JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 10, No. 5, May 2008, p. 1246 - 1250

An ant colony optimization solution to the integrated generation and transmission maintenance scheduling problem

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The integrated maintenance scheduling considers transmission line maintenance scheduling in generation maintenance scheduling. The inclusion of network constraints increases the complexity of the above scheduling problem. Ant colony optimization (ACO) is a metaheuristic in which a colony of artificial ants cooperate in finding good solutions to difficult optimization problems. This paper proposes an ant colony optimization-based approach to the unified maintenance scheduling problem of power generation and transmission systems. Results from the application of the proposed method on the IEEE 30 bus system demonstrate the feasibility and practicality of this approach.

(Received March 13, 2008; accepted May 5, 2008)

Keywords: Power Systems, Generation maintenance scheduling, Transmission maintenance scheduling, Ant colony optimization

1. Introduction

Generation maintenance scheduling not only reduces the overall energy cost but also increases the power system reliability by reducing forced outage rates. The generation maintenance scheduling determines the optimal starting time for each generating unit preventive maintenance outage in a weekly period for one year in advance, while satisfying the system constraints and maintaining system reliability. The generation maintenance scheduling is a large-scale, complex optimization problem. Solution methods for the generation maintenance scheduling problem include integer programming [1], dynamic programming [2], simulated annealing [3], fuzzy set theory [4], tabu search [5], and genetic algorithms [6].

Most generation maintenance scheduling methods represent only the generation system and do not take into account the transmission network constraints effects on generation maintenance. However, excluding planned outages of transmission lines for preventive maintenance might produce optimistic results for the generation maintenance scheduling. On the other hand, due to thermal capacity of the transmission lines, a serious overloading problem could take place if certain lines and/or generators were removed from the system for maintenance simultaneously. In this case, the optimal resulting maintenance schedule may not be suitable for the system at all times. To avoid this problem, the integrated generation and transmission maintenance scheduling problem should be solved. This makes the integrated maintenance scheduling (IMS) problem more complex than the pure generation maintenance scheduling problem. The Benders decomposition [7-10] and the evolutionary programming method [11] have been applied for the solution of the IMS problem.

Ant colony optimization (ACO) is a nature-inspired method for the solution of hard combinatorial optimization problems [12]. ACO has been successfully applied for the solution of a number of difficult optimization problems in power systems including unit commitment [13-14], planning of distribution circuits [15], constrained load flow [16], and distribution systems reinforcement planning [17]. This paper proposes a new method based on ant colony optimization for the solution of the integrated generation and transmission maintenance scheduling problem.

The paper is organized in six sections. Section 2 formulates the integrated generation and transmission maintenance scheduling problem. Section 3 presents the basic concepts of ant colony optimization. Section 4 describes the proposed ACO solution methodology to the IMS problem. Section 5 presents the application and results of using the proposed technique to solve the IMS problem of the IEEE 30 bus system. Section 6 concludes the paper.

2. IMS problem formulation

2.1 Objective function

The objective of the integrated maintenance scheduling problem is to minimize the overall production and maintenance cost over the operational planning period, subject to unit maintenance and operating constraints.

The objective function to be minimized is the sum of a) the unit production cost, b) the unit maintenance cost, and c) the transmission line maintenance cost, as expressed by equation (1):

$$\min \sum_t \left[\sum_i c_{it} \cdot (1 - y_{it}) + \sum_i C_{it} \cdot y_{it} + \sum_k C'_{kt} \cdot T_{kt} \right] \quad (1)$$

where c_{it} is the production cost of unit i at time t (the production cost of each unit is considered a quadratic function of the unit output P'_{it}), y_{it} is the maintenance status of unit i at time t (the maintenance status is one, if the unit is on maintenance and zero otherwise), C_{it} is the maintenance cost of unit i at time t, C'_{kt} is the maintenance cost of transmission line k at time t, and T_{kt} is the maintenance status of transmission line k at time t (the maintenance status is one, if the transmission line is on maintenance and zero otherwise).

This optimization is constrained by a) maintenance scheduling constraints, and b) power system constraints.

2.2 Maintenance scheduling constraints

The integrated maintenance scheduling problem has to satisfy the here below maintenance scheduling constraints (2) to (7).

