A Novel Straightforward Unit Commitment Method for Large-Scale Power Systems

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***Abstract*—In this paper, a novel fast straightforward method for thermal generating units scheduling is presented. The new method decomposes the solution of the unit commitment (UC) problem into three subproblems. In the first subproblem, the quadratic cost functions of units are linearized and hourly optimum solution of UC is obtained considering all constraints except the minimum up/down time constraints. In the second subproblem, the minimum up/down times are enforced through a novel optimization process by modifying the schedule obtained in the first step. Finally, in the third subproblem, the extra reserve is minimized using a new decommitment algorithm.**

For testing the proposed method, the conventional ten-unit test system and its multiples with 24-h scheduling horizon have been solved. Comparison of results with those of other methods justifies the effectiveness of the proposed method with regards to minimizing both the total operation cost and execution time. Also, the IEEE 118-bus system with 54 units and a practical large-scale system including 358 units have been analyzed to exhibit the superiority of the proposed approach.

***Index Terms*—Power generation scheduling, thermal power generation, unit commitment.**

NOMENCLATURE

A_j	Coefficient of the piecewise linear production cost function of unit j.
a_j, b_j, c_j	Coefficients of the quadratic production cost function of unit j.
cc_j,hc_j,t_j^{cold}	Coefficients of the startup cost function of unit j.
$c_j^d(k)$	Shutdown cost of unit j in period k.
$c_j^p(k)$	Production cost of unit j in period k.
$c_j^u(k)$	Startup cost of unit j in period k.
$c_j^A(k)$	Additional cost of unit j in period k.
$D(k)$	System load demand in period k.
DT_j	Minimum down time of unit j.
G_j	Number of periods unit j must be initially on due to its minimum up time constraint.
J	Set of indexes of the generating units.
j	Index of units.
K	Set of indexes of the time periods.
k	Index of time periods.
L_j	Number of periods unit j must be initially off due to its minimum down time constraint.
NL_j	Number of segments of the piecewise linear production cost function of unit j.
$p_j(k)$	Generation of unit j.
$\overline{P_j}$	Upper limit of real power generation of unit j.
$\underline{P_j}$	Lower limit of real power generation of unit j.
$\overline{p_j}(k)$	Maximum available output power of unit j in period k.
$\underline{p_j}(k)$	Minimum available output power of unit j in period k.
$R(k)$	Spinning reserve requirements.
RD_j	Ramp-down rate limit of unit j.
RU_j	Ramp-up rate limit of unit j.
$S_j(0)$	Number of periods unit j has been off prior to the first period of the time span.
T	Number of periods of the time span.
$t_j^{off}(k)$	Continuous offline period of unit j in period k.
$t_j^{on}(k)$	Continuous online period of unit j in period k.
T_{jl}	Upper limit of block l of the piecewise linear production cost function of unit j.
UT_j	Minimum up time of unit j.
U_j^0	Number of periods unit j has been on prior to the first period of the time span.
$u_j(k)$	Commitment state of unit j in period k for unit-based subproblem.
$V_j(0)$	Initial commitment state of unit j.
$v_j(k)$	Commitment state of unit j in period k for hour-based subproblem.
w_j	Auxiliary binary variable of unit j in reserve-based subproblem.

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λ_{jl} Slope of block l of the piecewise linear production cost function of unit j.

$\lambda^{max}(k)$ Maximum slope related to the last committed segment in period k.

$\delta_l(j,k)$ Power produced in block l of the piecewise linear production cost function of unit j in period k.

I. Introduction

THE competition has become more furious in the global electric power market, forcing electric utility companies to pay more attention to how to better schedule the electric power systems in order to better satisfy customer demands [1], [2]. Generally speaking, unit commitment (UC) algorithms provide the generators commitment schedule, an integer programming problem and generators production levels (economic dispatch), a nonlinear programming problem [2]–[4]. Therefore, the unit commitment problem can be modeled as a large-scale, nonlinear, mixed-integer problem with complex constraints.

The thermal unit commitment problem has been traditionally solved in centralized power systems to determine when to startup or shutdown thermal generating units and how to dispatch online generators to meet system demand and spinning reserve requirements while satisfying generation constraints (production limits, ramping limits, and minimum up/down times) over a specific short-term time span, so that the overall operation cost is minimized [1].

The generation scheduling problems solved by the independent system operator (ISO) in current electricity markets [5] are similar to the unit commitment problem in the centralized noncompetitive power systems, as promoted by FERC's Standard Market Design [6]. Sometimes, rather than minimizing operation costs, the ISO maximizes a measure of social welfare, which is a function of market participants' bids and offers. Nevertheless, different traditional, centralized unit commitment methods, more or less, can be used for the competitive power industry.

