Optimal Thermal Unit Commitment Solution integrating Renewable Energy with Generator Outage

S. Siva Sakthi*(C.A.), R. K. Santhi**, N. Murali Krishnan***, S. Ganesan**** and S. Subramanian**

Abstract: The increasing concern of global climate changes, the promotion of renewable energy sources, primarily wind generation, is a welcome move to reduce the pollutant emissions from conventional power plants. Integration of wind power generation with the existing power network is an emerging research field. This paper presents a meta-heuristic algorithm based approach to determine the feasible dispatch solution for wind integrated thermal power system. The Unit Commitment (UC) process aims to identify the best feasible generation scheme of the committed units such that the overall generation cost is reduced, when subjected to a variety of constraints at each time interval. As the UC formulation involves many variables and system and operational constraints, identifying the best solution is still a research task. Nowadays, it is inevitable to include power system reliability issues in operation strategy. The generator failure and malfunction are the prime influencing factor for reliability issues hence they have considered in UC formulation of wind integrated thermal power system. The modern evolutionary algorithm known as Grey Wolf Optimization (GWO) algorithm is applied to solve the intended UC problem. The potential of the GWO algorithm is validated by the standard test systems. Besides, the ramp rate limits are also incorporated in the UC formulation. The simulation results reveal that the GWO algorithm has the capability of obtaining economical resolutions with good solution quality.

Keywords: Grey Wolf Optimization, Ramp Rate Limit, Reliability Analysis, Unit Commitment, Wind Power Generation.

Nomenclatue

Indices:

i	Index of thermal generating unit.
t	Index of hour (sub interval).

Parameters:

a_i , b_i , c_i	Cost coefficients of generating unit i.
N	Number of generators.
T	Total scheduling period.
P_{imax}	Maximum real power generation limit of unit i (MW).
P_{imin}	Minimum real power generation limit of unit i (MW).
T_i^{on}	Minimum up time of unit i.
T_i^{off}	Minimum down time of unit i.
SC_i (t)	Start up cost of unit i at hour t ($).
SD_i (t)	Shut down cost of unit i at hour t ($).
$hcost_i$	Hot start cost of unit i ($).
$ccost_i$	Cold start cost of unit i ($).
$cshour_i$	Cold start time of unit i.
P_d (t)	Load demand at hour t.
P_{wmax}	Maximum real power generation limit of wind farm (MW).
P_{wmin}	Minimum real power generation limit of wind farm (MW).
T_i^{Mon}	Maximum up time limit of unit i.
T_i^{Moff}	Maximum down time limit of unit i.
T_i^o	Duration of the last cycle of the previous scheduling day.
BT_i^{c-1}	Scheduling time remaining after the allocation of the first c-1 cycles.
γ	Forced outage rate.
R^t	Spinning reserve requirement in the hour t (MW).
DR_i	Down ramp limit of unit i.
UR_i	Up ramp limit of unit i.

Variables:

P_i (t)	Real power generation of unit i at hour t

Iranian Journal of Electrical & Electronic Engineering, 2017.
Paper first received 20 March 2017 and in revised form 06 July 2017.
* The author is with the Department of Electrical and Electronics Engineering, Krishnasamy College of Engineering and Technology, Cuddalore - 607 109, Tamil Nadu, India.
E-mail: sivasakthi_gayu@yahoo.co.in.
** The authors are with the Department of Electrical Engineering, Annamalai University, Annamalai Nagar - 608 002, Tamil Nadu, India.
E-mails: rkscdm@gmail.com, dr_smani@yahoo.co.in.
*** The author is with the Department of Electrical and Electronics Engineering, Mailam Engineering College, Mailam - 604 304, Tamil Nadu, India.
E-mail: divyamuralikrishnan@yahoo.co.in.
**** The author is with the Department of Electrical and Electronics Engineering, Government College of Engineering, Dharmapuri - 636 704, Tamil Nadu, India.
E-mail: ganeshshriraj@gmail.com.
Corresponding Author: S. Siva Sakthi.

	(MW).
X_i^{on}	Duration during which unit i is continuously on.
X_i^{off}	Duration during which unit i is continuously off.
$F_i\ (P_i\ (t))$	Fuel cost of unit i at hour t (\$/h).
F_t	Total cost (\$).
$P_w\ (t)$	Real power generation of wind farm at hour t (MW).
T_i^c	Duration of operating cycle c for unit i.
NC	Number of operating cycle for each unit.
Rand	Random number generator with uniform distribution between 0 and 1.

1 Introduction

THE Unit Commitment (UC) is one of the vital divisions of the thermal power generation scheduling. This is significant because of today's energy paucity and economical impact of power utilities. UC problem minimizes the total production cost while satisfying the forecasted load demand, physical and operational constraints of thermal generating units. The constraints include real power generation limits, minimum up/down time, up/down ramp limits and unit initial status. Here, the schedule of thermal generating units combined with wind farm to meet the power requirement of each hour in the scheduling horizon by considering the generator outages.

Profuse literatures have been reported for determining thermal UC. Since the Wind Integrated UC (WIUC) is the emerging research field, very few research works have been reported. Hence, the solution quality of WIUC problem can be improvised by exploring the search space. This inspires, to develop a prominent method to determine the most feasible UC schedule for WIUC.

The UC problem is formulated as a large-scale, non-convex, mixed integer and non liner programming problem. Finding optimum schedule of generating units is very difficult within acceptable processing time and memory requirement. The complete enumeration method can yield exact solution of the UC problem. However, the excessive computational time requirement makes is not suitable for realistic power systems. Numerous solution techniques have been developed for solving UC problem and are classified as traditional, artificial intelligence and hybrid methods.

1.1 Review of Existing Methods

The traditional methods such as Priority List (PL) [1], Branch-and-Bound (BB) [2], Dynamic Programming (DP) [3], Integer Programming (IP) [4], Mixed Integer Programming (MIP) [5] and Lagrangian Relaxation (LR) [6] have been employed to solve thermal UC problems. These techniques are simple and fast, nevertheless most of them suffer to handle large and non-convex search space.

