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Application of a novel cost reduction index to preventive maintenance scheduling

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ABSTRACT

Preventive maintenance scheduling of generating units is addressed as a crucial issue that affects on both economy and reliability of power system. In this paper, a new formulation of preventive maintenance scheduling associated with a novel cost reduction index (CRI) is developed. Mainly, the objective of the cost-based preventive maintenance scheduling consists of the operation as well as maintenance cost over a specified time horizon. A cost reduction index is introduced in such a way to minimize the operation cost while determining the most appropriate maintenance scheme. Here, the proposed framework is structured as a mixed integer linear programming (MILP) and solved using CPLEX solver. Several analyzes are conducted to investigate the impacts of CRI on maintenance scheme as well as system expenditures. The IEEE reliability test system (RTS) is utilized to demonstrate the effectiveness of the proposed structure and simulation results are promising.

1. Introduction

Preventive maintenance scheduling of generating units is addressed as a crucial issue in power system studies due to its severe impacts on power systems' asset management by reducing operation cost while enhancing reliability worth. Preventive maintenance reduces the damaging cost of unexpected breakdown [1]. Basically, equipment failure, testing, unanticipated events, refueling, operator errors and regulatory restriction; may cause a generating unit's unavailability. Although refueling is compulsory, but planned periodic outage of generating units may control and reduce the ratio of unanticipated events that improves reliability as well as system performance [2,3]. Maintenance scheme of generating units is extremely substantial due to affecting on short-term generation scheduling such as fuel scheduling as well as unit commitment [4].

Several deterministic, heuristic and hybrid methods have been utilized in last decades for solving the preventive maintenance scheduling problem as a large scale, non-convex, and mixed-integer combinatorial optimization problem. In [1,5], Benders' decomposition has been used to overcome the complexity of the maintenance problem; while [3] has proposed a multi-objective programming model based on decision tree and mixed integer linear programming for midterm preventive maintenance in thermal power plants. A hybrid algorithm is presented in [4] to solve the generator maintenance scheduling which employs a new local search method in the genetic algorithm (GA). In [6–11], genetic algorithm has been employed via different models to optimize the time of units' outage in order to obtain the maintenance and surveillance program. In [12–14], simulated annealing (SA) has been used while in [15,16], a combination of GA and SA has been exercised to solve the problem. Reference [17], expressed a method based on the Monte Carlo simulation by integrating GA to tackle the preventive maintenance problem. In [18–20], a hybrid Fuzzy-genetic algorithm has been proposed while in [21] an MILP model based upon goal programming has been expressed for maintenance problem of thermal power plants. In [22], Tabu search (TS) algorithm has been used while an improved formulation by using ant colony (AC) technique to schedule the optimum power plant maintenance scheme has been used in [23,24]. In [25–27], a particle swarm optimization is utilized to determine the best maintenance schedule of power plants and in [28], a fuzzy dynamic programming (FDP) methodology has suggested for finding the best preventive maintenance scheme in a centralized power system.

In this paper, a new formulation of preventive maintenance scheduling problem associated with the cost reduction index (CRI) is presented. The cost-based preventive maintenance scheduling problem aims to determine the maintenance scheme of generating units while the operation cost is minimized. If maintenance time of a unit is placed in an inappropriate period, the operation cost might be increased due to unavailability of the aforementioned unit. In such a case, the required demand is supplied with more expensive units. Therefore, a cost reduction index is introduced here to prevent such complications. The impacts of CRI on maintenance scheduling problem is significant where it may

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change units' status as well as maintenance scheme to reduce the total operating cost. The presented framework is structured as mixed integer linear programming (MILP). One of the main features of the MILP method includes direct measure of optimality of a solution and more flexible and accurate modeling capabilities. Here, CPLEX [29] as a sophisticated and computationally efficient MILP solver is applied for solving the proposed model.

The rest of the paper is organized as follows: The proposed MILP based formulation for the preventive maintenance scheduling problem associated with the cost reduction index is provided in Section 2. Section 3 conducts the numerical simulations and finally, concluding remarks are explained in Section 4.

2. Model description and formulation

Preventive maintenance scheduling is a decision making problem with an objective to be minimized with respect to a series of prevailing equality and inequality constraints. The objective of the maintenance problem is minimizing both the operation as well as the maintenance expenditures. Here an alternative mixed integer linear programming (MILP) formulation of preventive maintenance scheduling, suitable for available MILP software is presented. A common way of solving an MILP problem is to relax some coupling constraints and decompose it into several sub problems, while in recent years some efficient MILP solvers are developed. Here, the employed optimization solver is General Algebraic Modeling System (GAMS) [30]; and CPLEX as a commercial and computationally efficient MILP solver is utilized for solving the maintenance problem [29].