Optimizing the UC solution is a challenging task [1], [7]. The solution may be obtained by enumerating all the feasible solutions which is often constrained by the combinatorial explosion and problem dimensions. The optimal solutions to the UC problems can save millions of dollars to the electric power companies. Therefore, in the past 30 years, much efforts have been devoted for developing more efficient, near-optimal solving methods that can be adopted to the large-scale power systems [7], [8].

The UC solving methods can be classified into nine categories: priority list method (PL), dynamic programming method (DP), integer and mixed-integer programming method (IP/MIP), linear programming method (LP), branch and bound method (BB), Benders decomposition method (BD), Lagrangian relaxation method (LR), interior point optimization (IPO), and the soft-computation or computationally intelligent methods, such as simulated annealing (SA), artificial neural network (ANN), expert system (ES), fuzzy mathematics (FM), and various algorithms of evolutionary computation.

In this paper, we focus on a new fast straightforward (SF) technique to solve the UC problem. The UC problem is decomposed into three subproblems. The quadratic cost functions of generating units are linearized as piecewise linear functions in the first subproblem. Then, the linearized cost functions are used to minimize the total production cost of units over the entire time span subject to satisfying hourly loads and spinning reserve requirements, units output limits and ramp-up/ramp-down rates constraints. This step is named the hour-based subproblem. In the second subproblem, the schedules obtained for different units in the first step are modified to include the minimum up/down time constraints. The proposed modifying method is so developed as to minimize the additional costs caused by rescheduling the units. This step is named the unit-based subproblem. In the third subproblem, some units are decommitted in order to minimize the difference between the scheduled reserve and the required reserve. This step is named the reserve-based subproblem.

The SF technique is applied to the widely used ten-unit test system and its multiples. Comparing our results with those of many UC solving methods presented in relevant publications reveals that the SF method is a more effective technique among the various methods from both the operation cost and execution time aspects. Therefore, this technique is much more efficient for applying to practical large-scale power systems generation scheduling. Also, the IEEE 118-bus system and a practical large-scale system consisting of 358 units are solved by SF approach and the results are presented.

This paper is organized as follows: Section II formulates the UC problem. Section III mainly elaborates on the proposed approach and decomposes the problem into hour-based, unit-based, and reserve-based subproblems. Also, the appropriate formulation of the decomposed subproblems is presented in this section. Section IV conducts the numerical simulations and presents comparison among various UC solving methods. Finally, concluding remarks are discussed as well in Section V.

II. Problem Formulation

In electric power systems, the unit commitment scheduling mainly determines the on/off pattern and generation output of all units from an initial status to meet load demands in a given time horizon. The objective is to find an optimal unit commitment schedule which can minimize the total production cost while satisfying the load demand, spinning reserve requirement, and other operational constraints.

A. *Objective Function*

The objective function of a UC problem mainly comprises the fuel cost of generating units, the startup cost of committed units, and the shutdown cost of decommitted units. Thus, the UC problem can be formulated as

$$Minimize \quad \sum_{k\in K}\sum_{j\in J} c_j^p(k) + c_j^u(k) + c_j^d(k) \tag{1}$$

where $c_j^p(k)$ is the generation cost function of unit j ($/h) which is a quadratic polynomial function as follows:

$$c_j^p(k) = a_j v_j(k) + b_j p_j(k) + c_j p_j^2(k), \quad \forall j \in J, \forall k \in K. \tag{2}$$

The startup cost function is denoted by $c_j^u(k)$ and is defined as follows:

$$c_j^u(k) = \begin{cases} hc_j, & \text{if } t_j^{off}(k) \le t_j^{cold} + DT_j \\ cc_j, & \text{if } t_j^{off}(k) \ge t_j^{cold} + DT_j \end{cases} \quad \forall j \in J, \forall k \in K \tag{3}$$

and $c_j^d(k)$ is shutdown cost that is assumed to be constant.

B. Constraints

The UC problem is subjected to the following constraints:

1) Power balance constraints

$$\sum_{j\in J} p_j(k) = D(k), \quad \forall k \in K. \tag{4}$$

2) Spinning reserve constraints

$$\sum_{j\in J} \overline{p_j}(k) \ge D(k) + R(k), \quad \forall k \in K. \tag{5}$$

3) Unit output limits

$$\underline{P}_j v_j(k) \le p_j(k) \le \overline{P_j} v_j(k), \quad \forall j \in J, \forall k \in K. \tag{6}$$

4) Unit ramp-up constraints

$$p_j(k) \le \overline{p_j}(k), \quad \forall j \in J, \forall k \in K \tag{7}$$

$$\overline{p_j}(k) = Min\left\{p_j(k-1) + RU_j v_j(k-1), \overline{P_j}\right\}, \quad \forall j \in J, \forall k \in K \tag{8}$$

5) Unit ramp-down constraints

$$p_j(k) \ge \underline{p}_j(k), \quad \forall j \in J, \forall k \in K \tag{9}$$

$$\underline{p}_j(k) = Max\left\{p_j(k-1) - RD_j v_j(k-1), \underline{P}_j\right\}, \quad \forall j \in J, \forall k \in K. \tag{10}$$