The enhanced versions of PL, MIP and LR have been developed to address their limitations. Extended PL (ExPL) [7], Enhanced PL (EPL) [8], Improved PL (IPL) [9], Improved MIP (IMIP) [10], Improved LR (ILR) [11] and Parallel Augment LR (PALR) [12] have been applied for the UC solution.

A straightforward (SF) [13] method has also been proposed in which the UC problem is decomposed into three sub problems that are solved in sequence. Most of the above approaches suffers with the curse of dimensionality and are commonly struck at a premature optimal solution point. These limitations can be overcome by using artificial intelligence techniques.

Soft computing techniques such as Simulated Annealing (SA) [14], Genetic Algorithm (GA) [15], Differential Evolution (DE) [16, 17], Expert System (ES) [18], Neural Network (NN) [19], Ant Colony System (ACS) algorithm [20], Evolutionary Programming (EP) [21], Bacterial Foraging Algorithm (BFA) [22], Shuffled Frog Leaping Algorithm (SFLA) [23], Gravitational Search Algorithm (GSA) [24], Quasi-Oppositional Teaching Learning Based Optimization (QOTLBO) algorithm [25] and Invasive Weed Optimization (IWO) [26] have been reported in the field of thermal UC.

The modified versions of these techniques have been developed in order to improve the solution quality. The altered versions of SA, Absolutely Stochastic SA (ASSA) [27] and Adaptive SA (ASA) [28] have been evolved to solve the UC problem. The improved versions of GA namely Integer Coded GA (ICGA) [29] and Binary-real Coded GA (BCGA) [30] have been applied to determine optimal solution for UC problem. The modified versions of Particle Swarm Optimization (PSO) namely fuzzy controlled binary PSO [31] and pseudo-inspired weight-improved crazy PSO [32] have also been applied to solve thermal UC problem. Fireworks Algorithm [33] is one of the recently developed swarm optimization algorithm which is also applied to solve for UC problem.

Various hybrid methods combining meta-heuristic with mathematical techniques or other meta-heuristic are developed to explore the search space in practical UC problems. Hybrid methods include Hybrid Taguchi (HT) - ACS [34], LR and PSO [35], GA-DE [36], hybrid harmony search/random search algorithm [37] and LR-DE [38] have been reported to solve thermal UC problems.

Quantum-inspired Evolutionary Algorithm (QEA) [39] yields feasible solutions even with small population compared with the EA. Advanced Quantum-inspired Evolutionary Algorithm (AQEA) [40] and Quantum-inspired Binary GSA (QBGSA) [41] have also been evolved for UC problem.

1.2 Present Work

The meta-heuristic approaches find difficult to determine the proximity of the estimated solution to the optimal solution. Parameter selection plays a vital role in success of these techniques but it is a time consuming process, as it requires complete knowledge about the algorithm.

A novel Swarm Intelligence (SI) technique, Grey Wolf Optimization (GWO) [42] has been developed to solve optimization problems. This technique has unique behaviour which other SI techniques not exhibit is mimicking the leadership hierarchy of grey wolves, well known for their pack hunting. This motivates the researchers to apply GWO for solving UC problems. The merits of the GWO are easy to handle, simple and require tuning of few parameters.

1.3 Research Gap and Contribution

The determination of thermal UC scheduling has been reported in several existing literature. In UC integrated wind power generation considering reliability analysis [43, 44], only few research works has been carried. The incorporation of wind power and forced outage rate make further the solution space as non-linear that leads to identification of optimum solution is a challenging work. Profuse artificial intelligence techniques exist for the UC solution, still improving their solution quality is interesting research task. The advantages of GWO against other population based algorithms motivate us to use it as the main optimization tool to solve the WIUC problem.

1.4 Paper Organization

The rest of the paper is organized as follows: In Section 2, the mathematical formulation of WIUC problem is presented. Section 3 describes the implementation of GWO. The numerical results and discussions are presented in Section 4. In section 5, the performance analysis of the GWO algorithm is included. Finally, the conclusion is presented in section 6.

2 Problem Formulation

2.1 Objective Function

The total cost, over the entire scheduling period is the sum of the running cost, start up cost and shut down cost of all the units [7]. Accordingly, the overall objective function of the UC problem is stated as:

$$\min \quad F_t = \sum_{t=1}^{T}\sum_{i=1}^{N}\left[F_i\left(P_i\left(t\right)\right)+SC_i\left(t\right)+SD_i\left(t\right)\right] \qquad (1)$$

Generally, the fuel cost, $F_i\,(P_i\,(t))$ of unit i in any given time interval t is a function of the generator power output. The production cost of unit i can be approximated as a quadratic function of the real power outputs from the generating units and can be expressed as:

$$F_i\left(P_i\left(t\right)\right)=a_i+b_iP_i\left(t\right)+c_iP_i^2\left(t\right) \qquad (2)$$

The generator start up cost depends on the time, the unit has been off prior to start up. In this work, time-dependent start up cost is used and is defined as follows:

$$SC_i=\begin{cases} hcost_i\ ; T_i^{off}\le X_i^{off}\le T_i^{off}+cshour_i \\ ccost_i\ ; X_i^{off}>T_i^{off}+cshour_i \end{cases} \qquad (3)$$

The SD cost is usually given a constant value for each unit. In this paper, the SD cost has been taken equal to zero for each unit.

The objective function, i.e., minimization of total cost F_t is subject to the system and generating unit constraints which are as follows.

