j,\max}-P_{j,h}\ ,\quad U_{R,h}\,T_l\right) \tag{5}$$

$$\sum_{n=1}^{NOU}u_{n,h}SR_{n,h}^h\ge R_D^h+W_u.P_{w,h} \tag{6}$$

a



b

```
Initialize the grey wolf population X_i (i=1, 2… n)
Initialize a, A and C
Calculate the fitness of each search agent
X_α =the best search agent
X_β =the second best search agent
X_δ =the third best search agent
while (iter<max number of iteration)
    for each search agent
        Update the position of current search agent by equation (20)
    end for
    Update a, A and C
    Calculate f+ ← f(X+Δ), f− ← f(X−Δ) and f ← f(X) for all search agents
    Evaluate best fitness using fitness ← min(f+, f−, f)
    Update X_α, X_β and X_δ
    iter=iter+1
end while
return X_α
```

Fig. 3 **a** Updating of position of alpha, beta and delta Grey Wolves in GWO. **b** PSEUDO code for proposed hybrid GWO-RES Algorithm

c) Minimum up and down time constraints

$$\left(P^{on}_{n,h-1}-P^{on}_{n,\min}\right)\left(U_{n,h-1}-U_{n,h}\right)\geq 0 \tag{7}$$

$$\left(T^{off}_{j,t-1}-T^{off}_{j,\min}\right)\left(U_{j,t-1}-U_{i,t}\right)\geq 0 \tag{8}$$

d) Maximum and Minimum Power Limit

$$P_n^{\min}\leq P_{n,h}\leq P_n^{\max} \tag{9}$$

The probability distribution function for the calculation of wind power can be mathematically represented [25].:

$$pdf(v;k,\lambda)=\frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1}\exp\left[-\left(\frac{v}{k}\right)^{k}\right] \tag{10}$$

Because of intermittent nature of wind power (WP), it is a Random variable. The mathematical function for wind power output and Wind speed can be mathematically described as:

$$P_W=\begin{cases}0 & \left(v^h\leq v_{in}\, or\, v^h\geq v_{out}\right)\\ P_{WR} & \left(v_r\leq v^h\leq v_{out}\right)\\ \frac{(v-vin)P_{WR}}{v_r-v_{in}} & \left(v_{in}\leq v^h\leq v_r\right)\end{cases} \tag{11}$$

For wind speed (v^h), between 0 and v_{in} or for wind speed greater that v_{out} the WP is zero. When wind speed (v^h) is between v_r and v_{out} Wind power is equal to the rated wind power. So for the first and second eventuality in Eq.(11), the Wind power is a discrete variable. The probability of Wind

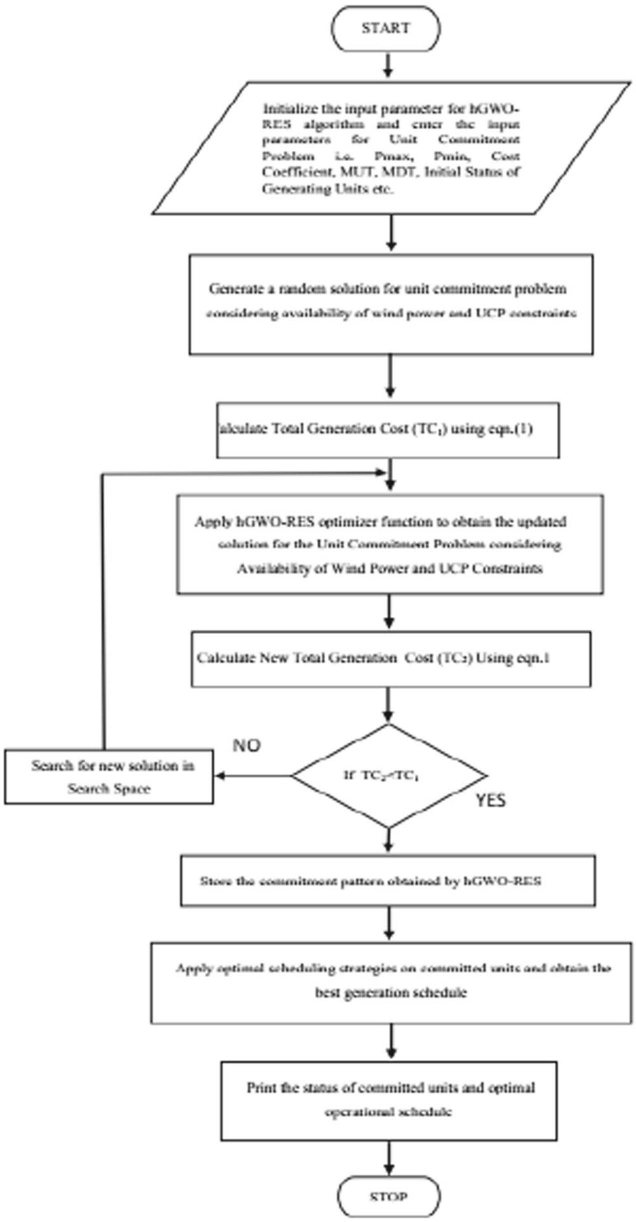


Fig. 4 Flow chart for solution of UCP using hGWO-RES

power being 0 or P_{WR} be calculated as per Eqs.(12) and (13) respectively described below:

$$\mathrm{P}_r(P_W=0)=cdf(v_{in})+[1-cdf(v_{out})] \tag{12}$$

$$\text{For } P_W=0,\quad \mathrm{P}_r=1-\exp\left[-\left(\frac{v_{in}}{\lambda}\right)^k\right]+\exp\left[-\left(\frac{v_{out}}{\lambda}\right)^k\right] \tag{13}$$

$$\text{For } P_W=P_{WR},\quad P_r=\exp\left[-\left(\frac{v_r}{\lambda}\right)^k\right]-\exp\left[-\left(\frac{v_{out}}{\lambda}\right)^k\right] \tag{14}$$

Between v_{in} and v_r Wind power is continuous variable and its probability density function can be written as

$$pdf(P_W)=\frac{kLv_{in}}{(P_{WR})\lambda}\left[\frac{\left(1+\left({}^{LP_W}/_{P_{WR}}\right)\right)v_{in}}{\lambda}\right]\times\exp\left[-\left(\frac{1+\left({}^{LP_W}/_{P_{WR}}\right)vin}{\lambda}\right)^k\right] \tag{15}$$

Ever since Correctness of Wind Power prediction is not meticulous and exact so based on above empirical formulas, Maximum generation scheduling can be computed. This maximum wind generation takes up base portion of load curve. In a time when the present position of unit commitment does not meet with the reserve demand a unit may be startup subject to satisfying constraint as described in Eq. (15).

3 Hybrid grey Wolf optimizer

Primarily developed Grey Wolf Optimizer, is a transformative calculation algorithm, based on grey wolves, which recreate the social stratum and chasing component of grey wolves in view of three principle ventures of chasing: scanning for prey, encompassing prey and assaulting prey and its mathematical model was designed in view point of hierarchy levels of different wolves. The fittest solution was designated as alpha (α). Accordingly, the second and third best solutions are named beta (β) and delta (δ) individually. Whatever is left of the hopeful solution are thought to be omega (ω), kappa (κ) and lambda (λ). For the fitness value calculation, the advancement (i.e. chasing) is guided by α, β and δ. The ω, κ and λ wolves trail these three wolves. In GWO, Encircling or Trapping of Prey was achieved by calculating $\overrightarrow{\mathrm{D}}$ and $\overrightarrow{\mathrm{X}}_{\mathrm{GWolf}}$ vectors described by Eqs. (16.1) and (16.2).

Table 2 Unimodal benchmark function

Function	Dim	Range	f_{min}
$f_1(x)=\sum_{i=1}^{n}x_i^2$	30	[−100, 100]	0
$f_2(x)=\sum_{i=1}^{n}\lvert x_i\rvert+\prod_{i=1}^{n}\lvert x_i\rvert$	30	[−10,10]	0
$f_3(x)=\sum_{i=1}^{n}\left(\sum_{j-1}^{i}x_j\right)^2$	30	[−100, 100]	0
$f_4(x)=\max_i\{\lvert x_i\rvert,1\le i\le n\}$	30	[−100, 100]	0
$f_5(x)=\sum_{i=1}^{n-1}\left[100\left(x_{i+1}-x_i^2\right)^2+(x_i-1)^2\right]$	30	[−30,30]	0
$f_6(x)=\sum_{i=1}^{n}([x_i+0.5])^2$	30	[−100, 100]	0
$f_7(x)=\sum_{i=1}^{n}ix_i^4+random[0,1]$	30	[−1.28, 1.28]	0

Table 3 Multi-modal benchmark functions

Function	Dim	Range	f_{min}
$F_8(x) = \sum_{i=1}^{n} -x_i \sin\left(\sqrt{\lvert x_i \rvert}\right)$	30	[−500,500]	−418.9829 × 5
$F_9(x) = \sum_{i=1}^{n} \left[x_i^2 - 10\cos(2\pi x_i) + 10\right]$	30	[−5.12,5.12]	0
$F_{10}(x) = -20\exp\left(-0.2\sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}\right) - \exp(\frac{1}{n}\sum_{i=1}^{n}\cos(2\pi x_i) + 20 + c$	30	[−32,32]	0
$F_{11}(x) = \frac{1}{4000}\sum_{i=1}^{n} x_i^2 - \prod_{i=1}^{n}\cos\left(\frac{x_i}{\sqrt{i}}\right) + 1$	30	[−600,600]	0
$F_{12}(x) = \frac{\pi}{n}\{10\sin(\pi y_1) + \sum_{i=1}^{n-1}(y_i - 1)^2\left[1 + 10\sin^2(\pi y_{i+1})\right] + (y_n - 1)^2\} + \sum_{i=1}^{n} u(x_i, 10, 100, 4) y_i = 1 + \frac{x_i + 1}{4}$ $u(x_i, a, k, m) = \begin{cases} k(x_i - a)^m & x_i > a \\ 0 & -a < x_i < a \\ k(-x_i - a)^m & x_i < -a \end{cases}$	30	[−50,50]	0
$F_{13}(x) = 0.1\{\sin^2(3\pi x_1) + \sum_{i=1}^{n}(x_i - 1)^2\left[1 + \sin^2(3\pi x_i + 1)\right] + (x_n - 1)^2\left[1 + \sin^2(2\pi x_n)\right]\} + \sum_{i=1}^{n} u$ $(x_i, 5, 100, 4)$	30	[−50,50]	0
$F_{14}(x) = -\sum_{i=1}^{n}\sin(x_i).\left(\sin\left(\frac{i x_i^2}{\pi}\right)\right)^{2m}, m = 10$	30	[0,π]	−4.687
$F_{15}(x) = \left[e - \sum_{i=1}^{n}(x_i/\beta)^{2m} - 2e - \sum_{i=1}^{n} x_i^2\right] - \prod_{i=1}^{n}\cos^2 x_i, m = 5$	30	[−20,20]	−1
$F_{16}(x) = \left\{\left[\sum_{i=1}^{n}\sin^2(x_i)\right] - \exp\left(-\sum_{i=1}^{n} x_i^2\right)\right\}.\exp\left[-\sum_{i=1}^{n}\sin^2\sqrt{\lvert x_i \rvert}\right]$	30	[−10,10]	−1

Table 4 Fixed dimension benchmark function

Function	Dim	Range	f_{min}
$F_{14}(x) = \left(\frac{1}{500} + \sum_{j=1}^{25}\frac{1}{j + \sum_{i=1}^{2}\left(x_i - a_{ij}\right)^6}\right)^{-1}$	2	[−65,65]	1
$F_{15}(x) = \sum_{i=11}^{11}\left[a_i - \frac{x_1\left(b_i^2 + b_i x_2\right)}{b_i^2 + b_i x_3 + x_4}\right]^2$	4	[−5,5]	0.00030
$F_{16}(x) = 4x_1^2 - 2.1x_1^4 + \frac{1}{3}x_1^6 + x_1 x_2 - 4x_2^2 + 4x_2^4$	2	[−5,5]	−1.0316
$F_{17}(x) = \left(x_2 - \frac{5.1}{4\pi^2}x_1^2 + \frac{5}{\pi}x_1 - 6\right)^2 + 10\left(1 - \frac{1}{8\pi}\right)\cos x_1 + 10$	2	[−5,5]	0.398
$F_{18}(x) = [1 + (x_1 + x_2 + 1)^2\left(19 - 14x_1 + 3x_1^2 - 14x_2 + 6x_1x_2 + 3x_2^2\right)] \times [30 + (2x_1 - 3x_2)^2 \times$ $\left(18 - 32x_1 + 12x_1^2 + 48x_2 - 36x_1x_2 + 27x_2^2\right)]$	2	[−2,2]	3
$F_{19}(x) = -\sum_{i=1}^{4} c_i \exp\left(-\sum_{j=1}^{3} a_{ij}\left(x_j - p_{ij}\right)^2\right)$	3	[1, 3]	−3.32
$F_{20}(x) = -\sum_{i=1}^{4} c_i \exp\left(-\sum_{j=1}^{6} a_{ij}\left(x_j - p_{ij}\right)^2\right)$	6	[0,1]	−3.32
$F_{21}(x) = -\sum_{i=1}^{5}\left[(x - a_i)(x - a_i)^T + c_i\right]^{-1}$	4	[0,10]	−10.1532
$F_{22}(x) = -\sum_{i=1}^{7}\left[(x - a_i)(x - a_i)^T + c_i\right]^{-1}$	4	[0,10]	−10.4028
$F_{23}(x) = -\sum_{i=1}^{10}\left[(x - a_i)(x - a_i)^T + c_i\right]^{-1}$	4	[0,10]	−10.5363

Table 5 Results of hybrid GWO-RES algorithm for unimodal benchmark function

Benchmark functions	Parameters			
	Mean value	SD	Worst value	Best value
F1	1.5066E-37	3.5976E-37	2.3685E-36	1.7935E-41
F2	1.5904E-22	1.6059E-22	7.6125E-22	7.3967E-24
F3	2.7467E-09	1.5616E-08	1.0932E-07	1.2011E-15
F4	5.0234E-11	5.0001E-11	2.0190E-10	3.5869E-13
F5	27.6775	0.7815	28.8199	26.0570
F6	2.0191	0.4567	3.2489	1.0135
F7	6.6614E-04	3.9632E-04	0.0017	8.0435E-05

$$\vec{D} = |\vec{C}.\vec{X}_{Prey}(iter) - \vec{X}_{GWolf}(iter)| \quad (16.1)$$

$$\vec{X}_{GWolf}(iter+1) = \vec{X}_{Prey}(iter) - \vec{A}.\vec{D} \quad (16.2)$$

Where, *iter* demonstrates the present iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X}_{Prey}$ is the position vector of the prey and $\vec{X}_{GWolf}$ shows the position vector of a grey wolf and the vectors $\vec{A}$ and $\vec{C}$ are calculated as follows:

$$\vec{A} = 2\vec{a}.\vec{\mu}_1 - \vec{a} \quad (16.3)$$

$$\vec{C} = 2.\vec{\mu}_2 \quad (16.4)$$

Where, $\vec{\mu}_1, \vec{\mu}_2 \in rand(0,1)$ and $\vec{a}$ decreases linearly from 2 to 0.

