A New Hybrid Heuristic Technique for Unit Commitment and Generation Scheduling

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Abstract:

This paper proposes a novel technique for solving generation scheduling and ramp rate constrained unit commitment. A modified objective function associated with a new start-up cost term is introduced in this paper. The proposed method is used to solve generating scheduling problem satisfying SRR, minimum up and down time as well as ramp rate constraints. Two case studies are conducted to implement and show the effectiveness of the proposed method. One is a conventional 10-unit system and its multiples while the other is a 26-unit system with 24-h scheduling horizon. A comparison between the results of the proposed technique with those of some methods demonstrates a significant improvement.

Keywords: Unit commitment, Generation scheduling, Spinning reserve, Economic dispatch, Metahuristic.

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1. Introduction

Fast growing load in power systems associated with a large gap between heavy load and light load periods, generating scheduling and unit commitment problem has become a crucial issue in operation time horizon [1]. In a vertically integrated power system the unit commitment determines when to start-up or shut-down units and how to dispatch online generators over a given scheduling horizon in order to minimize the operating costs, satisfying the forecasted load considering operating constraints. These constraints are: generation limits, system spinning reserve requirement (SRR), ramp rate limits and minimum up and down time limits [1-6].
Since unit commitment is a highly non-linear, non-convex in a form of mixed-integer problem, in literature lots of solution techniques have been proposed. Exhaustive enumeration that gives an exact optimal solution but it is time consuming, while priority list may have a fast solution that sometimes lead to a non-optima [7]. Dynamic programming (DP) is a well-known solution technique for unit commitment problem that needs more computational efforts [8]. Lagrangian relaxation (LR) technique is a suitable method for large-scale power systems in which both demand and SRR can be satisfied through lagrangian multipliers. An inappropriate method for updating lagrangian multipliers may cause a non optimal solution [9, 10]. In some studies the researchers has been used decommitment method, this method is work such that a unit with highest relative cost will be decommitted at a time until there is no excessive spinning reserve or minimum up time or ramp down rate constraints prevent the rest of units from decommitting [11, 12]. Application of heuristic optimization algorithms may have some advantages to solve such a complicated optimization problem, while the main drawback of heuristic methods is that they cannot guarantee the optimal solution [13]. Recently, some metaheuristic methods have been addressed like genetic algorithm (GA), ant colony (AC), tabu search (TS) as well as simulated annealing (SA) [14-18]. Since there exist a need for more improvement to the existing unit commitment solution techniques the hybrid models such as fuzzy dynamic programming [19], genetic based neural network [20], hybrid model between lagrangian relaxation and genetic algorithm [21], and annealing genetic algorithm [22] are experienced.
This paper presents a new method considering the next hours demand by minimizing the operating costs. The benefit of considering next hours demand can be facilitated for online units in the time horizon that is not optimal to be turned off. On the other hand, in the new formulation of unit commitment, generating units with higher start-up cost may have a chance to be turned on in order to minimize total scheduling horizon costs. Exactly the contributions of this paper are: 1- modifying the objective function that will be used in GA and 2- considering the next T_{off} hours of a unit that just has been off.
This paper is organized as follows: Section II presents unit commitment mathematical formulation. In section III the problem is decomposed to different stages.. Section IV presents case studies and results analysis, while finally concluding remarks are driven in section V.

2. Problem Formulation

Unit commitment involves determining generation outputs of all units from an initial hour to satisfy load demands associated with a start-up and shut-down schedule over a time horizon. The objective is to find the optimal schedule such that the total operating costs can be minimized while satisfying the load demand, SRR as well as other operational constraint.