2.2 System Constraint

2.2.1 Power balance constraint

The total power generated by the combination of thermal and wind generating units must meet the load demand $P_d\,(t)$ on hourly basis:

$$P_d\,(t)=\sum_{i=1}^{N}P_i\left(t\right)+P_w\left(t\right) \qquad (4)$$

2.3 Unit Constraints

The generating unit operational constraints are as follows [7, 16]:

2.3.1 Generation limits

The real power generation of each generator has a lower and upper limits, so that generation should lie within this boundary. This inequality is stated as follows:

$$P_{imin}\le P_i\left(t\right)\le P_{imax} \qquad (5)$$

$$P_{wmin}\le P_w\left(t\right)\le P_{wmax} \qquad (6)$$

2.3.2 Unit minimum up/down time constraints

The inequality constraints of minimum up/down time limits of generating units is given by

$$T_i^{on}\le X_i^{on} \qquad (7)$$

$$T_i^{off}\le X_i^{off} \qquad (8)$$

2.3.3 Generator forced outage rate

The equipment malfunction is considered as certain percentage of the load in each interval, by considering the generator forced outage rate, the UC solution should satisfy the condition as follows:

$$\sum_{i=1}^{N}U_i\left(t\right).P_i\,.P_{imax}\ge P_d\left(t\right)+R^t \qquad (9)$$

$$P_i = 1 - \gamma \tag{10}$$

2.3.4 Up/down ramp limits

The up and down ramp limits of the thermal units are given by

$$-DR_i \le P_i(t) - P_i(t-1) \le UR_i \tag{11}$$

3 Unit Commitment based on GWO

The GWO algorithm has essential steps such as social hierarchy, encircling, hunting, attacking and search for prey. The implementation of GWO algorithm for solving UC problem is detailed in this section.

3.1 Definition of Wolf and Initial Population

In the integer coded GWO, operating mode (ON/OFF) of thermal unit over the scheduling duration is indicated by a sequence of integer numbers which represents the Wolf Position (WP). The duration of continuous ON and OFF state is indicated by positive and negative integers in WP. Based on number of load peaks during the UC horizon and the sum of the minimum up and down times of the unit, the number of a unit's ON/OFF cycles are decided. For base, medium, and peak load units, the numbers of ON/OFF cycles are 2, 3, and 5 respectively. To overcome the restriction of search space for base and medium units due to reduction of cycles, the number of cycles of all units same as number of cycles peak load units are selected. For day scheduling (D), NC is equal to D × 5. Each solution contains N × D × 5 variables for D-day scheduling.

The initial population of the GWO is generated as follows:

The running duration of the first cycle of unit i, T_i^1 is initialized by considering unit i operating state of the last cycle of the previous scheduling day to avoid violation of minimum up/down time constraints.

$$T_i^1 = \begin{cases} +\text{Rand}\left(\max\left(0, T_i^{Mon} - T_i^0\right), T\right), \text{ if } T_i^0 > 0 \\ -\text{Rand}\left(\max\left(0, T_i^{Moff} + T_i^0\right), T\right), \text{ if } T_i^0 < 0 \end{cases} \tag{12}$$

For $c < NC$, the operating period of the c^{th} cycle of unit i, T_i^c is determined by taking into account of the minimum up and down time constraints of the generating units, the UC scheduling period and the operating period of the c -1 prior cycles of operation of the unit.

For $T_i^{c-1} < 0$, cycle c is in ON mode with duration

$$T_i^c = \begin{cases} +\text{Rand}\left(T_i^{Mon}, BT_i^{c-1}\right), \text{ if } BT_i^{c-1} > T_i^{Mon} \\ +BT_i^{c-1}, \quad \text{otherwise} \end{cases} \tag{13}$$

For $T_i^{c-1} > 0$, cycle c is in OFF mode with duration

$$T_i^c = \begin{cases} -\text{Rand}\left(T_i^{Moff}, BT_i^{c-1}\right), \text{if } BT_i^{c-1} > T_i^{Moff} \\ -BT_i^{c-1}, \quad \text{otherwise} \end{cases} \tag{14}$$

$$BT_i^{c-1} = T - \sum_{j=1}^{c-1} \left|T_i^j\right| \tag{15}$$

By taking into account the randomly generated cycle durations, the entire scheduling period is covered with the first $c < NC$ operating cycles. The remaining cycles are filled with zero. Once initial population is determined, the unit minimum up and down-time constraints are satisfied automatically.

3.2 GWO Execution for WIUC

In this section, the algorithmic steps of GWO for WIUC are presented. The constraint handling schemes are also briefed:

1) Read the system data and initialize GWO parameters such as population size (PS), maximum number of iterations (iter-max) and the vector value (a, A and C).

2) Initialization

The initial population (X_t) is generated as follows:

a) The entire scheduling period is divided into number of cycles and is denoted by NC.

b) All the units are committed based on their initial state conditions.

c) The operating duration is determined by considering the minimum up and down time constraints.

d) This process is repeated for all NC-1 cycles and the remaining time is computed which is the operating duration of the last segment.

e) Apply the constraint handling scheme to satisfy the operational constraints.

f) The online generating units along with dependent units are identified within their operational limits.

3) Compute the fitness of each individual, an individual having the minimum fitness is mimicked as the alpha, second minimum is beta and third minimum is delta.

$$\text{Fitness} = F_t + OCV \tag{16}$$

where, OCV is the Operational Constraint Violation and X_α , X_β and X_γ are the best, second and third search agents respectively.

4) iter-max = iter-max +1.

5) Search agent, SAg= SAg+1.

6) Modify the generation of N-1 online units based on the hunting mechanism.

$$X^{t+1} = \frac{1}{3}\Big[\left(X_\alpha - A_1.\left(D_\alpha\right)\right) + \left(X_\beta - A_2.(D_\beta)\right) + \left(X_\gamma - A_3.(D_\gamma)\right)\Big] \tag{17}$$

where, $D_\alpha = |C_1.X_\alpha - X|$; $D_\beta = |C_2.X_\beta - X|$; $D_\gamma = |C_3.X_\gamma - X|$;

$A = 2a.\text{rand} - a$.

7) Apply constraint handling strategy.
8) Repeat step 5 for all search agents. Otherwise go to next step.
9) Update the vector values of (a, A and C).
10) Compute the fitness for all search agents.
11) Update the values of X_α, X_β and X_γ.
12) Termination criterion.

Repeat the procedure from steps 4 to 6, until the maximum number of iteration is reached.

4 Simulation Results and Discussions

In this section, the effectiveness of the GWO method is tested on the standard test system having ten thermal generating units with one wind farm for a scheduling horizon of 24 hours. The algorithm is developed in Matlab platform and is executed on a personal computer configured with Intel core i3 processor 2.20 GHz and 4 GB RAM. The thermal unit data and load demands of ten thermal units are exerted from the literature [15]. The wind farm consists of similar type of 20 number of wind turbine generators which are operating in parallel. The wind power generation data [45] is presented in Table 1 which are calculated using forecasted wind power beforehand and converted into electrical power. The minimum and maximum output power delivered by the wind farm is 15 MW and 100 MW respectively. The wind farm generates 15.01 MW at 10th hour as minimum output and 98.559 MW at 16th hour as maximum output.