The IMS problem has to fulfill the generation maintenance window constraint:

$$y_{it} = \begin{cases} 1 & \text{for } x_i \le t \le x_i + d_i \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where x_i is the starting time of maintenance for generating unit i, and d_i is the duration of maintenance for generating unit i.

The generation crew constraint assigns one generating unit to one crew at a time:

$$\sum_i y_{it} = nc \quad \forall\, t \quad (3)$$

where nc is the number of available crews for generator maintenance.

The number of outages for the same generating unit is limited to one during the maintenance horizon:

$$\sum_t y_{it} = 1 \quad \forall\, i \quad (4)$$

The transmission line maintenance window constraint is the following:

$$T_{kt} = \begin{cases} 1 & \text{for } x'_k \le t \le x'_k + d'_k \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

where x'_k is the starting time of maintenance for transmission line k, and d'_k is the duration of maintenance for transmission line k.

The transmission line maintenance crew constraint is the following:

$$\sum_k T_{kt} = T_{nc} \quad \forall\, t \quad (6)$$

where T_{nc} is the number of available crews for transmission line maintenance.

The number of outages for each transmission line is limited to one during the maintenance horizon:

$$\sum_t T_{kt} = 1 \quad \forall\, k \quad (7)$$

2.3 Power system constraints

The IMS problem has also to satisfy the power system constraints (8) to (10).

The production of each generating unit must be between its lower and upper limits:

$$P_i^{\min} \le P'_{it} \le P_i^{\max} \quad \forall\, i, \forall\, t \quad (8)$$

where P'_{it} is the output power from generating unit i at time t, and $P_i^{\min}$ and $P_i^{\max}$ is the minimum and maximum output power from unit i, respectively.

The on line units must meet the system demand:

$$\sum_i P'_{it} \cdot (1 - y_{it}) = D_t \quad \forall\, t \quad (9)$$

where D_t is the demand at time t.

Finally, the IMS problem has to satisfy the network constraint (10) so as to maintain the flow on each transmission line below its maximum limit:

$$|F_k| \le F_k^{\max} \quad \forall\, k \quad (10)$$

where F_k is the flow on transmission line k and $F_k^{\max}$ is the maximum allowable flow on transmission line k.

3. Ant colony optimization

Ant colony optimization is a nature-inspired method for the solution of hard combinatorial optimization problems [12]. The inspiring source of ACO is the foraging behavior of real ants. When searching for food, ants initially explore the area surrounding their nest in a random manner. As soon as an ant finds a food source, it evaluates it and carries some food back to the nest. During the return trip, the ant deposits a pheromone trail on the ground. The pheromone deposited, the amount of which may depend on the quantity and quality of the food, guides other ants to the food source. Indirect communication among ants via pheromone trails enables them to find shortest paths between their nest and food sources.

After initialization of parameters and pheromone trails, the ACO metaheuristic algorithm iterates over three phases: at each iteration, the ants construct a number of solutions; the pheromone is updated, and finally daemon actions can by optionally used. In the following, these three phases are explained in more detail.

3.1 Construction of solutions

Artificial ants construct solutions from sequences of solution components taken from a finite set of *n* available solution components $\mathbf{Q} = \{q_{ij}\}$. A solution construction starts with an empty partial solution s^p. Then, at each construction step, the partial solution s^p is extended by adding a feasible solution component from the set $\mathbf{N}(s^p) \subseteq \mathbf{Q}$, which is defined as the set of components that can be added to the current partial solution s^p without violating any of the problem constraints. The process of constructed solutions can be regarded as a path on the construction graph $G_Q = (\mathbf{V}, \mathbf{E})$. The set of solution components $\mathbf{Q}$ may be associated either with the set $\mathbf{V}$ of vertices of the graph G_Q, or with the set $\mathbf{E}$ of its edges.

The choice of a solution component from $\mathbf{N}(s^p)$ is done probabilistically at each construction step, e.g.:

$$p(q_{ij} \mid s^p) = \frac{\tau_{ij}^{\alpha} \cdot \mathrm{n}(q_{ij})^{\beta}}{\sum_{q_{il} \in \mathbf{N}(s^p)} \tau_{il}^{\alpha} \cdot \mathrm{n}(q_{il})^{\beta}}, \quad \forall\, q_{ij} \in \mathbf{N}(s^p) \tag{11}$$

where τ_{ij} is the pheromone value associated with component q_{ij}, $\mathrm{n}(\cdot)$ is a weighting function that assigns at each construction step a heuristic value, called heuristic information, to each feasible solution $q_{ij} \in \mathbf{N}(s^p)$, and α, β are positive parameters, whose values determine the relation between pheromone information and heuristic information.

