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RELIABILITY AND SECURITY CONSTRAINED UNIT COMMITMENT PROBLEM FOR HYBRID POWER SYSTEM USING BI-LEVEL OPTIMIZATION TECHNIQUE

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Abstract

In this paper, hybrid nodal ant colony optimization (NACO) and real coded clustered gravitational search algorithm (CGSA) has been proposed for solving wind integrated thermal unit commitment problem. The reliability of the system will affected by high wind penetration. Hence, NACO-CGSA hybrid approach has been proposed for solving the reliability based security-constrained unit commitment (RSCUC) problem. NACO solves reliability constrained unit commitment (RCUC) problem and real coded CGSA solves security constrained economic dispatch (SCED) problem. The proposed method is implemented and tested using MATLAB programming. The feasibility and effectiveness of the proposed method is verified by IEEE Six bus system and the results are compared with those of other methods reported in literatures.

Index Terms: Bi-level optimization techniques, Nodal ant colony optimization, Reliability and security constrained unit commitment, clustered gravitational search algorithm, Security constrained economic dispatch, Transmission constraints.

1. INTRODUCTION

Unit commitment (UC) is a nonlinear mixed integer optimization problem to schedule the operation of the generating units at minimum operating cost while satisfying the demand and reserve requirements. The UC problem has to determine the on/off state of the generating units at each hour of the planning period and optimally dispatch the load and reserve among the committed units. The complexity of the UC problems grows exponentially to the number of generating units.

Several solution strategies have been proposed to provide quality solutions to the UC problem and increase the potential savings of the power system operator. These include deterministic and stochastic search approaches. Deterministic approaches include the priority list method [1], dynamic programming [2], branch and-bound methods [3] and Lagrangian Relaxation [4]. Although these methods are simple and fast, they suffer from numerical convergence and solution quality problems. The stochastic search algorithms such as particle swarm optimization [5], genetic algorithms [6], evolutionary programming [7], simulated annealing [8], ant colony optimization [9] and tabu search [10] are able to overcome the shortcomings of traditional optimization techniques. These methods can handle complex nonlinear constraints and provide high quality solutions. However, all these algorithms suffer from the curse of dimensionality. The increased problem size adversely effects the computational time and the quality of the solutions.

SCUC problem is a generalization of UCP, which considers transmission network security limits in addition to UCP constraints [11]. However, when using these existing methods, the SCUC problems encounter some inherent limitations, that of the unreasonable relaxations for the discrete variables, unstable computing efficiency, or excess decomposition for the problem model.

Recently, the significant development in the power industries is the integration of renewable energy resources with thermal power plant. The reliability of the system of generation is influenced by high penetration of wind energy due to the random nature of the wind availability. The introduction of renewable energy resources into conventional utilities creates new concerns for power engineers. Hence, this paper solves the RSCUC problem through effective application of hybrid NACO-CGSA algorithm. As hybridization, NACO solves the master UC problem and real coded CGSA solves the security constrained economic dispatch sub-problem. The performance of the hybrid NACO-CGSA in terms of solution quality is compared with that of other algorithms reported in literature.

2. PROBLEM FORMULATION

The objective of RSCUC is to minimize the fuel cost, simultaneously satisfying equality and inequality constraints with security and transmission network constraints. The objective function of the RSCUC can be formulated as follows;

Minimize

$$\sum_{t=1}^{T}\sum_{i=1}^{N} [F_i(P_{(i,t)})*I_{(i,t)} + SU_i^t * I_{(i,t)} *(1-I_{(i,t-1)}) + SD_i^t *(1-I_{(i,t)})] \quad (1)$$

$$F_i(P_{(i,t)}) = a + b * P_{(i,t)} + c * P_{(i,t)}^2 \quad (2)$$

Subject to the following constraints:

2.1 System constraints

2.1.1 Power balance constraints

$$P_{Gi,t} PWG_{i,t} - P_{Di,t} = V_{i,t}\sum_{j=1}^{N} V_{j,t}(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \quad i \in N_{B-1} \quad (3)$$

$$Q_{Gi,t} - Q_{Di,t} = V_{i,t} \sum_{j=1}^{N} V_{j,t}(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \qquad i \in N_{PQ} \qquad (4)$$

