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Optimal Scheduling Generation Maintenance

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Abstract: *Generally the electric power system encompasses three parts: generation, transmission, and distribution that all require maintenance to improve reliability and energy efficiency of the power system. Most of generation maintenance scheduling (GMS) packages focus on preventive maintenance scheduling for generating units over one or two years to decrease the total operation costs while system energy requirements are provided. In advanced power systems, the inclusion of system such as fuel, crew, budget limitations, and demand for electricity have highly increased as well as expansions in the size of system. So they have led to higher number of generators and lower reserve margins, making the generator maintenance scheduling problem more complex. This paper proposes budget and a static security margin constrained model for preventive generation maintenance scheduling problem. In order to have a better optimized scheduling, a multi objective function (economic cost and reliability) is solved. For more realistic study, a novel manpower constraint as well as relationship constraints for solving multi objective function is considered for the proposed maintenance scheduling problem. A test system including 21-genarators is employed for simulation and shows the accuracy of results.*

Keywords: Generation maintenance scheduling, multi objective function, GMS, system reserve, preventive maintenance, binary swarm, reliability, economic cost.

1. Introduction

Scheduling of preventive maintenance for generators' performance has been a debatable subject of study and analysis by many researchers. In the past, implicitly they recognized the importance of this topic in the sense that this was considered a complex problem, since the solution affected the daily unit commitment and the dispatch of the generation units. The problem had a variety of formulations and integrated a number of variables and constraints, reflecting different levels of refinements that were progressively introduced. Nevertheless, a number of features were common to all these formulations: one aimed at scheduling, the maintenance actions of a set of generators along a period of typically one or two years are discretized into weeks. It has to ensure that the expected demand is supplied, the maintenance period of each generator is continuous in time, the number of maintenance crews available for each generation technology is not exceeded, and at least one maintenance action is scheduled for each generator along the evaluation period. Typically this is corresponded to a combinatorial formulation of problem using binary variables having the value 1 if a particular generator is scheduled for maintenance in a particular week [1]. In modern power systems, the demand for electricity has greatly increased with related expansions in power system size, which has resulted in higher numbers of generators and lower reserve margins. The goal of GMS is to allocate a maintenance timetable for generators in order to maintain high reliability, reduce total operating costs, and extend generator's life time, whilst still satisfy constraints on the individual generators and the power system. There are generally two categories of criteria for GMS problem; based on economic cost and reliability [2-4]. The most common economic objective is to minimize the total operating cost, including the costs of energy production and maintenance [5-7]. The solution methods can fall into certain categories which are as follows: integer programming, decomposition methods [8], dynamic programming, simulated annealing method [9], probabilistic approach [10], and artificial intelligence method [11], [12].

In this paper, it has tried to cover weakness of past GMS models and adding some features to make better GMS model. MGMS (modified GMS) model in this paper contains two objectives, increasing reliability and decreasing annual cost in a realistic condition. This goal is followed by adding some new constraints and considering multi objective function. Maintenance scheduling and OPF (to compute unit's generation for fuel cost calculation) is solved by particle swarm optimization. OPF is solved by generic PSO and MGMS model is solved by discrete PSO.

2. Problem Description and Solution Methodology

Adding budget limitation and static security margin in annual reserve make maintenance schedule as a realistic programming and of course more complex.

The multi objective function of the proposed model is considered in order to maximize reliability and minimize total maintenance and production costs over the operational planning period. a_1 and a_2 in equation (1) are defined over programming and changed in each PSO iteration. Equation (2) shows reliability objective function. Power distribution among planning period is smoother; therefore, it leads to more reliable situation and lower value of reliability objective function.affiliation(s) should be centered, with the first character in every word in capital letters.

In this equation, x_(i,t) is discrete variable that shows ith generator in tth period which is either on maintenance or not. Equation (3) corresponds to a mixed- discrete and continuous programming problem since x_(i,t) & y_(i,t) are binary variables and g_(i,t) is continuous. The first term of the objective function is maintenance cost of generators and the second is startup and energy production cost. Both objective functions are minimization functions. Therefore, multi objective function converts to the single objective function by equation (1) that should be minimized.

