Wind Integrated Thermal Unit Commitment Solution using Grey Wolf Optimizer

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ABSTRACT

The augment of ecological shield and the progressive exhaustion of traditional fossil energy sources have increased the interests in integrating renewable energy sources into existing power system. Wind power is becoming worldwide a significant component of the power generation portfolio. Profuse literatures have been reported for the thermal Unit Commitment (UC) solution. In this work, the UC problem has been formulated by integrating wind power generators along with thermal power system. The Wind Generator Integrated UC (WGIUC) problem is more complex in nature that necessitates a promising optimization tool. Hence, the modern bio-inspired algorithm namely, Grey Wolf Optimization (GWO) algorithm has been chosen as the main optimization tool and real coded scheme has been incorporated to handle the operational constraints. The standard test systems are used to validate the potential of the GWO algorithm. Moreover, the ramp rate limits are also included in the mathematical WGIUC formulation. The simulation results prove that the intended algorithm has the capability of obtaining economical resolutions with good solution quality.

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1. INTRODUCTION

1.1. Wind Generator Integrated Unit Commitment

The aim of the Unit Commitment (UC) problem is to identify the optimum generating schedule, that minimizes the total operational costs and satisfying the system load demand, by considering several physical, inter-temporal constraints of generating units, transmission and system reliability requirements. In recent years, as wind power is sustainable and green power, its penetration in power system has increased significantly and is expected to persist rising in the future. Furthermore, it increases the complexity of power system operations due to its inadequate predictability and variability.

Numerous reports have been addressed for solving thermal UC problem. As the Wind Generator Integrated UC (WGIUC) is the emerging field of research, very few research reports detail the WGIUC solution. Hence, the solution quality of WGIUC problem can be improvised by exploring the search space. This motivates, to develop a prominent method to determine the most economic UC schedule for WGIUC.

1.2. Existing Solution Methods

The UC is a non-convex, large-scale mixed integer nonlinear programming problem. Determination of the optimal solution for UC problem within reasonable computational time and memory requirement is very difficult. The exact solution of the UC problem can be determined by complete enumeration approach. But this is not applicable to practical power systems, since the computational time requirement is high. The above has motivated the researchers, to investigate alternate approaches to obtain approximate solutions for realistic UC problem in reasonable computational time. Numerous techniques have been developed and applied to solve the UC problems. They can be classified into mathematical, meta-heuristic and hybrid methods.

a) **Mathematical Methods:** The deterministic methods for thermal UC include Priority List (PL) [1], Dynamic Programming (DP) [2], Branch-and-Bound (BB) [3], Lagrangian Relaxation (LR) [4] and Mixed Integer Programming (MIP) [5] methods. The improved versions of PL, DP and LR such as Extended PL (EPL) [6], Intelligent DP (IDP) [7], Enhanced Adaptive LR (EALR) [8] and Improved LR (ILR) [9] have been developed. Most of the above techniques suffer from numerical convergence and solution quality problem. They are inadequate in handling large number of generating units and non convex search space of the UC problem. Because of high nonlinearity and high complexity nature of the practical UC problem, soft computing methods are used as alternative to the classical approaches.
b) **Meta-Heuristic Methods:** Various artificial intelligence techniques such as Simulated Annealing (SA) [10], Genetic Algorithm (GA) [11], Expert System (ES) [12], Evolutionary Programming (EP) [13], Neural Network (NN) [14], fuzzy methods [15], Tabu Search (TS) [16], Particle Swarm Optimization (PSO) [17], Fire Fly (FF) algorithm [18], [19], Ant Colony System (ACS) algorithm [20], Differential Evolution (DE) [21], [22], Bacterial Foraging Algorithm (BFA) [23], Shuffled Frog Leaping Algorithm (SFLA) [24], Gravitational Search Algorithm (GSA) [25], [26] and Memetic Algorithm (MA) [27] have been applied to solve the thermal UC problems.

The improved versions of GA, parallel repair GA [28], Integer-Coded GA (ICGA) [29] and Binary-real-Coded GA (BCGA) [30] have been developed to solve thermal UC problem. The modified versions of SA namely, Enhanced SA (ESA) [31], [32], Adaptive SA (ASA) [33] and modified versions of PSO namely, Hybrid PSO [34], pseudo-inspired weight-improved crazy PSO [35] have been evolved to solve the UC problem. Fireworks algorithm [36] is one type swarm optimization algorithms recently developed and applied to solve the UC problem.