2.1. Objective Function

The objective function of a unit commitment problem is a function that comprises the fuel costs of generating units, the start-up cost of the committed units and shut-down cost of decommitted units. The start-up cost is available in two common forms: exponentially and constant. Moreover start-up cost is presented in two forms: hot start-up cost and cold start-up cost, while the shut-down cost is assumed to be fixed. Nevertheless the objective function of UC problem is formulated as:

$$\begin{aligned} Minimize \quad & \{ \sum_{t=1}^{T} \sum_{i=1}^{N} F_{i,t}(p_{it}) * u_{i,t} \\ & + \sum_{t=1}^{T} \sum_{i=1}^{N} SUC_{i,t} * u_{i,t} * (1 - u_{i,t-1}) \\ & + \sum_{t=1}^{T} \sum_{i=1}^{N} SDC_{i,t} * u_{i,t-1} * (1 - u_{i,t}) \} \end{aligned} \quad (1)$$

Fuel costs of generating units and the major component of the operating costs for thermal units, is generally given in a quadratic form as it is shown in Eq. (2). Operating cost coefficients can be given or they estimated using bidding strategies [23, 24].

$$F_{it}(P_{it}) = a_i + b_i P_{i,t} + c_i (P_{i,t})^2 \quad (2)$$

Start-up cost is defined as follow:

$$SUC_{i,t} = \begin{cases} HSC_i, & if \ T_{i,t}^{D} \leq MD_i^{ON} \leq T_{i,t}^{D} + CST_i \\ CSC_i, & if \ MD_i^{ON} > T_{i,t}^{D} + CST_i \end{cases} \quad (3)$$

$$or$$

$$SUC_{i,t} = \alpha_i + \beta_i [1 - e^{MD_i^{OFF}(t)/\tau_i}]$$

2.2. Constraints

Minimization of the objective function is subjected to a number of system and unit constraints such as: power balance, spinning reserve capacity of generating units, unit ramp-up rate and unit ramp-down rate constraints, minimum up/down time limit as well as SRR. Initial condition needed to be considered in scheduling problem.

2.2.1. Initial Conditions

Initial conditions of generating units include number of hours that a unit consequently has been on-line or off-line and its generation output at an hour before the scheduling will be started.

2.2.2. Power balance constraints

Real power generated must be sufficient to meet the load demand which is hard as an equality constraint. This constraint is given by Eq. (4)

$$\sum_{i=1}^{N} (P_{i,t}) * u_{i,t} = D_t \quad 1 \le t \le T \;, i \in N \qquad (4)$$

2.2.3. Unit output limits

The real power output of unit i at hour t can be varied within the range of unit power outputs due to unit ramp rate constraints.

$$P_{i,t}^{\min} * u_{i,t} \le P_{i,t}^{o} * u_{i,t} \le P_{i,t}^{\max} * u_{i,t} \qquad (5)$$
$$1 \le t \le T \;, i \in N$$

2.2.4. Unit ramp-up constraints

According to Eq. (5) real power output must be less than P_i^{max} and the unit output at hour t cannot be more than the unit output at hour t-1 plus ramp-up rate. $P_{i,t}^{min}$ can be given by Eq. (6).

$$P_{i,t}^{\max} = Min\{P_{i,t-1}^{o} + RUR_i , P_i^{\max}\} \qquad (6)$$
$$1 \le t \le T \;, i \in N$$

2.2.5. Unit ramp-down constraints

According to Eq.(5) real power output must be more than P_i^{min} and the unit output at hour t cannot be less than the unit output at hour t-1 minus ramp-down rate. $P_{i,t}^{min}$ can be given by Eq. (7).

$$P_{it}^{\min} = Max\{P_{i,t-1}^{o} - RDR_i , P_i^{\min}\} \qquad (7)$$
$$1 \le t \le T \;, i \in N$$

2.2.6. Minimum up time limit

Minimum number of hours that a unit must be on-line since it has been turned on.

$$MU_i^{ON} \ge T_i^{U} \qquad (8)$$

2.2.7. Minimum down time limit

Minimum number of hours that a unit must be off-line since it has been turned off.

$$MD_i^{OFF} \ge T_i^{D} \qquad (9)$$

2.2.8. Spinning reserve requirement

Spinning reserve is the total amount of real power generation available from all synchronized units minus the present load plus the losses. SRR is usually a pre-specified amount or equal to the largest unit or a given percentage of the forecasted load demand. It must be sufficient enough to maintain the desired reliability in a power system that is shown by Eq. (10).

$$\sum_{i=1}^{N} (P_{i,t}^{\max} * u_{i,t}) - D_t = SRC_t \qquad (10)$$
$$1 \le t \le T, \, i \in N$$

3. Optimization Method

The proposed optimization method consists of six stages that are shown in Fig. 1. In each stage some of constraints are taken into consideration and in stage 6, the objective function is minimized via genetic algorithm (GA). These six stages are explained in details as follows.