2.1.2 Spinning reserve constraints

$$\sum_{i=1}^{N}(P_{i,\max} * I_{(i,t)}) + PWG_{i,t} \geq Load_t,\ k \in [1,T] \qquad (5)$$

2.2 Unit constraints

2.2.1 Minimum Up and Down time constraints

$$[X^{on}(i,t-1) - T^{on}(i)] * [I_{(i,t-1)} - I_{(i,t)}] \geq 0 \qquad (6)$$

$$[X^{off}(i,t-1) - T^{off}(i)] * [I_{(i,t)} - I_{(i,t-1)}] \geq 0 \qquad (7)$$

2.2.2 Unit ramp constraints

$$P_{(i,t)} - P_{(i,t-1)} \leq UR(i) \qquad (8)$$

$$P_{(i,t-1)} - P_{(i,t)} \leq DR(i) \qquad (9)$$

2.3 Security constraints

$$V_i^{\min} \leq V_{i,t} \leq V_i^{\max} \qquad i \in N_{B-1} \qquad (10)$$

$$\left|BF_{i,t}\right| \leq BF_i^{\max} \qquad i \in N_B \qquad (11)$$

These security constraints are related to steady state conditions and it should be considered in the post-contingency states.

2.3.1 Reactive power generation limits

$$Q_{Gi}^{\min} \leq QGi,t \leq Q_{Gi}^{\max} \qquad (12)$$

2.4 Reliability constraints

In wind integrated thermal power system, high wind penetration can lead to high-risk level in power system reliability. The wind energy dispatch restrictions and reliability level of the power system are considered as in ref. [18, 19] and is given in equation (13).

$$\text{Min } EENS = \sum_{j=LC} PR_j L_j \quad \text{(KWh)} \qquad (13)$$

3. IMPLEMENTATION OF HYBRID NACO-CGSA FOR RSCUC PROBLEM

Nodal ant colony optimization solves reliability constrained unit commitment (RCUC) problem and Real coded clustered gravitational search algorithm solves security constrained economic dispatch (SCED) problem.

3.1 Theory of Nodal Ant Colony Optimization (NACO)

ACO is an intelligent optimization algorithm that searches the optimal solution, mimicking real ants. Ants choose their own path to arrive at a destination. Initially the movement of ants is random i.e., once an ant comes across any barrier it chooses its path randomly. While moving from source to destination and vice versa, ants deposit a chemical substance called pheromone on the path, forming a pheromone trail. Ants which move in the shortest path, reach the destination faster than the ants which move in other possible paths. More pheromone is deposited in the shortest path. By smelling the pheromone trail, ants find their way to the source by their nest mates. The ant's search is based on pseudo- random probability function based on problem-dependent heuristic and the amount of pheromone previously deposited in this trail.