6) Minimum up time limit

$$\left[t_j^{on}(k-1) - UT_j\right] \times [v_j(k-1) - v_j(k)] \ge 0 \tag{11}$$

$$\sum_{k=1}^{G_j} [1 - v_j(k)] = 0, \quad \forall j \in J \tag{12}$$

$$G_j = Min\left\{T, \left[UT_j - U_j^0\right] \times V_j(0)\right\}. \tag{13}$$

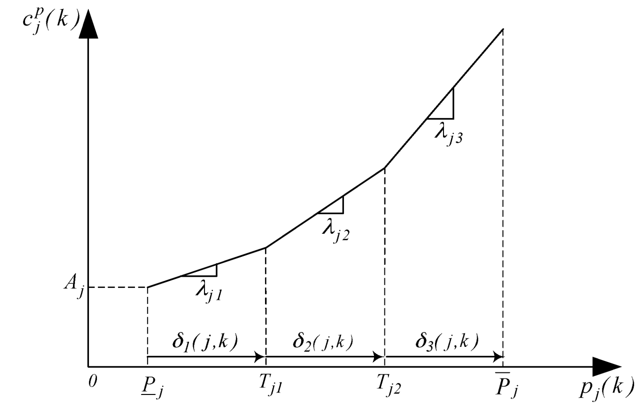

Fig. 1. Piecewise linear production cost.

7) Minimum down time limit

$$\left[t_j^{off}(k-1) - DT_j\right] \times [v_j(k) - v_j(k-1)] \ge 0 \tag{14}$$

$$\sum_{k=1}^{L_j} v_j(k) = 0, \quad \forall j \in J \tag{15}$$

$$L_j = Min\left\{T, [DT_j - S_j(0)] \times [1 - V_j(0)]\right\}. \tag{16}$$

III. Methodology

The SF approach consists of three subproblems or steps. In each subproblem, an object function is minimized subject to appropriate constraints. The details of these steps are explained below.

A. Hour-Based Subproblem

The hour-based subproblem is formulated as

$$Minimize \quad \sum_{j\in J} c_j^p(k) + c_j^u(k) + c_j^d(k), \quad \forall k \in K \tag{17}$$

subject to power balance (4), spinning reserve (5), units output limits (6), units ramp-up constraints (7), (8), and units ramp-down constraints (9), (10). To minimize the objective function, the generating units quadratic cost functions are approximated by piecewise linear segments as illustrated in Fig. 1. For all practical purposes, the piecewise linear function of Fig. 1 is indistinguishable from the nonlinear model if enough segments are used. The analytical representation of this linear approximation is given in the following[11]:

$$c_j^p(k) = A_j v_j(k) + \sum_{l=1}^{NL_j} \lambda_{jl}\delta_l(j,k), \quad \forall j \in J, \forall k \in K \tag{18}$$

$$p_j(k) = \sum_{l=1}^{NL_j} \delta_l(j,k) + \underline{P}_j v_j(k), \quad \forall j \in J, \forall k \in K \tag{19}$$

$$\delta_1(j,k) \leq T_{jl} - \underline{P}_j, \quad \forall j \in J, \forall k \in K \tag{20}$$

$$\delta_l(j,k) \leq T_{jl} - T_{j,l-1}, \quad \forall j \in J, \forall k \in K, \forall l = 2, \ldots, NL_j - 1 \tag{21}$$

$$\delta_{NL_j}(j,k) \leq \overline{P}_j - T_{j,NL_j-1}, \quad \forall j \in J, \forall k \in K \tag{22}$$

$$\delta_l(j,k) \geq 0, \ \forall j \in J, \forall k \in K, \forall l = 1, \ldots, NL_j \tag{23}$$

where $A_j = a_j + b_j\underline{P}_j + c_j\underline{P}_j^2$.

The minimization of object function is carried out for all time periods, and the optimum schedule of units at each time period is found. The only coupling link between two successive periods is ramp rate constraint. In this subproblem, it is not possible to encounter an infeasible solution because there are no restrictions for turning on or turning off units. Therefore, the maximum ramping capabilities of all units are available to follow the load variations.

Feasibility Check: In the unit-based subproblem, as will be discussed, we just have permission to turn on units to satisfy minimum up/down time constraints. Since this action for each unit would be independent of the other units, it is possible, in some specific time periods, to encounter a situation that constraint (4) cannot be satisfied. It means that the sum of minimum available power output of all online units exceeds the system load demand. To overcome such an infeasible situation, before passing the results of hour-based subproblem to the unit-based subproblem, a feasibility check is performed on them. This is a preventive action to ensure that the required adjustments for satisfying minimum up/down time constraints can be performed in the unit-based subproblem without encountering infeasible conditions.