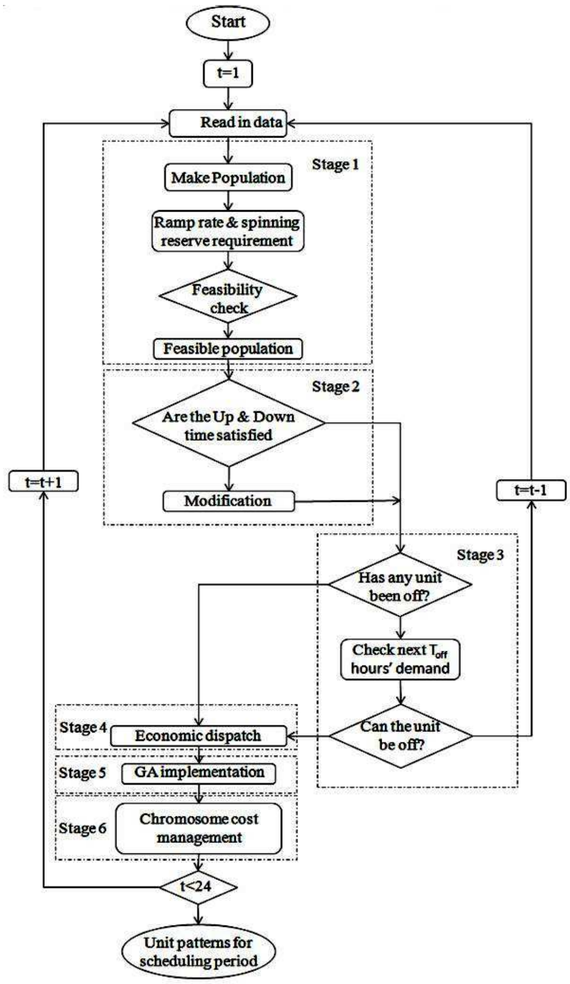

Figure 1. Flowchart of the proposed optimization method

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3.1. Ramp Rate & Spinning Reserve Requirement

This stage considers two main constraints such as SRR and unit ramp rate constraint. In order to generate an initial feasible population only those chromosomes that can satisfy the SRR constraint will be selected while ramp rate constraint is taken into consideration afterwards. As it is known, ramp rate constraints may impose the upper and lower bounds of the output of generating units in conjunction with their outputs at previous hour. It can be said that, at this stage both ramp rate and spinning reserve constraints should be satisfied.

3.2. Up time & Down time Satisfaction

In this stage minimum up time (MUT) and minimum down time (MDT) constraints are taken into consideration. Only the status of those units that can satisfy MUT/ MDT constraints may be changed, while the status of other units kept constant. In this regard, there would not be any problem if a unit is turned on but when a unit is turned off the feasible solution may not be achieved. In the later case, feasibility must be checked and when it is not feasible a modified chromosome that can satisfy the MDT constraint is needed to be generated.

3.3. Next T_i^D Hours Checking

After satisfying some constraints like spinning reserve, ramp rate, minimum up time and minimum down time, the demands of next T_i^D hours are taken into account, if any unit that is required to be turned off. When a unit became off, its status cannot be changed for T_i^D hours, then the feasibility of satisfying the next T_i^D hours load demand without including this unit will be checked. If the condition is not feasible for one of the next T_i^D hours the time of scheduling get back to the previous hour and the scheduling of this hour is done again in which the later unit is kept online. This process guarantees the scheduling of unit commitment at all hours during the time horizon.