The hunting of prey are achieved by calculating the corresponding fitness score and positions of alpha, beta and delta wolves using Eqs. (17), (18) and (19) respectively and final position for attacking towards the prey was calculated by Eq. (20).

$$\vec{D}_{Alpha} = abs\left(\vec{C}_1.\vec{X}_{Alpha} - \vec{X}\right) \quad (17a)$$

Table 6 Comparison of unimodal benchmark functions

Algorithms	Parameters	Unimodal benchmark functions						
		F1	F2	F3	F4	F5	F6	F7
GWO [71]	Mean	6.59E-28	7.18E-17	3.29E-06	5.61E-07	26.81258	0.816579	0.002213
	SD	6.34E-05	0.029014	79.14958	1.315088	69.90499	0.000126	0.100286
PSO [55]	Mean	0.000136	0.042144	70.12562	1.086481	96.71832	0.000102	0.122854
	SD	0.000202	0.045421	22.11924	0.317039	60.11559	8.28E-05	0.044957
BA [33]	Mean	0.773622	0.334583	0.115303	0.192185	0.334077	0.778849	0.137483
	SD	0.528134	3.816022	0.766036	0.890266	0.300037	0.67392	0.112671
FPA [21]	Mean	1.06E-07	0.000624	5.67E-08	0.0038379	0.7812	1.08E-07	0.00310527
	SD	1.27E-07	0.000176	3.90E-08	0.002186	0.366891	1.25E-07	0.001367
GA	Mean	0.118842	0.145224	0.13902	0.157951	0.714157	0.167918	0.010073
	SD	0.125606	0.053227	0.121161	0.862029	0.972711	0.868638	0.003263
DA [6]	Mean	2.85E-18	1.49E-05	1.29E-06	0.000988	7.6	4.17E-16	0.0103
	SD	7.16E-18	3.76E-05	2.10E-06	0.00278	6.79	1.32E-15	0.00469
BDA [6]	Mean	0.282	0.0589	14.2	0.248	23.6	0.0953	0.0122
	SD	0.418	0.0693	22.7	0.331	34.7	0.13	0.0146
BPSO	Mean	5.59	0.196	15.5	1.9	86.4	6.98	0.0117
	SD	1.98	0.0528	13.7	0.484	65.8	3.85	0.00693
BGSA [39]	Mean	83	1.19	456	7.37	3100	107	0.0355
	SD	49.8	0.228	272	2.21	2930	77.5	0.0565
hGWO-RES	Mean	1.51E-37	1.59E-22	2.75E-09	5.02E-11	27.6775	2.0191	0.00066614
	SD	3.60E-37	1.61E-22	1.56E-08	5.00E-11	0.7815	0.4567	0.00039632

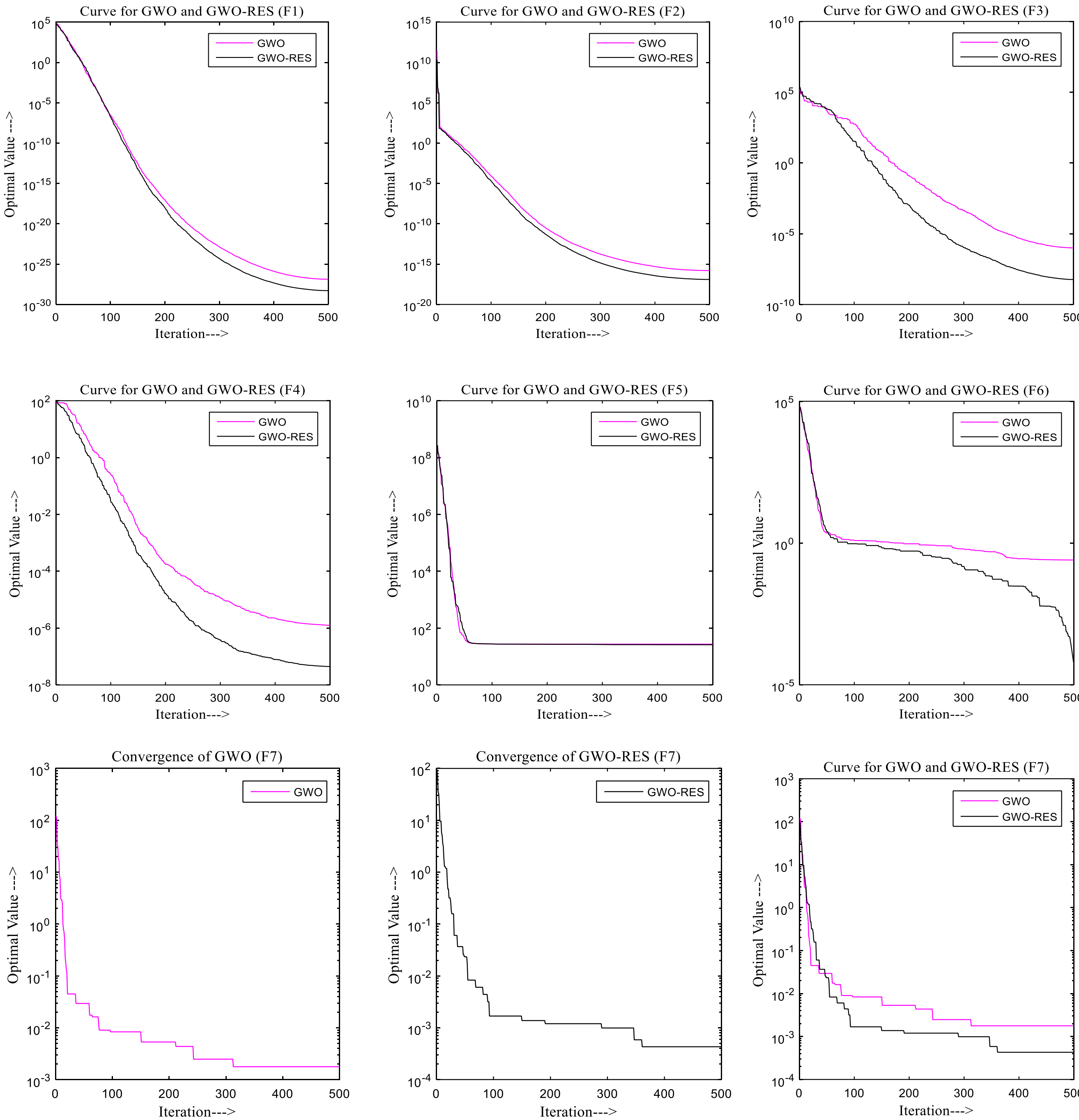


Fig. 5 Convergence curve of hGWO-RES for unimodal benchmark functions

$$\vec{X}_1 = \vec{X}_{Alpha} - \vec{A}_1 . \vec{D}_{Alpha} \tag{17b}$$

$$\vec{D}_{Beta} = abs\left(\vec{C}_2 . \vec{X}_{Beta} - \vec{X}\right) \tag{18a}$$

$$\vec{X}_2 = \vec{X}_{Beta} - \vec{A}_2 . \vec{D}_{Beta} \tag{18b}$$

$$\vec{D}_{Delta} = abs\left(\vec{C}_3 . \vec{X}_{Delta} - \vec{X}\right) \tag{19a}$$

$$\vec{X}_3 = \vec{X}_{Delta} - \vec{A}_3 . \vec{D}_{Delta} \tag{19b}$$

$$\vec{X}(iter + 1) = \frac{\left(\vec{X}_1 + \vec{X}_2 + \vec{X}_3\right)}{3} \tag{20}$$

In the proposed hybrid Grey-Wolf Optimizer-Random Exploratory search (hGWO-RES) algorithm, the position vector $\vec{X}_i$ is perturbed by Δ_i and new position vectors $\left(\vec{X}_i + \Delta_i\right)$ and $\left(\vec{X}_i - \Delta_i\right)$ has been obtained. The variation

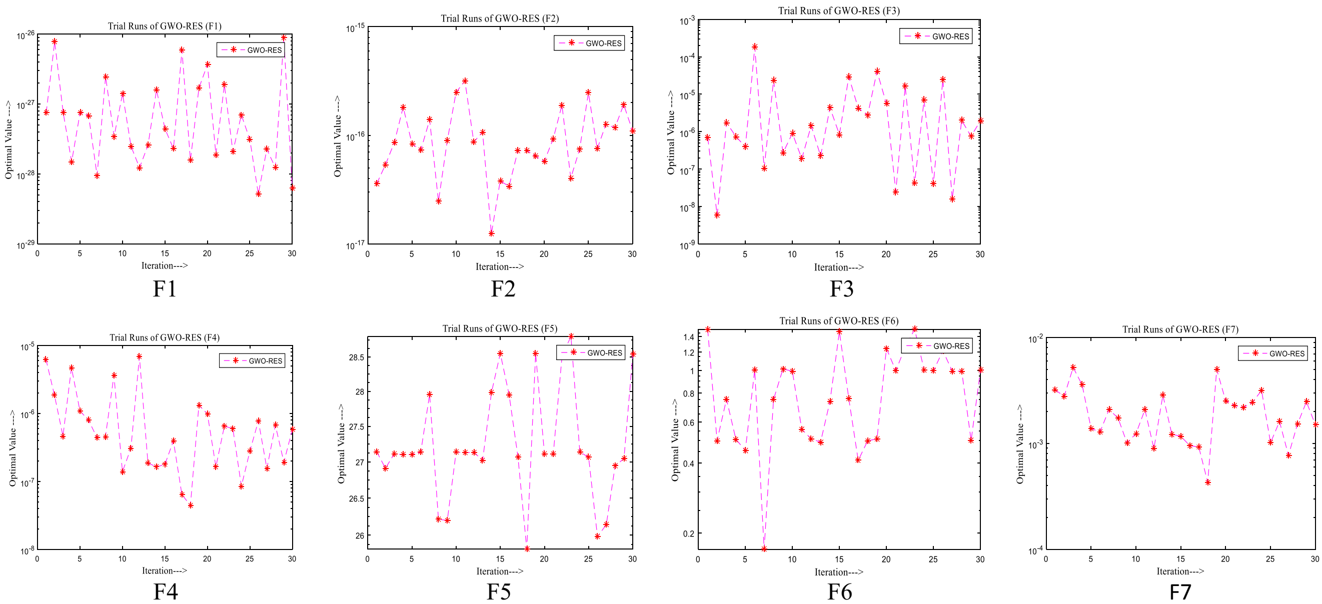


Fig. 6 Trial solutions for unimodal benchmark functions

of parameter Δ_i has been taken randomly within local search space to exploit the search space in a better way. The new fitness solutions $f^+ \leftarrow f(X+\Delta)$ and $f^- \leftarrow f(X-\Delta)$ has been obtained along with previous fitness solution $f \leftarrow f(X)$ and final fitness has been evaluated taking minimum values out of these newly obtained solutions using Eq. (21).

$$f_{final} \leftarrow \min(f^+, f^-, f) \tag{21}$$

The impact of newly obtained positions vectors as 2-Dimentional position vectors and conceivable neighbors are outlined in Fig. 1. As per Fig. 1, a grey wolf poser of (X, Y) can update its position w.r.t. newly obtained position vectors $((X+\Delta), (Y+\Delta))$ and $((X-\Delta), (Y-\Delta))$ indicated by the position of the prey (X^*, Y^*) and exploit the search space in better way. Better places around as well as can be expected regarding the present position by altering the estimation of $\vec{A}$ and $\vec{C}$ vectors. Figure 1 shows the 2-D view of Position Vectors along with perturbed position vectors $\left(\vec{X}_i + \Delta_i\right)$, $\left(\vec{X}_i - \Delta_i\right)$ and possible next Location w.r.t. Prey. The 3-D view of position vectors along with perturbed position vectors $\left(\vec{X}_i + \Delta_i\right)$, $\left(\vec{X}_i - \Delta_i\right)$ and possible next location w.r.t. prey has been shown in Fig. 2.

The random positions vectors, which allow grey wolves to reach any position between the points including perturbed position vectors $\left(\vec{X}_i + \Delta_i\right)$ and $\left(\vec{X}_i - \Delta_i\right)$ are shown in Fig. 3a.

The exploration phase in hGWO-RES is similar to GWO., In order to explore the search space globally, vector $\vec{A}$ and $\vec{C}$ are used, which mathematically model divergence. The PSEUDO code for the proposed hybrid GWO-RES algorithm is shown in Fig. 3b.

4 Solution strategy for unit commitment problem

In grey wolf optimizer, the search agent explore and exploit their updated position to a suitable real value in given search space considering various constraints impose upon them.