Various hybrid methods combining metaheuristic with traditional techniques or other metaheuristic are developed to explore the search space in large size UC problems. Hybrid methods include hybrid fuzzy NN-ES [37], LR and GA [38], LR and EP [39], EP and TS [40], ES and Elite PSO [41], Hybrid Taguchi (HT) - ACS [42], LR and PSO [43], GA and DE [44] and hybrid harmony search/random search algorithm [45]. Quantum-inspired evolutionary computing techniques such as Quantum-inspired Evolutionary Algorithm (QEA) [46], Quantum-inspired Binary PSO (QBPSO) [47], Advanced Quantum-inspired Evolutionary Algorithm (AQEA) [48] and Quantum-inspired Binary GSA (QBGSA) [49] have been applied to solve UC problem.

1.3. Why Grey Wolf Optimization Algorithm?

The existing metaheuristic 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. Recently, in the field of swarm intelligence computations, a new optimization algorithm, namely Grey Wolf Optimization (GWO) [50] has been developed. This is inspired by democratic behaviour and the hunting mechanism of gray wolves in the nature. In a pack, the wolves follow social leadership hierarchy. Seyedali Mirjalili *et al.*, have proposed the GWO algorithm and the algorithm is inspected with standard test functions. It yields competitive solutions compared with other heuristic algorithms. The merits of the GWO are simple, easy implementation and require few parameters to adjust.

1.4. Research Gap and Contribution

Profuse literatures have been addressed thermal UC solution. Few research works has been carried in the field of UC considering wind power generation [26], [49], [51]. The integration of wind power increases further the non-linear solution space, hence determining the best feasible schedule has become crucial. Though, numerous soft computing techniques have been reported for the UC solution, improving their solution quality is still a 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 WGIUC problems. The real coded scheme is adopted in GWO algorithm in order to handle the operational constraints and is applied for the first time to solve WGIUC problems.

1.5. Paper Organization

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

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 [6]. Accordingly, the overall objective function of the UC problem is stated as:

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

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:

$$F_t(P_i(t)) = a_i + b_i P_i(t) + c_i P_i^2(t) \quad (2)$$

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:

$$SC_i = \begin{cases} h - \text{cost}_i \;;\; T_i^{off} \le X_i^{off} \le T_i^{off} + c - s - hour_i \\ c - \text{cost}_i \;;\; X_i^{off} > T_i^{off} + c - s - hour_i \end{cases} \quad (3)$$

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

Power Balance Constraint: The total power generated by the combination of thermal and wind generating units must meet the load demand $Pd(t)$ on hourly basis:

$$Pd(t) = \sum_{i=1}^{N} P_i(t) + P_w \quad (4)$$

2.3. Unit Constraints

The generating unit operational constraints [6], [21] are as follows:

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

a. $$P_{i\min} \le P_i(t) \le P_{i\max} \quad (5)$$

b. $$P_{w\min} \le P_w(t) \le P_{w\max} \quad (6)$$

b) **Unit Minimum Up/Down Time Constraints:** The inequality constraints of minimum up/down time limits of generating units is given by:

a. $$T_i^{on} \le X_i^{on} \\ T_i^{off} \le X_i^{off} \quad (7)$$

c) **Up/Down Ramp Limits:** The up and down ramp limits of the thermal units are given by,

a. $$-DR_i \le P_i(t) - P_i(t-1) \le UR_i \quad (8)$$

d) **Unit Initial Status:** The initial status at the start of the scheduling period must be taken into account.