3.4. Economic Dispatch

Unit commitment and economic dispatch, when combined together, is a useful tool to find the most economical generation schedule. The economic dispatch determines the output of all online units with an objective of a minimum total operating cost at a given hour, which is subjected to the power balance constraint Eq. (4) and output limits Eq. (5). A lambda iteration method is applied in this paper to determine the optimal unit commitment and economic dispatch.

3.5. GA Implementation

By determining the output of all online units economically the fitness of all chromosomes should be calculated and the best chromosomes will be selected. Since in scheduling problems the objective is to minimize the cost function Eq. (1), the units with more expensive start-up costs have no chance to be turned on before they must be, while they may cause less total operation costs. In this paper a modified objective function is defined in order to select the best chromosomes for crossover and mutation to generate new chromosomes and finally get a better generation scheduling. After crossover and mutation processes for achieving feasible chromosomes two following task will be handled.

3.5.1. Chromosomes elimination:

Infeasible chromosomes that can not satisfy the SRR constraint will be eliminated as redundant.

3.5.2. Chromosome modification:

Since the number of chromosomes must be remained constant, chromosomes with the best fitness are replaced instead of eliminated chromosomes.

In order to accelerate the convergence of the proposed method the fitness function is adopted as follows:

$$adopted \quad fitness \quad function = \frac{A}{1 + Cost\ (chr\ , itr\ )}$$

where, A is a big positive number (assumed 1E+4), *chr* and *itr* are chromosomes and iteration counter respectively.

A modified objective function is shown by Eq. (12, 13).

$$Min \sum_{t=1}^{T} \sum_{i=1}^{N} F_{i,t}(p_{i,t}) * u_{i,t} + SUC_{i,t} * u_{i,t} * (1 - u_{i,t-1})\} \quad (12)$$

where,

$$SUC_{i,t} = \begin{cases} CSC_{i,t} & if \quad MD_i^{OFF} > T_i^D + CST_{i,t} \\ (1+\frac{MD_i^{OFF}}{T_i^D + CST_{i,t}})HSC & if \quad T_i^D \le MD_i^{OFF} \le T_i^D + CST_{i,t} \end{cases} \quad (13)$$

At this paper the cold start-up cost (CSC) is twice of hot start-up cost (HSC).

3.6. Chromosome Cost Management

In this stage the chromosome with the least cost is selected and the scheduling of current hour according to the latest selected chromosome is implemented.

By using Eq.(12) as a new objective function associated with the same constraints Eq. (2-10) the unit status will be determined while the operating costs of units will be calculated using the objective function expressed by Eq.(1).

4. CASE STUDIES & RESULTS ANALYSIS

In this section two case studies are presented, where case 1 is a commonly used unit commitment problem based on ten-unit test system and case 2 is a 26-unit for considering ramp rate constraints.

Table 1. Load demand of 10-unit base problem

hour	1	2	3	4	5	6	7	8	9	10	11	12
load	700	750	850	950	1000	1100	1150	1200	1300	1400	1450	1500
hour	13	14	15	16	17	18	19	20	21	22	23	24
load	1400	1300	1200	1050	1000	1100	1200	1400	1300	1100	900	800

Table 2. Comparison of total production cost for 10-unit based system

Total cost of different methods							
Methods / No. of units	SPL[26] [26]	EP[27] [27]	PSO[28] [28]	BPSO[29] [29]	PSO-LR[30] [30]	LR[30] [30]	LRGA[31] [31]
10	564950	565352	574153	565804	565869	566107	564800
20	1123938	1127256	1125983	–	1128072	1128362	1122622
40	2248645	2252612	2250012	–	2251116	2250223	2242178
60	3371178	3376255	3374174	–	3376407	3374994	3371079
80	4492909	4505536	4501538	–	4496717	4496729	4501844
100	5615530	5633800	5625376	–	5623607	5620305	5613127
Total cost of different methods							
Methods / No. of units	ALR[32] [32]	GA[15] [15]	BCGA[33] [33]	ICGA[33] [33]	DP[15] [15]	MA[34] [34]	PM
10	565508	565825	567367	566404	565825	565827	564703
20	1126720	1126243	1130291	1127244	–	1128192	1125998
40	2249790	2251911	2256590	2254123	–	2249589	2247026
60	3371188	3376625	3382913	3378108	–	3370820	3369508
80	4494487	4504933	4511438	4498943	–	4494214	4490013
100	5615893	5627437	5637930	5630838	–	5616314	5616096