2.1 Multi-Objective Function and Related Constraints

$$\mathrm{Min}\ \{\ F = a_1 f_1 + a_2 f_2\ \} \tag{1}$$

Reliability objective function

$$f_1 = \sum_{t=1}^{T}\left(\sum_{i=1}^{I} g_{i,t}^{c} - \sum_{i\in I_t}\sum_{k\in S_{i,t}} x_{i,k} g_{i,t}^{c} - D_t\right)^2 \tag{2}$$

Economic cost objective function

$$f_2 = \sum_{i=1}^{I}\sum_{t=1}^{T} c_t x_{i,t} + \sum_{i=1}^{I}\sum_{t=1}^{T}\left(f_i y_{i,t} + k_i g_{i,t}\right) \tag{3}$$

Constraints in this problem categorize into 3 parts; maintenance constraints, system constraints, budget limitation and relationship constraints. This category of constraints shows that variables in preventive generator maintenance scheduling are not independent and multi objective function in this problem is nonlinear. Production and maintenance could not be simultaneous.

$$x_{i,t} g_{i,t} = 0 \quad , \quad \text{for all } i \ \&\ t \tag{4}$$

The unit will be exploited after completely started up.

$$y_{i,t} g_{i,t} = 0 \quad , \quad \text{for all } i \ \&\ t \tag{5}$$

$$x_{i,t} + y_{i,t} = \begin{cases} 1, \text{Gen. is on maintenance or starting} \\ 0, \quad \text{o.w.} \end{cases} \quad \text{for all } i\&t \tag{6}$$

To specify maintenance window, (7) or (8) can be used.

$$\begin{cases} \sum_{t\in Ti} x_{i,t} = 1 & \text{for all } i = 1,2,\dots,I \\ \sum_{t=1}^{T} x_{i,t} = N_i & \text{for all } i = 1,2,\dots,I \end{cases} \tag{7}$$

$$\begin{cases} \sum_{t=1}^{T-N_i+1} x_{i,t} x_{i,t+1} \dots x_{i,t+N_i-1} = 1, & \text{for all } i = 1,2,\dots,I \\ \sum_{t=1}^{T} x_{i,t} = N_i \quad , & \text{for all } i = 1,2,\dots,I \end{cases} \tag{8}$$

For reducing maintenance periods and cost, available crews can be rise α_t^1 percent of total available crews in tth period.

$$\sum_{i\in I_t}\sum_{k\in S_{i,t}} x_{i,k} M_{i,k} < (1+\alpha_t^1) A_t, \quad \text{for all } t = 1,2,\dots,T. \tag{9}$$

Each generator can start after maintenance only once over planning periods.

$$\sum_{t=1}^{T} y_{i,t} = 1 \ , \quad \text{for all } i = 1,2,\dots,I \tag{10}$$

Meet demand with enough reliability is the main purpose in any power plants [13-27].

$$\sum_{i=1}^{I} g_{i,t} = D_t \quad \text{for all } t = 1,2,\dots,T, \tag{11}$$

To maintain the stability of power plant and grid, there must be enough reserve at all planning periods.

$$\sum_{i=1}^{I} g_{i,t}^{c} = (D_t + R_t) \quad \text{for all } t = 1,2,\dots,T, \tag{12}$$

Equation (10) considers reliability of programming. For having flatter distribution of reserve during planning period, we could consider α_t^2 percent of demand in each period as an obligatory demand. This trick helps distributing reserve more smoothly and increasing security and stability margin through the planning period.

$$\sum_{i=1}^{I} g_{i,t}^{c} - \sum_{i\in I_t}\sum_{k\in S_{i,t}} x_{i,k} g_{i,t}^{c} \geq (1+\alpha_t^2) D_t, \quad \text{for all } t = 1,2,\dots,T \tag{13}$$

To compute fuel cost for active generators in economic cost objective function, power generation for each unit at all periods should be considered.