In the feasibility check block, first for each time period, the committable and uncommittable units are determined based on the results of hour-based subproblem. To do this, units are sorted in the ascending order of number of ON periods over the entire time span. Thus, a unit with more ON states would have a higher order compared to others with less ON states.

The committable units in each time period, includes all of the units from top of the list that the sum of their minimum available power outputs does not exceed the system load demand at that time period. The remaining units in that time period are considered as uncommittable.

Any unit that in the hour-based subproblem is scheduled to be OFF in a particular time period but, is among the "committable units" of that time period, is allowed to be turned ON in order to eliminate minimum up/down time constraints violation of that unit, if there exists any.

For all units experiencing minimum up/down time constraints violations such that these violations cannot be eliminated by the idea of "committable units" explained above, their state in the violated time periods will be set to OFF. For each unit that its ON states are switched to OFF in some time periods, two cases regarding to constraint (5) may occur. In the first case, we assume constraint (5) is not violated in those time periods the unit is switched OFF. In such case, the hour-based subproblem is performed forcing the particular unit to be OFF in certain time periods. Since these fixed OFF states are uncommittable, they would not be considered in determining the "committable units" at the next iteration of feasibility check. In the second case, we assume turning OFF this unit violates constraint (5), which means there are not enough units to satisfy demand and reserve in those specific time periods. In this case, we move the corresponding unit to the top of the list of the sorted units and then continue with performing the feasibility check. Putting a unit at the top of the list ensures that this unit would be committable in the entire time span.

Once the solution of the hour-based subproblem passes the feasibility check, the committable units guarantee a feasible solution in the unit-based subproblem.

B. Unit-Based Subproblem

The output of hour-based subproblem gives the optimal solution to the UC problem, ignoring the units minimum up/down time constraints, in the form of an on/off (one/zero) pattern for each unit over the entire time span. Thus, any deviation from this pattern imposes additional cost. In this paper, the on/off pattern of all units violating minimum up/down time constraints is modified using a novel approach. Note that the output results of hour-based subproblem have already passed the feasibility check to avoid encountering infeasible solution in this subproblem.

The unit-based subproblem starts by analyzing the on/off pattern of each unit obtained in the hour-based subproblem for unit minimum up/down time violations. To overcome such violations, if any, all possible feasible patterns resulting from turning on the violating units are compared in order to find a new on/off pattern that imposes the least additional costs due to unit rescheduling. In generating feasible patterns, only the "committable units" are considered. The additional costs are defined as follows.

1) *Additional cost imposed by committing a unit*: when the state of uncommitted unit j in period k changes from zero to one, its output power is set to $\underline{P}_j$. This power must be subtracted from the output of other online units to hold the power balance constraint (4) satisfied. The added cost due to this change is A_j and the reduced cost is $\lambda^{max}(k)\underline{P}_j$, where $\lambda^{max}(k)$ is the largest incremental cost in period k according to

$$\lambda^{max}(k) = Max\left(\lambda_{jl}v_j(k)\right), \quad \forall j \in J \tag{24}$$

where index l includes the committed segments of piecewise linear production cost function of each unit.

Thus, the additional cost imposed by committing unit j in period k is as follows:

$$A_j - \lambda^{max}(k)\underline{P}_j. \tag{25}$$

It should be noted that the value of $\lambda^{max}(k)$ is assumed to be constant in each period in spite of units rescheduling.

2) *Startup and shutdown costs*: by changing the on/off status of units, the number of startups and shutdowns and also their types (hot or cold) will change. These costs are as follows:

$$u_j(k)\left[1-u_j(k-1)\right]c_j^u - v_j(k)\left[1-v_j(k-1)\right]c_j^u + u_j(k-1)\left[1-u_j(k)\right]c_j^d - v_j(k-1)\left[1-v_j(k)\right]c_j^d. \quad (26)$$

In this expression, $v_j(k)$ is state of unit j obtained from subproblem one and $u_j(k)$ is the state of unit j in new considered pattern.

Since the first term in (26) is startup cost of the new pattern (for unit j in period k), previously startup cost obtained from hour-based subproblem should be eliminated. This is done by the second term. Similarly, the third term in (26) is shutdown cost of the new pattern and the forth term eliminates shutdown cost obtained in the first subproblem.

The summation of two aforementioned additional costs forms the unit-based objective function and it must be minimized as much as possible. The unit-based subproblem is developed as follows:

$$Minimize \quad \sum_{k\in K} c_j^A(k) \quad (27)$$

where

$$c_j^A(k)=u_j(k)[1-v_j(k)]\left[A_j-\lambda^{max}(k)\underline{P}_j\right] + u_j(k)[1-u_j(k-1)]\,c_j^u - v_j(k)[1-v_j(k-1)]\,c_j^u + u_j(k-1)[1-u_j(k)]\,c_j^d - v_j(k-1)[1-v_j(k)]\,c_j^d. \quad (28)$$

After determining the pattern with minimum additional costs, the power dispatches of online units must be determined in periods that unit j is committed by second subproblem. In such periods, since the unit j is set to $\underline{P}_j$, therefore this amount of power must be subtracted from outputs of other online units. For this purpose, the output of unit with the largest incremental cost is reduced by $\underline{P}_j$. If the minimum available output power of this unit obstructs this reduction, the output of this unit is set to this value and the output of next unit with the largest incremental cost is reduced. This process is continued until the total reduction reaches $\underline{P}_j$. At the end of this subproblem, variables $u_j(k)$ are representative of unit states. It is recognized that only the violating units are involved in the unit-based subproblem. Therefore, for the remaining units, $u_j(k)$ will be equal to $v_j(k)$.