Table 7 Results of hybrid GWO-RES algorithm for multi modal benchmark function

Benchmark functions	Parameters			
	Mean value	SD	Worst value	Best value
F8	−5.007E + 03	990.1043	−2.8135E + 03	−6.7082E + 03
F9	0	0	0	0
F10	2.1352E-14	4.0956E-15	3.2863E-14	1.5099E-14
F11	3.5591E-04	0.0025	0.0178	0
F12	0.1559	0.0977	0.6548	0.0319
F13	1.4189	0.2363	2.0189	0.9452

Table 8 Comparison of multi modal benchmark functions

Algorithms	Parameters	Multi modal benchmark functions					
		F8	F9	F10	F11	F12	F13
GWO [2]	Mean	−6.12E + 03	3.11E-01	1.06E-13	4.49E-03	5.34E-02	6.54E-01
	SD	−4.09E + 03	4.74E + 01	7.78E-02	6.66E-03	2.07E-02	4.47E-03
PSO [55]	Mean	−4.84E + 03	4.67E + 01	2.76E-01	9.22E-03	6.92E-03	6.68E-03
	SD	1.15E + 03	1.16E + 01	5.09E-01	7.72E-03	2.63E-02	8.91E-03
BA [33]	Mean	−1.07E + 03	1.23E + 00	1.29E-01	1.45E + 00	3.96E-01	3.87E-01
	SD	8.58E + 02	6.86E-01	4.33E-02	5.70E-01	9.93E-01	1.22E-01
FPA [21]	Mean	−1.84E + 03	2.73E-01	7.40E-03	8.50E-02	2.66E-04	3.67E-06
	SD	5.04E + 01	6.86E-02	7.10E-03	4.00E-02	5.53E-04	3.51E-06
GA [85]	Mean	−2.09E + 03	6.59E-01	9.56E-01	4.88E-01	1.11E-01	1.29E-01
	SD	2.47E + 00	8.16E-01	8.08E-01	2.18E-01	2.15E-03	6.89E-02
DA [6]	Mean	−2.86E + 03	1.60E + 01	2.31E-01	1.93E-01	3.11E-02	2.20E-03
	SD	3.84E + 02	9.48E + 00	4.87E-01	7.35E-02	9.83E-02	4.63E-03
BDA [6]	Mean	−9.24E + 02	1.81E + 00	3.88E-01	1.93E-01	1.49E-01	3.52E-02
	SD	6.57E + 01	1.05E + 00	5.71E-01	1.14E-01	4.52E-01	5.65E-02
BPSO [86]	Mean	−9.89E + 02	4.83E + 00	2.15E + 00	4.77E-01	4.07E-01	3.07E-01
	SD	1.67E + 01	1.55E + 00	5.41E-01	1.29E-01	2.31E-01	2.42E-01
BGSA [39]	Mean	−8.61E + 02	1.03E + 01	2.79E + 00	7.89E-01	9.53E + 00	2.22E + 03
	SD	8.06E + 01	3.73E + 00	1.19E + 00	2.51E-01	6.51E + 00	5.66E + 03
hGWO-RES	Mean	−5.01E + 03	0.00E + 00	2.14E-14	3.56E-04	1.56E-01	1.42E + 00
	SD	9.90E + 02	0.00E + 00	4.10E-15	2.50E-03	9.77E-02	2.36E-01

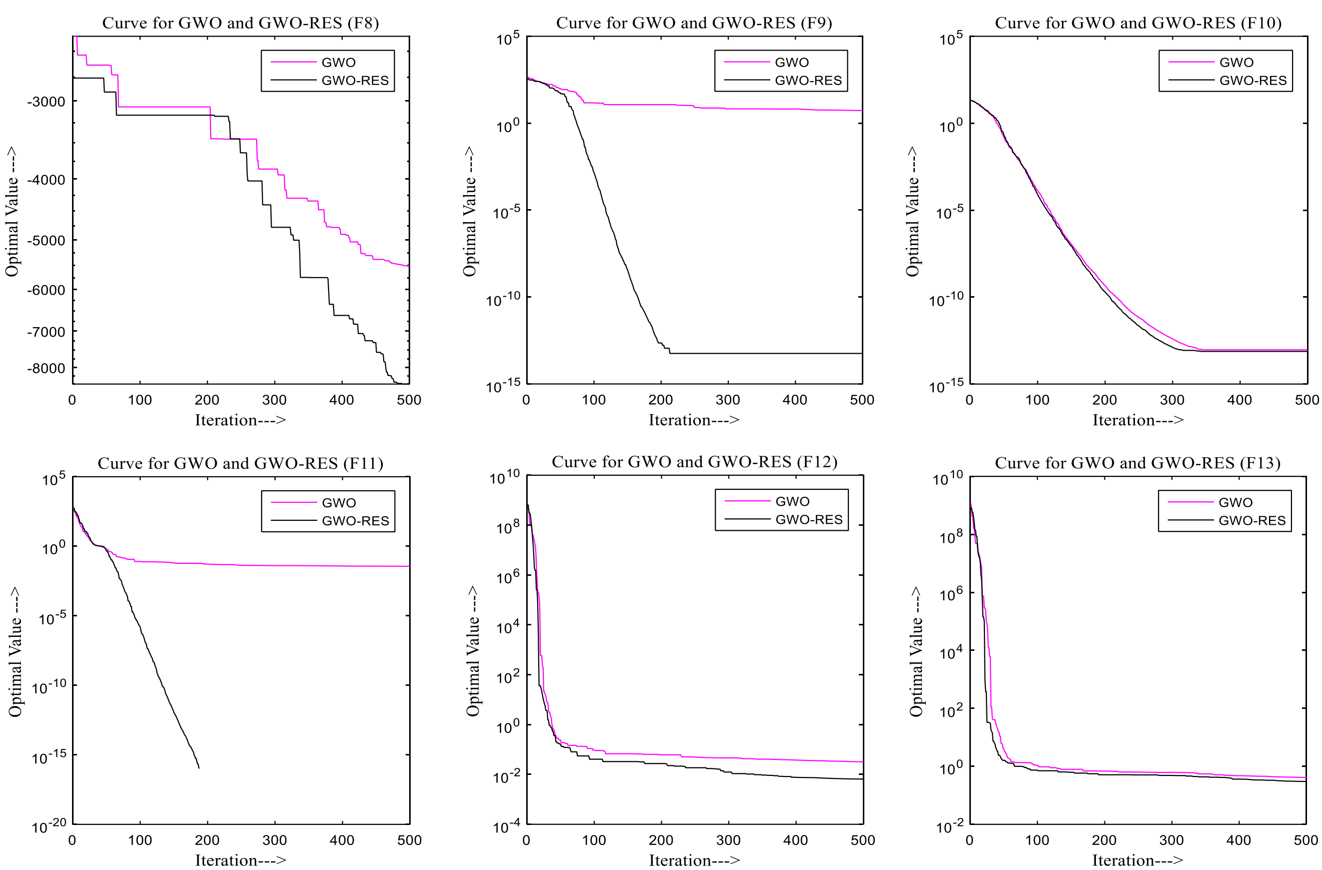


Fig. 7 Convergence curve of hGWO-RES for multi-modal benchmark functions

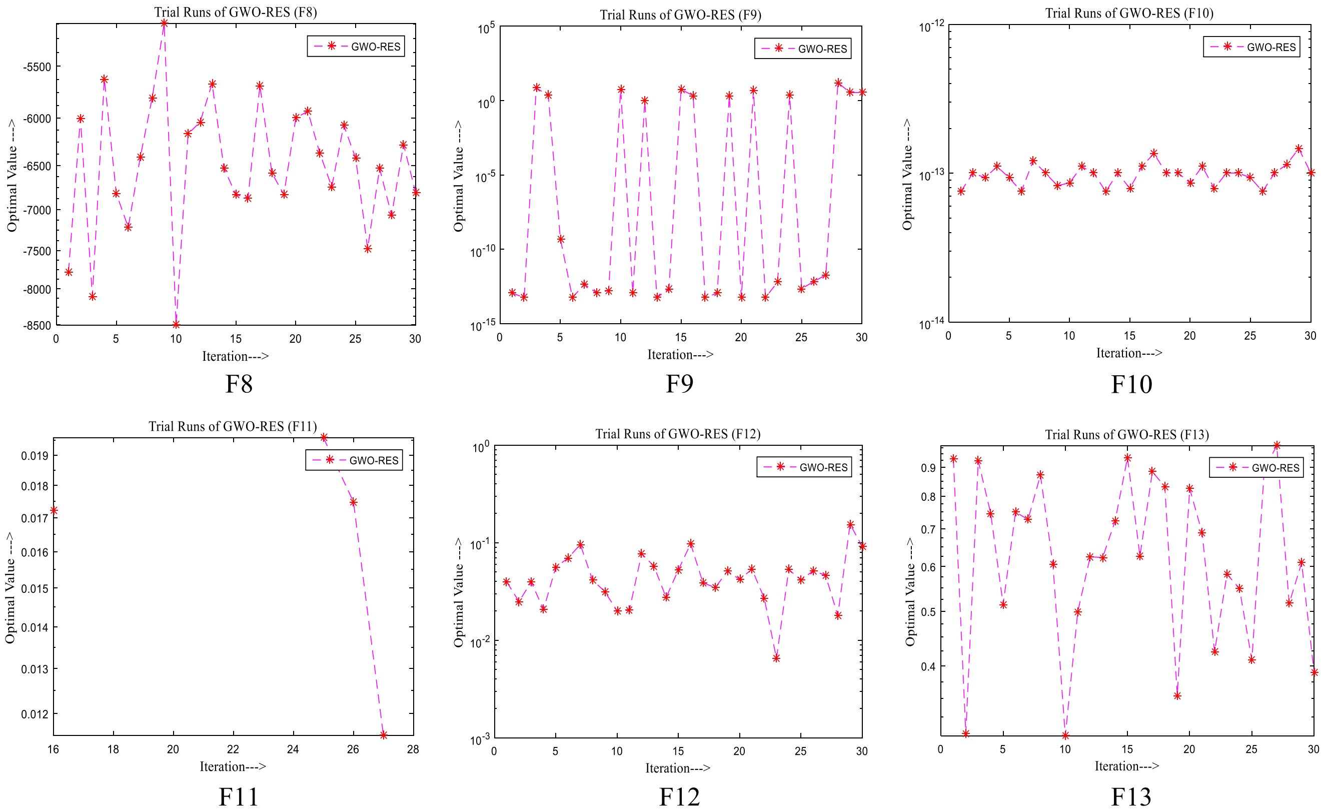


Fig. 8 Trial solutions of hGWO-RES for multi-modal benchmark functions

Since unit commitment problem is highly constrained in nature, they have both binary and discrete values. Thus mapping of continuous value of search agent updated to binary value is mandatory. Before solving unit commitment problem by using hGWO-RES algorithm we represent agent as a binary string .each unit “on state” as 1 and “off state” as a 0. So, unit state U is basically matrix of {N*T} following steps clarify modus operandi of unit commitment problem.

Step-1: To solve single area unit commitment problem, every individual is defined as units ON/OFF status showed as 1/0 correspondingly. An individual would display the unit commitment schedule over the time horizon H. The on/off schedule of the units is stored as an integer-matrix U, which is mathematically defined as:

$$U_{NP} = \begin{bmatrix} u_1^1 & u_1^2 & \cdots & u_1^H \\ u_2^1 & u_2^2 & \cdots & u_2^H \\ \vdots & \vdots & \vdots & \vdots \\ u_G^1 & u_G^2 & \cdots & u_G^H \end{bmatrix},$$

Table 9 Results of hybrid GWO-RES algorithm for fixed dimension benchmark function

Benchmark functions	Parameters			
	Mean value	SD	Worst value	Best value
F14	5.9633	4.6787	12.6705	0.9980
F15	0.0044	0.0081	0.0209	3.0750E-04
F16	−1.0316	2.4868E-08	−1.0316	−1.0316
F17	0.3979	8.4205E-05	0.3985	0.3979
F18	3.0000	4.3667E-05	3.0002	3.0000
F19	−3.8605	0.0030	−3.8549	−3.8628
F20	−3.2335	0.0822	−3.0850	−3.3220
F21	−8.6292	2.5069	−2.5843	−10.1531
F22	−10.1886	1.0518	−5.0876	−10.4028
F23	−10.2111	1.2932	−5.1284	−10.5360

Table 10 Comparison of fixed dimension benchmark functions

Algorithms	Parameters	Composite benchmark functions					
		F14	F15	F16	F17	F18	F19
GWO [2]	Mean	4.04E + 00	3.37E-04	−1.03E + 00	3.98E-01	3.000028	−3.86263
	SD	4.25E + 00	0.000625	−1.03163	0.397887	3	−3.86278
PSO [55]	Mean	3.627168	0.000577	−1.03163	0.397887	3	−3.86278
	SD	2.560828	0.000222	6.25E-16	0	1.33E-15	2.58E-15
BA [33]	Mean	182.476	487.2021	588.1938	756.9757	542.2006	818.5043
	SD	117.0248	161.4107	137.7861	160.097	220.2014	152.501
FPA [21]	Mean	3.37E-01	18.23309	2.24E + 02	362.0262	10.1592	5.04E + 02
	SD	2.36E-01	3.074685	5.03E + 01	54.01816	1.393908	1.16E + 00
GA [85]	Mean	114.6139	95.46331	325.4427	466.3074	90.36913	521.1935
	SD	26.96248	7.163383	51.66827	29.56841	13.72977	27.98507
DA [6]	Mean	1.04E + 02	1.93E + 02	4.58E + 02	596.6629	229.9515	6.80E + 02
	SD	9.12E + 01	8.06E + 01	1.65E + 02	171.0631	184.6095	1.99E + 02
hGWO-RES	Mean	5.9633	0.0044	−1.0316	0.3979	3	−3.8605
	SD	4.6787	0.0081	2.49E-08	8.42E-05	4.37E-05	0.003

Where, u_n^h is unit on/off status of n^{th} unit at h^{th} hour (i.e. u_n^h =1/0 for ON/OFF).

Step-2: Generating units are prioritized according to their Average Full Load generation Capacity in descending order.
Step-3: Status of individual units is modified in the population to satisfy the spinning reserve constraints
Step-4: Individual units in the population are repaired for minimum up/down time violations

Table 11 Comparison of results for fixed dimension benchmark functions

Algorithms	Parameters	Benchmark functions			
		F20	F21	F22	F23
GWO [2]	Mean	−3.28654	−10.1514	−10.4015	−10.5343
	SD	−3.25056	−9.14015	−8.58441	−8.55899
PSO [55]	Mean	−3.26634	−6.8651	−8.45653	−9.95291
	SD	0.060516	3.019644	3.087094	1.782786
GSA [35]	Mean	−3.31778	−5.95512	−9.68447	−10.5364
	SD	0.023081	3.737079	2.014088	2.60E-15
DE [52]	Mean	NA	−10.1532	−10.4029	−10.5364
	SD	NA	2.50E-06	3.90E-07	1.90E-07
FEP [87]	Mean	−3.27	−5.52	−5.53	−6.57
	SD	0.059	1.59	2.12	3.14
hGWO-RES	Mean	−3.2335	−8.6292	−10.1886	−10.2111
	SD	0.0822	2.5069	1.0518	1.2932

Step-5: Units of some search agents are de-committed in the population to reduce excessive spinning reserve due to minimum up/down time repairing
Step-6: Economic Load Dispatch Problem is then solved using MIQP and Fuel Cost is calculated for each Hour.
Step-7: Calculate Start-up cost for each hour using Eq. (3).
Step-8: Overall generation cost for 1st position is evaluated and it is assumed as global fitness and its position as global position.
Step-9: Overall generation costs for all positions are then evaluated in the population and then local generation cost and local commitment schedule for whole population is determined.
Step-10: Overall global generation cost is compared with Local generation cost in whole population. If global generation cost is greater than local generation cost, replace global generation cost with local generation cost and take local commitment schedule as global commitment.
Step-11: Modify the individual position using hGWO-RES algorithm and determine overall best generation cost and commitment schedule.
Step-12: If the maximum iteration number is reached, then go to next step (Step 14.)
Step-13: Otherwise, increase iteration number and go back to step 3.
Step-14: Stop and obtain the optimal solution of single area unit commitment problem from the individual position in the population that generated the least total generation cost (Fig. 4).