$$g_i^{min}\left(1 - x_{i,t}\right) \leq g_{i,t} \leq g_i^{max}\left(1 - x_{i,t}\right) \quad \text{for all } i \ \&\ t. \tag{14}$$

For specific power plants like nuclear or high capacity ones, ramp rate limitation of units should be considered for having exact and realistic programming.

$$LR_i \leq g_{i,t+1} - g_{i,t} \leq UR_i \quad , \quad \text{for all } i \ \&\ t \tag{15}$$

Undoubtedly, finding budget for implementing generator maintenance and supply power feed is the most challenging issue in the planning of power plants both public and private. Unfortunately, this problem is not considered in proposed system maintenance planning. Generator maintenance scheduling should be based on provided cost in given periods. GMS problem in this paper is solved according to N budget period.

$$J_n \le C_n^{cost} \quad , \quad \text{for } n = 1, \dots, N \qquad (16)$$

3. Solution Method

Figure 1 shows some possible methods to solve GMS problem. In this paper main problem is solved by DPSO and optimum power flow to compute fuel cost is solved by generic PSO. PSO particles could be discretized to multiple methods. Since being binary variables in GMS problem taking the bracket of the numbers between 0 and 2 or rounding numbers between 0 and 1 is proposed.

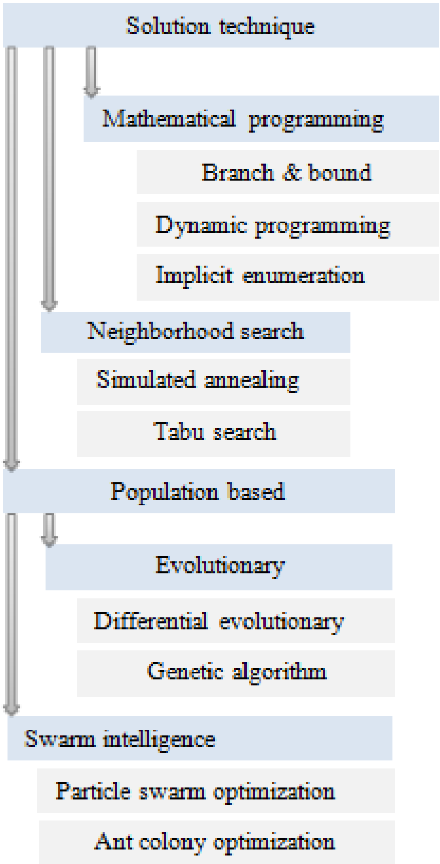


Fig. 1. Solution Methodologies

Because of discrete nature of GMS problem, any variation in particles may cause totality particle variation and worse particle production. Decreasing randomly variations can eliminate random functions in order to compute new velocity vector of particles. These variations are presented in (17). New position of particles and weight of old velocity for computing new velocity are considered in (18) and (19).

$$V_i^{k+1} = \mathrm{round}\left(wV_i^k + c_1\left(P_{i,best}^k - x_i^k\right) + c_2\left(P_g^k - x_i^k\right)\right) \qquad (17)$$

$$x_i^{k+1} = x_i^k + V_i^{k+1} \qquad (18)$$

$$w = w^{max} - k(w^{max} - w^{min})/k^{max} \qquad (19)$$

Where

V_i^k current velocity.
x_i^k current position of particle i at iteration k.
W inertia weight factor.
K number of iterations.
c_1 & c_2 acceleration constants.

TABLE I: Data of the Considered System

Units	Capacity/g_i^{max}(MW)	g_i^{min} (MW)	Allowed period	Outage (weeks)	Crews needed in each week
1	555	462	1-26	7	10+10+5+5+5+5+3
2	180	150	1-26	2	15+15
3	180	150	1-26	1	20
4	640	533	1-26	3	15+15+15
5	640	533	1-26	3	15+15+15
6	276	230	1-26	10	3+2+2+2+2+2+2+2+2+3
7	140	117	1-26	4	10+10+5+5
8	90	75	1-26	1	20
9	76	63	1-26	2	15+15
10	94	78	1-26	4	10+10+10+10
11	39	32	1-26	2	15+15
12	188	152	1-26	2	15+15
13	52	43	27-52	3	10+10+10
14	555	462	27-52	5	10+10+10+5+5
15	640	533	27-52	5	10+10+10+10+10
16	555	462	27-52	6	10+10+10+5+5+5
17	76	63	27-52	3	10+15+15
18	58	48	27-52	1	20
19	48	40	27-52	2	15+15
20	137	114	27-52	4	10+10+10+10
21	469	392	27-52	4	10+10+10+10
Total	5688	4732			