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, each unit sequence of the operating mode (ON/OFF) cycle duration is indicated by a sequence of integer numbers which represents the Wolf Position (WP) in the UC horizon. 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 is 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.

$$T_i^1 = \begin{cases} +Rand(\max(0, T_i^{on} - T_i^0), T), & \text{if } T_i^0 > 0 \\ -Rand(\max(0, T_i^{off} + T_i^0), T), & \text{if } T_i^0 < 0 \end{cases} \tag{9}$$

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

$$T_i^c = \begin{cases} +Rand(T_i^{on}, BT_i^{c-1}), & \text{if } BT_i^{c-1} > T_i^{on} \\ +BT_i^{c-1}, & \text{otherwise} \end{cases} \tag{10}$$

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

$$T_i^c = \begin{cases} -Rand(T_i^{off}, BT_i^{c-1}), & \text{if } BT_i^{c-1} > T_i^{off} \\ -BT_i^{c-1}, & \text{otherwise} \end{cases} \tag{11}$$

where BT_i^{c-1} corresponds to the scheduling time remaining after the allocation of the first c -1 cycles.

$$BT_i^{c-1} = T - \sum_{j=1}^{c-1} \left| T_i^j \right| \tag{12}$$

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 WGIUC

In this section, the algorithmic steps of GWO for WGIUC 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

a. 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 mimimum is delta.

a. $\text{Fitness} = F_t + OCV$ (13)

b. 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 = iter +1.
5. Search agent, *SAg*= *SAg*+1.
6. Modify the generation of *N*-1 online units based on the hunting mechanism.

a. $$X^{t+1} = \frac{(X_\alpha - A_1.(D_\alpha)) + (X_\beta - A_2.(D_\beta)) + (X_\gamma - A_3.(D_\gamma))}{3}$$ (14)

b. Where: $D_\alpha = |C_1.X_\alpha - X|$; $D_\beta = |C_2.X_\beta - X|$; $D_\gamma = |C_3.X_\gamma - X|$; $A = 2a.rand - a$.

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

4. SIMULATION RESULTS AND DISCUSSIONS

The algorithm is developed in Matlab platform which is executed on a personal computer configured with Intel core i3 processor 2.20 GHz and 4 GB RAM. The performance of the GWO method is tested on the standard test system which consists of ten thermal generating units and one wind farm over a planning horizon of 24 hours. The generating unit data and load demands are adopted from [11]. The wind farm consists of 20 number of same model wind turbine generators which are operating in parallel. The wind power generation data [51] are provided in Table 1. They are calculated using forecasted wind power beforehand and converted into electrical power. The minimum and maximum output power of wind farm is 15 MW and 100 MW respectively. The wind farm yields the minimum and maximum output of 15.01 MW at 10th hour and 98.559 MW at 16th hour respectively.

Table 1. Wind power generation data

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

The simulation runs, for standard 10 unit system with the scheduling period of 24 hours. The maximum number of cycles for each unit is taken as 5. For each problem set, 50 test trials are made with random initial population for each run. Multiple runs have been performed, to verify the robustness of the GWO in solving UC problem. The following two case studies have been conducted in order to show the effectiveness of GWO in solving UC problem. The Table 2 illustrates the configuration for final population to WGIUC problem using GWO.

Table 2. Configuration for final population to WGIUC problem using GWO

	Cycles				
Unit	1	2	3	4	5
U1	24	0			
U2	24	0			
U3	-5	16	-3		
U4	-4	17	-3		
U5	-2	20	-2		
U6	-8	6	-5	4	-1
U7	-8	6	-5	3	-2
U8	-9	4	-6	1	-4
U9	-10	2	-12	0	0
U10	-11	1	-12	0	0

4.1. UC Considering Ramp Rates

In general, the amount of power generated by thermal units at each time period will not consider the dynamic of thermal units. But it is essential to include ramp rate constraints in large practical UC problem. These dynamic constraints enforce limitation on drastic change in thermal unit generation output in successive time interval. These make generation levels of two successive periods are interrelated. Thus ramp rate restricts the rate of increase or decrease of power generation of each unit considering the thermal and mechanical inertia of the thermal units. However, this reduces the search space for obtaining more and better feasible solutions.

Table 3 demonstrates that the best, worst and average operating costs obtained by Iterative Linear Algorithm (ILA) [52], Quadratic Model (QM) [25], Semi-Definite Programming (SDP) [52], GSA, Teaching Learning Based Optimization (TLBO) algorithm [52], Quasi-Oppositional TLBO (QOTLBO) [52] and GWO. This illustrates the GWO can overcome the early convergence when compared with other optimization algorithms.