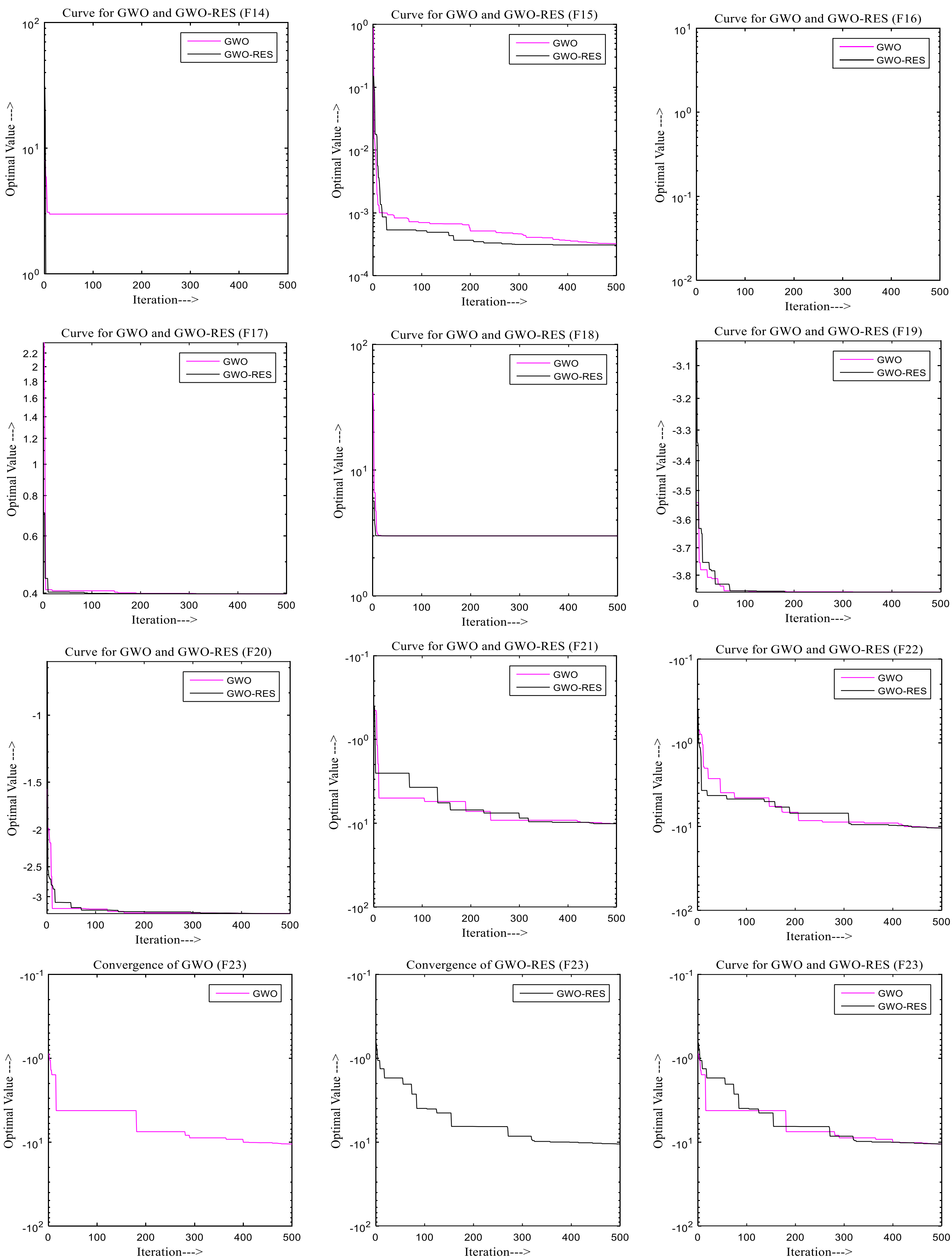


Fig. 9 Convergence curve of hGWO-RES for fixed dimension benchmark functions

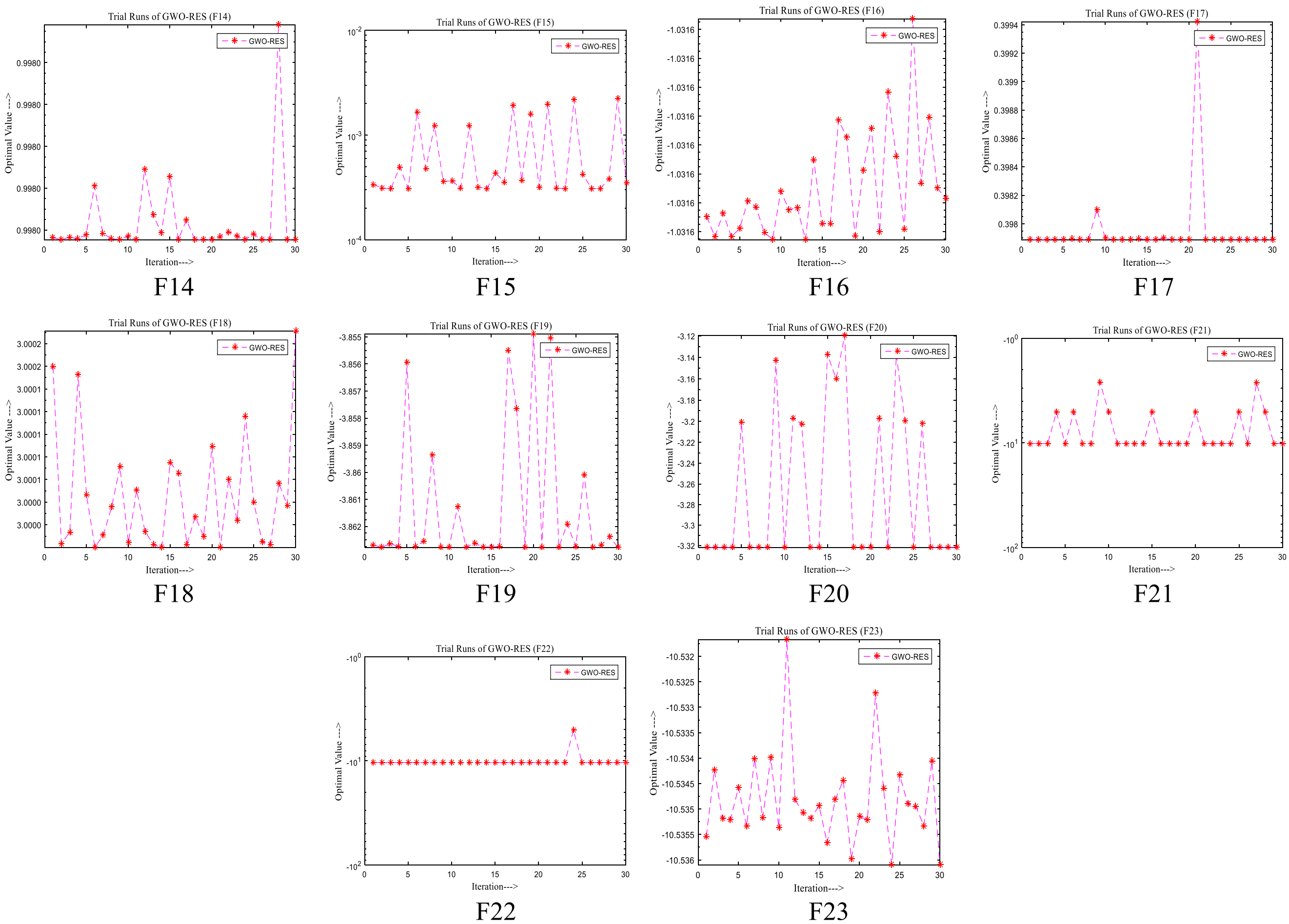


Fig. 10 Trial solutions of hGWO-RES for fixed dimension benchmark functions

5 Constraints handling strategy/ repair mechanism of constraints

The achieved major unit scheduling by hGWO-RES may not fulfill the certain crucial constraints such as MDT, MUT, Spinning reserve etc. So, the constraints defilements are to be repaired. In this paper a heuristic search strategy is adopted to tackle such problem.

5.1 Minimum up and minimum down time handling strategy

Minimum up and down time of specific unit is defined as connective hours that unit is 'on' or 'off' 'when it 'on' or 'off'. Any unit that is 'on' should not be turned 'off' immediately without reaching to 'MUT' and similarly any unit which is once "off" should not be turned "on" immediately without reaching to MDT. These constraints are calculated beforehand by using following recursive relation

$$T^h_{n.on} = \begin{cases} T^{h-1}_{n,on} + 1 & if\ u^h_n = 1 \\ 0 & if\ u^h_n = 0 \end{cases} \quad (26)$$

$$T^h_{n,off} = \begin{cases} T^{h-1}_{n,off} + 1 & if\ u^h_n = 0 \\ 0 & if\ u^h_n = 1 \end{cases} \quad (27)$$

Where $T^h_{n,on}$ and $T^h_{n,off}$ are number of continuous time when unit is on and off.

When crowning load duration appreciably inferior to the minimum down time of a particular unit. Minimum up time is violated. And constraint associated with minimum down time is violated at low load level where low load duration is considerably shorter than minimum up time. Since repapering of MDT, MUT, can lead to excessive spinning reserve, which results into high operating cost, thus if this remains it would defeat the whole purpose of optimizing cost. Hence we again us heuristic technique to de-commit excess of reserve.

The methodology to adjust/repair defilement of constraints associated with MDT, MUT are done as given below.

Table 12 Results for 56-bus system using hGWO-RES (considering thermal units)

Hour	Status of committed units							Scheduling of committed units						
	P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
1	1	0	0	0	1	0	0	287.7251	0	0	0	252.2749	0	0
2	1	0	0	0	1	0	0	328.648	0	0	0	291.352	0	0
3	1	0	0	0	1	0	0	499.5011	0	0	0	454.4989	0	0
4	1	0	0	0	1	0	1	447.1869	0	0	0	404.5443	0	174.2688
5	1	0	0	0	1	0	1	438.1869	0	0	0	395.9502	0	167.8629
6	1	0	0	0	1	0	0	518.9395	0	0	0	473.0605	0	0
7	1	0	0	0	1	0	0	511.778	0	0	0	466.222	0	0
8	1	0	0	0	1	0	0	500.5242	0	0	0	455.4758	0	0
9	1	0	0	0	1	0	0	493.3627	0	0	0	448.6373	0	0
10	1	0	0	0	1	0	0	483.132	0	0	0	438.868	0	0
11	1	0	0	0	1	0	0	472.9012	0	0	0	429.0988	0	0
12	1	0	0	0	1	0	0	395.6593	0	0	0	355.3407	0	0
13	1	0	0	0	1	0	0	344.5056	0	0	0	306.4944	0	0
14	1	0	0	0	1	0	0	312.2788	0	0	0	275.7212	0	0
15	1	0	0	0	1	0	0	319.4403	0	0	0	282.5597	0	0
16	1	0	0	0	1	0	0	404.3554	0	0	0	363.6446	0	0
17	1	0	0	0	1	0	0	459.6013	0	0	0	416.3987	0	0
18	1	0	0	0	1	0	0	452.9513	0	0	0	410.0487	0	0
19	1	0	0	0	1	0	0	442.7206	0	0	0	400.2794	0	0
20	1	0	0	0	1	0	0	421.7476	0	0	0	380.2524	0	0
21	1	0	0	0	0	0	1	542.144	0	0	0	0	0	241.856
22	1	0	0	0	1	0	1	325.6868	0	0	0	288.5243	0	87.78893
23	1	0	0	0	1	0	0	365.4786	0	0	0	326.5214	0	0
24	1	0	0	0	1	0	0	341.4364	0	0	0	303.5636	0	0
												Overall Generation Cost = 49,184 $		

Table 13 Results for 56-bus system using hGWO-RES (considering wind-thermal units)

Hour	Status of committed units							Scheduling of committed units						
	P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
1	1	0	0	0	0	0	0	458	0	0	0	0	0	0
2	1	0	0	0	0	0	0	510	0	0	0	0	0	0
3	1	0	0	0	1	0	0	457.8621	0	0	0	414.7379	0	0
4	1	0	0	0	1	0	0	480.6766	0	0	0	436.5234	0	0
5	1	0	0	0	1	0	0	453.4117	0	0	0	410.4883	0	0
6	1	0	0	0	1	0	0	471.0086	0	0	0	427.2914	0	0
7	1	0	0	0	1	0	0	458.834	0	0	0	415.666	0	0
8	1	0	0	0	1	0	0	453.8721	0	0	0	410.9279	0	0
9	1	0	0	0	1	0	0	456.8902	0	0	0	413.8098	0	0
10	1	0	0	0	1	0	0	449.9333	0	0	0	407.1667	0	0
11	1	0	0	0	1	0	0	427.8349	0	0	0	386.0651	0	0
12	1	0	0	0	1	0	0	361.8979	0	0	0	323.1021	0	0
13	1	0	0	0	1	0	0	315.6038	0	0	0	278.8962	0	0
14	1	0	0	0	1	0	0	243.6818	0	0	0	210.2182	0	0
15	1	0	0	0	0	0	0	513.3	0	0	0	0	0	0
16	1	0	0	0	1	0	0	361.6932	0	0	0	322.9068	0	0
17	1	0	0	0	1	0	0	400.2119	0	0	0	359.6881	0	0
18	1	0	0	0	1	0	0	384.0474	0	0	0	344.2526	0	0
19	1	0	0	0	1	0	0	375.9651	0	0	0	336.5349	0	0
20	1	0	0	0	1	0	0	361.2329	0	0	0	322.4671	0	0
21	1	0	0	0	1	0	0	361.3352	0	0	0	322.5648	0	0
22	1	0	0	0	1	0	0	319.3892	0	0	0	282.5108	0	0
23	1	0	0	0	1	0	0	321.998	0	0	0	285.002	0	0
24	1	0	0	0	1	0	0	316.7292	0	0	0	279.9708	0	0
												Overall Generation Cost = 42,355 $		

Table 14 Thermal commitment and generation schedule for 10-unit test system with 5% spinning reserve using hGWO-RES