4. Case Study

This paper considers a test problem of scheduling the maintenance of 21 generating units over a planning period of 52 weeks. This test problem is loosely derived from the example presented in [16] with some simplifications and additional constraints, and has been previously studied in [18], [19]. Table 1 gives the capacities, power generation limitations, allowed periods and duration of maintenance and the manpower required for each unit. Power system peak load is 4739MW, and there are 20 technical staffs available for maintenance work in each week. The problem involves the reliability criterion of minimizing the sum of squares of the reserves in each weekly time period and minimizing total cost of planning periods. Each unit must be maintained (without interruption) for a given duration within an allowed period. The allowed period for each generator is the result of a technical assessment and the experience of the maintenance personnel, which ensures adequate maintenance frequency. Due to its complexity, the exact optimum solution for this problem is unknown. Fuel cost of generators is calculated by equation (20). Coefficient 168 is the conversion cost of each hour to week.

$$\mathrm{k_i g_{i,t}} = 168\left(\mathrm{a_i g_{i,t}^2} + \mathrm{b_i g_{i,t}} + \mathrm{c_i}\right) \tag{20}$$

Since reliability and economic cost objective functions are minimization problem, maintenance outages for generating units are scheduled to minimize the multi objective function (1) As it is mentioned, coefficients in multi objective function are determined in each iteration, and may be different for each swarm.

$\mathrm{C_t}$is assumed 2.5 million dollars. If there is any generator maintenance at period t or another one, this coefficient is zero.

It is planned to three set of constraints:

$$\text{Case1: } \begin{cases} 6.5\%\ security\ margin \\ 20\ crews\ per\ periods \\ 4\ budget\ periods \end{cases}$$

$$\text{Case2: } \begin{cases} 1\%\ security\ margin \\ 20\ crews\ per\ periods \\ 4\ budget\ periods \end{cases}$$

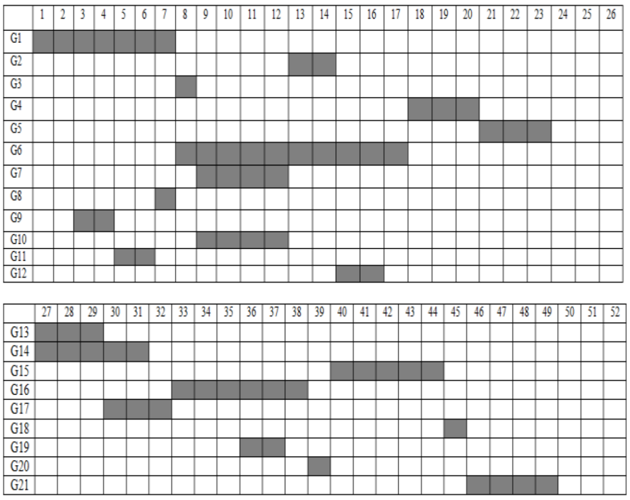
$$\text{Case3: } \begin{cases} without\ security\ margin \\ 30\ crews\ per\ periods \\ without\ budget\ limitation \end{cases}$$

c_t in MGMS model is considered 2.5 million in the weeks that are any maintenance regardless of the number of generators are held.

Case3 gives from [15].

Demand is considered 4739 MW at all periods.

TABLE II: Final Maintenance Schedule for Case 1



Tables II, III and IV show maintenance scheduling according to Case 1, 2 and 3 respectively. Additional cost for increasing crew is considered 3 percent of total cost of maintenance in Case1 and Case2.