C. Reserve-Based Subproblem

In this subproblem, we consider the time periods having a large amount of excess reserve. At these periods, we search for units that can be turned off, whereas satisfying problem constraints. To do this, the following reserve objective function is defined:

$$c^r(k) = \sum_{j\in J}\left[w_j - u_j(k)\right], \quad \forall k \in K. \quad (29)$$

In (29), $u_j(k)$ is state of unit j obtained from subproblem two and w_j is an auxiliary binary variable that can be either one or zero. After reduction of extra reserve at time period k, the values of $u_j(k)$ are replaced by the values of w_j. This process is consecutively performed from first to the end of time span.

The reserve-based subproblem is as follows:

$$Minimize\ c^r(k), \quad \forall k \in K \quad (30)$$

subject to

$$\sum_{j\in J}\overline{p_j}w_j - D(k) - R(k) \geq 0, \quad \forall k \in K \quad (31)$$

$$[1-w_j]u_j(k-1)u_j(k)u_j(k+1) = 0, \quad \forall k \in K \quad (32)$$

$$u_j(k+1)\sum_{n=1}^{UT_j}[1-u_j(k+n)] + u_j(k-1)\sum_{n=1}^{UT_j}[1-u_j(k-n)] = 0, \quad \forall k \in K. \quad (33)$$

According to (29), the binary variable w_j tries to catch a value of zero in period k to minimize the objective function, but it is restricted by (31)–(33). Constraint (31) means that we are free to turn off units until the amount of required reserve in each period is met. Constraints (32) and (33), both, define periods that unit j can be turned off, whereas its minimum up time limit is not violated. In this subproblem, the minimum down time constraint needs not to be included because the presented formulation permits decommitment of units in a way to increase hours the units are being off continuously.

Ultimately, economic dispatch program is run for committed units considering linear cost functions and units constraints. Fig. 2 illustrates the procedure of the proposed straightforward UC solving approach.

IV. Numerical Simulation

We conduct three case studies consisting of the ten-unit test system, the IEEE 118-bus system, and a relatively large-scale power system representing the Iranian national power grid to illustrate the performance of the proposed method. Quadratic production costs are linearized through a piecewise linear approximation with ten segments. Once the final UC scheduling is obtained, a linear-programming-based economic dispatch is run to facilitate the assessment of the results.

The proposed method was implemented on a Dell Inspiron 6000 with a 1.86-GHz processor and 512 MB of RAM using MATLAB optimization toolbox [12].

TABLE I
TOTAL COST COMPARISON OF SEVERAL METHODS

	Total Cost ($)													
No.of Units	SPL [24]	EP [26]	EPL [19]	PLEA [25]	PSO [23]	IPSO [23]	HPSO [16]	BPSO [18]	PSO-LR [20]	LR [20]	LRGA [10]	ELR [22]	ALR [22]	GA [9]
10	564,950	565,352	563,977	563,977	574,153	-	563,942	565,804	565,869	566,107	564,800	563,977	565,508	565,825
20	1,123,938	1,127,256	1,124,369	1,124,295	1,125,983	1,125,279	-	-	1,128,072	1,128,362	1,122,622	1,123,297	1,126,720	1,126,243
40	2,248,645	2,252,612	2,246,508	2,243,913	2,250,012	2,248,163	-	-	2,251,116	2,250,223	2,242,178	2,244,237	2,249,790	2,251,911
60	3,371,178	3,376,255	3,366,210	3,363,892	3,374,174	3,370,979	-	-	3,376,407	3,374,994	3,371,079	3,363,491	3,371,188	3,376,625
80	4,492,909	4,505,536	4,489,322	4,487,354	4,501,538	4,495,032	-	-	4,496,717	4,496,729	4,501,844	4,485,633	4,494,487	4,504,933
100	5,615,530	5,633,800	5,608,440	5,607,904	5,625,376	5,619,248	-	-	5,623,607	5,620,305	5,613,127	5,605,678	5,615,893	5,627,437
	Total Cost ($)													
No.of Units	FPGA [15]	BCGA [14]	ICGA [14]	UCC-GA [27]	ACSA [17]	DP [9]	DPLR [22]	TS-RP [21]	TS-IRP [21]	MA [28]	MILP [13]	MRCGA [29]	SF	Minimum Value
10	564,094	567,367	566,404	563,977	564,049	565,825	564,049	564,551	563,937	565,827	-	564,244	563,865	563,865
20	1,124,998	1,130,291	1,127,244	1,125,516	-	-	1,128,098	-	-	1,128,192	-	1,125,035	1,125,161	1,122,622
40	2,248,235	2,256,590	2,254,123	2,249,715	-	-	2,256,195	-	-	2,249,589	-	2,246,622	2,246,849	2,242,178
60	3,368,375	3,382,913	3,378,108	3,375,065	-	-	3,384,293	-	-	3,370,820	-	3,367,366	3,365,980	3,363,491
80	4,491,169	4,511,438	4,498,943	4,505,614	-	-	4,512,391	-	-	4,494,214	-	4,489,964	4,489,062	4,485,633
100	5,614,357	5,637,930	5,630,838	5,626,514	-	-	5,640,488	-	-	5,616,314	5,605,189	5,610,031	5,615,960	5,605,189