Table 3. Statistical total operating cost result of 10 unit system with ramp rate constraints

Methods	Best Cost ($)	Worst Cost ($)	Mean Cost ($)
ILA[52]	570396.4	NR	NR
QM[25]	570396.4	NR	NR
SDP[52]	564482	NR	NR
GSA[25]	564384	NR	NR
TLBO[52]	564402.9	564594.6	564497.4
QOTLBO[52]	564394.0	564443.7	564405.3
GWO	564006.63	564149.19	564098.59

4.2. UC Integrated with Wind

The wind becoming an increasingly common electric energy source. This introduces new technical and economical challenges to power system operators. This makes Wind Thermal Generating Scheduling (WTGS) problem plays a vital role in producing zero carbon emission power. The preparation of generating scheduling is a complex optimization problem that has to determine the optimal schedule of generating units within a power system subject to all prevailing constraints. Here the thermal units generating schedule is determined by using GWO algorithm.

Table 4 shows that the minimum up/down time limits and initial status of units are satisfied for all thermal generating units. U1 and U2 are committed for whole scheduling period, since their commitment priorities are high when compared to other thermal units. These units will operate as "Must-Run" units. The Table 4 illustrates the optimum UC schedule obtained by GWO and real power sharing of online generating units. The integration of wind farm with thermal generating units made the following changes in thermal unit scheduling when compared with [45]. The power generation of U2 is reduced significantly in the scheduling hour 1st to 8th , 15th to 19th and 21th hour. Since the incremental fuel cost of this unit is high compared with U1. The considerably reduction of dispatch on U5 for the scheduling period hours 5 to 9, 13 to 15 and 18 to 21. The lesser power dispatch can be realized on U6 during 10th, 11th and 13th hour. Similarly, the load dispatch by U8 is less at 12th hour. These reduced dispatches by thermal units realize significant amount of fuel and cost savings.

Table 4. Wind combined schedule of 10-unit system without ramp rate by GWO

Hour	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	Wind Generation (MW)	Total PD (MW)	Fuel Cost($)	Startup Cost($)	Total Cost($)
1	455	202.39	0	0	0	0	0	0	0	0	42.602	700	12941.9	0	12941.9
2	455	259.59	0	0	0	0	0	0	0	0	35.409	750	13937.23	0	13937.23
3	455	310.00	0	0	25	0	0	0	0	0	60	850	15761.2	900	16661.2
4	455	452.80	0	0	25	0	0	0	0	0	17.193	950	18259.83	0	18259.83
5	455	370.00	0	130	25	0	0	0	0	0	20	1000	19670.11	560	20230.11
6	455	328.69	130	130	25	0	0	0	0	0	31.309	1100	21839.97	1100	22939.97
7	455	370.00	130	130	25	0	0	0	0	0	40	1150	22561.92	0	22561.92
8	455	427.19	130	130	25	0	0	0	0	0	32.802	1200	23563.29	0	23563.29
9	455	455	130	130	63.21	20	25	0	0	0	21.784	1300	26809.08	860	27669.08
10	455	455	130	130	159.99	20	25	10	0	0	15.01	1400	29721.11	60	29781.11
11	455	455	130	130	162	48.61	25	10	10	0	24.383	1450	31352.2	60	31412.2
12	455	455	130	130	162	80	25	15.94	10	10	27.058	1500	33182.25	60	33242.25
13	455	455	130	130	133.76	20	25	10	0	0	41.233	1400	29173.86	0	29173.86
14	455	455	130	130	34.52	20	25	0	0	0	50.478	1300	26232.64	0	26232.64
15	455	380.00	130	130	25	0	0	0	0	0	80	1200	22736.84	0	22736.84
16	455	211.46	130	130	25	0	0	0	0	0	98.559	1050	19796.95	0	19796.95
17	455	187.80	130	130	25	0	0	0	0	0	72.194	1000	19385.74	0	19385.74
18	455	310.34	130	130	25	0	0	0	0	0	49.655	1100	21519.69	0	21519.69
19	455	423.56	130	130	25	0	0	0	0	0	36.44	1200	23499.54	0	23499.54
20	455	455	130	130	117.81	20	25	10	0	0	57.185	1400	28843.63	490	29333.63
21	455	450.75	130	130	25	20	25	0	0	0	64.243	1300	25968.37	0	25968.37
22	455	455	0	0	59.45	20	25	0	0	0	85.541	1100	20980.77	0	20980.77
23	455	354.32	0	0	0	20	0	0	0	0	70.677	900	16408.41	0	16408.41
24	455	283.70	0	0	0	0	0	0	0	0	61.298	800	14357.45	0	14357.45
											Total Cost ($)		**538504.00**	**4090.00**	**542594.00**

By observing Table 4, it can be concluded that the generated power for each hour by thermal generating units (U1-U10) along with wind power plants is equivalent to the power demand *Pd(t).* The generation limits are also satisfied in this case study. The fuel, start up and total costs obtained in this case are $538504.00, $4090.00 and $542594.00 respectively.