TABLE III: Final Maintenance Schedule for Case 2

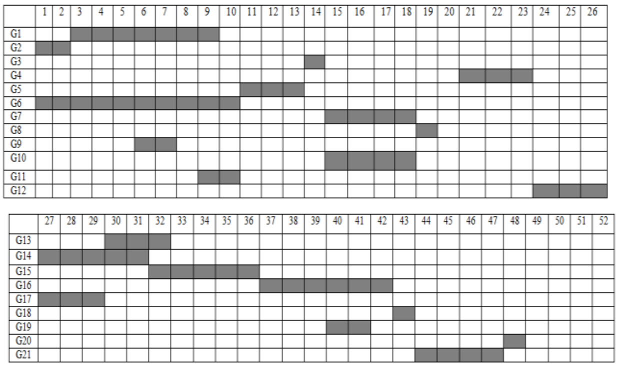


TABLE IV: Final Maintenance Schedule for Case 3

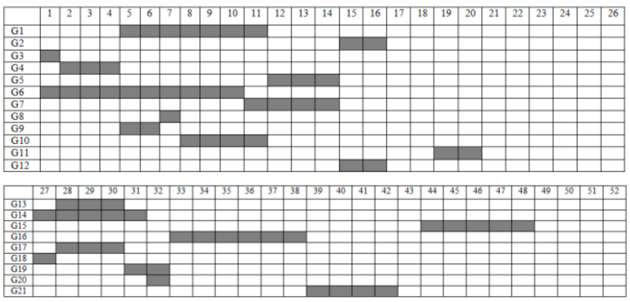


TABLE V: Cost of Objective Function

	Multi objective function	Reliability objective function (SSR)	Economic cost objective function($)
Case1	0.4899	14635000	1055400000
Case2	0.4891	16033000	1026600000
Case3	0.5094	18112009	1017200000

Because of lower limitations in Case3, maintenance schedule is smoother in this case than the others. Table 5 gives values of objective functions. SSR in Case1 is lower than the others, so reliability in this case is higher than other cases; however, economic cost is higher than Case2 and Case3. Therefore there is a compromise between reliability and economic costs, increasing reliability leads to increasing economic costs, and it is quite reasonable. Figure 2 compares available generation in Case1 and Case2. In Case1 available generation through the planning periods is more smoothly than Case2. Up and down horizontal lines in this Figure are total capacity and network demand, respectively. If available generation approaches to demand, security margin and reserve decrease, endangering stability. Adversely, if available generation approaches to capacity, reserve as well as security margin increases. Consequently, static stability is guaranteed. The main purpose in multi objective function is planning to increase reliability and security margin, and of course decreasing economic cost. Figure 3 shows employed maintenance staffs through the planning periods, that extra and total operators in Case1 are lower than other cases. Figures 4 and 5 compare these problems between Case1 and Case2.