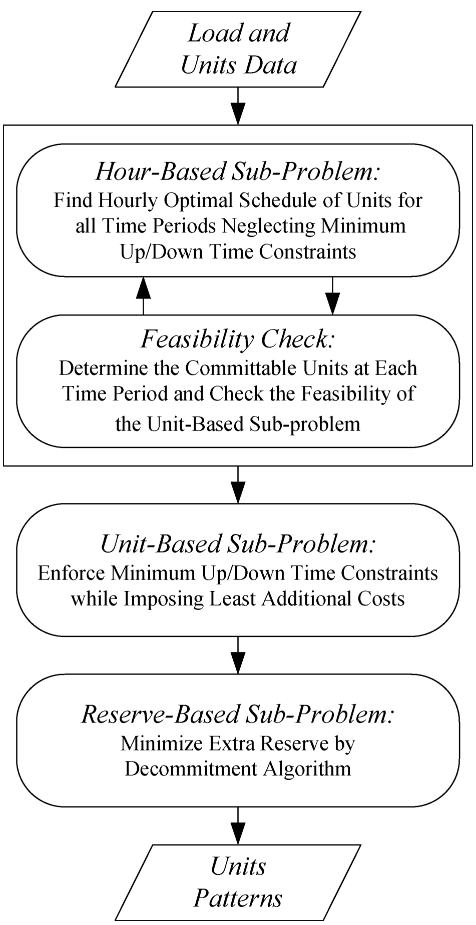

Fig. 2. Flowchart of proposed SF approach.

A. Ten-Unit Base Problem

The proposed formulation has been applied to solve a commonly used UC problem based on the ten-unit test system. This problem consists of a group of unit commitment problems. The basic problem includes ten units with a scheduling time horizon of 24 h. The 20-unit, 40-unit,. . ., and 100-unit UC problems are generated by scaling the generating units and load demand by 2, 4,. . ., and 10 times, respectively. The spinning reserve is held as 10% of the scaled load in each case. For quick reference, the hourly load distribution over 24-h time horizon and the generating units data are given in Tables V and VI of the Appendix, respectively.

The results of applying 26 different methods to the ten-unit system and its multiples were taken directly from [13]–[29], tabulated and compared with the results obtained from our method in Tables I and II from the view points of total operating cost and execution time. The abbreviation list of all considered methods is given in Table VII of Appendix.

Table I summarizes the total cost of different UC solving techniques that consists of production and startup costs. As shown in this table, for the case with ten units, the proposed method gives the best result, and for the other cases, the method came up with the total costs that are less than that of many other methods while very close to the least costs.

Execution times of different UC solving methods are presented in Table II. Although the CPU times shown in Table II may not be directly comparable due to different computers or programming languages used, but some insight can be gained. It is obvious that except for the ten-unit case, our run times are significantly lower than the run times of all other methods. The 21.3 s that we obtained for 100-unit case is less than one third of the next least CPU time. Therefore, the proposed method is efficient and suitable for large-scale practical cases. Table III gives the 24-h units outputs for the ten-unit case. Fig. 3 illustrates the hourly demand plus the required reserve curve and the summation of maximum available outputs of committed units curve. The small difference between two curves shows the outstanding UC scheduling using SF method.