Table 3. Comparison of CPU time for 10-unit based system

Total cost of different methods							
Methods / No. of units	SPL[26] [26]	EP[27] [27]	PSO[28] [28]	BPSO[29] [29]	PSO-LR[30] [30]	LR[30] [30]	LRGA[31] [31]
10	7.24	100	-	-	42	257	518
20	16.32	340	-	-	91	514	1147
40	46.32	1176	-	-	213	1066	2165
60	113.85	2267	-	-	360	1594	2414
80	215.77	3584	-	-	543	2122	3383
100	374.03	6120	-	-	730	2978	4045
Total cost of different methods							
Methods / No. of units	ALR[32] [32]	GA[15] [15]	BCGA[33] [33]	ICGA[33] [33]	DP[15] [15]	MA[34] [34]	PM
10	3.2	221	3.7	7.4	-	290	12.62
20	12	733	15.9	22.4	-	538	41.8
40	34	2697	63.1	58.3	-	1032	78
60	67	5840	137	117.3	-	2740	157
80	111	10036	257	176	-	3159	233
100	167	15733	397	242.5	-	6365	418

4.1. 10–unit based system

The proposed method has been applied to solve a commonly used 10-unit based system that can be extended to a group of unit commitment problems. At first the proposed method apply to a 10-unit base system and then to 20-unit, 40-unit, 60-unit, 80 unit and 100-unit respectively [25]. The spinning reserve in this problem held as 10% of the load demand at each hour. The load demand of 10-unit base problem is illustrated in Table 1. The results of the total costs by implementing the proposed technique to different cases for 24-h is shown in Table 2. This table includes a comparison between the outcomes of the proposed technique and other methods. Table 4 presents the 24-h generating 10-unit outputs. The characteristic and cost coefficients of 10-unit problem are shown in Table 5. For 10-unit system 70 chromosomes with 100 iterations are used while the probability of crossover and mutation are assumed to be 0.9 and 0.002, respectively. With a comparison of the obtained results shown in Table 2**Error! Reference source not found.**, it can be seen that PM may create a better outcomes than the other methods.

Table 4. Units output power for 10-unit system

U \ H	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455
2	245	295	370	455	455	455	455	430	455	455	455	455	455	455	455	315	260	360	455	455	455	455	425	344
3	0	0	0	0	0	0	0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	0	0	0
4	0	0	0	0	0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	0	0	0
5	0	0	25	40	70	40	90	25	85	162	162	162	162	85	30	25	25	25	30	162	85	145	0	0
6	0	0	0	0	20	20	20	20	20	33	68	80	33	20	0	0	0	0	0	33	20	20	20	0
7	0	0	0	0	0	0	0	0	25	25	25	25	25	25	0	0	0	0	0	25	25	25	0	0
8	0	0	0	0	0	0	0	0	0	10	10	43	10	0	0	0	0	0	0	10	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	10	10	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0

Table 5. Unit characteristic and cost coefficients for 10-unit based system

Unit No	P_{max}	P_{min}	a	b	C	T^U	T^D	HSC	CSC	CST	Init condition
1	455	150	1000	16.19	0.00048	8	8	9000	4500	5	8
2	455	150	970	17.26	0.00031	8	8	10000	5000	5	8
3	130	20	700	16.6	0.002	5	5	1100	550	4	-5
4	130	20	680	16.5	0.00211	5	5	1120	560	4	-5
5	162	25	450	19.7	0.00398	6	6	1800	900	4	-6
6	80	20	370	22.26	0.00712	3	3	340	170	2	-3
7	85	25	480	27.74	0.00079	3	3	520	260	2	-3
8	55	10	660	25.92	0.00413	1	1	60	30	0	-1
9	55	10	665	27.27	0.00222	1	1	60	30	0	-1
10	55	10	670	27.79	0.00173	1	1	60	30	0	-1