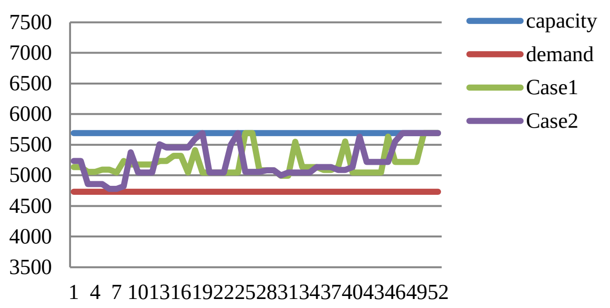


Fig. 2. Available Generation

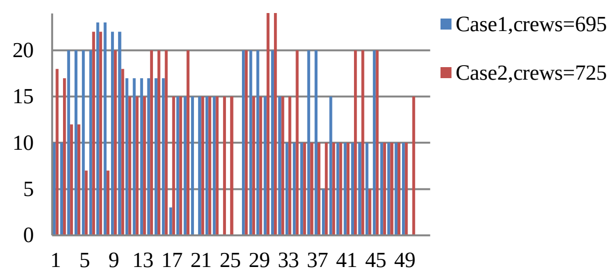


Fig. 3. Crew thorough the Planing Period

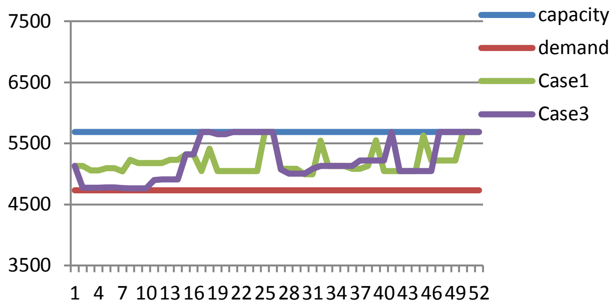


Fig. 4. Available Generation

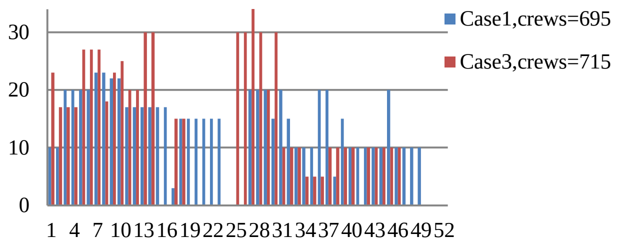


Fig. 5. Crew thorough Planing Period

5. Conclusion

Preventive maintenance scheduling considering security margin in reserve constraint, leads to more smoothly distribution in available generation through the planning periods. More smoothly distributed generation contributes to increasing the number of weeks including any maintenance. This problem causes enhancement economic cost. So there is a compromise between reliability and economic cost through the planning periods. Better security margin and stability result in more economic condition of power plant. Adding constraints such as budget supplying limitation and security margin in reserve through the planning period improve GMS model and make it more realistic.

6. Nomenclature

F	Multi objective function for GMS problem.
a_1 & a_2	Weight of reliability and economic cost objective functions in multi objective function.
f_1 & f_2	respectively, reliability and economic cost objective functions.
t	Index of time periods, $t = 1,2,\dots,T$.
T	total number of planned horizons.
i	Index of the number of generators, $i = 1,2,\dots,I$.
I	total number of generators.
$g^c_{i,t}$	Generating capacity of each generator (MW).
$g_{i,t}$	Variable of GMS problem that is generation of generator i at time t.

I_t The set of indices of generators in maintenance in time t.

K Index of start periods of maintenance for each generator, $k = 1, \ldots, S$.

$S_{i,t}$ Set of start time periods k such that if the maintenance of unit i starts at period k that unit will be in maintenance at period t, $S_{i,t} = \{k \in T_i : t - N_i + 1 \leq k \leq t\}$.

T_i Set of periods when maintenance of generator i may starts, $T_i = \{t \in T : e_i \leq t \leq l_i - N_i + 1\}$.

e_i Earliest period for generator i to start maintenance.

l_i Latest period for generator i to start maintenance.

N_i Duration of maintenance of generatori.

$x_{i,k}$ Variable of GMS problem, if generator i at time k is on maintenance $x_{i,k} = 1$, else 0.

D_t demand per time.

R_t reserve of plant at time t.

c_t Maintenance cost coefficient that if exist any generators in maintenance at time t, c_t is a fixed cost else is zero.

f_i Starting cost coefficient that if generator i restarted at any periods f_i is a fixed cost else is zero.

k_i Fuel cost coefficient.

$y_{i,t}$ Variable of GMS problem, if generator i at period t is restarted $y_{i,t}$ is 1 else is 0.

$M_{i,k}$ Number of crew that are needed for maintenance of generator i at periodk.

A_t available crews at time t.

α_t^1 percentage of total crews that can be added to minimizing cost of power plant.

α_t^2 percentage of demand that presents security margin in reserve.

LR_i maximum down ramp rate per time period for each generator.

UR_i maximum up ramp rate per time period for each generator.

J_n total cost of power plant in n th budget period.

n index of the number of budget period.

C_n^{cost} available budget in n'th budget period.

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