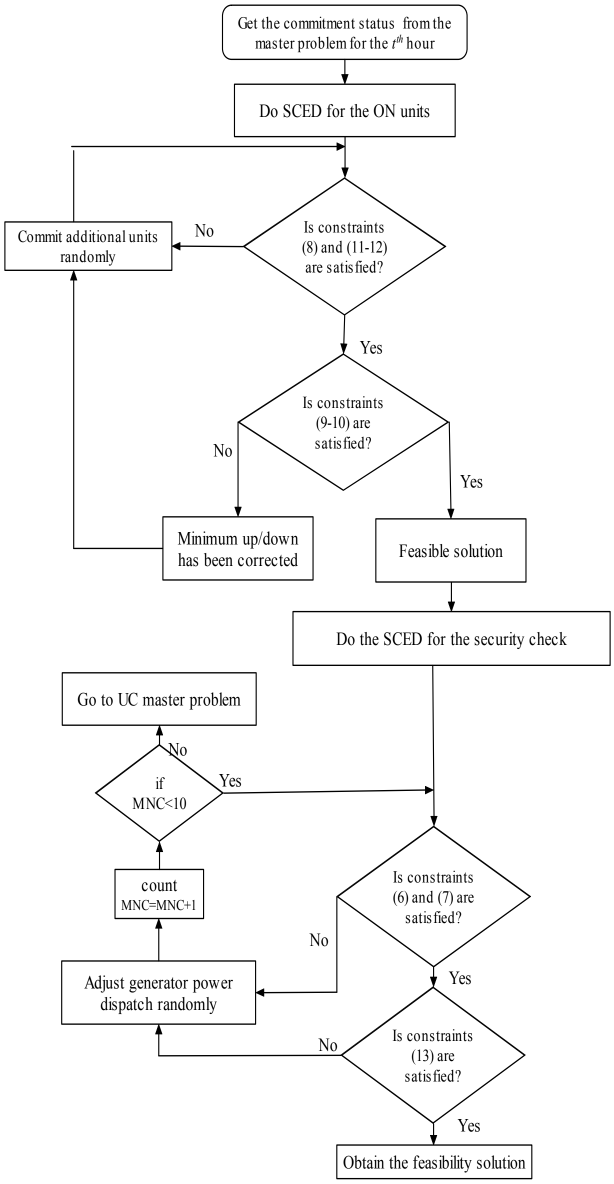

Fig 1 Flowchart of SCED constraint handling

The pheromone updation is based on evaporation rate and quality of current solution which is given detailed in ref. [12].

3.2 Gravitational Search Algorithm

The algorithm was proposed by Rashedi et.al [13-14] that uses the Newton's Gravitational Principle to search the optimum solution. In this algorithm, the coordinates or the agents in the search space are considered as masses. All these masses attract each other according to laws of Gravity and form a direct means of communication through it. Recently, in many article GSA is successfully implemented for solving discrete and continuous optimization problem. In the proposed work new methodology is implemented to improve the convergence and solution quality of GSA .

