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STRENGTH PARETO EVOLUTIONARY ALGORITHM FOR UNIT COMMITMENT PROBLEM

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Abstract- Unit commitment (UC) has reached growing interest from researchers owing to its influence on power systems reliability as well as generation resource management in the recent decades. But, the core problem in this regard is its difficulty of being optimal tasks of the power system. Furthermore, the reliability analysis of the power system is nowadays critical to be incorporated into its design of operation strategy. Hence, in unit commitment problem, the equipment failure should be taken into account. To do so, a UC model based on outages of generator is formulated which the spinning reserve constraint is incorporated into the reliability requirement in the design process. The optimum generation combination is then located by employing Strength Pareto Evolutionary Algorithm (SPEA). In order to have better demonstration of effectiveness of the proposed scheme, it is carried on IEEE 39-bus test systems including 10 generators in case of different operation inertias. A comparison analysis is also carried out between the proposed SPEA and other algorithm such as ACS and LRGA regarding total cost and computational time to illustrate the robustness of the proposed schemes.

Keywords: Unit Commitment, Generator Outage, SPEA, System Constraints.

I. INTRODUCTION

The assurance of the optimal combination of generators connected to the system is the main goal of the economic scheduling so as to supply the load demand. Two separate steps are engaged in the economic dispatch problem; unit commitment and on-line economic load dispatch. The choice of units to provide the predicted load of the system at minimum cost over a needed period of time and also providing an indicated margin of the spinning reserve are the main duties of the unit commitment. While the on-line economic dispatch is responsible for load distribution among the operating units paralleled with the system in order to reduce the total cost of providing the system requirements. The main problem of running too many generating units is being very expensive. In this case by turning units off when they are not required, a lot of money can be saved.

In order to minimize the operational cost, the generic UC can be formulated. The operational cost is limited by some factors including constraints, ramp constraints, unit capability limits, duration of units, unit status, generation constraints, reserve constraints and minimum up-time and downtime constraints [1]. Numerous optimization schemes have been employed by researchers to solve UC problem. The priority list method (PL) [2-3], branch and bound method (BB) [4], dynamic programming (DP) [5], mixed integer programming (MIP) [6] and Lagrangian Relaxation (LR) [7, 8] are categorized as the traditional techniques. Some meta-heuristics based techniques such as genetic algorithm (GA) [9-11], evolutionary programming (EP) [12], simulated annealing (SA) (PSO) [14-17], tabu search [18], ant colony optimization (ACO) [19], improved honey bee mating optimization (IHBMO) [20] has recently been proposed.

On account of not being dependable and effective for solving UC problem, research is being proceeded to acquire the best approach. UC is a challenging problem owing to the nonlinearity, randomness and combativeness nature of UC which makes it be a combinatorial optimization problem. Two different approaches are taken into account to UC problems, the conventional mathematical programming based techniques which include nonlinear programming, linear programming, dynamic programming, network flows, and etc and the modern heuristics based techniques. Despite of being robustness in mathematical analysis, the conventional methods have poor performance in dealing with nonlinearity and high dimensionality. Hence, guided stochastic search based meta-heuristics approaches have been employed as a robust substitute for the conventional techniques.

In the recent decades, the power system reliability has drawn much attention. Meanwhile, various optimization techniques have been applied to power system operations and planning. Unit commitment (UC) is one of the most difficult optimal tasks of the power system. Unit commitment (UC) is an important function in generation resource management. Moreover, it is nowadays critical to incorporate reliability analysis of the power system into its design of operation strategy.

For this purpose, equipment malfunction or failure should be considered in unit commitment Although, first the model for UC considering generator outages is formulated, where the reliability requirement is incorporated into the spinning reserve constraint in the optimization design and real-coded Strength Pareto Evolutionary Algorithm (SPEA) is developed to locate the optimum generation combination. The effectiveness of the proposed approach is demonstrated by comparing its performance with other optimization schemes.