The GWO algorithm has been tested on the standard 10 unit system with the scheduling horizon of 24 hours. For each unit, the maximum number of cycles is 5. For each problem set, 50 test trials are made. The random initial population is generated for each run. Multiple runs have been carried out, to ascertain the robustness of the GWO in determining optimum UC scheduling. Two case studies have been conducted in order to show the effectiveness of GWO in solving UC problem. The configuration for final population to UC problem using GWO is illustrated in the Fig. 1.

4.1 Reliability Constrained UC

Recently, the reliability becomes vital criteria in the

Table 1 Output of wind farm.

Period (h)	Wind Power (MW)	Period (h)	Wind Power (MW)
1	42.602	13	41.233
2	35.409	14	50.478
3	60	15	80
4	17.193	16	98.559
5	20	17	72.194
6	31.309	18	49.655
7	40	19	36.44
8	32.802	20	57.185
9	21.784	21	64.243
10	15.01	22	85.541
11	24.383	23	70.677
12	27.058	24	61.298

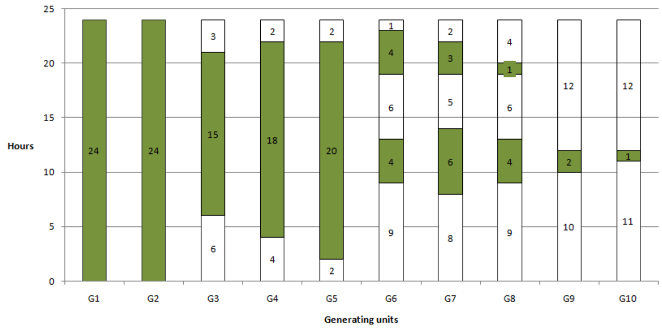

Fig. 1 Configuration for final population to WIUC problem considering FOR using GWO.

power system operations. To enhance the better operations and scheduling in the power system, many optimization tools have been developed. By integrating the above, reliability constrained optimization is developed to improve the performance of power system. The uncertainties in power system scheduling is taken into account. By considering, the various combination of all component states, system state is prepared. The probability of component is appears in the component state. The evaluation of power generation systems is carried out by ascertaining the generation capability to meet the requirement of the system load. Here, we assume that the transmission and distribution facilities are completely reliable. That means the generated energy are transmitted and distributed to the load centres without failure. The generating system reliability indices are treated as the expected value of a test function applied to a system state. The state of each component presented in vector to determine whether the specific generation combination yields to a feasible or infeasible solution. The mathematical expectation of a given reliability index is considered as fundamental parameter in reliability evaluation.

4.2 Reliability Constrained WIUC

In recent past, a number of initiatives have been taken to enhance the utilization of wind power in the electric power generation sector. Limited predictability and variability of wind power makes the operation of power system is problematic. The Wind Integrated Thermal Scheduling (WITS) problem plays a vital role in generating green power. The optimal selection and optimal dispatch of thermal units require to be modified based on wind farm output. This makes WITS is a complex optimization problem, that has to identify the optimal schedule of generating units while satisfying all prevailing constraints. GWO algorithm is used to determine the generating schedule of thermal units.

By observing Table 3, it can be understood that the minimum up/down time constraints and initial status of units are satisfied for all thermal generating units. First two thermal units are committed for whole scheduling horizon, because these units have high commitment priorities than other thermal units. They function as

[DOI: 10.22068/IJEEE.13.2.112]

Table 2 Maximum possible output of thermal units Forced Outage Rate by GWO.

Unit	1	2	3	4	5
Maximum output considering FOR (MW)	441.35	441.35	126.1	126.1	157.14
Unit	6	7	8	9	10
Maximum output considering FOR (MW)	77.6	82.45	53.35	53.35	53.35

Table 3 Wind Combined Schedule of 10-Unit System with Forced Outage Rate by GWO.

Hour	Real power output of units in MW										P_w in MW	P_d in MW	$F_i(P_i(t))$ in $	$SC_i(t)$ in $	F_t in $
	G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}					
1	441.35	216.04	0	0	0	0	0	0	0	0	42.602	700	12952.40	0	12952.40
2	441.35	273.24	0	0	0	0	0	0	0	0	35.409	750	13948.22	0	13948.22
3	441.35	323.65	0	0	25	0	0	0	0	0	60	850	15772.62	900	16672.62
4	441.35	441.35	0	0	50.10	0	0	0	0	0	17.193	950	18334.12	0	18334.12
5	441.35	387.55	0	126.10	25	0	0	0	0	0	20	1000	19683.83	560	20243.83
6	441.35	441.35	0	126.10	59.89	0	0	0	0	0	31.309	1100	21325.35	0	21325.35
7	441.35	391.45	126.10	126.10	25	0	0	0	0	0	40	1150	22577.15	1100	23677.15
8	441.35	441.35	126.10	126.10	32.29	0	0	0	0	0	32.802	1200	23596.70	0	23596.70
9	441.35	441.35	126.10	126.10	118.36	0	25	0	0	0	21.784	1300	26516.85	520	27036.85
10	441.35	441.35	126.10	126.10	157.14	57.94	25	10	0	0	15.01	1400	29988.18	400	30388.10
11	441.35	441.35	126.10	126.10	157.14	77.60	25	20.97	10	0	24.383	1450	31607.97	60	31667.97
12	441.35	441.35	126.10	126.10	157.14	77.60	25	53.35	14.95	10	27.058	1500	33540.40	60	33600.40
13	441.35	441.35	126.10	126.10	157.14	31.72	25	10	0	0	41.233	1400	29327.28	0	29327.28
14	441.35	441.35	126.10	126.10	89.62	0	25	0	0	0	50.478	1300	25927.84	0	25927.84
15	441.35	401.45	126.10	126.10	25	0	0	0	0	0	80	1200	22752.20	0	22752.20
16	441.35	232.91	126.10	126.10	25	0	0	0	0	0	98.559	1050	19810.08	0	19810.08
17	441.35	209.25	126.10	126.10	25	0	0	0	0	0	72.194	1000	19398.55	0	19398.55
18	441.35	331.79	126.10	126.10	25	0	0	0	0	0	49.655	1100	21534.13	0	21534.13
19	441.35	441.35	126.10	126.10	28.65	0	0	0	0	0	36.44	1200	23524.15	0	23524.15
20	441.35	441.35	126.10	126.10	152.91	20	25	10	0	0	57.185	1400	28973.47	660	29633.47
21	441.35	441.35	126.10	126.10	55.85	20	25	0	0	0	64.243	1300	26061.16	0	26061.16
22	441.35	377.00	0	126.10	25	20	25	0	0	0	85.541	1100	21491.43	0	21491.43
23	441.35	367.97	0	0	0	20	0	0	0	0	70.677	900	16420.20	0	16420.20
24	441.35	297.35	0	0	0	0	0	0	0	0	61.298	800	14368.64	0	14368.64
											Total Cost($)		539432.90	4260	543692.90