B. IEEE 118-Bus System

The IEEE 118-bus system consisting of 54 units is considered to study using the SF method. The data for this system are

TABLE II
EXECUTION TIME COMPARISON OF SEVERAL METHODS

	Execution Time (Sec)													
No.of Units	SPL [24]	EP [26]	EPL [19]	PLEA [25]	PSO [23]	IPSO [23]	HPSO [16]	BPSO [18]	PSO-LR [20]	LR [20]	LRGA [10]	ELR [22]	ALR [22]	GA [9]
10	7.24	100	0.72	-	-	-	-	-	42	257	518	4	3.2	221
20	16.32	340	2,97	-	-	-	-	-	91	514	1147	16	12	733
40	46.32	1176	11.9	-	-	-	-	-	213	1066	2165	52	34	2697
60	113.85	2267	23	-	-	-	-	-	360	1594	2414	113	67	5840
80	215.77	3584	44.4	-	-	-	-	-	543	2122	3383	209	111	10036
100	374.03	6120	64.5	-	-	-	-	-	730	2978	4045	345	167	15733
	Execution Time (Sec)													
No.of Units	FPGA [15]	BCGA [14]	ICGA [14]	UCC-GA [27]	ACSA [17]	DP [9]	DPLR [22]	TS-RP [21]	TS-IRP [21]	MA [28]	MILP [13]	MRCGA [29]	SF	Minimum Value
10	-	3.7	7.4	85	-	-	108	107	77	290	0.97	3.6	0.91	0.72
20	-	15.9	22.4	225	-	-	299	-	-	538	4.49	12.6	1.39	1.39
40	-	63.1	58.3	614	-	-	1200	-	-	1032	19.53	43.2	4.72	4.72
60	-	137	117.3	1085	-	-	3199	-	-	2740	37.83	102.9	7	7
80	-	257	176	1975	-	-	8447	-	-	3159	133.88	169.7	13.47	13.47
100	-	397	242.5	3547	-	-	12437	-	-	6365	123	260.5	21.3	21.3

TABLE III
UNITS OUTPUT POWER FOR THE TEN-UNIT CASE

Units	Hours (1-24)																							
	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	390	360	410	455	455	455	455	455	455	455	455	310	260	360	455	455	455	455	420	345
3	0	0	0	0	0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	0	0	0
4	0	0	0	0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	0	0	0
5	0	0	25	40	25	25	25	30	85	162	162	162	162	85	30	25	25	25	30	162	85	145	25	0
6	0	0	0	0	0	0	0	0	20	33	73	80	33	20	0	0	0	0	0	33	20	20	0	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

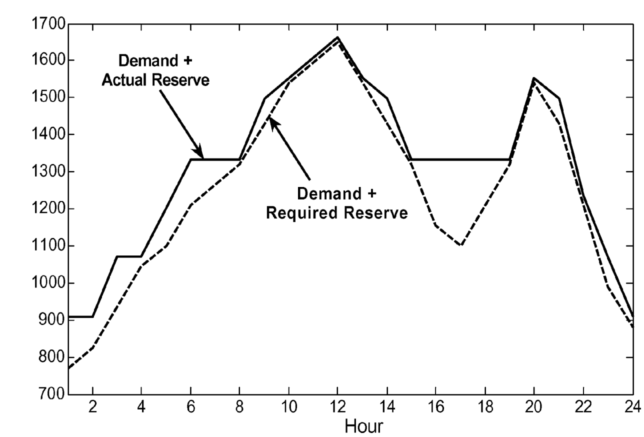

Fig. 3. Comparison between demand plus required reserve and summation of maximum available outputs of committed units.

given at http://ee.sharif.edu/IEEE_118_BUS.doc. All the constraints involved in this problem are regarded, and a more practical constraint is considered that is: each committed unit must be scheduled to operate at its lower generation limit in the first and last hours of being committed. Table IV presents the units' output powers for 24-h time horizon with a total operating cost of $1 643 818 and execution time of 6.57 s.

C. *Iranian Power System With 358 Units*

In order to present the performance of the proposed approach for the solution of a relatively large power system, the Iranian power system including 358 units is studied. The proposed method provided, in 118 s, a solution including hourly on/off patterns and the total economical operation cost. Comparing to the results obtained using a genetic algorithm-based UC program running on a 3.0-GHz computer having 512 MB of RAM at the Iranian Grid Management Company, our method was more than ten times faster. Also, our total operating cost was 1.10% less than theirs.

V. CONCLUSION

In this paper, a fast straightforward method for solving the UC problem was proposed. This method decomposes the UC problem into three subproblems which are solved in order. The salient feature of the proposed approach is its extremely short execution time that makes it applicable and efficient for large-scale practical power systems generation scheduling. The proposed technique has been successfully tested on three realistic case studies. Accuracy and computational efficiency of the new method were revealed by numerical results obtained.