II. UC PROBLEM FORMULATION

The UC problem is to minimize the system cost while satisfying certain constraints. In this study, the generator outages are considered in the problem formulation. The nomenclature used herein is listed in the following: M: number of units; T: total scheduling period in hours; P_{Dj}: system load demand at time j; P_{Rj}: system spinning reserve required at time j; P_{ij}: output of generator i at time j; u_{ij}: ON ('1') / OFF ('0') status of unit i at time j; minimum generation limit of unit i; $P_i^{\max}$: maximum generation limit of unit i; p_i: probability of unit i operated in normal operating state; r_i: forced outage rate (FOR) of unit i, i.e., $r_i = 1-p_i$; D_{ij}: shutdown cost of unit i at time j; T_{ij}^{ON} : ON period of unit i at time j; T_{ij}^{OFF} :OFF period of unit i at time j; MUT$_i$: minimum up time of unit i; MDTi: minimum down time of unit i; Si j: start-up cost of unit i at time j, where $S_{ij} = \sigma_i + \delta_i (1 - e^{((-T_{ij}^{OFF})/\tau_i)})$ and σ_i, δ_i and τ_i are start-up cost coefficients of unit i; $C_i(P_{ij})$: fuel cost of unit i for generating power P_i at time j, where $C_i(P_{ij} = a_i + b_i P_{ij} + C_i P_{ij}^2)$ and a_i, b_i, c_i are cost coefficients of unit i; INSi: initial status of unit i.

A. Decision Variables

The decision variables involved in this problem are generator status u_{ij} and generator output P_{ij}. The former is a binary and the latter is a real number, thus the UC problem is essentially a mixed integer programming (MIP) problem.

B. Objective Function

The design objective is to minimize operating cost of the generating system over the planning horizon, which can be represented as follows:

$$\begin{aligned} \min F = &\left[\sum_{j=1}^{T}\sum_{i=1}^{M}(C_i(P_{ij}))\right] + u_{ij} + \left[\sum_{j=1}^{T}\sum_{i=1}^{M} S_{ij}\right] + \\ &+ u_{ij}(1-u_{ij-1}) + \left[\sum_{j=1}^{T}\sum_{i=1}^{M} D_{ij}\right] u_{ij}(1-u_{ij-1}) \end{aligned} \quad (1)$$

The first term is the production cost and the sum of the latter two terms is the transition cost. In this study, the shutdown cost is not considered to simplify the problem.

C. System Constraints

Many constraints can be applied on the unit commitment problem. Power balance of the entire power system, spinning reserve with reliability requirement consideration due to possible generator outages, generation capacity of each generator, and minimum up/down time of each unit.

- Constraint 1: Real power balance

$$\sum_{i=1}^{M}(P_{ij})u_{ij} - P_{Dj} = 0 \quad (2)$$

- Constraint 2: Spinning reserve considering generator outages

It is assumed that the original spinning reserve requirement for each scheduling period does not consider the equipment malfunction. It is set as a certain percentage of the load in each period. By explicitly taking into account the generator outages, a feasible solution should satisfy the following condition:

$$\sum_{i=1}^{M} p_i (P_i^{\max}) u_{ij} \geq P_{Dj} + P_{Rj} \quad (3)$$

where the left-hand-side term is actually the expectation of the overall capacity of committed generators. This constraint has an impact on the selection of generators but does not affect the optimum generation output.

- Constraint 3: Generation capacity of each unit

For normal system operations, real power output of each generator is restricted by lower and upper bounds as follows:

$$P_i^{\min} \leq P_{ij} \leq P_i^{\max} \quad (4)$$

- Constraint 4: Minimum up/down time of each unit

$$\begin{aligned} &T_{ij}^{ON} \geq MUT_i \\ &T_{ij}^{OFF} \geq MDT_i \end{aligned} \quad (5)$$

III. STRENGTH PARETO EVOLUTIONARY ALGORITHM

One of the most successful multi-objective optimization approaches is the SPEA [21] which is based on Pareto optimality concept.

Definition: Concept of Pareto optimality can be described mathematically as below:

The vector a in the search space dominates vector b if

$$\begin{aligned} &\forall_i \in \{1,2,...,k\} : f_i(a) \geq f_i(b) \\ &\exists_j \in \{1,2,...,k\} : f_j(a) > f_j(b) \end{aligned} \quad (6)$$

If at least one vector dominates b, then b is considered dominated vector, otherwise it is called non-dominated. Each non-dominated solution is regarded optimal in the sense of Pareto or called Pareto optimal. Obviously, any Pareto optimal solution is comparatively the most optimal one in terms of at least one of the objective functions. The set of all non-dominated solutions is called Pareto Optimal Set (POS) and the set of the corresponding values of the objective functions is called Pareto Optimal Front (POF) or simply Pareto front.