4.2. 26- unit system

In this section a 26 thermal units from IEEE RTS [35] is studied. For 26-unit system, 15-min spinning reserve response time is assumed for all units. Spinning reserve is calculated based upon the unit reserve contribution within 15 min, which is set to 4% of the total load demand [5]. Two different load demands that are employed, is shown in Table 6, while Table 7 presents the characteristic and cost coefficient of 26-unit system. Table 8 shows a comparison between the derived results from the proposed method (PM) and the other methods from literature [36- 37], for both loads.

Table 6. Load demand for 26-unit system

Hourly load demand												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Load 1	1700	1730	1690	1700	1750	1850	2000	2430	2540	2600	2600	2590
Load 2	1430	1450	1400	1350	1350	1470						
Hourly load demand												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Load 1	2590	2550	2620	2650	2550	2530	2500	2550	2600	2480	2200	1840
Load 2	2290	2260	2190	2130	2190	2200	2300	2340	2300	2180	1910	1650

For example units output for satisfying load 1 is presented in Table 9. For 26-units system, 130 chromosomes with 150 iterations are used while the probability of crossover and mutation are 0.9 and 0.002, respectively. With a comparison of the obtained results shown in Table 8, it can be seen that PM may create a better outcomes than the other methods. Also it can be seen that the PM make 7799.8$ (1.08%) and 2869.3$ (0.5%) saving in comparison with best results from literature for the first and second load pattern respectively.

Table 7. Unit characteristic and cost coefficients for 26-unit system

Unit	*Pmin*	*Pmax*	a_i	b_i	c_i	T^U	T^D	RUR	RDR	Init condition
1	2.4	12	24.3891	25.5472	0.02533	0	0	48	60	-1
2	2.4	12	24.4110	25.6753	0.02649	0	0	48	60	-1
3	2.4	12	24.6382	25.8027	0.02801	0	0	48	60	-1
4	2.4	12	24.7605	25.9318	0.02842	0	0	48	60	-1
5	2.4	12	24.8882	26.0611	0.02855	0	0	48	60	-1
6	4	20	117.7551	37.5510	0.01199	0	0	30.5	70	-1
7	4	20	118.1083	37.6637	0.01261	0	0	30.5	70	-1
8	4	20	118.4576	37.8896	0.01359	0	0	30.5	70	-1
9	4	20	118.8206	13.8896	0.01433	0	0	30.5	70	-1
10	15.2	76	81.1364	13.3272	0.00876	3	2	38.5	80	3
11	15.2	76	81.2980	13.3538	0.00895	3	2	38.5	80	3
12	15.2	76	81.4641	13.3805	0.00910	3	2	38.5	80	3
13	15.2	76	81.6259	13.4073	0.00932	3	2	38.5	80	3
14	25	100	217.8952	18.0000	0.00623	4	2	51	74	-3
15	25	100	218.3350	18.1000	0.00612	4	2	51	74	-3
16	25	100	218.7752	18.2000	0.00598	4	2	51	74	-3
17	54.25	155	142.7348	10.6940	0.00463	5	3	55	78	5
18	54.25	155	143.0288	10.7154	0.00473	5	3	55	78	5
19	54.25	155	143.3179	10.7367	0.00481	5	3	55	78	5
20	54.25	155	143.5972	10.7583	0.00487	5	3	55	78	5
21	68.95	197	259.1310	23.0000	0.00259	5	4	55	99	-4
22	68.95	197	259.6490	23.1000	0.00260	5	4	55	99	-4
23	68.95	197	260.1760	23.2000	0.00263	5	4	55	99	-4
24	140	350	177.0575	10.8616	0.00153	8	5	70	120	10
25	100	400	310.0021	7.4921	0.00194	8	5	50.5	100	10
26	100	400	311.9102	7.5031	0.00195	8	5	50.5	100	10