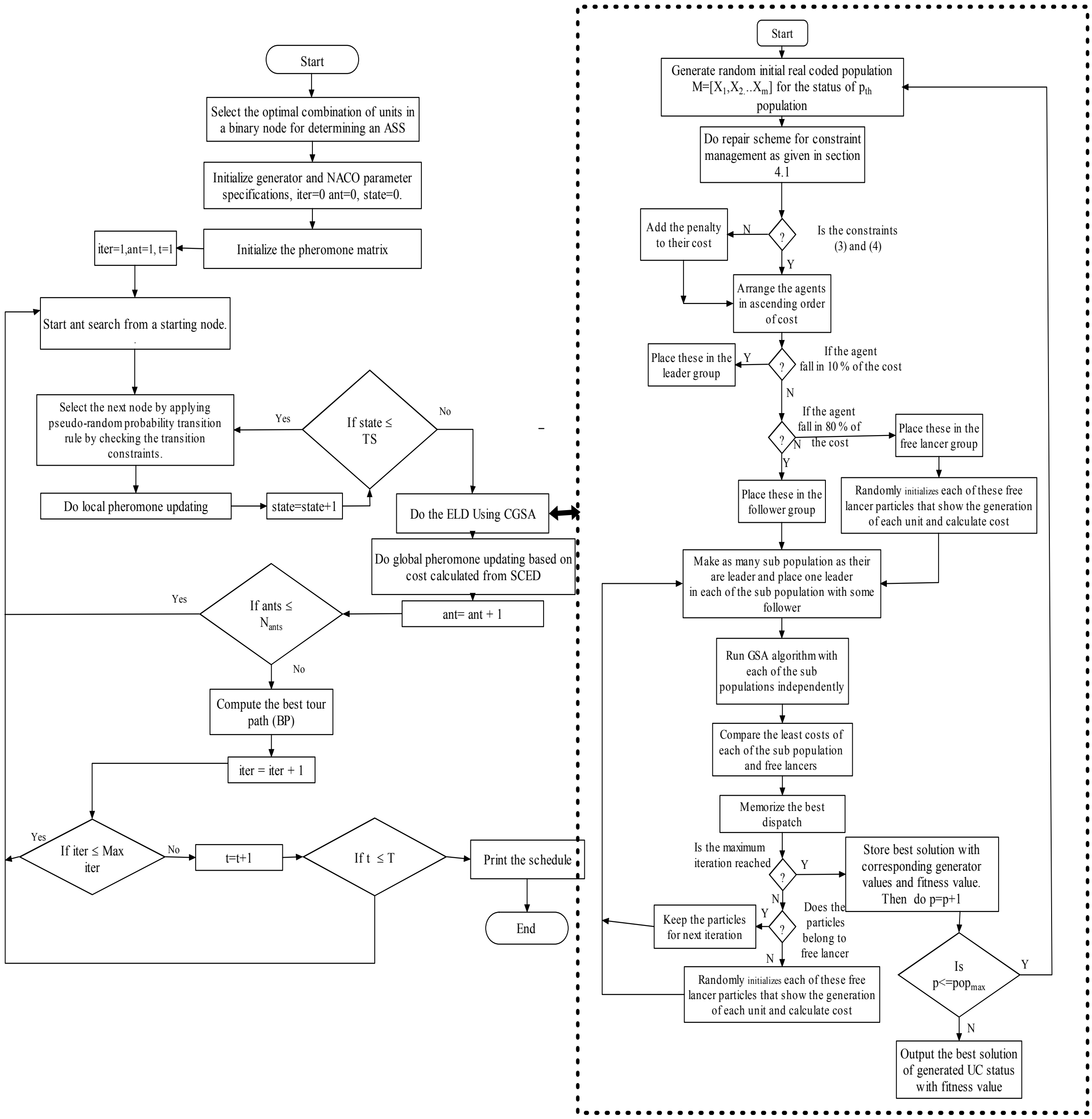

Fig. 2 Flow chart of Hybrid NACO-CGSA for SCUC problem

3.3 Constraint handling

Repair mechanism is utilized to overcome the violations with the minimum up/down time constraints. For instance the minimum up/down time for unit 1 is 4. For a scheduling interval of 12 hour, if the actual off time for unit 1 is 3 hour (5^{th}–7^{th} hour), then it violates the minimum down time constraint. In this case, the unit status before 5^{th} hour or after 7^{th} hour can be made '0'. By doing so, if it violates the minimum up time constraint, then the status of the units are made 1 during the violated down time period.

The modified position is then checked for spinning reserve constraint violation. Less expensive unit should be turned on randomly for unsatisfied constraints. This continues until the reserve constraints are satisfied. The minimum up/down time constraints are checked for the new updated status as in Fig. 1. For the feasible status of UC, the real values are generated and checked for power balance constraints. On violation, adjust the dispatched power randomly until constraints are satisfied. Next the security constraints are checked for violation. If violation exists, power dispatch is shared and violation is mitigated. If the security violations exist even after the minimum number of counts i.e., MNC (It is an integer parameter, which records the number of counts). The setting of a threshold, favours the flexibility in generating a new string and checks its convergence and repair mechanism up to the minimum number of count times. Therefore, a new string will be generated once the minimum count is greater than the threshold value. The minimum count value is fixed based on the trial and error method to have fast convergence. Step by step procedure for implementation of NACO-CGSA is given in flowchart shown in Fig.2

4. CASE STUDY

The hybrid NACO-CGSA is implemented for SCUC problem using 3 GHz Pentium IV, Windows XP with 1 GB of RAM and has been simulated in the MATLAB environment. Three test cases (UCP, SCUC and RSCUC problem) are carried out on the well-known six-bus [15,16] for a scheduling time horizon of 24 hours. The test systems are subject to (n-1) security criterion [11,17] characterized by the loss of a generation unit. The unit shut down cost is not included because the cost is considered as negligible and can be assumed to be zero.

4.1 Parameter settings

NACO and CGSA parameters are obtained by trial and error method for both the test systems. The guidelines for setting the parameters are given in ($\alpha \geq 0, \beta \geq 0, 0 \leq \rho < 1,$ C-Positive value) [12,9].

