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 generators 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

Min \{ \( F = a_1f_1 + a_2f_2 \) \} \hspace{1cm} (1)

Reliability objective function

\[
f_1 = \sum_{t=1}^{T} \left( \sum_{i=1}^{I} \alpha_i \cdot x_{i,t} \cdot g_{i,t} - D_t \right)^2
\]

Economic cost objective function

\[
f_2 = \sum_{i=1}^{I} \sum_{t=1}^{T} c_i \cdot x_{i,t} + \sum_{i=1}^{I} \sum_{t=1}^{T} \left( y_{i,t} + k_i \cdot g_{i,t} \right)
\]

(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.

\[
x_{i,t} \cdot g_{i,t} = 0 \hspace{1cm} \text{for all } i \& t
\]

The unit will be exploited after completely started up.

\[
y_{i,t} \cdot g_{i,t} = 0 \hspace{1cm} \text{for all } i \& t
\]

(4)

\[
x_{i,t} + y_{i,t} =
\begin{cases}
1, \text{Gen. is on maintenance or starting} \\
0, \text{otherwise}
\end{cases}
\hspace{1cm} \text{for all } i \& t
\]

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

\[
\sum_{t=1}^{T} x_{i,t} = 1 \hspace{1cm} \text{for all } i = 1,2,...,I
\]

\[
\sum_{t=1}^{T} x_{i,t} = N_i \hspace{1cm} \text{for all } i = 1,2,...,I
\]

(7)

\[
\sum_{t=1}^{T-N_i+1} x_{i,t+1} \cdots x_{i,t+N_i-1} = 1 \hspace{1cm} \text{for all } i = 1,2,...,I
\]

\[
\sum_{t=1}^{T} x_{i,t} = N_i \hspace{1cm} \text{for all } i = 1,2,...,I
\]

(8)

For reducing maintenance periods and cost, available crews can be rise \( \alpha^T \) percent of total available crews in tth period.

\[
\sum_{i \in I} \sum_{k \in S_{i,t}} x_{i,t} \cdot M_{i,k} < (1 + \alpha^T)A_t \hspace{1cm} \text{for all } t = 1,2,...,T
\]

(9)

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

\[
\sum_{t=1}^{T} y_{i,t} = 1 \hspace{1cm} \text{for all } i = 1,2,...,I
\]

(10)

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

\[
\sum_{i=1}^{I} \sum_{t=1}^{T} x_{i,t} \cdot g_{i,t} = D_t \hspace{1cm} \text{for all } t = 1,2,...,T
\]

(11)

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

\[
\sum_{i=1}^{I} \sum_{t=1}^{T} x_{i,t} \cdot g_{i,t} = (D_t + R_t) \hspace{1cm} \text{for all } t = 1,2,...,T
\]

(12)

Equation (10) considers reliability of programming. For having flatter distribution of reserve during planning period, we could consider \( \alpha^T \) 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.

\[
\sum_{i=1}^{I} \sum_{t=1}^{T} x_{i,t} \cdot g_{i,t} - \sum_{i \in I} \sum_{k \in S_{i,t}} x_{i,k} \cdot g_{i,k} \geq (1 + \alpha^T)D_t \hspace{1cm} \text{for all } t = 1,2,...,T
\]

(13)

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

\[
g_{i,t} \cdot (1 - x_{i,t}) \leq g_{i,t} \leq g_{i,t} \cdot (1 - x_{i,t}) \hspace{1cm} \text{for all } i \& t
\]

(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.

\[
LR_i \leq g_{i,t+1} - g_{i,t} \leq UR_i \hspace{1cm} \text{for all } i \& t
\]

(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.
\[ I_n \leq c_{n}^{\text{Cost}}, \quad \text{for } n = 1, \ldots, N \]  

(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.

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).

\[ V_{i}^{k+1} = \text{round}(wV_{i}^{k} + c_{1}(P_{i}^{\text{best}} - x_{i}^{k}) + c_{2}(P_{g}^{k} - x_{i}^{k})) \]  

(17)

\[ x_{i}^{k+1} = x_{i}^{k} + V_{i}^{k+1} \]  

(18)

\[ w = w_{\text{max}} - k(w_{\text{max}} - w_{\text{min}})/k_{\text{max}} \]  

(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>
<thead>
<tr>
<th>TABLE I: Data of the Considered System</th>
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<tbody>
<tr>
<td>Units</td>
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<tr>
<td>1</td>
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<tr>
<td>21</td>
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<tr>
<td>Total</td>
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</tbody>
</table>
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.

$$k_{g_{i,t}} = 168(a_{g_{i,t}}^2 + b_{g_{i,t}} + c_t)$$  (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. $c_t$ 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:

Case 1: 6.5% security margin
        20 crews per periods
        4 budget periods

Case 2: 1% security margin
        20 crews per periods
        4 budget periods

Case 3: without security margin
        30 crews per periods
        without budget limitation

demand is considered 4739 MW at all periods.

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

Case 3 gives from [15].

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 Case 1 and Case 2.
TABLE V: Cost of Objective Function

<table>
<thead>
<tr>
<th></th>
<th>Multi objective function</th>
<th>Reliability objective function (SSR)</th>
<th>Economic cost objective ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>0.4899</td>
<td>14635000</td>
<td>1055400000</td>
</tr>
<tr>
<td>Case2</td>
<td>0.4891</td>
<td>16033000</td>
<td>1026600000</td>
</tr>
<tr>
<td>Case3</td>
<td>0.5094</td>
<td>18112009</td>
<td>1017200000</td>
</tr>
</tbody>
</table>

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.

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, \( t = 1, 2, ..., T \).
- \( T \) total number of planned horizons.
- \( i \) Index of the number of generators, \( i = 1, 2, ..., I \).
- \( I \) 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 \( t \).
\[ l_t \] The set of indices of generators in maintenance in time \( t \).
\[ K \] Index of start periods of maintenance for each generator, \( k = 1, \ldots, S \).
\[ S_{1k} \] 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 \( t \), \( S_{1k} = \{ k \in T; t - N_i + 1 \leq k \leq t \} \).
\[ T_i \] 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 generator \( i \).
\[ x_{ik} \] Variable of GMS problem, if generator \( i \) at time \( k \) is on maintenance \( x_{ik} = 1 \), else 0.
\[ D_i \] 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.
\[ y_{ik} \] Variable of GMS problem, if generator \( i \) at period \( t \) is restarted \( y_{ik} = 1 \) else 0.
\[ M_{ik} \] Number of crew that are needed for maintenance of generator \( i \) at period \( k \).
\[ A_t \] Available crews at time \( t \).
\[ \alpha_t^1 \] Percentage of total crews that can be added to minimizing cost of power plant.
\[ \alpha_t^2 \] 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.

7. References