Table 8. Comparison of total production costs for 26-unit system with 15 min SR response time

Load	Method	CPU time	Total cost
1	ILR [36]	161.5	720641.9
	IPL-ALH [5]	2.17	718642.1
	PM	109.21	710842.3
2	ILR [36]	122	576625.7
	IPL-ALH [5]	1.71	570116.5
	PM	103.97	567247.2

5. CONCLUSIONS

In this paper a reliable and efficient method using hybrid heuristic technique for unit commitment problem is presented. By introducing a new formulation for generating unit scheduling the performance of unit commitment may increase. On the other hand, by implementing the next T_i^D hours load checking may improve the reliability as well as the economics of scheduling problem in power systems. The proposed method is successfully applied to a 10-unit based system and a 26-unit system, while the significant results are compared with the other methods. The results for 26-unit system show the cost effectiveness technique that lead to saving cost and may also improve the reliability of power systems. The results also can prove the usefulness of the proposed method which is capable of solving both small-scale and large-scale power systems scheduling problem.

Table 9. Units output power of 26-unit system for load demand1

U \ H	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	0	0	2.4	0	0	0	0	0	0	2.4	0	0	2.4	0	0	2.4	2.4	2.4	0	0	2.4	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.4	2.4	2.4	2.4	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	2.4	0	0	2.4	2.4	2.4	2.4	2.4	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.4	0	2.4	2.4	0	2.4	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.4	0	2.4	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
10	15.2	15.2	15.2	0	0	28.67	55	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	0
11	0	0	0	0	15.2	26.6	52.4	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	74.89	0
12	0	0	0	0	0	24.7	50	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	72.19	0
13	15.2	15.2	15.2	0	0	0	47.45	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	69.04	0
14	0	0	0	0	0	0	25	76	100	100	100	100	100	100	100	100	100	100	100	100	100	94.97	0	0
15	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	88.51	0	0
16	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	82.22	0	0
17	136.9	144.62	134.35	144.1	153.67	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	145.26
18	131.76	139.3	129.2	138.8	148.16	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	139.94
19	127.35	134.77	124.88	134.28	143.48	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	135.39
20	123.56	130.89	121.12	130.41	139.49	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	131.5
21	0	0	0	0	0	0	0	0	92.79	88.1	117.7	78.1	78.1	102.251	130.461	111.791	152.1	142.41	118.81	95.851	0	0	0	0
22	0	0	0	0	0	0	0	80	73.2	68.95	98	68.95	68.95	0	110.7	92.13	0	0	0	0	122	68.95	68.95	68.95
23	0	0	0	0	0	0	0	0	0	68.95	77.88	68.95	68.95	68.95	0	72.07	0	0	0	68.95	101.6	68.95	68.95	68.95
24	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350
25	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
26	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400

NOMENCLATURE

a_i, b_i, a_i:	Fuel cost coefficients for unit *i*
$u_{i,t}$:	On or off status of unit *i* at hour *t*
$SUC_{i,t}$:	Start-up cost of unit *i* at hour *t*
$SDC_{i,t}$:	Shut-down cost of unit *i* at hour *t*
$P_{i,t}^{O}$:	Power output of unit *i* at hour *t*
HSC_i:	Hot start-up cost of unit *i*
CSC_i:	Cold start-up cost of unit *i*
$T_{i,t}^{U}$:	Minimum up-time of unit i
$T_{i,t}^{D}$:	Minimum down-time of unit *i*
MU_i^{ON}:	Duration during which the i^{th} unit is continuously on
MD_i^{OFF}:	Duration during which the i^{th} unit is continuously off
CST_i:	Cold start time of unit *i*
N:	Number of units
T:	Unit commitment horizon
τ_i:	Time constant in the start-up cost function for unit *i*
α_i, β_i:	Coefficient of start-up cost function
D_t:	Demand during hour *t*
R_t:	Reserve requirement during hour *t*
RUR_i:	Ramp up rate limit of unit *i*
RDR_i:	Ramp down rate limit of unit *i*

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