3.2 Pheromone update

The aim of pheromone update is to increase the pheromone values associated with good solutions and decrease those that are associated with bad ones. Usually, this is achieved by increasing the pheromone levels associated with chosen good solution s_{ch} by a certain value $\Delta\tau$, and by decreasing all the pheromone values through pheromone evaporation:

$$\tau_{ij} \leftarrow \begin{cases} (1-\rho)\cdot\tau_{ij} + \rho\cdot\Delta\tau & \text{if } \tau_{ij} \in s_{ch} \\ (1-\rho)\cdot\tau_{ij} & \text{otherwise} \end{cases} \tag{12}$$

where $\rho \in (0, 1]$ is the evaporation rate. Pheromone evaporation is needed to avoid too rapid convergence of the ACO algorithm. It implements a useful form of forgetting, favoring the exploration of new areas in the search space.

3.3 Daemon actions

Daemon actions can be optionally used to implement centralized actions that cannot be performed by single ants. Examples include the application of local search to the constructed solutions, or the collection of global information that can be used to decide whether it is useful or not to deposit additional pheromone to bias the search process from a non-local perspective.

4. Proposed ACO solution to IMS problem

Due to the complexity of the IMS problem and because of the ability of ACO to solve difficult optimization problems, this paper proposes the ACO method for the solution of the IMS problem.

It is considered that the scheduling horizon for the IMS problem is one year (i.e., 52 weeks), while the time step is one week.

4.1 Initial solutions

As shown in Section 3, the ACO metaheuristic requires the generation of initial solutions. Proper care has to be taken in the initial random generation of the candidate solutions due to the following IMS problem constraints:

1. Each generator *i* should be taken off for maintenance in consecutive weeks according to its duration for maintenance d_i. Similarly, each transmission line *k* should be taken off for maintenance in consecutive weeks according to its duration for maintenance d'_k.

2. In each week, the number of generators that can be maintained is limited to *nc* due to resources and crew constraints. Similarly, in each week, the number of transmission lines that can be maintained is limited to T_{nc} due to resources and crew constraints.

After much consideration, the candidate solution space has the two-dimensional matrix form of Fig. 1. The rows of the matrix represent the stages, i.e., the number of weeks in the scheduling horizon (52 weeks in our case) while the columns represent the states, i.e., the index of the generators and transmission lines that are to be taken off for maintenance.

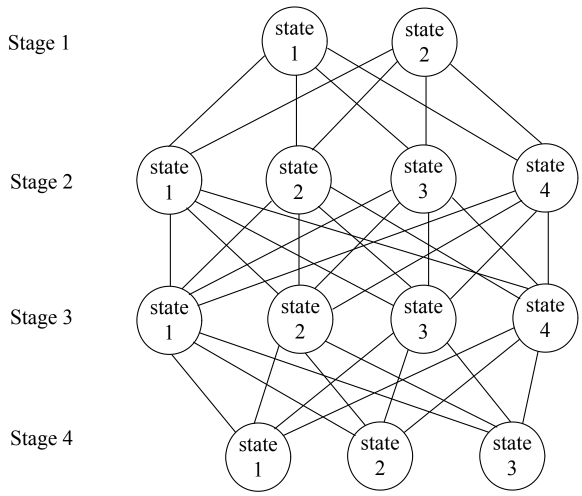

Fig. 1. The multi-stage search space.

4.2 Solution methodology

The proposed ACO solution for the IMS problem is composed of the following steps:

1. ACO parameters are set and initial solutions are generated using the steps described in Section 4.1.
2. While the termination criterion is not met, the ACO metaheuristic iterates over the following two phases:
   a. At each iteration, a number of solutions are constructed by the artificial ants. For each solution, calculate the on and the off weeks for each generating unit and transmission line. For each feasible solution, solve the economic dispatch problem to obtain the optimal output of each generating unit. Next, solve the DC power flow problem to calculate the optimal power flow of each transmission line. Finally, calculate the overall production and maintenance cost of each feasible solution.
   b. The pheromone is updated.
3. As soon as the termination criterion is met, the solution proposed by ACO is the one with the minimum overall production and maintenance cost, which simultaneously satisfies all the maintenance scheduling and power system constraints.