For a six-bus system, the control parameters are selected, based on the minimum average cost, obtained out of 10 simulations (AvgC) are shown as the darkened areas in Table 1. Total number of ants is taken as 50 and the maximum cycle number is taken as 20. The parameter setting of NACO and CGSA is given in table 2 and Table 3.

Table 1 Ant parameter settings for 6 bus system

A	Avg C	β	Avg C	ρ	Avg C	n	Avg C	C	Avg P
0	8.50	0	8.46	0.	8.51	1	8.42	0.1	8.46
0.	8.51	1	8.44	0.	8.52	3	8.46	1	8.52
0.	8.42	2	8.50	0.	8.01	-	-	10	8.42
0.	8.52	4	8.51	0.	8.46	-	-	50	8.45
1	8.01	7	8.52	0.	8.42	-	-	-	-
1.	1.51	1	8.01	-	-	-	-	-	-
2	8.46	1	8.46	-	-	-	-	-	-
5	8.44	1	8.02	-	-	-	-	-	-
-	-	2	8.42	-	-	-	-	-	-

Table 2 Statistical evaluation of NACO parameters

Parameters	Standard six-bus system
α	02
β	18
ρ	0.9
n	2
C	100
N_{ants}	50
maxiter	100

Table 3 Statistical evaluation of CGSA parameters

Parameters	Standard six-bus system
Population size	100
G0	100
Alfa	21

4.2 Six bus system

The six-bus test system has three units, five transmission lines, two tap-changing transformers and three demand sides. The characteristics of the generators are listed in Table 4 and the hourly load distribution over the 24 h time horizon is in [17]. The system diagram and other system data are in [15].

Table 4 Generation data for six unit system

Unit / Parameters		G1	G2	G3
Bus No		1	2	6
Unit cost coefficients	a MBtu	176.9	129.9	137.4
	b MBtu/MWH	13.5	32.6	17.6
	c MBtu/MW²H	0.0004	0.001	0.001
Active power	Maximum	220	100	20
	Minimum	100	10	10
Reactive power	Maximum	200	70	50
	Minimum	-80	-40	-40
Initial status of unit h		4	2	2
Min down of unit h		4	2	2
Min up of unit h		4	2	2
Ramp MW/H		55	50	20
Startup MBtu		100	200	0
Fuel price $/MBtu		1	1	1

4.2.1 UCP-six-bus

The UCP formulation, which is a simplified form of the SCUC model, does not include the line flow constraints, and security constraints. The constraints such as minimum up/down time and ramp up/down are included. The unit status and dispatch of each generating unit is given in Table 5.

Table 5 Status and dispatch of UCP and SCUCP- six-bus system

Hr	UCP-six-bus Total cost $ 82962.94				SCUCP-six-bus Total cost $ 84228.51			
	G1, MW	G2, MW	G3, MW	SR, MW	G1, MW	G2, MW	G3, MW	SR, MW
1	168.69	10.00	0	141.31	169.34	10	0	140.66
2	168.45	0	0	51.55	169.09	0	0	50.91
3	161.84	0	0	58.16	162.43	0	0	57.57
4	157.83	0	0	62.17	158.39	0	0	61.61
5	158.16	0	0	61.84	158.72	0	0	61.28
6	163.69	0	0	56.31	164.29	0	0	55.71
7	176.86	0	0	43.14	177.56	0	0	42.44
8	198.21	0	0	21.79	199.09	0	0	20.91
9	209.67	0	0	10.33	200.54	10.00	0	19.46
10	213.54	10.00	0	96.46	204.44	10.00	10.00	105.56
11	213.18	10.00	10.00	106.82	213.72	10.44	10.00	105.84
12	220.00	10.00	10.80	99.2	219.26	10.00	18.81	91.93
13	220.00	10.00	17.03	92.97	220.00	10.51	17.58	91.91
14	220.00	10.00	18.47	91.53	219.61	10.00	19.90	90.49
15	220.00	13.83	20.00	86.17	219.60	15.62	20.00	84.78
16	220.00	30.90	20.00	69.1	219.94	32.00	20.00	68.06
17	220.00	50.12	20.00	49.88	219.66	51.50	20.00	48.84
18	220.00	11.68	20.00	88.32	219.21	13.50	20.00	87.29
19	220.00	10.89	20.00	89.11	218.41	13.50	20.00	88.09
20	220.00	10.00	12.10	97.9	212.95	10.00	20.00	97.05