2.1. Preventive maintenance scheduling associated with CRI

The objective function for the proposed framework is presented as:

$$Min:\sum_{t=1}^{T}\sum_{i=1}^{N_g}[F_C(i)P(i,t)CRI(i,t)+M_C(i)x(i,t)] \tag{1}$$

The objective function is subjected to the following constraints.

$$\sum_{i=1}^{N_g}P(i,t)=D(t);\quad \forall t\in T. \tag{2}$$

$$\sum_{i=1}^{Ng}\overline{P}(i)u(i,t)\geq D(t)+SRR(t);\quad \forall t\in T. \tag{3}$$

$$\underline{P}(i)\leq P(i,t)\leq \overline{P}(i);\quad \forall t\in T,\forall i\in N_g. \tag{4}$$

$$\sum_{t=1}^{T}x(i,t)=M_d(i);\quad \forall i\in N_g. \tag{5}$$

$$\sum_{t=1}^{T}s(i,t)=1;\quad \forall i\in N_g. \tag{6}$$

$$x(i,t)-x(i,t-1)\leq s(i,t);\quad \forall t\in T,\forall i\in N_g. \tag{7}$$

$$x(i_1,t)+u(i_1,t)\leq 1;\quad \forall i_1\in \text{Thermal units},\forall t\in T.$$
$$x(i_2,t)+u(i_2,t)=1;\quad \forall i_2\in \text{Nuclear units},\forall t\in T.$$

$$x(i,t)+x(j,t)\leq 1;\quad \forall t\in T. \tag{9}$$

$$\sum_{i=1}^{N_g}\upsilon(i)x(i,t)\leq \Gamma(t);\quad \forall t\in T. \tag{10}$$

where T, N_g, $F_C(i)$, $P(i,t)$, $M_C(i)$, $D(t)$, and $SRR(t)$ represent the scheduling time horizon, number of generating units, the fuel cost of a unit ($/MWh), the generated power of a unit (MW) at period t, the maintenance cost of ith unit, the load demand (MW) at period t, and the system reserve requirement in each period respectively. Furthermore, maintenance duration for ith unit, number of crews needed for a unit inspection at each period, and total available manpower in a period are symbolized by $M_d(i)$, $\upsilon(i)$, and $\Gamma(t)$, respectively. $CRI(i,t)$ is an index so-called cost reduction index that is explained in details in the next subsection. Moreover, $\underline{P}(i)$ and $\overline{P}(i)$ are the minimum and the maximum generating capacity of ith unit, respectively. The maintenance binary variables are notated by $x(i,t)$, and $s(i,t)$ as expressed by Eqs. (11) and (12).

$$x(i,t)=\begin{cases}1 & \text{if } i^{\text{th}} \text{ generator is under the maintenance at period } t.\\ 0 & \text{otherwise.}\end{cases} \tag{11}$$

$$s(i,t)=\begin{cases}1 & \text{if } i^{\text{th}} \text{ generator maintenance starts at the beginning of period } t.\\ 0 & \text{otherwise.}\end{cases} \tag{12}$$

Moreover, $u(i,t)$ is a binary variable which shows the commitment status of a unit and is expressed as follows:

$$u(i,t)=\begin{cases}1 & \text{if } i^{\text{th}} \text{ generator is committed in period } t.\\ 0 & \text{otherwise.}\end{cases} \tag{13}$$

- Constraint (2) represents the power balance. Generated power from committed units must satisfy the required demand in each period.
- Constraint (3) shows the safety margin. It indicates that the maximum power of committed units should be greater than the summation of the system demand as well as the system reserve. System reserve ensures the system reliability when a failure happens in a generator which is considered as the largest unit capacity or a portion of the maximum demand.
- Constraint (4) bounds the generated power of a unit between its maximum and minimum power capacity.
- Constraint (5) determines the unit maintenance duration in a specified time horizon.
- Constraint (6) indicates that each unit is taken under maintenance just once during the time horizon.
- Constraint (7) shows that the maintenance of each unit must be performed in successive periods.
- Constraints (8) illustrate the relation between the maintenance status and the commitment status of a unit. Since nuclear units are low cost with higher startup time as well as shutdown time; nuclear units are always committed except their maintenance durations. However thermal units can be connected or not, even though they are not under inspection.
- Constraint (9) is the exclusive constraint. Generating units i and j cannot be in maintenance at the same time.
- Constraint (10) is the crew constraint. The total available technical staffs as well as the required manpower for the specified unit inspection in each period are definite. Hence, number of the generating units which can be maintained simultaneously is limited.

2.2. Cost reduction index (CRI)

Preventive maintenance scheduling of generating units is performed before generation scheduling. If maintenance time of units is selected inappropriately, the operation cost might be increased due to unavailability of inexpensive units in generation scheduling. Therefore, it is extremely crucial to determine the best mainte-