"Must-Run" units. The optimum UC schedule considering Forced Outage Rate (FOR) limits obtained by GWO is presented in Table 3. Assume that FOR of all thermal unit is 0.03. Table 2 shows the maximum possible output of all thermal units considering FOR.

Table 3 also shows the optimum thermal UC schedule considering thermal generator outage and real power sharing of committed generating units. It is observed that the real power generation by thermal units (G_1-G_{10}) and wind power plants is equivalent to the power demand P_d (t) for each hour. The operational constraints such as generation limits, minimum up/down time and initial status of units are also satisfied in this case study. The fuel, start up and total costs obtained in this case are $539432.90, $4260 and $543692.90 respectively.

4.3 Reliability Constrained WIUC considering Ramp Rates

In this case, the ramp rate constraints are introduced in the same test system over 24 hour of schedule and the effectiveness of the GWO algorithm is verified [46]. It has been assumed that the value of down and up ramp rate of each unit are equal [47]. The ramp rate limits of thermal unit are as follows: First two units have ramp rate of 160 MW/h, unit 3, 4 and 5 have 100 MW/h as ramp rate. The value for unit 6 and 7 are 60 MW/h. Last three units have 40 MW/h as ramp rate.

Referring Tables 3 and 4, the following changes in the scheduling of thermal generating units are observed. At 13th interval, the increase and decrease in real power generation in G_8 and G_6 respectively to fulfil the down ramp constraint of G_8. Similarly, to satisfy the down ramp rate of G_2 at 16th hour, increased dispatch is made in that unit and reduced dispatch in G_3. Finally, to meet the up ramp constraint of G_5 at 20th period, decreased generation is allotted in that unit and increased dispatch in G_6. The sharing of real power generation among the committed units increases the fuel and total costs.

The scheduling schemes of case 2 and 3 are same. The introduction of ramp rate constraints made changes only in the dispatches of the committed generating units.

The wind generating units along with thermal units meet the power demand in each interval. The obtained fuel, start up and total costs are $539494.80, $4260 and $543754.80 respectively. The total operating hours of all thermal units for both cases are illustrated in Fig. 2.

Table 4 Wind Combined Schedule of 10-Unit System with Forced Outage Rate and Ramp Rate by GWO.

Hour	Real power output of units in MW										P_w in MW	P_d in MW	$F_i(P_i(t))$ in $	$SC_i(t)$ in $	F_t in $
	G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}					
1	441.35	216.04	0	0	0	0	0	0	0	0	42.602	700	12952.33	0	12952.33
2	441.35	273.23	0	0	0	0	0	0	0	0	35.409	750	13948.16	0	13948.16
3	441.35	323.65	0	0	25	0	0	0	0	0	60	850	15772.76	900	16672.76
4	441.35	441.35	0	0	50.09	0	0	0	0	0	17.193	950	18333.94	0	18333.94
5	441.35	387.55	0	126.10	25	0	0	0	0	0	20	1000	19683.97	560	20243.97
6	441.35	441.35	0	126.10	59.88	0	0	0	0	0	31.309	1100	21325.17	0	21325.17
7	441.35	391.45	126.10	126.10	25	0	0	0	0	0	40	1150	22577.25	1100	23677.25
8	441.35	441.35	126.10	126.10	32.28	0	0	0	0	0	32.802	1200	23596.53	0	23596.53
9	441.35	441.35	126.10	126.10	118.32	0	25	0	0	0	21.784	1300	26517.04	520	27037.04
10	441.35	441.35	126.10	126.10	157.14	57.94	25	10	0	0	15.01	1400	29988.39	400	30388.39
11	441.35	441.35	126.10	126.10	157.14	77.60	25	20.98	10	0	24.383	1450	31608.20	60	31668.20
12	441.35	441.35	126.10	126.10	157.14	77.60	25	53.35	14.96	10	27.058	1500	33540.65	60	33600.65
13	441.35	441.35	126.10	126.10	157.14	28.38	25	13.35	0	0	41.233	1400	29338.63	0	29338.63
14	441.35	441.35	126.10	126.10	89.63	0	25	0	0	0	50.478	1300	25928.02	0	25928.02
15	441.35	401.45	126.10	126.10	25	0	0	0	0	0	80	1200	22752.33	0	22752.33
16	441.35	241.45	117.56	126.10	25	0	0	0	0	0	98.559	1050	19812.95	0	19812.95
17	441.35	209.26	126.10	126.10	25	0	0	0	0	0	72.194	1000	19398.69	0	19398.69
18	441.35	331.80	126.10	126.10	25	0	0	0	0	0	49.655	1100	21534.28	0	21534.28
19	441.35	441.35	126.10	126.10	28.65	0	0	0	0	0	36.44	1200	23523.98	0	23523.98
20	441.35	441.35	126.10	126.10	128.65	44.27	25	10	0	0	57.185	1400	29019.70	660	29679.70
21	441.35	441.35	126.10	126.10	55.86	20	25	0	0	0	64.243	1300	26061.34	0	26061.34
22	441.35	377.01	0	126.10	25	20	25	0	0	0	85.541	1100	21491.52	0	21491.52
23	441.35	367.97	0	0	0	20	0	0	0	0	70.677	900	16420.30	0	16420.30
24	441.35	297.34	0	0	0	0	0	0	0	0	61.298	800	14368.53	0	14368.53
											Total Cost($)		539494.80	4260	543754.80