4.3. Ramp Rate Constrained WGIUC

To verify the efficiency and superiority of the GWO algorithm, the ramp rate is considered for the same test system over 24 hour horizon. When the ramp rate constraints are included, it has been assumed that the value of *DR* and *UR* of each unit is same [53]. The ramp rate limits of each unit are presented in the Table 5. Referring Tables 4 and 7, the real power output of U2 is increased in the 16th interval due to inclusion of ramp rate limits. The generation reallocation among online units is required that leads to slight increase in fuel cost hence raise in the total operating cost for the planning horizon. It is also observed from Tables 4 and 7, that no change in scheduling of committed units. However the dispatches of on-line thermal units are changed because of ramp rate constraints. The obtained UC schedule and real power sharing of online generating units for standard 10 unit system considering ramp rate limits are presented in the Table 7. The wind generating units along with thermal units meet the power demand in each interval. The obtained fuel, start up and total costs are $538509.10, $4090.00 and $542599.10 respectively.

The total operating hours of all thermal units for both cases are listed in Table 6. It is observed that the units with higher commitment priorities have longer operating hours in the planning horizon except U6 and U7.

Table 5. Ramp rate limits of thermal generating units

Unit	Up/Down ramp rate (MW/hr)	Unit	Up/Down ramp rate (MW/hr)
U1	160	U6	60
U2	160	U7	60
U3	100	U8	40
U4	100	U9	40
U5	100	U10	40

Table 6. Total operating hours of thermal units

Unit	Operating hours	Unit	Operating hours
U1	24	U6	10
U2	24	U7	9
U3	16	U8	5
U4	17	U9	2
U5	20	U10	1

Table 7. Wind combined schedule of 10-unit system with ramp rate by GWO

Hour	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	Wind Generation (MW)	Total PD (MW)	Fuel Cost($)	Startup Cost($)	Total Cost($)
1	455	202.38	0	0	0	0	0	0	0	0	42.602	700	12941.74	0	12941.74
2	455	259.58	0	0	0	0	0	0	0	0	35.409	750	13937.16	0	13937.16
3	455	310.00	0	0	25	0	0	0	0	0	60	850	15761.28	900	16661.28
4	455	452.81	0	0	25	0	0	0	0	0	17.193	950	18259.99	0	18259.99
5	455	370.00	0	130	25	0	0	0	0	0	20	1000	19670.23	560	20230.23
6	455	328.69	130	130	25	0	0	0	0	0	31.309	1100	21840.11	1100	22940.11
7	455	370.00	130	130	25	0	0	0	0	0	40	1150	22562.01	0	22562.01
8	455	427.20	130	130	25	0	0	0	0	0	32.802	1200	23563.39	0	23563.39
9	455	455	130	130	63.22	20	25	0	0	0	21.784	1300	26809.26	860	27669.26
10	455	455	130	130	159.99	20.61	25	10	0	0	15.01	1400	29721.3	60	29781.3
11	455	455	130	130	162	48.62	25	10	10	0	24.383	1450	31352.41	60	31412.41
12	455	455	130	130	162	80	25	15.95	10	10	27.058	1500	33182.49	60	33242.49
13	455	455	130	130	133.77	20	25	10	0	0	41.233	1400	29174.04	0	29174.04
14	455	455	130	130	34.53	20	25	0	0	0	50.478	1300	26232.83	0	26232.83
15	455	380.00	130	130	25	0	0	0	0	0	80	1200	22736.93	0	22736.93
16	455	220.00	121.46	130	25	0	0	0	0	0	98.559	1050	19799.59	0	19799.59
17	455	187.81	130	130	25	0	0	0	0	0	72.194	1000	19385.83	0	19385.83
18	455	310.35	130	130	25	0	0	0	0	0	49.655	1100	21519.77	0	21519.77
19	455	423.56	130	130	25	0	0	0	0	0	36.44	1200	23499.63	0	23499.63
20	455	455	130	130	117.82	20	25	10	0	0	57.185	1400	28843.82	490	29333.82
21	455	450.76	130	130	25	20	25	0	0	0	64.243	1300	25968.48	0	25968.48
22	455	455	0	0	59.46	20	25	0	0	0	85.541	1100	20980.96	0	20980.96
23	455	354.32	0	0	0	20	0	0	0	0	70.677	900	16408.48	0	16408.48
24	455	283.69	0	0	0	0	0	0	0	0	61.298	800	14357.37	0	14357.37
											Total Cost ($)		**538509.10**	**4090.00**	**542599.10**