5. Results and discussion

The proposed technique is extensively tested on the IEEE 30 bus system [18] of Fig. 2 that has 12 generating units and 41 transmission lines. The maintenance operational planning horizon is 52 weeks. It is considered that all the generating units are to be maintained once during the scheduling horizon. It is also considered that all the transmission lines are to be maintained once during the planning horizon.

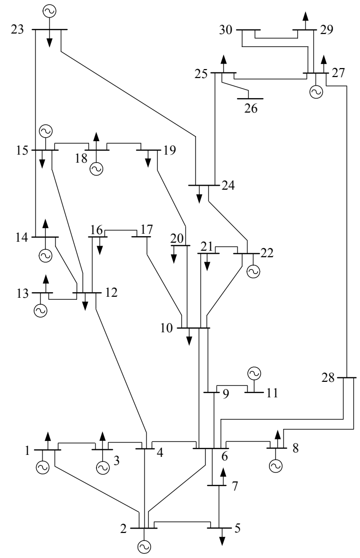

Fig. 2. Single line diagram of the IEEE 30-bus system.

Table 1 compares the results of the proposed ACO approach with the results obtained by Benders decomposition [7]. As can be seen from Table 1, the ACO method provides an integrated generation and transmission maintenance scheduling with an overall cost of $ 17 177 770, which is $ 78 720 cheaper than the schedule obtained by Benders decomposition. This 0.46% cost reduction validates the efficiency and practicality of the ACO solution for the integrated generation and transmission maintenance scheduling.

Table 1. Comparison of solution provided by Benders decomposition and ACO.

Cost	Benders decomposition	Proposed ACO
Production ($)	6 607 410	6 577 510
Generation maintenance ($)	210 180	209 220
Transmission maintenance ($)	10 438 900	10 391 040
Total cost ($)	17 256 490	17 177 770

Table 2. Comparison of solution provided by ACO with and without considering the transmission line maintenance.

Cost	With transmission	Without transmission
Production cost ($)	6 577 510	6 577 280
Generation maintenance cost ($)	209 220	199 385
Production + generation maintenance cost ($)	6 786 730	6 776 665
Transmission line maintenance cost ($)	10 391 040	0
Total cost ($)	17 177 770	6 776 665

Table 2 presents a comparison of the solution provided by ACO with and without considering the transmission line maintenance. Due to the tight thermal capacity limits of the transmission lines, removing some lines for maintenance causes a larger number of transmission lines to violate their limits. Some of the transmission line violations cannot be removed by simply redispatching the generators. In such cases, the maintenance schedule has to be shifted within the feasible region away from the optimal solution, which changes the maintenance and production costs. As Table 2 shows, when considering the transmission line maintenance, the generation maintenance cost is $ 9 835 higher (i.e., 4.93% higher) in comparison with generation maintenance cost when not considering the transmission line maintenance. This result indicates that considering the transmission lines maintenance has a noticeable effect on the generation maintenance cost. This 4.93% cost increase in the generation maintenance cost is the price for ensuring that the obtained maintenance schedule maintains system security.

As can be seen from Table 2, the sum of the production and generation maintenance cost is increased by $ 10 065 for the case of considering the transmission line maintenance in comparison with the case of not considering the transmission line maintenance. Finally, Table 3 shows that the total cost for the case of considering the transmission line maintenance is $ 10 401 105 higher in comparison with the total cost for the case of not considering the transmission line maintenance and this cost difference is mainly attributed to the transmission line maintenance cost.

6. Conclusions

The integrated generation and transmission maintenance scheduling is a complex combinatorial optimization problem. Ant colony optimization is a nature-inspired method for the solution of hard combinatorial optimization problems. In this paper, an ant colony optimization method is proposed for the solution of the integrated generation and transmission maintenance scheduling problem. Test results on the IEEE 30 bus system indicate the efficiency of the proposed approach and its ability to solve the integrated maintenance scheduling problem.

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