Hour	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	1	1	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	455	295	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	455	395	0	0	0	0	0	0	0	0
4	1	1	0	1	0	0	0	0	0	0	455	365	0	130	0	0	0	0	0	0
5	1	1	0	1	1	0	0	0	0	0	455	390	0	130	25	0	0	0	0	0
6	1	1	0	1	1	0	0	0	0	0	455	455	0	130	60	0	0	0	0	0
7	1	1	1	1	1	0	0	0	0	0	455	410	130	130	25	0	0	0	0	0
8	1	1	1	1	1	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
9	1	1	1	1	1	1	0	0	0	0	455	455	130	130	110	20	0	0	0	0
10	1	1	1	1	1	1	1	0	0	0	455	455	130	130	162	43	25	0	0	0
11	1	1	1	1	1	1	1	1	0	0	455	455	130	130	162	80	25	13	0	0
12	1	1	1	1	1	1	1	1	1	0	455	455	130	130	162	80	25	53	10	0
13	1	1	1	1	1	1	1	0	0	0	455	455	130	130	162	43	25	0	0	0
14	1	1	1	0	1	1	1	0	0	0	455	455	130	0	162	73	25	0	0	0
15	1	1	1	0	1	0	1	0	0	0	455	455	130	0	135	0	25	0	0	0
16	1	1	1	0	1	0	0	0	0	0	455	440	130	0	25	0	0	0	0	0
17	1	1	1	0	1	0	0	0	0	0	455	390	130	0	25	0	0	0	0	0
18	1	1	1	0	1	0	0	0	0	0	455	455	130	0	60	0	0	0	0	0
19	1	1	1	1	1	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
20	1	1	1	1	1	1	1	0	0	0	455	455	130	130	162	43	25	0	0	0
21	1	1	0	1	1	1	1	0	0	0	455	455	0	130	162	73	25	0	0	0
22	1	1	0	1	0	1	1	0	0	0	455	455	0	130	0	35	25	0	0	0
23	1	1	0	1	0	0	0	0	0	0	455	315	0	130	0	0	0	0	0	0
24	1	1	0	0	0	0	0	0	0	0	455	345	0	0	0	0	0	0	0	0
																				Overall Generation cost = 557,830$

Table 15 Wind-thermal commitment and generation schedule for 10-unit test system with 5% spinning reserve using hGWO-RES

Hour	Committed status of generating units for wind-thermal UCP										Generation scheduling for wind-thermal scheduling UCP									
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	1	1	0	0	0	0	0	0	0	0	455	163	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	455	185	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	455	313.6	0	0	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0	0	455	386.2	0	0	0	0	0	0	0	0
5	1	1	0	0	1	0	0	0	0	0	455	381.9	0	0	25	0	0	0	0	0
6	1	1	0	0	1	0	0	0	0	0	455	455	0	0	96.3	0	0	0	0	0
7	1	1	0	1	1	0	0	0	0	0	455	436.5	0	130	25	0	0	0	0	0
8	1	1	0	1	1	0	0	0	0	0	455	455	0	130	68.8	0	0	0	0	0
9	1	1	1	1	1	0	0	0	0	0	455	455	130	130	58.7	0	0	0	0	0
10	1	1	1	1	1	1	0	0	0	0	455	455	130	130	145.1	20	0	0	0	0
11	1	1	1	1	1	1	1	0	0	0	455	455	130	130	146.9	20	25	0	0	0
12	1	1	1	1	1	1	1	0	0	1	455	455	130	130	162	67	25	0	0	10
13	1	1	1	1	1	0	1	0	0	0	455	455	130	130	148.5	0	25	0	0	0
14	1	1	1	1	1	0	0	0	0	0	455	425.9	130	130	25	0	0	0	0	0
15	1	1	1	0	1	0	0	0	0	0	455	455	130	0	71.3	0	0	0	0	0
16	1	1	1	0	1	0	0	0	0	0	455	356.6	130	0	25	0	0	0	0	0
17	1	1	1	0	1	0	0	0	0	0	455	273.9	130	0	25	0	0	0	0	0
18	1	1	1	0	1	0	0	0	0	0	455	355.3	130	0	25	0	0	0	0	0
19	1	1	1	0	1	0	0	0	0	0	455	455	130	0	29.5	0	0	0	0	0
20	1	1	1	1	1	1	0	0	0	0	455	455	130	130	91.7	20	0	0	0	0
21	1	1	0	1	1	1	0	0	0	0	455	455	0	130	139.9	20	0	0	0	0
22	1	1	0	1	0	1	0	0	0	0	455	394.9	0	130	0	20	0	0	0	0
23	1	1	0	1	0	0	0	0	0	0	455	230	0	130	0	0	0	0	0	0
24	1	1	0	1	0	0	0	0	0	0	455	166.7	0	130	0	0	0	0	0	0
																				Overall Generation Cost = 505,520$

Table 16 Thermal commitment and generation schedule for 10-unit test system with 10% spinning reserve using hGWO-RES

Hour	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	1	1	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	455	295	0	0	0	0	0	0	0	0
3	1	1	0	0	1	0	0	0	0	0	455	370	0	0	25	0	0	0	0	0
4	1	1	0	0	1	0	0	0	0	0	455	455	0	0	40	0	0	0	0	0
5	1	1	0	1	1	0	0	0	0	0	455	390	0	130	25	0	0	0	0	0
6	1	1	1	1	1	0	0	0	0	0	455	360	130	130	25	0	0	0	0	0
7	1	1	1	1	1	0	0	0	0	0	455	410	130	130	25	0	0	0	0	0
8	1	1	1	1	1	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
9	1	1	1	1	1	1	1	0	0	0	455	455	130	130	85	20	25	0	0	0
10	1	1	1	1	1	1	1	1	0	0	455	455	130	130	162	33	25	10	0	0
11	1	1	1	1	1	1	1	1	1	0	455	455	130	130	162	73	25	10	10	0
12	1	1	1	1	1	1	1	1	1	1	455	455	130	130	162	80	25	43	10	10
13	1	1	1	1	1	1	1	1	0	0	455	455	130	130	162	33	25	10	0	0
14	1	1	1	1	1	1	1	0	0	0	455	455	130	130	85	20	25	0	0	0
15	1	1	1	1	1	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
16	1	1	1	1	1	0	0	0	0	0	455	310	130	130	25	0	0	0	0	0
17	1	1	1	1	1	0	0	0	0	0	455	260	130	130	25	0	0	0	0	0
18	1	1	1	1	1	0	0	0	0	0	455	360	130	130	25	0	0	0	0	0
19	1	1	1	1	1	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
20	1	1	1	1	1	1	1	1	0	0	455	455	130	130	162	33	25	10	0	0
21	1	1	1	1	1	1	1	0	0	0	455	455	130	130	85	20	25	0	0	0
22	1	1	0	0	1	1	1	0	0	0	455	455	0	0	145	20	25	0	0	0
23	1	1	0	0	1	0	0	0	0	0	455	420	0	0	25	0	0	0	0	0
24	1	1	0	0	0	0	0	0	0	0	455	345	0	0	0	0	0	0	0	0
Overall Generation cost = 563,980$																				

Table 17 Wind-thermal scheduling and dispatch for 10-unit test system with 10% spinning reserve using hGWO-RES

Hour	Committed status of generating units for wind-thermal UCP										Generation scheduling for wind-thermal scheduling UCP									
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	1	1	0	0	0	0	0	0	0	0	455	163	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	455	185	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	455	313.6	0	0	0	0	0	0	0	0
4	1	1	0	0	1	0	0	0	0	0	455	361.2	0	0	25	0	0	0	0	0
5	1	1	0	0	1	0	0	0	0	0	455	381.9	0	0	25	0	0	0	0	0
6	1	1	1	0	1	0	0	0	0	0	455	396.3	130	0	25	0	0	0	0	0
7	1	1	1	0	1	0	0	0	0	0	455	436.5	130	0	25	0	0	0	0	0
8	1	1	1	1	1	0	0	0	0	0	455	368.8	130	130	25	0	0	0	0	0
9	1	1	1	1	1	0	1	0	0	0	455	455	130	130	33.7	0	25	0	0	0
10	1	1	1	1	1	1	1	0	0	0	455	455	130	130	120.1	20	25	0	0	0
11	1	1	1	1	1	1	1	1	0	0	455	455	130	130	136.9	20	25	10	0	0
12	1	1	1	1	1	1	1	1	1	0	455	455	130	130	162	57	25	10	10	0
13	1	1	1	1	1	1	1	0	0	0	455	455	130	130	128.5	20	25	0	0	0
14	1	1	1	1	1	0	0	0	0	0	455	425.9	130	130	25	0	0	0	0	0
15	1	1	1	0	1	0	0	0	1	0	455	455	130	0	61.3	0	0	0	10	0
16	1	1	1	0	1	0	0	0	0	0	455	356.6	130	0	25	0	0	0	0	0
17	1	1	1	0	1	0	0	0	0	0	455	273.9	130	0	25	0	0	0	0	0
18	1	1	1	0	1	0	0	0	0	0	455	355.3	130	0	25	0	0	0	0	0
19	1	1	1	0	1	0	0	0	0	0	455	455	130	0	29.5	0	0	0	0	0
20	1	1	1	1	1	0	0	0	1	1	455	455	130	130	91.7	0	0	0	10	10
21	1	1	1	1	1	0	0	0	0	0	455	455	130	130	29.9	0	0	0	0	0
22	1	1	0	1	1	0	0	0	0	0	455	389.9	0	130	25	0	0	0	0	0
23	1	1	0	1	0	0	0	0	0	0	455	230	0	130	0	0	0	0	0	0
24	1	1	0	1	0	0	0	0	0	0	455	166.7	0	130	0	0	0	0	0	0
Total cost = 511,680$																				

Table 18 Commitment status and generation schedule of IEEE-118 bus system using hGWO-RES (considering thermal units)

Hours	Generation scheduling for committed generating units																		
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19
1	464.8711	0	0	224.2784	0	0	0	0	0	0	363.634	0	900	517.2165	0	700	0	0	0
2	471.6118	0	0	229.3339	0	0	0	5	0	0	369.7006	0	900	524.3537	0	700	0	0	0
3	468.5735	0	61.2685	227.0551	0	0	0	5	0	0	366.9662	0	900	521.1367	0	700	0	0	0
4	448.0393	0	49.3454	0	0	0	0	5	0	0	348.4854	349.7354	900	499.3946	0	700	0	0	0
5	476.8248	0	66.05959	0	0	0	37.20749	0	0	0	374.3924	375.6424	900	529.8734	0	700	0	0	0
6	500	0	0	0	0	0	100	0	20	20	400	400	900	600	0	700	0	0	0
7	488.9805	0	0	242.3604	0	0	0	0	20	20	385.3325	386.5825	900	542.7441	0	700	0	0	0
8	483.3392	0	0	238.1294	0	0	0	0	20	0	380.2553	381.5053	900	536.7709	0	700	0	0	0
9	454.4649	0	53.0764	216.4737	0	0	0	0	20	0	354.2684	355.5184	900	506.1981	0	700	0	0	0
10	500	0	92.98987	268.0286	0	0	0	0	0	0	400	0	900	578.9815	0	700	0	0	0
11	438.4326	0	43.76729	0	0	0	0	0	0	0	339.8393	341.0893	897.6488	489.2227	0	700	0	0	0
12	422.873	0	0	0	0	0	0	0	0	0	325.8357	327.0857	874.3096	472.7479	0	687.9796	89.16838	0	0
13	419.4425	0	0	0	0	0	0	0	0	0	322.7482	323.9982	869.1637	469.1155	0	683.5689	86.96301	0	0
14	483.0366	0	0	237.9025	0	0	0	0	0	0	379.983	381.233	900	0	0	700	127.845	0	0
15	439.958	0	0	205.5935	0	0	0	0	0	0	341.2122	342.4622	899.9364	490.8378	0	700	0	0	0
16	469.8808	0	62.02754	228.0356	0	0	0	0	0	0	368.1427	369.3927	900	522.5208	0	700	0	0	0
17	469.8808	0	62.02754	228.0356	0	0	0	0	0	0	368.1427	369.3927	900	522.5208	0	700	0	0	0
18	483.3879	0	69.87042	0	0	0	0	0	0	0	380.2991	381.5491	900	536.8225	0	700	128.0708	0	0
19	465.3744	0	0	0	0	0	30.96178	0	0	0	364.0869	365.3369	900	517.7493	0	700	116.4907	0	0
20	428.362	0	0	0	0	0	30	0	0	0	330.7758	332.0258	882.543	478.5597	0	695.0368	92.69698	0	0
21	470.2637	0	0	228.3228	0	0	0	0	20	0	368.4873	0	900	522.9262	0	700	0	0	0
22	454.5579	0	0	216.5434	0	0	0	0	20	0	0	355.6021	900	506.2966	0	700	0	0	0
23	453.2098	0	0	215.5323	0	0	0	0	20	0	0	354.3888	900	504.8692	0	700	0	0	0
24	0	0	0	240.0703	0	0	0	0	20	0	382.5844	383.8344	900	539.511	0	700	0	0	0

Overall Generation cost = 208,690$

Table 19 Commitment status and generation schedule of IEEE-118 bus system using hGWO-RES (considering wind-thermal)

Hours	Generation scheduling for committed generating units																		
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19
1	442.7617	0	0	207.6963	0	0	0	0	0	0	343.7355	0	900	493.8065	0	700	0	0	0
2	443.301	0	0	208.1007	0	0	0	0	0	0	344.2209	0	900	494.3775	0	700	0	0	0
3	464.4937	0	0	223.9952	0	0	0	0	0	0	363.2943	0	900	516.8168	0	700	0	0	0
4	407.6711	0	0	181.3783	0	0	0	0	0	0	312.154	313.404	851.5066	456.6517	0	668.4342	0	0	0
5	425.3463	0	0	194.6347	0	0	0	0	0	0	328.0617	329.3117	878.0194	475.3667	0	691.1595	0	0	0
6	455.6789	0	53.7813	217.3842	0	0	0	0	0	0	355.361	356.611	900	507.4836	0	700	0	0	0
7	462.6546	0	57.83169	222.6159	0	0	0	0	0	0	361.6391	362.8891	900	514.8696	0	700	0	0	0
8	456.1607	0	54.06103	217.7455	0	0	0	0	0	0	355.7946	357.0446	900	507.9936	0	700	0	0	0
9	454.8504	0	0	216.7628	0	0	0	0	0	0	354.6153	355.8653	900	506.6063	0	700	0	0	0
10	485.3076	0	0	239.6057	0	0	0	0	0	0	382.0268	0	900	538.8551	0	700	129.3049	0	0
11	437.2596	0	0	203.5697	0	0	0	0	0	0	338.7836	0	895.8894	487.9808	0	700	98.41689	0	0
12	432.4917	0	0	199.9938	0	0	0	0	0	0	334.4926	0	888.7376	482.9324	0	700	95.35183	0	0
13	450.9853	0	0	213.864	0	0	0	0	0	0	351.1368	0	900	502.5139	0	700	0	0	0
14	417.6158	0	0	0	0	0	0	0	0	0	321.1043	322.3543	866.4238	467.1815	0	681.2204	0	0	0
15	500	0	94.43014	0	0	0	0	0	0	0	0	400	900	581.6079	0	700	155.2619	0	0
16	500	0	82.06233	253.9138	0	0	0	0	0	0	0	400	900	559.0548	0	700	141.569	0	0
17	496.7758	0	77.644	248.2068	0	0	0	0	0	0	0	393.5982	900	550.9979	0	700	136.6773	0	0
18	445.4336	0	0	209.7002	0	0	0	0	0	0	346.1403	347.3903	900	496.6356	0	700	0	0	0
19	426.3741	0	0	195.4056	0	0	0	0	0	0	328.9867	330.2367	879.5611	476.4549	0	692.481	0	0	0
20	459.937	0	0	220.5777	0	0	0	0	0	0	359.1933	0	900	511.9921	0	700	0	0	0
21	448.6665	0	0	212.1249	0	0	0	0	0	0	349.0499	0	900	500.0587	0	700	0	0	0
22	414.1544	0	0	0	0	0	0	0	0	0	317.9889	319.2389	861.2315	463.5164	0	676.7699	0	0	0
23	480.9497	0	68.45467	0	0	0	0	0	0	0	0	379.3547	900	534.2409	0	700	0	0	0
24	0	0	97.59177	273.9727	0	0	0	0	0	0	0	400	900	587.3732	0	700	158.7623	0	0