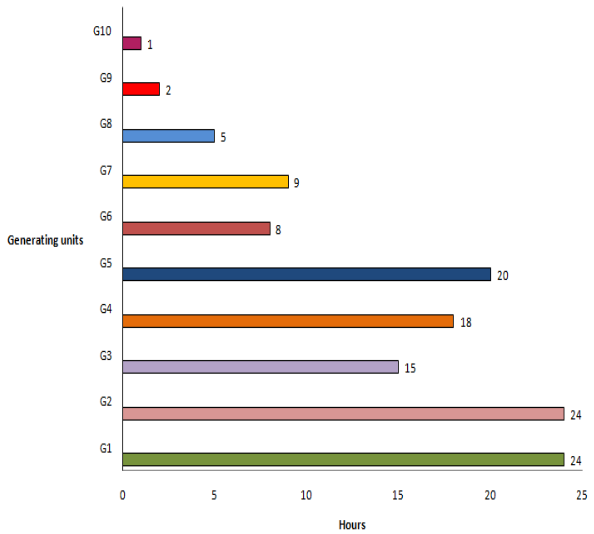

Fig. 2 Operating period of thermal generating units.

5 Performance Analysis

5.1 Robustness

Since the GWO algorithm is a stochastic soft computing technique, the initial population is made using random numbers. Hence, number of trails should be made to ensure the performance of GWO. Hence the optimal solution is determined by carrying out several trails. For real time problems like UC, it is desired that each trail of the execution should approach near to global optimum solution. To ascertain the robustness of GWO, 50 number of trails are made to determine the optimal scheduling. For particular load demand, the frequency of convergence to best cost is presented in Figs. 3 and 4. Both figures illustrate that when compared with existing algorithms, GWO algorithm has significant robustness.

5.2 Success Rate

It indicates that in how many trails the determined total cost is less than the mean cost. The success rate of GWO is greater than 85% in both cases. It can be concluded that GWO algorithm has good success rate and robustness compared with other reported algorithms.

6 Conclusions

Application of GWO is a novel swarm intelligence approach in solving the UC problem with significant amount of wind power considering reliability analysis. The total objective function is the sum of the objectives and constraints, which are fuel cost, start-up cost and power demand. The up and down ramp constraints are also satisfied for each unit. The GWO algorithm is used to validate the numerical results for standard ten unit system. The inclusion of ramp rate constraints with above system also presented. It can be concluded that

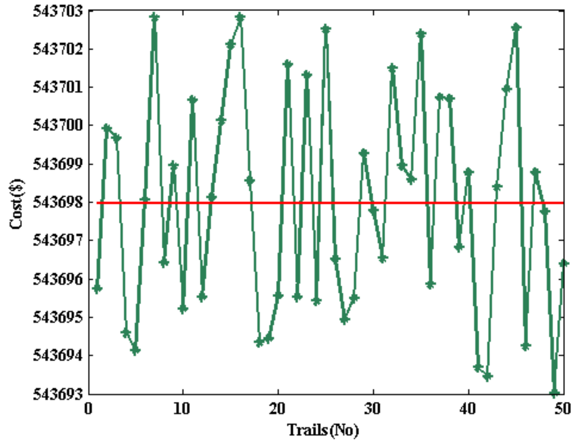

Fig. 3 Robustness characteristics of wind power combined 10-unit test system with FOR.

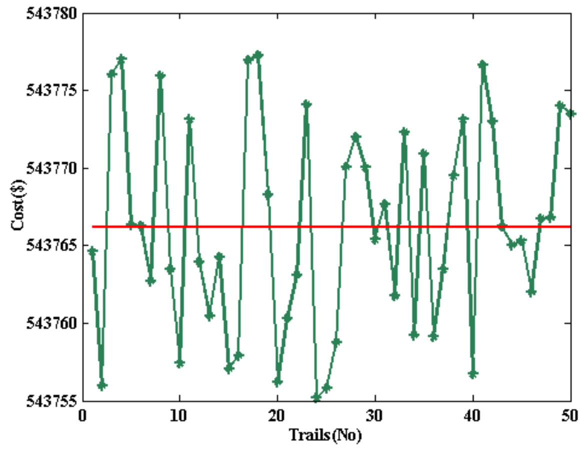

Fig. 4 Robustness characteristics of wind power combined 10-unit test system with FOR and Ramp Rate.

the intended scheme saves the operating cost in addition to less fuel consumption and emission of thermal units. The implementation of GWO is simple and it successfully handled the operational constraints. The optimum solution for WIUC problem can be consistently obtained by GWO. Results illustrate that intended algorithm is a powerful tool for solving WIUC problem.

References

[1] A.J. Wood and B.F. Wollenberg, Power generation, operation and control, New York: Wiley, 2002.

[2] A.I. Cohen and M. Yoshimura, “A branch-and-bound algorithm for unit commitment”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 2, pp. 444–451, Feb. 1983.

[3] Walter L. Snyder Jr., H. David Powell Jr. and John C. Rayburn, “Dynamic programming approach to unit commitment”, IEEE Transactions on Power Systems, Vol. PWRS-2, No. 2, pp. 339–348, May 1987.