21	220.00	10.00	12.05	97.95	219.59	10.00	13.50	96.91
22	220.00	11.68	0	88.32	211.74	10.00	10.89	98.26
23	198.07	0	0	21.93	198.95	0	0	21.05
24	190.69	0	0	29.31	191.51	0	0	28.49

The total operating cost is $82,962.94, and is found to be the best optimal cost so far reported in the literature. From the economic view point, UCP schedule makes a cost effective generating unit to supply power to the load. However, from the security check, such UCP might result line flow violation and/or voltage violation. These violations can be mitigated by solving SCUC problem. The average CPU time is about 145.14 sec, approximately.

4.2.2 SCUC Problem-six-bus

The SCUC problem is solved by considering power flow constraints, transmission flow and bus voltage violations using the proposed hybrid NACO-CGSA method. The power flow observed in line (1-4) at 9th and 10th hour is 102.58 MW and 102.10 MW, respectively. This power flow exceeds the maximum specified allowable limit of 100 MW. However in the SCUC schedule, anticipating the violations, the G2 unit is turned ON at 9th and 10th hour. The voltage observed in buses 2 and 4 at 10th hour is 0.94p.u and 0.93p.u, respectively. These values are lesser than the allowed voltage limit of 0.95p.u. However in the SCUC schedule, anticipating the violation, the G3 unit is turned ON at 10th hour. Since ISO performs SCUC, the transmission line voltages are strictly monitored and the power is dispatched. Table 5 gives the commitment schedule and power dispatch of each unit for SCUC problem for the standard six-bus system. The total operating cost of the SCUC problem is $84,228.51. This operating cost is higher than the operating cost ($82,962.94) observed in the traditional UCP since security constraints are not considered. The average CPU time is about 1,348.47 sec, approximately. The comparison of result of UCP and SCUCP is given in Table 6. The convergence graph of the proposed method for UC and SCUC problems is shown in Figs. 3 and 4.

Table 6 Comparison of results for six-bus system

Solution method	Total operating cost ($)	
	UCP	SCUCP
SDP [17]	83,429.10	84,268.79
Hybrid ABPSO-RCGA [11]	83,414.67	84,243.46
ACO	83,408.24	84,242.27
Hybrid NACO-ABC	82,962.94	84,228.51

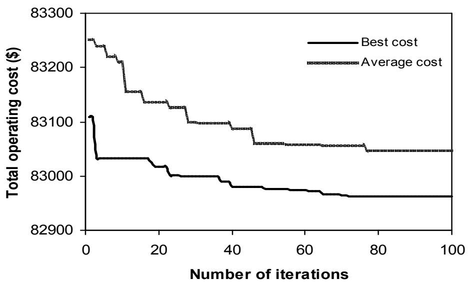

Fig 3 Convergence graph for six bus system –UCP

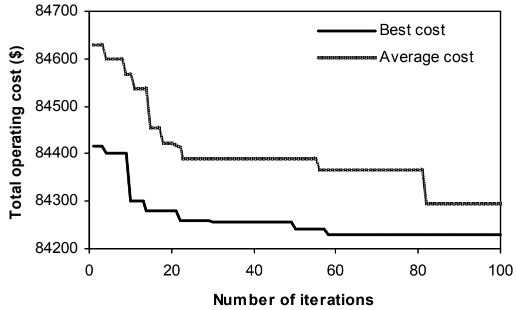

Fig 4 Convergence graph for six bus system –SCUCP

4.2.3 RSCUCP-Wind Integrated Thermal Power system

In this section, the wind power is integrated with thermal power system. When integrating the wind power with thermal power system, the reliability function is considered as constraint in UC problem. It is noted that based on the reserve capacity in case 2, the reliability level maintained at each hour and is given in Table 7.