Overall cost = 200,490$

Table 20 Commitment status of 20 unit thermal unit with 10% spinning reserve using hGWO-RES

Hours	Committed status of generating units																			
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0
5	1	1	0	0	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0
6	1	1	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0
7	1	1	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0
8	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
9	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	1	0	0	0
10	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0
14	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	0	0
15	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
16	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
17	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
18	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
19	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
20	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	0
21	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	1	1	0	0	0
22	1	1	1	0	1	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0
23	1	1	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
24	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0

Table 21 Generation scheduling of 20 unit thermal unit with 10% spinning reserve using hGWO-RES

Hours	Generation scheduling for committed generating units																			
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
1	455	245	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	455	295	0	0	0	0	0	0	0	0	455	295	0	0	0	0	0	0	0	0
3	455	330	0	0	0	0	0	0	0	0	455	330	130	0	0	0	0	0	0	0
4	455	417.5	0	0	0	0	0	0	0	0	455	417.5	130	0	25	0	0	0	0	0
5	455	455	0	0	25	0	0	0	0	0	455	455	130	0	25	0	0	0	0	0
6	455	425	130	130	25	0	0	0	0	0	455	425	130	0	25	0	0	0	0	0
7	455	455	130	130	45	0	0	0	0	0	455	455	130	0	45	0	0	0	0	0
8	455	455	130	130	30	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
9	455	455	130	130	95	20	25	0	0	0	455	455	130	130	95	0	25	0	0	0
10	455	455	130	130	162	33	25	10	10	0	455	455	130	130	162	33	25	0	0	0
11	455	455	130	130	162	73	25	10	10	10	455	455	130	130	162	73	25	10	0	0
12	455	455	130	130	162	80	25	43	10	10	455	455	130	130	162	80	25	43	10	10
13	455	455	130	130	162	33	25	10	10	0	455	455	130	130	162	33	25	0	0	0
14	455	455	130	130	95	0	25	0	0	0	455	455	130	130	95	20	25	0	0	0
15	455	455	130	130	30	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
16	455	310	130	130	25	0	0	0	0	0	455	310	130	130	25	0	0	0	0	0
17	455	260	130	130	25	0	0	0	0	0	455	260	130	130	25	0	0	0	0	0
18	455	360	130	130	25	0	0	0	0	0	455	360	130	130	25	0	0	0	0	0
19	455	455	130	130	30	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
20	455	455	130	130	162	33	25	0	10	0	455	455	130	130	162	33	25	10	0	0
21	455	455	130	130	150	20	25	0	0	0	455	455	130	0	150	20	25	0	0	0
22	455	455	130	0	160	20	25	0	0	0	455	455	0	0	0	20	25	0	0	0
23	455	432.5	0	0	25	0	0	0	0	0	455	432.5	0	0	0	0	0	0	0	0
24	455	345	0	0	0	0	0	0	0	0	455	345	0	0	0	0	0	0	0	0

Overall Generation Cost = 1,125,100$

Table 22 Wind-thermal commitment status for 20-unit test system with 10% spinning reserve using hGWO-RES algorithm

Commitment status for wind-thermal scheduling UCP																				
Hour	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20
1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0
5	1	1	0	0	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0
6	1	1	0	0	1	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0
7	1	1	0	1	1	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0
8	1	1	0	1	1	1	0	0	0	0	1	1	1	0	1	1	0	0	0	0
9	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0
10	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0
11	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
13	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	0	0
14	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	0	0	0
15	1	1	1	1	1	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0
16	1	1	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0
17	1	1	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0
18	1	1	1	1	1	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0
19	1	1	1	1	1	1	0	0	0	0	1	1	1	0	1	0	1	0	0	0
20	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	0	0	0
21	1	1	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1	0	0	0
22	1	1	0	0	1	0	0	0	0	0	1	1	1	1	0	1	0	0	0	0
23	1	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0
24	1	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0

Table 23 Wind-thermal generation schedule for 20-unit test system with 10% spinning reserve using hGWO-RES algorithm

Generation scheduling for wind-thermal scheduling UCP																				
Hour	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20
1	455	204	0	0	0	0	0	0	0	0	455	204	0	0	0	0	0	0	0	0
2	455	240	0	0	0	0	0	0	0	0	455	240	0	0	0	0	0	0	0	0
3	455	354.3	0	0	0	0	0	0	0	0	455	354.3	0	0	0	0	0	0	0	0
4	455	428.1	0	0	0	0	0	0	0	0	455	428.1	0	0	25	0	0	0	0	0
5	455	450.95	0	0	25	0	0	0	0	0	455	450.95	0	0	25	0	0	0	0	0
6	455	455	0	0	68.15	20	0	0	0	0	455	455	130	0	68.15	0	0	0	0	0
7	455	455	0	130	48.25	20	0	0	0	0	455	455	130	0	48.25	0	0	0	0	0
8	455	455	0	130	94.4	20	0	0	0	0	455	455	130	0	94.4	20	0	0	0	0
9	455	455	130	130	61.85	20	25	0	0	0	455	455	130	130	61.85	20	0	0	0	0
10	455	455	130	130	147.55	20	25	0	0	10	455	455	130	130	147.55	20	25	0	0	0
11	455	455	130	130	162	38.95	25	10	10	0	455	455	130	130	162	38.95	25	0	0	0
12	455	455	130	130	162	80	25	15	10	10	455	455	130	130	162	80	25	15	0	10
13	455	455	130	130	151.75	20	25	10	0	0	455	455	130	130	151.75	20	25	0	0	0
14	455	455	130	130	52.95	20	0	0	0	0	455	455	130	130	52.95	0	0	0	0	0
15	455	455	130	130	40.65	20	0	0	0	0	455	455	130	0	40.65	0	0	0	0	0
16	455	333.3	130	130	25	0	0	0	0	0	455	333.3	130	0	25	0	0	0	0	0
17	455	266.95	130	130	25	0	0	0	0	0	455	266.95	130	0	25	0	0	0	0	0
18	455	345.15	130	130	25	0	0	0	0	0	455	345.15	130	0	25	0	25	0	0	0
19	455	437.25	130	130	25	20	0	0	0	0	455	437.25	130	0	25	0	25	0	0	0
20	455	455	130	130	133.35	20	0	0	0	10	455	455	130	130	133.35	20	25	0	0	0
21	455	455	0	130	112.45	20	0	0	0	0	455	455	130	130	112.45	20	25	0	0	0
22	455	442.45	0	0	25	0	0	0	0	0	455	442.45	130	130	0	20	0	0	0	0
23	455	337.5	0	0	0	0	0	0	0	0	455	337.5	0	130	0	0	0	0	0	0
24	455	255.85	0	0	0	0	0	0	0	0	455	255.85	0	130	0	0	0	0	0	0
																	Overall cost = 1,071,700$			

Table 24 Commitment status of 40 unit with 10% spinning reserve using hGWO-RES (considering thermal units)

Commitment status for units 1-20 for 40-generating unit system

Hour	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
4	1	1	0	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
5	1	1	0	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
6	1	1	0	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
7	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
8	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
9	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
14	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	0	1	0	0	0
15	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
16	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	1	0	0
17	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
18	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0
19	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	1	0	0	0
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
21	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
22	1	1	1	0	1	1	1	0	0	0	1	1	0	0	1	1	0	0	0	0
23	1	1	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0
24	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0

Commitment status for units 21-40 for 40-generating unit system

Hour	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40
1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
4	1	1	0	0	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
5	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
6	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
7	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
8	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	0	0	0	0	0
9	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	0	0	0	0
10	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
11	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
14	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	0	0
15	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
16	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
17	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
18	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
19	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
20	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
21	1	1	1	1	1	1	1	0	0	0	1	1	0	0	1	1	1	0	0	0
22	1	1	0	1	1	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0
23	1	1	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	1	0	0
24	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0

Table 25 Generation scheduling of 40 unit with 10% spinning reserve using hGWO-RES (considering thermal units)

Generation scheduling for units 1-20 for 40-generating unit system

Hour	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
1	455	245	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	455	262.5	0	0	0	0	0	0	0	0	455	262.5	0	0	0	0	0	0	0	0
3	455	362.5	0	0	0	0	0	0	0	0	455	362.5	0	0	0	0	0	0	0	0
4	455	346.25	0	130	25	0	0	0	0	0	455	346.25	0	130	25	0	0	0	0	0
5	455	357.5	0	130	25	0	0	0	0	0	455	357.5	0	130	25	0	0	0	0	0
6	455	455	0	130	27.5	0	0	0	0	0	455	455	0	130	27.5	0	0	0	0	0
7	455	455	130	130	45	0	0	0	0	0	455	455	0	130	45	0	0	0	0	0
8	455	455	130	130	56.25	0	0	0	0	0	455	455	0	130	56.25	0	0	0	0	0
9	455	455	130	130	102.5	20	25	0	0	0	455	455	130	130	102.5	20	0	0	0	0
10	455	455	130	130	162	33	25	10	10	10	455	455	130	130	162	33	25	10	0	0
11	455	455	130	130	162	73	25	10	10	10	455	455	130	130	162	73	25	10	10	10
12	455	455	130	130	162	80	25	43	10	10	455	455	130	130	162	80	25	43	10	10
13	455	455	130	130	162	33	25	10	10	10	455	455	130	130	162	33	25	10	0	0
14	455	455	130	130	100	0	25	0	0	0	455	455	130	130	100	0	25	0	0	0
15	455	455	130	130	30	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
16	455	307.5	130	130	25	0	0	0	0	0	455	307.5	130	130	25	0	0	10	0	0
17	455	260	130	130	25	0	0	0	0	0	455	260	130	130	25	0	0	0	0	0
18	455	357.5	130	130	25	0	0	10	0	0	455	357.5	130	130	25	0	0	0	0	0
19	455	453.75	130	130	25	0	0	0	0	0	455	453.75	130	130	25	0	25	0	0	0
20	455	455	130	130	162	33	25	10	10	10	455	455	130	130	162	33	25	10	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	130	0	115	20	25	0	0	0	455	455	0	0	115	20	0	0	0	0
23	455	422.5	0	0	0	0	25	0	0	0	455	422.5	0	0	0	0	0	0	0	0
24	455	345	0	0	0	0	0	0	0	0	455	345	0	0	0	0	0	0	0	0

Generation scheduling for units 21-40 for 40-generating unit system

Hour	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40
1	455	245	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	455	262.5	0	0	0	0	0	0	0	0	455	262.5	130	0	0	0	0	0	0	0
3	455	362.5	0	0	0	0	0	0	0	0	455	362.5	130	0	0	0	0	0	0	0
4	455	346.25	0	0	25	0	0	0	0	0	455	346.25	130	130	0	0	0	0	0	0
5	455	357.5	130	0	25	0	0	0	0	0	455	357.5	130	130	25	0	0	0	0	0
6	455	455	130	0	27.5	0	0	0	0	0	455	455	130	130	27.5	0	0	0	0	0
7	455	455	130	0	45	0	0	0	0	0	455	455	130	130	45	0	0	0	0	0
8	455	455	130	130	56.25	0	25	0	0	0	455	455	130	130	56.25	0	0	0	0	0
9	455	455	130	130	102.5	0	25	0	0	0	455	455	130	130	102.5	20	0	0	0	0
10	455	455	130	130	162	33	25	0	0	0	455	455	130	130	162	33	25	0	0	0
11	455	455	130	130	162	73	25	10	10	0	455	455	130	130	162	73	25	0	0	0
12	455	455	130	130	162	80	25	43	10	10	455	455	130	130	162	80	25	43	10	10
13	455	455	130	130	162	33	25	0	0	0	455	455	130	130	162	33	25	0	0	0
14	455	455	130	130	100	0	25	0	0	0	455	455	130	130	100	20	25	0	0	0
15	455	455	130	130	30	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
16	455	307.5	130	130	25	0	0	0	0	0	455	307.5	130	130	25	0	0	0	0	0
17	455	260	130	130	25	0	0	0	0	0	455	260	130	130	25	0	0	0	0	0
18	455	357.5	130	130	25	0	0	0	0	0	455	357.5	130	130	25	0	0	0	0	0
19	455	453.75	130	130	25	0	0	0	0	0	455	453.75	130	130	25	0	0	0	0	0
20	455	455	130	130	162	33	25	0	0	0	455	455	130	130	162	33	25	0	0	0
21	455	455	130	130	150	20	25	0	0	0	455	455	0	0	150	20	25	0	0	0
22	455	455	0	130	115	20	25	0	0	0	455	455	0	0	0	20	25	0	0	0
23	455	422.5	0	0	0	20	25	10	0	0	455	422.5	0	0	0	0	0	10	0	0
24	455	345	0	0	0	0	0	0	0	0	455	345	0	0	0	0	0	0	0	0

Overall Generation Cost = 2,255,000$

Table 26 Generation scheduling of 40-unit with 10% spinning reserve using hGWO-RES (considering wind-thermal system)

Commitment status for units 1-20 for 40-generating unit system(wind-thermal)

Hour	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
2	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
3	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
4	1	1	1	0	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0
5	1	1	1	0	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
6	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
7	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
8	1	1	1	1	1	1	0	0	0	0	1	1	0	1	1	0	0	0	0	0
9	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	0	0	0
10	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	0
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	1
14	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	0	1	0	0	0
15	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
16	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
17	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
18	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	0	0	0
19	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	0	0	0
20	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	0	1	0	0	0
21	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	0	1	0	0	0
22	1	1	0	0	1	1	1	0	0	0	1	1	0	0	1	0	0	0	0	0
23	1	1	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0
24	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0