The SPEA which takes benefits from many features of some other approaches is used in this paper. Figure 1, shows a flowchart of the approach which includes the following major steps [21]:

Step 1. Generate an initial population P and create the empty external non-dominated set P.

Step 2. Paste non-dominated members of *P* into *P'*.
Step 3. Remove all solutions within *P'* covered by any other members of *P'*.
Step 4. If the number of externally stored non-dominated solutions exceeds a given maximum *N'*, prune *P'* by means of clustering.
Step 5. Calculate the fitness of all individuals in *P* and *P'*.
Step 6. Use binary tournament selection with replacement and select individuals from *P* and *P'* until the mating pool is filled.
Step 7. Apply crossover and mutation operators as usual.
Step 8. If the maximum number of generations is reached, then stop, else go to step 2.

Fitness evaluation is also performed in two steps. First, the individuals in the external non-dominated set P' are ranked. Then, the individuals in the population P are evaluated. For more details, refer to [21].

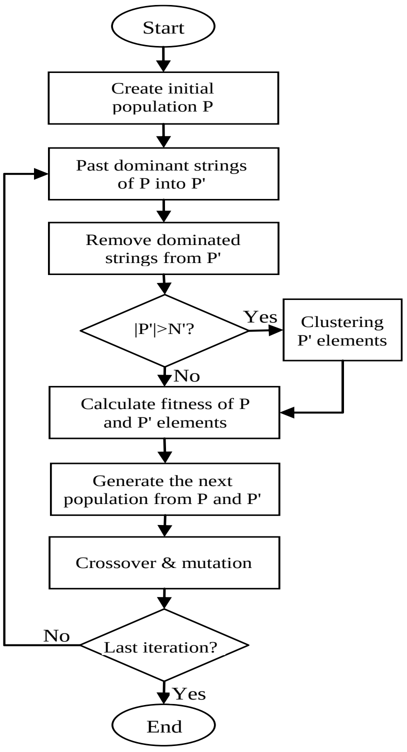

Figure 1.SPEA flowchart

IV. SIMULATION RESULTS

In this study, a 10-generator power system is used to test the effectiveness of the proposed approach. The one line diagram is shown in Figure 2.

Its parameters are shown in Table 1 and the 24-h loads are listed in Table 2. Also, we assume the original spinning reserve power is 5% of the load at each scheduling period, which does not consider the unit outages. During the stochastic search process, there are candidate solutions (i.e., generation combinations of units) which satisfy original spinning reserve constraint

$$\sum_{i=1}^{M} P_i^{\max} u_{ij} \geq P_{Dj} + P_{Rj} \qquad (7)$$

while not satisfying the spinning reserve constraint (3) with the generator malfunction consideration.

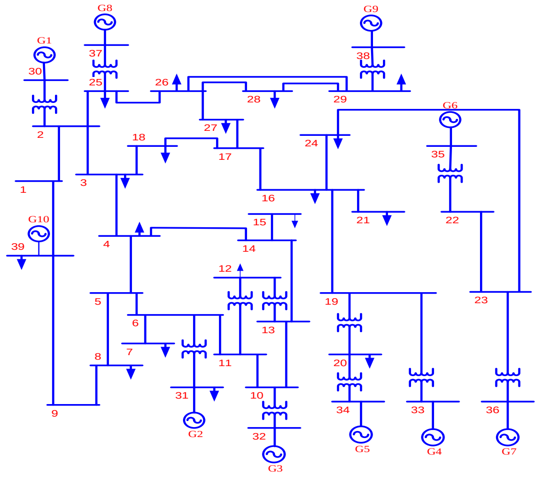

Figure 2. One-line diagram of the 10-generator power system.

For instance, at scheduling period Hour 5, the expected generation capacity of committed generators 1, 2, 7, and 8 is 1050 MW, without considering unit outages. The expected generation capacity is 1018.5 MW when taking unit malfunction probability into account.