Table 7 Reliability level, EENS (case 2)

Hour	EENS, MWh	Hour	EENS, MWh
1	0.333827376	13	0.868207896
2	0.70358349	14	0.886669122
3	0.67587123	15	0.960904054
4	0.65906079	16	1.178278494
5	0.66043392	17	1.428155093
6	0.68361069	18	0.928271886
7	0.73882716	19	0.917871195
8	0.82841349	20	0.801383457
9	0.463650576	21	0.803203578
10	0.560737471	22	0.667214544
11	0.687105866	23	0.82783095
12	0.867947879	24	0.79687311

The reliability data for the conventional generating unit is given in Table 8. Here it is assumed that the wind farm with 50 identical 1.75 MW WTG units with forced outage rate (FOR) of 0.04, and almost 25 % of the installed system capacity is integrated with the 6 bus system. The wind penetration in this case is 20 % of the system load at each hour of the dispatch period [18,19].

Table 8 Reliability data-3 unit system

Unit No.	Maximum Capacity, MW	Forced outage rate (FOR)
1	220	0.04
2	100	0.1
3	20	0.1

Table 9 RCSUC problem for Wind integrated Thermal Power system

Unit No.	G1	G2	G3	WP	PL	EENS
1	153.34	10	0	17.5	2.15	0.003457
2	169.09	0	0	0	0.64	0.703583
3	162.43	0	0	0	0.59	0.675871
4	158.39	0	0	0	0.56	0.659061
5	158.72	0	0	0	0.56	0.660434
6	164.29	0	0	0	0.6	0.683611
7	177.56	0	0	0	0.7	0.738827
8	199.09	0	0	0	0.88	0.828413
9	189.54	10	0	12.5	2.37	0.111474
10	204.44	10	0	12.5	3.4	0.169311
11	213.72	10.44	0	12.5	3.48	0.209756
12	219.26	14	0	17.5	9.96	0.268425
13	220	14	0	17.5	4.47	0.271504
14	220	14.5	0	17.5	3.53	0.273585
15	220	20.62	0	17.5	4.29	0.29905
16	220	35	0	17.5	1.6	0.358884
17	220	56	0	17.5	3.38	0.446264
18	220	18.5	0	17.5	4.32	0.290229
19	220	15.5	0	17.5	2.11	0.277746
20	212.95	14	0	17.5	2.35	0.24217
21	219.59	10	0	17.5	5.04	0.253155
22	208.74	10	0	17.5	4.56	0.208008
23	198.95	0	0	0	0.88	0.827831
24	191.51	0	0	0	191.51	190.69

The total number of dispatching unit in the system is four, including one wind energy resources (consolidated sources). From Table 7, it is noted that, a cost saving of 79364.87 $. From the Table 9, it is clear, that the scheduled spinning reserve with wind power and losses (Case 3) is higher than the scheduled spinning reserve without wind power (Case 2). Although the wind capacity integration requires scheduling additional reserve (due to uncertainty present in that hour) and increases the system losses that significantly increases the operating cost.

4.3 Performance analysis

The reported results for the proposed approach in Tables 6 and 9 are the best among the 30 trial runs. To evaluate the robustness of the proposed method, the best cost and average results are tabulated in Table 10. The tabulated results of the proposed solution strategy are taken from 30 trial runs. As seen, the best and average results of the proposed strategy are close to each other for both the UC and SCUC problems, indicating the robustness of the proposed method.