[4] T.S. Dillon, K.W. Edwin, H.D. Kochs and R.J. Taud, “Integer programming approach to the problem of optimal unit commitment with probabilistic reserve determination”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, No. 6, pp. 2154–2166, Nov/Dec. 1978.
[5] H. Monsef and N.T. Mohamadi, “Generation scheduling in a competitive environment”, Iranian Journal of Electrical & Electronic Engineering, Vol. 1, No. 2, pp. 68–73, Apr. 2005.
[6] S. Virmani, E.C. Adrian, K. Imhof and S. Mukherjee, “Implementation of a Lagrangian relaxation based unit commitment problem”, IEEE Transactions on Power Systems, Vol. 4, No. 4, pp. 1373–1380, Oct. 1989
[7] Tomonobu Senjyu, Kai Shimabukuro, Katsumi Uezato and Toshihisa Funabashi, “A fast technique for unit commitment problem by extended priority list”, IEEE Transactions on Power Systems, Vol. 18, No. 2, pp. 882–888, May 2003.
[8] E. Delaruea, D. Cattrysse and W. D’haeseleer, “Enhanced priority list unit commitment method for power systems with a high share of renewables”, Electric Power Systems Research, Vol. 105, pp. 115–123, Dec. 2013.
[9] Ran Quan, Jinbao Jian and Linfeng Yang, “An improved priority list and neighborhood search method for unit commitment”, Electrical Power and Energy Systems, Vol. 67, pp. 278–285, May 2015.
[10] Yonghong Chen and Fengyu Wang, “MIP formulation improvement for large scale security constrained unit commitment with configuration based combined cycle modeling”, Electric Power Systems Research, Vol. 148, pp.147–154, Jul. 2017.
[11] T. Seki, N. Yamashita and K. Kawamoto, “New local search methods for improving the Lagrangian-relaxation-based unit commitment solution”, IEEE Transactions on Power Systems, Vol. 25, No. 1, pp. 272–283, Feb. 2010.
[12] Q. Jiang, B. Zhou and M. Zhang, “Parallel Augment Lagrangian Relaxation Method for Transient Stability Constrained Unit Commitment”, IEEE Transactions on Power Systems, Vol. 28, No. 2, pp. 1140–1148, May 2013.
[13] Seyed Hamid Hosseini, Amin Khodaei and Farrokh Aminifar, “Novel straightforward unit commitment method for large scale power systems”, IEEE Transactions on Power Systems, Vol. 22, No. 4, pp. 2134–2143, Nov. 2007.
[14] A.H. Mantawy, Youssef L. Abdel-Magid and Shokri Z. Seliin, “A simulated annealing algorithm for unit commitment”, IEEE Transactions on Power Systems, Vol. 13, No. 1, pp. 197–204, Feb. 1998.
[15] S.A. Kazarlis, A.G. Bakirtzis and V. Petridis, “A genetic algorithm solution to the unit commitment problem”, IEEE Transactions on Power Systems, Vol. 11, No. 1, pp. 83–92, Feb. 1996.
[16] S. Patra, S.K. Goswami and B. Goswami, “Differential evolution algorithm for solving unit commitment with ramp constraints”, Electric Power Components and Systems, Vol. 36, No. 8, pp. 771–787, Jun. 2008.
[17] Dilip Datta and Saptarshi Dutta, “A binary-real-coded differential evolution for unit commitment problem”, Electrical Power and Energy Systems, Vol. 42, No. 1, pp. 517–524, Nov. 2012.
[18] Z. Ouyang and S.M. Shahidehpour, “Short-term unit commitment expert system”, Electric Power Systems Research, Vol. 20, No. 1, pp. 1–13, Feb. 1990.
[19] M.R. Aghamohammadi, “Static security constrained generation scheduling using sensitivity characteristics of neural network”, Iranian Journal of Electrical & Electronic Engineering, Vol. 4, No. 3, pp. 104–114, Jul. 2008.
[20] S.P. Simon, N.P. Padhy and R.S. Anand, “An ant colony system approach for unit commitment problem”, Electrical Power and Energy Systems, Vol. 28, No. 5, pp. 315–323, Jun. 2006.
[21] K.A. Juste, H. Kita, E. Tanaka, and J. Hasegawa, “An evolutionary programming solution to the unit commitment problem”, IEEE Transactions on Power Systems, Vol. 14, No. 4, pp. 1452–1459, Nov. 1999.
[22] M. Eslamian, S.H. Hosseinian and B. Vahidi, “Bacterial foraging-based solution to the unit-commitment problem”, IEEE Transactions on Power Systems, Vol. 24, No. 3, pp. 1478–1488, Aug. 2009.
[23] Javad Ebrahimi, Seyed Hossein Hosseinian and Gevorg B. Gharehpetian, “Unit commitment problem solution using shuffled frog leaping algorithm”, IEEE Transactions on Power Systems, Vol. 26, No. 2, pp. 573–581, May 2011.
[24] Bin Ji, Xiaohui Yuan, Zhihuan Chen and Hao Tian, “Improved gravitational search algorithm for unit commitment considering uncertainty of wind power”, Energy, Vol. 67, pp. 52–62, Apr. 2014.
[25] Provas Kumar Roy and Ranadhir Sarkar, “Solution of unit commitment problem using quasi-oppositional teaching learning based algorithm”, Electrical Power and Energy Systems, Vol. 60, pp. 96–106, Sep. 2014.
[26] B. Saravanan, E. R. Vasudevan and D. P. Kothari, “Unit Commitment Problem Solution Using Invasive Weed Optimization Algorithm”, Electrical Power and Energy Systems, Vol. 55, pp. 21–28, Feb. 2014.
[27] A.Y. Saber, T. Senjyu, T. Miyagi, N. Urasaki and T. Funabashi, “Fuzzy Unit Commitment Scheduling Using Absolutely Stochastic Simulated Annealing”, IEEE Transactions on Power Systems, Vol. 21, No. 2, pp. 955–964, May 2006.

[28] Grzegorz Dudek, "Adaptive simulated annealing schedule to the unit commitment problem", Electric Power Systems Research, Vol. 80, No. 4, pp. 465–472, Apr. 2010.

[29] Ioannis G. Damousis, Anastasios G. Bakirtzis and Petros S. Dokopoulos, "A solution to the unit-commitment problem using integer-coded genetic algorithm", IEEE Transactions on Power Systems, Vol. 19, No. 2, pp. 1165–1172, May 2004.

[30] Dilip Datta, "Unit commitment problem with ramp rate constraint using a binary-real-coded genetic algorithm", Applied Soft Computing, Vol. 13, No. 9, pp. 3873–3883, Sep. 2013.

[31] S.Chakraborty, T. Ito, T. Senjyu and A.Y. Saber, "Unit commitment strategy of thermal generators by using advanced fuzzy controlled binary particle swarm optimization algorithm", Electrical Power and Energy Systems, Vol. 43, No. 1, pp. 1072–1080, Dec. 2012.