It is obvious that this combination becomes infeasible in terms of (3). As a result, the revised spinning reserve constraint can be deemed a filter since it eliminates the candidate solutions which satisfy but do not fulfill (3). To sum up, the revised spinning reserve constraint is intended to enhance system robustness in the presence of unit malfunctions or failures. The optimal solution derived by the proposed algorithm using the original spinning reserve constraint is shown in Table 3, which matches the result in [22].

The transition cost value shown in each scheduling period in the table indicates the transition cost incurred by the state change between two consecutive scheduling periods. In this combination for unit scheduling and generation output, the total operation cost is $561,511. If checked against the revised spinning reserve constraint, some unit schedules are not feasible anymore. For instance, for the scheduling period of Hour 10, at least more 16.72 MW generation is needed to meet the modified spinning reserve demand. The optimal solution derived by the proposed algorithm using the modified spinning reserve constraint is shown in Table 4.

We can appreciate that some additional units need to start up in some scheduling intervals in order to satisfy this constraint. The total cost in this operation scenario becomes $571.076. Thus, extra costs are incurred for achieving reliability improvement. For comparison, both analytical and meta-heuristic methods are used to deal with operation scenario (i.e., UC with reliability constraints). Besides the result from the proposed method (i.e., SPEA), Table 5 shows the results of total costs using other methods including Lagrangian relaxation combined with genetic algorithm (LRGA) [23] and ant colony system (ACS) [24]. Meanwhile, the computational expenses are also indicated. We can appreciate from the table that the proposed method achieves the best solution in terms of both solution quality and computational efficiency.

Table 1. Parameters of the 10 generating units

Units	Variable											
	P_i^{max}(MW)	P_i^{min}(MW)	a_i($)	b_i($/MWh)	C_i($/MWh^2)	*MUTi*(h)	MDT_i(h)	INS_i(h)	σ_i ($)	δ_i ($)	τ_i (h)	r_i
G_1	455	150	1000	16.19	0.00048	5	5	8	4500	4500	4	0.03
G_2	455	150	970	17.26	0.00031	5	5	8	5000	5000	4	0.03
G_3	130	20	700	16.60	0.00200	2	2	-5	550	550	2	0.03
G_4	130	20	680	16.50	0.00211	2	2	-5	560	560	2	0.03
G_5	162	25	450	19.70	0.00398	2	2	-6	900	900	2	0.03
G_6	80	20	370	22.26	0.00712	2	2	-3	170	170	2	0.03
G_7	85	25	480	27.74	0.00079	1	1	-3	260	260	2	0.03
G_8	55	10	660	25.92	0.00413	0	0	-1	30	30	1	0.03
G_9	55	10	665	27.27	0.00222	0	0	-1	30	30	1	0.03
G_{10}	55	10	670	27.79	0.00173	0	0	-1	30	30	1	0.03

Table 2. Hourly load demand

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Demand (MW)	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
Demand (MW)	1400	1300	1200	1050	1000	1100	1200	1400	1300	1100	900	800

Table 3. Best solution for the original spinning reserve constraint

Hour	Unit schedule	Production cost ($)	Transition cost ($)	Spinning reserve (MW)	Generation output (MW)
1	1110100000	14,641	2850	402	455 150 20 0 25 0 0 0 0 0
2	1110100000	15,698	0	452	455 150 120 0 25 0 0 0 0 0
3	1111100000	18,0418	1203	482	455 150 90 130 25 0 0 0 0 0
4	1111100000	19,772	0	382	455 210 130 130 25 0 0 0 0 0
5	1111100000	20,241	0	362	455 260 130 130 25 0 0 0 0 0
6	1111100000	22,387	0	232	455 360 130 130 25 0 0 0 0 0
7	1111100000	23,262	0	182	455 410 130 130 25 0 0 0 0 0
8	1111100000	24,150	0	132	455 455 130 130 30 0 0 0 0 0
9	1111110000	27,089	349	112	455 455 130 130 110 20 0 0 0 0
10	1111111000	29,466	419	97	455 455 130 130 162 43 25 0 0 0
11	1111111100	31,222	60	102	455 455 130 130 162 80 25 13 0 0
12	1111111110	32,105	60	107	455 455 130 130 162 80 25 53 10 0
13	1111111000	29,336	0	89	455 455 130 130 162 43 25 0 0 0
14	1111110000	25,981	0	112	455 455 130 130 110 20 0 0 0 0
15	1111110000	24,606	0	212	455 440 130 130 25 20 0 0 0 0
16	1111100000	21,514	0	302	455 310 130 130 25 0 0 0 0 0
17	1111100000	20,642	0	292	455 260 130 130 25 0 0 0 0 0
18	1111100000	22,387	0	302	455 360 130 130 25 0 0 0 0 0
19	1111100000	24,150	0	132	455 455 130 130 30 0 0 0 0 0
20	1111111000	29,366	799	89	455 455 130 130 162 43 25 0 0 0
21	1111110000	22,580	0	112	455 455 130 130 110 20 0 0 0 0
22	1111100000	22,387	0	232	455 360 130 130 25 0 0 0 0 0
23	1111100000	19,902	0	403	455 160 130 130 25 0 0 0 0 0
24	1111100000	15,201	0	482	455 150 40 130 25 0 0 0 0 0