5. PERFORMANCE ANALYSIS

5.1. Solution Quality

The numerical values presented in Tables 3, 4 and 7 show that GWO algorithm yields the optimal scheduling of thermal units compared with earlier reported algorithms. The statistical analysis is carried out and presented in Table 3 for standard 10 unit system with ramp rate constraint. It can be concluded from Table 3, the best, worst and mean cost obtained by the GWO are significantly less compared with other existing methods. The mean cost of generation is better for optimal scheduling problems, it means GWO had an ability of reaching global minimum in consistent manner. GWO method exhibits excellent performance in finding the better solution.

5.2. Robustness

In case of stochastic simulation techniques like GWO, the initial population is generated using random numbers. This makes randomness is inherent property of GWO. Hence the performance should be ascertained by number of trails. Several trails have been carried out to find the optimal solution. Since UC is a real time problem, it is expected that each run 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. Figures 1 and 2 that clearly illustrates that GWO algorithm has significant robustness compared with other reported algorithms.

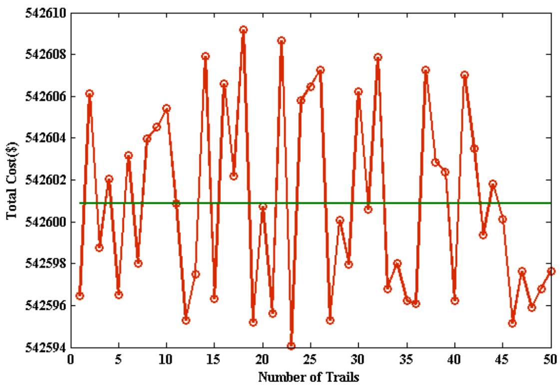

Figure 1. Robustness characteristics of 10 unit test system without ramp rate

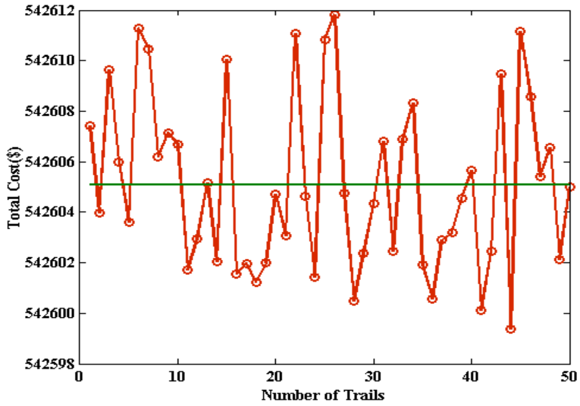

Figure 2. Robustness characteristics of 10 unit test system with ramp rate

5.3. Success Rate

It is the indication that in how many trails the obtained total cost is less than the mean cost. In both cases, the success rate of GWO is greater than 85%. It is also noticed that the difference between the mean and worst cost is less. It can be inferred that GWO algorithm has good success rate and robustness compared with other existing algorithm.

6. CONCLUSION

This paper presents a novel swarm intelligence approach known as GWO to solve the WGIUC problem. The 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 numerical results for standard ten unit system are validated using GWO algorithm. The incorporation of ramp rate constraints with above system also presented. It is clear from the results that the intended scheme not only yields monetary benefit and also the fuel consumption and emission of thermal generating units are reduced significantly. The implementation of GWO is easy and it handled the operational constraints successfully. GWO consistently find optimum solution for WGIUC problem. Results reveal that GWO is a competent method to solve the WGIUC problem. Further GWO can be extended to long term, reliability and security constrained thermal power scheduling problems along with wind energy.

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