[32] Anup Shukla and S.N. Singh, "Advanced three-stage pseudo-inspired weight-improved crazy particle swarm optimization for unit commitment problem", Energy, Vol. 96, pp. 23–36, Feb. 2016.

[33] B. Saravanan, C. Kumar and D.P. Kothari, "A solution to unit commitment problem using fire works algorithm", Electrical Power and Energy Systems, Vol. 77, pp. 221–227, May 2016.

[34] Wu Yuan-Kang, Huang Chih-Cheng and Lin Chun-Liang, "Resolution of the unit commitment problems by using the hybrid Taguchi-ant colony system algorithm", Electrical Power and Energy Systems, Vol. 49, pp. 188–198, Jul. 2013.

[35] Xiang Yu and Xueqing Zhang, "Unit commitment using Lagrangian relaxation and particle swarm optimization", Electrical Power and Energy Systems, Vol. 61, pp. 510–522, Oct. 2014.

[36] Anupam Trivedi, Dipti Srinivasan, Subhodip Biswas and Thomas Reindl, "A genetic algorithm - differential evolution based hybrid framework: Case study on unit commitment scheduling problem", Information Sciences, Vol. 354, pp. 275–300, Aug. 2016.

[37] Vikram Kumar Kamboj, S.K. Bath and J.S. Dhillon, "Implementation of hybrid harmony search/random search algorithm for single area unit commitment problem", Electrical Power and Energy Systems, Vol. 77, pp. 228–249, May 2016.

[38] A.V.V. Sudhakar, Chandram Karri and A. Jaya Laxmi, "Profit based unit commitment for GENCOs using Lagrange relaxation-differential evolution", Engineering Science and Technology, an International Journal, Vol. 20, No. 2, pp. 738–747, Apr. 2017.

[39] T.W. Lau, C.Y. Chung, K.P. Wong, T.S. Chung and S.L. Ho, "Quantum-inspired evolutionary algorithm approach for unit commitment", IEEE Transactions on Power Systems, Vol. 24, No. 3, pp. 1503–1512, Aug. 2009.

[40] C.Y. Chung, H. Yu and K.P. Wong, "An advanced quantum-inspired evolutionary algorithm for unit commitment", IEEE Transactions on Power Systems, Vol. 26, No. 2, pp. 847–854, May 2011.

[41] Bin Ji, Xiaohui Yuan, Xianshan Li, Yuehua Huang and Wenwu Li, "Application of quantum-inspired binary gravitational search algorithm for thermal unit commitment with wind power integration", Energy Conversion and Management, Vol. 87, pp. 589–598, Nov. 2014.

[42] Seyedali Mirjalili, Seyed Mohammad Mirjalili and Andrew Lewis, "Grey wolf optimizer", Advances in Engineering Software, Vol. 69, pp. 46–61, Mar. 2014.

[43] Lingfeng Wang and Chanan Singh, "Unit commitment considering generator outages through a mixed-integer particle swarm optimization algorithm", Applied Soft Computing, Vol. 9, No. 3, pp. 947–953, Jun. 2009.

[44] Chariklia A. Georgopoulou and Kyriakos C. Giannakoglou, "Metamodel-assisted evolutionary algorithms for the unit commitment problem with probabilistic outages", Applied Energy, Vol. 87, No. 5, pp. 1782–1792, May 2010.

[45] Jia-Chu Lee, Whei-Min Lin, Gwo-Ching Liao and Ta-Peng Tsao, "Quantum genetic algorithm for dynamic economic dispatch with valve-point effects and including wind power system", Electrical Power and Energy Systems, Vol. 33, pp. 189–197, Feb. 2011.

[46] Carlos M. Correa-Posada, German Morales-Espana, Pablo Duenas and Pedro Sanchez-Martin, "Dynamic ramping model including intraperiod ramp-rate changes in unit commitment", IEEE Transactions on Sustainable Energy, Vol. 8, No. 1, pp. 43–50, Jan. 2017.

[47] S.N. Mhanna and R.A. Jabr, "Application of semi definite programming relaxation and selective pruning to the unit commitment problem", Electric Power Systems Research, Vol. 90, pp. 85–92, Sep. 2012.

S. Siva Sakthi received the B.E. degree in electrical and electronics engineering from the University of Madras, Madras, 1999; the M.E. degree in power systems engineering from the Annamalai University, Chidambaram, India, 2008; He is perusing the Ph.D. degree in electrical engineering from the Annamalai University, Chidambaram, India. He is an Associate Professor in electrical and electronics engineering at the Krishnasamy College of Engineering & Technology, Cuddalore, India.

R. K. Santhi received the B.E. degree in electrical and electronics engineering from the Government College of Technology, Coimbatore, India, 1984; the M.E. degree in power systems engineering from the Annamalai University, Chidambaram, India, 1986; the Ph.D. degree in electrical engineering from the Annamalai University, Chidambaram, India. She is a Professor in electrical and electronics engineering at the Annamalai University, Chidambaram, India. Her field of interest are economic dispatch, relaying, reliability etc. She has more than 30 years of teaching experience.

N. Murali Krishnan received the B.E. degree in electrical and electronics engineering and M.E. degree in power systems engineering from the Annamalai University, Chidambaram, India, 1997 and 2005 respectively; the Ph.D. degree in electrical engineering from the Anna University, Chennai, India,2012. He is a Professor and Head in electrical and electronics engineering at the Mailam Engineering College, Mailam, India. His field of interest are unit commitment, regulated and deregulated power systems, state estimation, etc. He has more than 17 years of teaching experience.

S. Ganesan (Senior Member IEEE) is currently working as Assistant Professor in the Department of Electrical and Electronics Engineering, Government College of Engineering, Dharmapuri, Tamil Nadu and previously worked in the Department of Electrical Engineering, Annamalai University, Annamalai Nagar, Tamil Nadu, India. He has authored 10 SCI research articles. His research interests include power system operation and control.

S. Subramanian (Senior Member IEEE) is working as Professor in the Department of Electrical Engineering, Annamalai University, Annamalai Nagar, Tamil Nadu, India. He has authored 32 SCI research articles. His research interests include power system operation and control.