Table 4. Best solution for the revised spinning reserve constraint

Hour	Unit schedule	Production cost ($)	Transition cost ($)	Spinning reserve (MW)	Generation output (MW)
1	1110100000	14,849	2712	501	455 150 10 0 25 0 0 0 0 0
2	1110100000	15,698	0	422	455 150 100 0 25 0 0 0 0 0
3	1111100000	18,048	1203	482	455 150 80 130 25 0 0 0 0 0
4	1111100000	19,772	0	482	455 210 120 130 25 0 0 0 0 0
5	1111100000	20,642	0	352	455 250 130 130 25 0 0 0 0 0
6	1111100000	22,387	0	232	455 360 130 130 25 0 0 0 0 0
7	1111100000	23,262	0	282	455 410 130 130 20 0 0 0 0 0
8	1111100000	24,150	0	132	455 455 130 130 25 0 0 0 0 0
9	1111110000	26,589	239	212	455 455 130 130 120 20 0 0 0 0
10	1111111100	30,058	539	105	455 455 130 130 165 36 25 10 0 0
11	1111111110	31,924	60	146	455 455 130 130 162 75 25 13 10 0
12	1111111111	33,890	60	112	455 455 130 130 162 80 25 43 10 10
13	1111111100	30,058	0	122	455 455 130 130 162 35 25 0 0 0
14	1111110000	26,589	0	89	455 455 130 130 110 20 0 0 0 0
15	1111110000	24,606	0	196	455 440 130 130 25 20 0 0 0 0
16	1111100000	21,514	0	301	455 310 130 130 25 0 0 0 0 0
17	1111100000	20,642	0	353	455 260 130 130 23 0 0 0 0 0

18	1111100000	22,387	0	206	455 360 130 130 23 0 0 0 0 0
19	1111100000	24,150	0	101	455 455 130 130 30 0 0 0 0 0
20	1111111100	30,058	874	161	455 455 130 130 162 33 25 10 0 0
21	1111110000	26,589	0	99	455 455 130 130 110 20 0 0 0 0
22	1111100000	22,387	0	245	455 360 130 130 20 0 0 0 0 0
23	1111100000	18,903	0	432	455 160 130 130 20 0 0 0 0 0
24	1111100000	17,205	0	521	455 150 40 130 20 0 0 0 0 0

Table 5. Comparison of different algorithms in terms of solution quality and computational time

Method	Total cost ($)	Computational time (s)
LRGA	573,401	17.5
ACS	572,497	15.6
SPEA	571.076	14.2

V. CONCLUSIONS

In this paper a novel optimization technique namely Strength Pareto Evolutionary Algorithm (SPEA) employed to solve the Unit Commitment problem. It is a complex optimization problem considering its high nonlinearity and mixed-integer characteristics. Also, reliability-based constraint is introduced into the problem formulation to enhance system robustness in the presence of generator outages. The applicability of the proposed model has been illustrated using the standard IEEE 10-unit system. Over the 24-h planning horizon validate the effectiveness of the proposed optimization algorithm as well as the necessity of considering generator outages. The results are compared with the existing Intelligent Optimization methods in the literature. A comparative study is carried out to illustrate the impact of the revised spinning reserve constraint on the final solution derived. The comparison results confirmed the higher performance of the proposed method, also lower operational cost and execution time in (UC) compared with the other methods.

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