Commitment status for units 21-40 for 40-generating unit system (wind-thermal)

Hour	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40
1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
5	1	1	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
6	1	1	0	0	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0
7	1	1	1	0	1	0	0	0	0	0	1	1	1	0	1	1	0	0	0	0
8	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
9	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0
10	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
11	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	1	0
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
13	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
14	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	0	0	0
15	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
16	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
17	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0
18	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	1	0	0	0	0
19	1	1	1	1	1	1	0	1	0	0	1	1	0	1	1	1	0	0	0	0
20	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	0	0
21	1	1	0	0	1	1	1	0	0	0	1	1	1	1	1	1	1	0	1	1
22	1	1	0	0	1	0	1	0	0	0	1	1	1	1	0	1	1	0	0	0
23	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
24	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0

Table 27 Generation scheduling of 40-unit with 10% spinning reserve using hGWO-RES (considering wind-thermal)

Unit commitment schedule for units 1-20 for 40-generating unit system(wind-thermal)																				
Hour	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
1	455	224.5	0	0	0	0	0	0	0	0	455	224.5	0	0	0	0	0	0	0	0
2	455	235	130	0	0	0	0	0	0	0	455	235	0	0	0	0	0	0	0	0
3	455	342.15	130	0	0	0	0	0	0	0	455	342.15	0	0	0	0	0	0	0	0
4	455	422.8	130	0	25	0	0	0	0	0	455	422.8	0	0	25	0	0	0	0	0
5	455	426.725	130	0	25	0	0	0	0	0	455	426.725	0	130	25	0	0	0	0	0
6	455	455	130	130	36.575	0	0	0	0	0	455	455	0	130	36.575	0	0	0	0	0
7	455	455	130	130	46.625	0	0	0	0	0	455	455	0	130	46.625	0	0	0	0	0
8	455	455	130	130	62.2	20	0	0	0	0	455	455	0	130	62.2	0	0	0	0	0
9	455	455	130	130	89.675	20	0	0	0	0	455	455	130	130	89.675	0	25	0	0	0
10	455	455	130	130	162	21.775	25	10	10	0	455	455	130	130	162	21.775	25	0	0	0
11	455	455	130	130	162	55.975	25	10	10	10	455	455	130	130	162	55.975	25	10	10	0
12	455	455	130	130	162	80	25	31.5	10	10	455	455	130	130	162	80	25	31.5	10	10
13	455	455	130	130	162	21.375	25	10	10	0	455	455	130	130	162	21.375	25	0	0	10
14	455	455	130	130	72.725	0	25	0	0	0	455	455	130	130	72.725	0	25	0	0	0
15	455	455	130	130	40.325	0	0	0	0	0	455	455	130	130	40.325	0	0	0	0	0
16	455	321.65	130	130	25	0	0	0	0	0	455	321.65	130	130	25	0	0	0	0	0
17	455	263.475	130	130	25	0	0	0	0	0	455	263.475	130	130	25	0	0	0	0	0
18	455	348.825	130	130	25	20	0	0	0	0	455	348.825	130	130	25	0	0	0	0	0
19	455	436.125	130	130	25	20	0	0	0	0	455	436.125	130	130	25	0	25	0	0	0
20	455	455	130	130	152.925	20	25	10	0	0	455	455	130	130	152.925	0	25	0	0	0
21	455	455	130	130	157.475	20	25	0	0	0	455	455	130	0	157.475	0	25	0	0	0
22	455	455	0	0	94.96667	20	25	0	0	0	455	455	0	0	94.96667	0	0	0	0	0
23	455	385	0	0	0	0	0	0	0	0	455	385	0	0	25	0	0	0	0	0
24	455	300.425	0	0	0	0	0	0	0	0	455	300.425	0	0	0	0	0	0	0	0
Unit commitment schedule for units 21-40 for 40-generating unit system (wind-thermal)																				
Hour	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40
1	455	224.5	0	0	0	0	0	0	0	0	455	224.5	0	0	0	0	0	0	0	0
2	455	235	0	0	0	0	0	0	0	0	455	235	0	0	0	0	0	0	0	0
3	455	342.15	0	0	0	0	0	0	0	0	455	342.15	0	0	0	0	0	0	0	0
4	455	422.8	0	0	0	0	0	0	0	0	455	422.8	0	0	0	0	0	0	0	0
5	455	426.725	0	0	25	0	0	0	0	0	455	426.725	0	0	0	0	0	0	0	0
6	455	455	0	0	36.575	0	0	0	0	0	455	455	130	0	36.575	0	0	0	0	0
7	455	455	130	0	46.625	0	0	0	0	0	455	455	130	0	46.625	20	0	0	0	0
8	455	455	130	0	62.2	0	0	0	0	0	455	455	130	130	62.2	20	0	0	0	0
9	455	455	130	130	89.675	0	0	0	0	0	455	455	130	130	89.675	20	25	0	0	0

Table 27 (continued)

10	455	455	130	130	162	21.775	25	0	0	0	455	455	130	130	162	21.775	25	0	0	0
11	455	455	130	130	162	55.975	25	0	0	0	455	455	130	130	162	55.975	25	0	10	0
12	455	455	130	130	162	80	25	31.5	10	10	455	455	130	130	162	80	25	31.5	0	0
13	455	455	130	130	162	21.375	25	0	0	0	455	455	130	130	162	21.375	25	0	0	0
14	455	455	130	130	72.725	20	0	0	0	0	455	455	130	130	72.725	0	25	0	0	0
15	455	455	130	130	40.325	0	0	0	0	0	455	455	0	130	40.325	0	0	0	0	0
16	455	321.65	130	130	25	0	0	0	0	0	455	321.65	0	130	25	0	0	0	0	0
17	455	263.475	130	130	25	0	0	0	0	0	455	263.475	0	130	25	0	0	0	0	0
18	455	348.825	130	130	25	0	0	0	0	0	455	348.825	0	130	25	20	0	0	0	0
19	455	436.125	130	130	25	20	0	10	0	0	455	436.125	0	130	25	20	0	0	0	0
20	455	455	130	130	152.925	20	25	0	0	10	455	455	130	130	152.925	20	25	10	0	0
21	455	455	0	0	157.475	20	25	0	0	0	455	455	130	130	157.475	20	25	0	10	10
22	455	455	0	0	94.96667	0	25	0	0	0	455	455	130	130	0	20	25	0	0	0
23	455	385	0	0	0	0	0	0	0	0	455	385	130	0	0	0	0	0	0	0
24	455	300.425	0	0	0	0	0	0	0	0	455	300.425	130	0	0	0	0	0	0	0

Overall Cost = 2,198,400$

Step1: Calculate the duration on and off times of all units for the whole schedule time horizon.
Step2: set $h = 1$
Step3: set iteration count $n = 1$
Step4: *if* $u_n^h = 0$ and $u_n^{h-1} = 1$ and $T_{n,on}^{h-1} \le MUT$ then set $u_n^h = 1$
Step5: if $u_n^h = 0$ and $u_n^{h-1} = 1$ and $h + MDT - 1 \le T$ and $T_{n,off}^{off+MDT-1} \le MDT$ SET $u_n^h = 1$
Step6: if *if* $u_n^h = 0$ and $u_n^{h-1} = 1$ and $t + MDT - 1 > T$ and $\sum_{n=h}^{H} u_n^h > 0$ set $u_n^h = 1$
Step7: update the time period of ON/OFF times for unit i
Step8: Do $n = n + 1$ return to step 4.
Step9: *if* $h < H$, $h = h + 1$, return to step 3,
Step10: If condition at step 9, found false, stop.

6 Test system and standard benchmark

In order to validate the performance of the proposed hGWO-RES algorithms, 23 benchmark functions [2] has been taken into consideration and has been shown in Tables 2, 3, and 4. Table 2 depicts the Unimodal Benchmark Function, Table 3 depicts the Multi-modal Benchmark functions and Table 4 depicts the fixed dimensions benchmark problems.

In order to show the efficacy of the anticipated hGWO-RES algorithms for generation scheduling and dispatch problem, different types of test systems have been taken into consideration, which includes 7-, 10-, 19-, 20- and 40-Generating Units system [58]. The load demand pattern of 24-h are taken into consideration for effective research study. In the whole research study, 30 search agents are taken into considerations and algorithm is simulated for maximum iterations of 500.

7 Results and discussion

In order to overcome the stochastic nature of proposed hGWO-RES algorithm and validate the results, 30 trial runs are taken into consideration and each objective function has been evaluated for average, standard deviation, worst and best values. In order to validate the exploitation phase of proposed algorithm, unimodal benchmark function F1, F2, F3, F4, F5, F6 and F7 are taken into consideration. Table 5 shows the solution of unimodal benchmark function using hGWO-RES algorithm. The comparison results for unimodal benchmark functions has been shown in Table 6, which are compared with other recently developed metaheuristics search algorithms GWO [2], PSO [55], BA [33], FPA [21], GA [85], DA [6], BDA [6], BPSO [86] and BGSA [39] in terms of average and standard deviation. The convergence curve and

Table 28 Comparative cost analysis for various test systems (% saving in cost)

Number of units	Cost of thermal system	Cost of wind thermal system	% Cost saving
7 (SR = 10%)	49,184 $	42,355$	13
10 (SR = 5%)	557,830 $	505,520$	9
10 (SR = 10%)	563,980$	511,680$	9
19 (SR = 10%)	208,690$	200,490$	3.9
20 (SR = 10%)	1,125,100$	1,071,700$	4.7
40 (SR = 10%)	2,255,000$	2,198,400$	2.5

trial solutions for hGWO-RES for unimodal benchmark functions are shown in Figs. 5 and 6.

In order to validate the exploration phase of proposed algorithm, the multi-modal benchmark functions F8, F9, F10, F11, F12 and F13 are taken into consideration, as these functions have many local optima with the number increasing exponentially with dimension. Table 7 shows the solution of multi-modal benchmark function using hGWO-RES algorithm. The comparison results for multi-modal benchmark functions has been shown in Table 8, which are compared with other recently developed metaheuristics search algorithms GWO [2], PSO [55], BA [33], FPA [21], GA [85], DA [6], BDA [6], BPSO [86] and BGSA [39] in terms of average and standard deviation. The convergence curve and their corresponding trial solutions of hGWO-RES for multi-modal benchmark functions are shown in Figs. 7 and 8.

The test results for fixed dimension benchmark problems are shown in Table 9. The comparison results for multi-modal benchmark functions has been shown in Tables 10 and 11, which are compared with other recently developed metaheuristics search algorithms GWO [2], PSO [55], BA [33], FPA [21], GA [85], DA [6], FEP [87], GSA [35] and DE [52] in terms of average and standard deviation. The trial solutions for fixed dimension benchmark functions along with their convergence curve are shown in Figs. 9 and 10.

In order to verify the performance of proposed hGWO-RES algorithm for generation scheduling and dispatch problems, the conventional UCP and UCP considering wind power as renewable energy sources are solved and their corresponding solutions are represented in Tables 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, and 28 . Table 29 depicts the optimal cost analysis for 10-generating unit systems considering wind power have been compared with recently developed algorithms.

8 Conclusion

In the proposed research, a hybrid version of grey wolf optimizer with random exploratory search has been presented to solve benchmark problems and generation scheduling and dispatch problem of electric power system with due consideration of wind energy as renewable energy source. Results of hGWO-RES has been tested for non-linear, highly constrained, non-convex engineering design and optimization problems, which include 23 benchmark problems and

Table 29 Comparative cost analysis for 10-unit system considering wind power (for 10% spinning reserve)

Method	Best cost	Worst cost	Mean	CPU time (in seconds)
QBGSA [88]	515,339.6	517,156.8	516,425.4	49
BPSO [88]	516,778.5	519,963.0	518,304.5	61
BGSA [88]	517,736.6	520,577.2	519,254.8	61
GA [89]	563,977	565,606	564,275	221
EP [90]	564,551	566,231	565,352	100
EACO [91]	563,938	565,869	564,831	–
HPSO [92]	563,942	565,785	564,772	–
BF [93]	564,842	565,872	NA	110
DBDE [94]	563,977	564,241	564,028	3.6
SGA [89]	565,943	570,121	569,042	–
PSO [89]	564,212	565,783	565,103	120
Clustering method [95]	563,938	563,976	563,945	39.6
Operational cycle based algorithm [96]	563,937.70	–	564,227	19.4
hGWO-RES [proposed method]	511,680	511,687	511,683	80.3

combinatorial unit commitment problem of electric power system. Experimentally, it has been found that the exploitation phase of the existing GWO algorithm has been improved. Also, the authors have presented the solution of scalar objective generation scheduling and dispatch of thermal generating units considering impact of wind power using hGWO-RES algorithm. The results for IEEE test system consisting of 7-, 10-, 19-, 20- and 40-generating units has been evaluated, analyzed for percentage cost saving and has been compared with recently developed algorithms, while considering wind power as a renewable energy source. Also, it is evident from analysis that by integrating wind power source along with conventional thermal power system, power production cost per megawatt is significantly reduced. Hence it is envisaged to incorporate wind energy source to tackle price hiking problem. Moreover, hGWO-RES accelerates the progress towards the near global optimum point thereby enabling one to obtain improved solutions with a reduced computation overhead.