Table 10 Comparison of robustness evaluation of proposed solution strategy

Test Systems	Total operating cost ($)					
	UCP		SCUC problem		RSCUC problem	
	Best cost	Average cost	Best cost	Average cost	Best cost	Average cost
6 bus System	82,962.94	83,046.75	84,228.51	84,294.03	79364.87	79941.29

5. CONCLUSION

In this paper, a new combinatorial RSCUC problem solution strategy is proposed and problem is solved by hybrid NACO-CGSA. NACO effectively searches the RCUC problem solution space with an aid of enhanced evolutionary operators and the CGSA solves SCED as a part of RSCUC problem. This method spends the search capability of the proposed strategy in a cost-effective manner to search the feasible RSCUC problem solution space without entering into the infeasible region. The proposed methodology has been implemented and tested 6 bus systems, successfully. When the proposed method is executed for UC problem, a least operating cost of $ 82,962.94 is achieved. This leads to a social benefit of $ 451.73 per day when compared with Hybrid ABPSO-RCGA method, which is considered to be the best result available in the literature. When the hybrid NACO-CGSA method is applied to SCUC problem, saving in cost is $14.95. Also, it is observed that for thermal integrated wind power system, the percentage decrease of the cost saving by the wind power is greater than the increase in the added cost from the additional reserves and increase in losses which is confirmed from the numerical results using NACO-CGSA approach. Therefore, the proposed hybrid NACO-CGSA approach can be used efficiently in the load dispatch centers.

List of Symbols

AvgC- Average minimum cost($) obtained in 10 simulations

$BF_{i,t}$ - flow through branch *i* at time *t* (MVA)

BF_i^{max}- Maximum flow limits for branch *i* (MVA)

C_i- Production cost ($)

$$C_i(P_{(i,t)}) = a + b * P_{(i,t)} + c * P_{(i,t)}^2$$

a-Cost co-efficient of i^{th} generator unit ($/hr)

b-Cost co-efficient of i^{th} generator unit ($/MWhr)

c-Cost co-efficient of i^{th} generator unit ($/MW^{2}hr)

D_t- Total system demand at time *t*

DR(i)- Ramp-down rate limit of i^{th} generator unit

Fit_p - Fitness value of the solution *p*

G_{IJ},B_{ij} - Conductance and susceptance between bus *i* and bus *j*

$I_{i,t}$ - Commitment state of i^{th}unit at t^{th} hour

L_{gb} - Maximum total profit incurred till the current tour

Maxit - Maximum number of iterations

n- Number of units in each node

N- Total number of generating units

N_{ants} - Total number of ants

N_B - Number of busses

N_{B-1} - Number of busses excluding slack bus

N_{PQ} - Number of *PQ* buses

$P_{(i,t)}$- Power level of i^{th} generator unit at t^{th} hour (MW)

$P_{Gi,t}$,$Q_{Gi,t}$-Active and reactive power generation at bus *i* ,time *t*

$P_{Di,t}$,$Q_{Di,t}$ - Active and reactive power demand at bus *i* at time *t*

$P_{i,min}$, $P_{i,max}$ – Minimum and Maximum power output of i^{th} generator unit (MW)

Q_{Gi}^{min},Q_{Gi}^{max}- Minimum and maximum reactive power generation limit for unit *i*

SU_i^t,SD_i^t - Start up cost and shut down cost of unit *i* at time *t*

SR_t - Total system spinning reserve at time *t*

TS - Total number of stages

T^{on}(i) - Minimum up-time of i^{th} generator unit

T^{off} (i) - Minimum down-time of i^{th} generator unit

T- Dispatch period in hours

TC - Total cost ($)

UR(i)- Ramp-up rate limit of i^{th} generator unit

$V_{i,t}$ - Voltage magnitude of bus *i* at time *t* (pu)
V_{pq} - Modified position of employed or onlooker bees
- Minimum and maximum voltage magnitude limit at bus *i* (pu)
$X^{on}(i,t)$,$X^{off}(i,t)$- "ON" and "OFF" duration of i^{th} generator unit α- Relative importance pheromone trail intensity
β- Relative importance of heuristic function
P- Evaporation factor
τ_{rs} (st)- Pheromone trail intensity of stage (st) r to s
η_{rs} (st)- Heuristic function of stage (st) r to s
$\Delta\tau_{rs}$ - The updating co-efficient
I,t - Index for generator unit and time

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