TABLE IV
UNITS OUTPUT POWER FOR IEEE 118-BUS SYSTEM

Units	Hours (1-24)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	203	180	150	150	150	150	203	270	255	270	270	264	225	195	270	270	270	270	285	300	300	270	270	255
5	200	180	140	100	100	160	200	260	240	280	280	260	240	200	280	280	277	280	280	300	300	280	280	240
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	25	40	40	25	25	25	40	40	25	40	55	62.5	70	40	40	25
8-9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	200	180	140	100	100	157	200	260	240	280	280	260	240	200	280	280	260	280	280	300	300	280	280	240
11	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350
12-13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	25	40	40	25	25	25	40	40	25	40	55	62.5	70	40	40	25
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	25	40	40	25	25	25	40	40	25	40	55	62.5	70	40	32	25
17-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	25	40	40	25	25	25	40	40	25	40	55	62.5	70	40	25	25
20	250	250	250	134	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
21	250	250	250	130	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
22-23	0	0	0	0	0	0	0	0	25	40	40	25	25	25	40	40	25	40	55	62.5	70	40	25	25
24	200	200	200	100	155	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
25	200	200	200	100	151	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
26	0	0	0	0	0	0	0	0	25	32	40	25	25	25	32	40	25	40	55	62.5	70	40	25	25
27-28	420	388	356	178	292	356	420	420	420	420	420	420	420	420	420	420	420	420	420	420	420	420	420	420
29	212	189	124	80	80	146	212	256	256	278	278	256	234	205	278	278	278	278	278	300	300	278	278	256
30-33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	25	25	40	25	25	25	25	40	25	40	55	62.5	70	40	25	25
35	0	0	0	0	0	0	0	0	25	25	40	25	25	25	25	40	25	40	55	60	70	40	25	25
36	195	180	150	150	150	150	195	264	244	270	270	255	225	195	270	270	270	270	285	300	300	270	270	244
37	0	0	0	0	0	0	0	0	25	25	40	25	25	25	25	40	25	40	55	55	67.5	40	25	25
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
40	200	185	125	50	80	155	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
41-42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	200	180	140	100	100	140	200	260	240	280	280	260	231	200	280	280	260	280	280	300	300	280	280	240
44	200	180	129	100	100	140	200	260	240	280	280	260	220	200	280	280	260	280	280	300	300	280	280	240
45	200	180	120	100	100	140	200	260	240	280	280	260	220	200	280	280	260	280	280	300	300	280	280	240
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	25	25	32	25	25	25	25	40	25	32	55	55	62.5	40	25	25
48	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	40	25	25	54.5	55	62.5	40	25	25
49-50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51-52	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	40	25	25	47.5	55	62.5	40	25	25
53	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	32	25	25	47.5	55	62.5	32	25	25
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE V
LOAD DEMAND OF TEN-UNIT BASE PROBLEM

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

APPENDIX

The load pattern and the generating units characteristics of the ten-unit system are provided in Tables V and VI, respectively. Table VII gives the abbreviations list of different UC solving techniques which appeared in Tables I and II.

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TABLE VI
UNIT CHARACTERISTICS AND COST COEFFICIENTS OF TEN-UNIT BASE PROBLEM

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
$\overline{P_j}$	455	455	130	130	162	80	85	55	55	55
$\underline{P_j}$	150	150	20	20	25	20	25	10	10	10
a_j	1000	970	700	680	450	370	480	660	665	670
b_j	16.19	17.26	16.6	16.5	19.7	22.26	27.74	25.92	27.27	27.79
c_j	0.00048	0.00031	0.002	0.00211	0.00398	0.00712	0.00079	0.00413	0.00222	0.00173
UT_j	8	8	5	5	6	3	3	1	1	1
DT_j	8	8	5	5	6	3	3	1	1	1
hc_j	4500	5000	550	560	900	170	260	30	30	30
cc_j	9000	10000	1100	1120	1800	340	520	60	60	60
t_j^{cold}	5	5	4	4	4	2	2	0	0	0
ini state	+8	+8	-5	-5	-6	-3	-3	-1	-1	-1

TABLE VII
ABBREVIATION OF UC SOLUTION TECHNIQUES

SPL:	Stochastic Priority List
EP:	Evolutionary Programming
EPL:	Extended Priority List
PLEA:	Priority List-based Evolutionary Algorithm
PSO:	Particle Swarm Optimization
IPSO:	Improved Particle Swarm Optimization
HPSO:	Hybrid Particle Swarm Optimization
BPSO:	Binary Particle Swarm Optimization
PSO-LR:	Particle Swarm Optimization combined with Lagrangian Relaxation
LR:	Lagrangian Relaxation
LRGA:	Lagrangian Relaxation combined with Genetic Algorithm
ELR:	Enhanced adaptive Lagrangian Relaxation
ALR:	Adaptive Lagrangian Relaxation
GA:	Genetic Algorithm
FPGA:	Floating Point Genetic Algorithm
BCGA:	Binary Coded Genetic Algorithm
ICGA:	Integer Coded Genetic Algorithm
UCC-GA:	Unit Characteristic Classification Genetic Algorithm
ACSA:	Ant Colony Search Algorithm
DP:	Dynamic Programming
DP-LR:	Dynamic Programming combined with Lagrangian Relaxation
TS-RP:	Tabu Search Random Perturbation
TS-IRP:	Tabu Search Improved Random Perturbation
MA:	Memetic Algorithm
MILP:	Mixed Integer Linear Programming
MRCGA:	Matrix Real Coded Genetic Algorithm
SF:	Straightforward (Our Proposed Approach)

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