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References

1. Simon D (2008) Biogeography-based optimization. IEEE Trans Evol Comput 12(6):702–713
2. Mirjalili S, Mirjalili SM, Lewis A (2014) Grey wolf optimizer. Adv Eng Softw 69:46–61
3. Mirjalili S (2015) The ant lion optimizer. Adv Eng Softw 83:80–98
4. Mirjalili S (2015) Moth-flame optimization algorithm: a novel nature-inspired heuristic paradigm. Knowl-Based Syst 89:228–249
5. Mirjalili S, Mirjalili SM, Hatamlou A (2016) Multi-verse optimizer: a nature-inspired algorithm for global optimization. Neural Comput Applic 27(2):495–513
6. Mirjalili S (2016) Dragonfly algorithm: a new meta-heuristic optimization technique for solving single-objective, discrete, and multi-objective problems. Neural Comput Applic 27(4):1053–1073
7. Mirjalili S (2016) SCA: a sine cosine algorithm for solving optimization problems. Knowl-Based Syst 96:120–133
8. Shareef H, Ibrahim AA, Mutlag AH (2015) Lightning search algorithm. Appl Soft Comput 36:315–333
9. Chaohua D, Weirong C, Yunfang Z (2007) Seeker optimization algorithm. 2006 Int. Conf. Comput. Intell. Secur. ICCIAS 2006, vol. 1, p 225–229
10. Li MD, Zhao H, Weng XW, Han T (2016) A novel nature-inspired algorithm for optimization: virus colony search. Adv Eng Softw 92: 65–88
11. Mirjalili S, Lewis A (2016) The whale optimization algorithm. Adv Eng Softw 95:51–67
12. Bayraktar Z, Komurcu M, Werner DH (2010) Wind Driven Optimization (WDO): a novel nature-inspired optimization algorithm and its application to electromagnetics. 2010 IEEE Int. Symp. Antennas Propag. CNC-USNC/URSI Radio Sci. Meet. - Lead. Wave, AP-S/URSI 2010, no. 1, p 0–3
13. Eskandar H, Sadollah A, Bahreininejad A, Hamdi M (2012) Water cycle algorithm - a novel metaheuristic optimization method for solving constrained engineering optimization problems. Comput Struct 110–111:151–166
14. Mirjalili S, Gandomi AH, Mirjalili SZ, Saremi S, Faris H, Mirjalili SM (2017) Salp swarm algorithm: a bio-inspired optimizer for engineering design problems. Adv Eng Softw 114:163–191
15. Cheng MY, Prayogo D (2014) Symbiotic organisms search: a new metaheuristic optimization algorithm. Comput Struct 139:98–112
16. Gonçalves MS, Lopez RH, Miguel LFF (2015) Search group algorithm: a new metaheuristic method for the optimization of truss structures. Comput Struct 153:165–184
17. Salimi H (2015) Stochastic fractal search: a powerful metaheuristic algorithm. Knowl-Based Syst 75:1–18
18. Merrikh-Bayat F (2015) The runner-root algorithm: a metaheuristic for solving unimodal and multimodal optimization problems inspired by runners and roots of plants in nature. Appl Soft Comput 33:292–303
19. Dorigo M, Birattari M, Stutzle T (2006) Ant colony optimization. IEEE Comput Intell Mag 1(4):28–39
20. Eusuff M, Lansey K, Pasha F (2006) Shuffled frog-leaping algorithm: a memetic meta-heuristic for discrete optimization. Eng Optim 38(2):129–154
21. Yang X-S (2012) Flower pollination algorithm for global optimization. In: Unconventional computation and natural computation, Springer, p 240-249
22. Husseinzadeh Kashan A (2014) A new metaheuristic for optimization: optics inspired optimization (OIO). Comput Oper Res 55:99–125
23. Kuo HC, Lin CH (2013) Cultural evolution algorithm for global optimizations and its applications. J Appl Res Technol 11(4):510–522
24. Saremi S, Mirjalili S, Lewis A (2017) Grasshopper optimisation algorithm: theory and application. Adv Eng Softw 105:30–47
25. Gandomi AH (2014) Interior search algorithm (ISA): a novel approach for global optimization. ISA Trans 53(4):1168–1183
26. Kaveh A, Mahdavi VR (2015) Colliding bodies optimization: extensions and applications. Colliding Bodies Optim Extensions Appl, p 1–284
27. Gandomi AH, Alavi AH (2012) Krill herd: a new bio-inspired optimization algorithm. Commun Nonlinear Sci Numer Simul 17(12):4831–4845
28. Mohseni S, Gholami R, Zarei N, Zadeh AR (2014) Competition over resources: a new optimization algorithm based on animals behavioral ecology. 2014 Int. Conf. Intell. Netw. Collab. Syst., p 311–315
29. Nakamura RYM, Pereira LAM, Costa KA, Rodrigues D, Papa JP, Yang XS (2012) BBA: a binary bat algorithm for feature selection. Brazilian Symp. Comput. Graph. Image Process., p 291–297
30. Sadollah A, Bahreininejad A, Eskandar H, Hamdi M (2013) Mine blast algorithm: a new population based algorithm for solving constrained engineering optimization problems. Appl Soft Comput 13(5):2592–2612
31. Du D, Simon D, Ergezer M (2009) Biogeography-based optimization combined with evolutionary strategy and immigration refusal. In: IEEE Proc International Conference on Systems, p 997–1002
32. Mareli M, Twala B (2017) An adaptive cuckoo search algorithm for optimisation. Appl Comput Informatics
33. Yang X-S. (2010) A new metaheuristic bat-inspired algorithm. In: Nature inspired cooperative strategies for optimization (NICSO 2010), Springer, p 65-74
34. Li X, Zhang J, Yin M (2014) Animal migration optimization: an optimization algorithm inspired by animal migration behavior. Neural Comput Applic 24(7–8):1867–1877
35. Rashedi E, Nezamabadi-Pour H, Saryazdi S (2009) GSA: a gravitational search algorithm. Inf Sci 179:2232
36. Cohen AI, Yoshimura M (1983) A branch-and-bound algorithm for unit commitment. IEEE Trans Power App Syst 102(2):444–451
37. Kothari DP, Ahmad A (1995) An expert system approach to the unit commitment problem. Energy Convers Manag 36(4):257–261

38. Kazarlis SA, Bakirtzis AG, Petridis V (1996) A genetic algorithm solution to the unit commitment problem. IEEE Trans. Power Syst 11(1):83–92
39. Rashedi E, Nezamabadi-Pour H, Saryazdi S (2010) BGSA: binary gravitational search algorithm. Nat Comput 9(3):727–745
40. Cuevas E, González M, Zaldivar D, Pérez-Cisneros M, García G (2012) An algorithm for global optimization inspired by collective animal behavior. Discret Dyn Nat Soc 2012
41. Meng XB, Gao XZ, Lu L, Liu Y, Zhang H (2016) A new bio-inspired optimisation algorithm: bird swarm algorithm. J Exp Theor Artif Intell 28(4):673–687
42. Li M, Zhao H, Weng X, Han T (2016) Cognitive behavior optimization algorithm for solving optimization problems. Appl Soft Comput 39:199–222
43. Abedinpourshotorban H, Mariyam Shamsuddin S, Beheshti Z, Jawawi DNA (2016) Electromagnetic field optimization: a physics-inspired metaheuristic optimization algorithm. Swarm Evol Comput 26:8–22
44. Tan Y, Tan Y, Zhu Y (2015) Fireworks algorithm for optimization fireworks algorithm for optimization. 355–364
45. Zheng YJ (2015) Water wave optimization: a new nature-inspired metaheuristic. Comput Oper Res 55:1–11
46. Wang GG, Deb S, Coelho LDS (2015) Earthworm optimization algorithm: a bio-inspired metaheuristic algorithm for global optimization problems. Int J Bio Inspir Com 1(1):1
47. Ghaemi M, Feizi-Derakhshi MR (2014) Forest optimization algorithm. Expert Syst Appl 41(15):6676–6687
48. Erlich I, Venayagamoorthy GK, Worawat N (2010) A mean-variance optimization algorithm. 2010 IEEE World Congr. Comput. Intell. WCCI 2010 - 2010 IEEE Congr. Evol. Comput. CEC 2010
49. Husseinzadeh Kashan A (2014) League championship algorithm (LCA): an algorithm for global optimization inspired by sport championships. Appl Soft Comput 16:171–200
50. Wang GG, Guo L, Gandomi AH, Hao GS, Wang H (2014) Chaotic krill herd algorithm. Inf Sci 274:17–34
51. Wang GG, Deb S, Coelho LDS (2016) Elephant herding optimization. Proc. - 2015 3rd Int. Symp. Comput. Bus. Intell. ISCBI 2015, p 1–5
52. Storn R, Price K (1997) Differential evolution – a simple and efficient heuristic for global optimization over continuous spaces. J Glob Optim 11(4):341–359
53. Atashpaz-Gargari E, Lucas C (2007) Imperialist competitive algorithm: an algorithm for optimization inspired by imperialistic competition. 2007 IEEE Congr Evol Comput CEC 2007, p 4661–4667
54. Karimkashi S, Kishk AA (2010) Invasive weed optimization and its features in electromagnetics. IEEE Trans Antennas Propag 58(4): 1269–1278
55. Kennedy J, Eberhart RC (1995) Particle swarm optimization. In: Proceedings of the IEEE International Conference on Neural Networks, p 1942–1948
56. Askarzadeh A (2016) A novel metaheuristic method for solving constrained engineering optimization problems: crow search algorithm. Comput Struct 169:1–12
57. Bavafa F, Azizipanah-Abarghooee R, Niknam T (2014) New self-adaptive bat-inspired algorithm for unit commitment problem. IET Sci Meas Technol 8(6):505–517
58. Mirjalili S, Lewis A (2014) Adaptive gbest-guided gravitational search algorithm. Neural Comput Applic 25(7–8):1569–1584
59. Mirjalili S, Wang G-G, Coelho L d S (2014) Binary optimization using hybrid particle swarm optimization and gravitational search algorithm. Neural Comput Applic 25(6):1423–1435
60. Mirjalili S, Mirjalili SM, Lewis A (2014) Let a biogeography-based optimizer train your multi-layer perceptron. Inf Sci 269:188–209
61. Ghorbani N, Babaei E (2014) Exchange market algorithm. Appl Soft Comput 19:177–187
62. Singh N, Singh SB (2017) A novel hybrid GWO-SCA approach for optimization problems. Eng Sci Technol Int J 20(6):1586–1601
63. Dai C, Chen W, Ran L, Zhang Y, Du Y (2011) Human group optimizer with local search. Lect Notes Comput Sci (including Subser Lect Notes Artif Intell Lect Notes Bioinformatics), vol 6728 LNCS, no PART 1:310–320
64. Deb K (2001) Multi-objective optimization using evolutionary algorithms. Wiley, Hoboken
65. Dhillon JS, Kothari DP (2010) Power system optimization, 2nd edn. Prentice Hall India, New Delhi
66. Wood AJ, Wollenberg BF (1996) *Power generation, operation, and control*. Wiley, Hoboken
67. Guan Y, Wang Y, Tan Z (2012) Environmental protection and security considered dynamic economic dispatch for wind farm integrated systems. In: 2012 Asia-Pacific Power and Energy Engineering Conference, p 1–4
68. Tewari S, Geyer CJ, Mohan N (2011) A statistical model for wind power forecast error and its application to the estimation of penalties in liberalized markets. IEEE Trans Power Syst 26(4):2031–2039
69. Zhang Z-S, Sun Y-Z, Gao DW, Lin J, Cheng L (Aug. 2013) A versatile probability distribution model for wind power forecast errors and its application in economic dispatch. IEEE Trans. Power Syst. 28(3):3114–3125
70. Jadhav HT, Bhatia M, Roy R (2011) An application of craziness based shuffled frog leaping algorithm for wind-thermal generation dispatch considering emission and economy. In: 2011 10th International Conference on Environment and Electrical Engineering, p 1–4
71. De Giorgi MG, Ficarella A, Tarantino M (2011) Error analysis of short term wind power prediction models. Appl Energy 88(4): 1298–1311
72. Bludszuweit H, Dominguez-Navarro JA, Llombart A (2008) Statistical analysis of wind power forecast error. IEEE Trans Power Syst. 23(3):983–991
73. Zhang N, Kang C, Xia Q, Liang J (2014) Modeling conditional forecast error for wind power in generation scheduling. IEEE Trans Power Syst. 29(3):1316–1324
74. Bruninx K, Delarue E (2014) A statistical description of the error on wind power forecasts for probabilistic reserve sizing. IEEE Trans Sustainable Energy 5(3):995–1002
75. Lyu J-K, Heo J-H, Kim M-K, Park J-K (2013) Impacts of wind power integration on generation dispatch in power systems. J Electr Eng Technol 8(3):453–463
76. Sturt A, Strbac G (2012) Efficient stochastic scheduling for simulation of wind-integrated power systems. IEEE Trans Power Syst. 27(1):323–334
77. Ravi CN, Selvakumar G, Christober C, Rajan A Hybrid real coded genetic algorithm - differential evolution for optimal power flow
78. Zhang Y, Yao F, Iu HHC, Fernando T, Trinh H (2015) Wind–thermal systems operation optimization considering emission problem. Int J Electr Power Energy Syst 65:238–245
79. Hou J, Guo J, Liu J (2016) An economic load dispatch of wind-thermal power system by using virtual power plants, 2016 35th Chinese Control Conf., p 8704–8709
80. Ardabili M (2014) Optimal thermal generating unit commitment with wind power impact : a PSO-IIW procedure
81. Bhatt A, Shrivastava A, Pandit M, Dubey HM (2014) Cost and profit optimization of integrated wind-thermal system by dynamic dispatch using swarm intelligence. In: International Conference on Recent Advances and Innovations in Engineering (ICRAIE-2014), p 1–6
82. Lu M, Zhao M (2013) The research of wind-thermal power random multi-objective scheduling based on combined MIPSO. Int J Hybrid Inf Technol 6(6):359–368

83. Chaudhary V, Pandit M, Dubey HM Optimal operation of wind-thermal generation using differential evolution. IOSR J Electr Electron Eng 5(4):2278–1676
84. Wolpert DH, William GM, Macready WG (1997) No free lunch theorems for optimization. IEEE Trans Evol Comput 1(1):67–82
85. John H (1992) Holland, adaptation in natural and artificial systems. MIT Press, Cambridge
86. Kennedy J, Eberhart RC (1997) A discrete binary version of the particle swarm algorithm. 1997 IEEE Int Conf Syst Man, Cybern Comput Cybern Simul, vol. 5, p 4104–4108
87. Yao X, Liu Y, Lin G (1999) Evolutionary programming made faster. 3:82
88. Ji B, Yuan X, Chen Z, Tian H (2014) Improved gravitational search algorithm for unit commitment considering uncertainty of wind power. Energy 67:52–62
89. Zhao B, Guo CX, Bai BR, Cao YJ (2006) An improved particle swarm optimization algorithm for unit commitment. Int J 28:482–490
90. Juste K a, Kita H, Tanaka E, Hasegawa J (1999) An evolutionary programming solution to the unit commitment problem. IEEE Trans Power Syst 14(4):1452–1459
91. Vaisakh K, Srinivas LR (2011) Evolving ant colony optimization based unit commitment. Appl Soft Comput 11(2):2863–2870
92. Ting TO, Rao MVC, Loo CK (2006) A novel approach for unit commitment problem via an effective hybrid particle swarm optimization. IEEE Trans Power Syst. 21(1):411–418
93. Eslamian M, Ahosseinian AA, Vahidi B (2009) Bacterial foraging based solution to the unit commitment problem. IEEE Trans 24(3):1478–1488
94. Yuan X, Su A, Nie H, Yuan Y, Wang L (2009) Application of enhanced discrete differential evolution approach to unit commitment problem. Energy Convers Manag 50(9):2449–2456
95. Shukla A, Singh SN (2016) Clustering based unit commitment with wind power uncertainty. Energy Convers Manag 111:89–102
96. Bavafa F, Niknam T, Azizipanah-Abarghooee R, Terzija V (2017) A new biobjective probabilistic risk-based wind-thermal unit commitment using heuristic techniques. IEEE Trans Ind Inf 13(1):115–124

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