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Coordination of Generation Maintenance Scheduling in Electricity Markets

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***Abstract*—Generation maintenance scheduling (GMS) plays an important role in power system operations. The restructuring of the power industry has forced changes to the traditional maintenance mechanism. On one hand, the generation companies seek to maximize their profit. On the other hand, the independent system operator (ISO) strives to maintain the operational reliability of the system while maximizing the social welfare. This paper proposes a coordination mechanism for generation maintenance scheduling in electricity markets. In order to solve the resulting large mixed integer programming (MIP) problem, a relaxation induced algorithm is utilized. This technique is based on the solution of the linear relaxed problem. The features of the coordination mechanism and the performance of the algorithm are demonstrated using the IEEE-118 bus system and a provincial power system in China. Case studies show that the proposed mechanism not only ensures the maintenance preference of the generating companies, but also maintains the operational reliability of the system. They also demonstrate that the algorithm is quite efficient at solving the optimization problem.**

***Index Terms*—Generation maintenance scheduling, generation company, independent system operator, coordination mechanism, mixed integer programming, relaxation induced.**

Nomenclature

Indices

c	Index for generation companies
e	Index for maintenance exclusive set
i	Index for generating units
j	Index for maintenance windows
l	Index for transmission interfaces
n	Index for buses
p	Index for maintenance priority set
s	Index for maintenance simultaneous set

Parameters

$C_{i,t}^b$	Bid of unit i at period t Number of periods in each interval
D_t	System forecasted load in period t
$D_{n,t}$	Nodal load of bus n at time t
G_{l-i}	Shift factor of line l and unit i
G_{l-j}	Shift factor of line$l$ and bus$j$
MD_i	Duration of the maintenance of generating unit i
MT_i	Number of maintenance windows of generating unit i
MT_i^b	Number of bidding maintenance windows of bidding unit i
N_b	Number of "bidding units"
NG	Number of generating units
NG_m	Number of units to be maintained
NN	Number of buses
$N_{s,t}$	Number of units in the maintenance simultaneous set s
$P_{i,\max}$	Upper limit of power generation of unit i
$P_{i,\min}$	Lower limit of power generation of unit i
$P_{l,\max}$	Maximum capacity of transmission interface l
$P_{l,\min}$	Minimum capacity of transmission interface l
R	System positive spinning reserve requirement
RI_{R-MS}	Reliability index of the reliability-based maintenance schedule
S_t	System reserve during period t
T	Number of periods in each interval
λ	Reliability index decremental percentage
Φ_p	Maintenance priority set
Φ_e	Maintenance exclusive set
Φ_s	Maintenance simultaneous set

Variables

$P_{i,t}$	Real power output of unit i at time t
$X_{i_j,t}$	Maintenance status of generating unit i for maintenance window j during period t. ($1 =$ on maintenance, 0 otherwise)

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Models

$\mathrm{Prob}_{\mathrm{R-MS}}$	Reliability-based maintenance scheduling model
$\mathrm{Prob}_{\mathrm{C-MS}}$	Coordination maintenance scheduling model of ISO

I. Introduction

A. Background and Motivation

GENERATION maintenance scheduling (GMS) plays an important role in power system operations. For example, an inadequate GMS increases the risk of power shortage especially for power systems with a low reserve margin. GMS is closely linked to generation adequacy, which affects other short-term planning activities such as unit commitment and economic dispatch. In a traditional vertically integrated power system, the utility determines all aspects of the GMS because all the generating units are within its control. The restructuring has forced changes to the traditional maintenance scheduling practices because one organization no longer controls all of the facilities that must be maintained. In addition, the objectives of the various entities that are involved are not necessarily aligned. On one hand, the generation companies (GENCOs) seek to maximize the profits that they obtain from producing energy and delivering ancillary services. When one of their units is on maintenance, these GENCOs incur a lost opportunity cost [1]. On the other hand, the independent system operator (ISO) must maintain the operational reliability of the power system while maximizing the social welfare. Since these objectives usually conflict and the GENCOs are competitors, the ISO must coordinate maintenance schedules to ensure fairness between the GENCOs while meeting its own objective of maintaining operational reliability [1].

B. Literature Review

Marwali and Shahidehpour proposes an integrated generation and transmission maintenance scheduling model for the first time [2]. Billinton *et al.* [3] presented a method to coordinate composite system maintenance scheduling in a deregulated environment and proposed an index to quantify the effect of a planned outage during a designated period. Fu *et al.* [4], [5] introduced coordinated generation and transmission maintenance scheduling with security-constrained unit commitment model to further improve the security and economy of power system operations. Marwali and Shahidehpour [6] also discussed the long-term and short-term generation scheduling coordination model. Long term generation maintenance scheduling first considers the fuel allocation, the emission allowances and other resources. These results are used as an indicator for the short-term scheduling. To improve the accuracy of the GMS and Security-Constrained Unit Commitment (SCUC) coordination model, uncertainties including forced outages of units and transmission lines, load forecast errors, fuel price fluctuations are considered in Wu's model [7]. Pandzic *et al.* [8] considered the yearly generation maintenance scheduling in a market environment. Other factors, such as wind power [9], demand response [10] have also been included in the GMS model. However, the coordination of maintenance schedules between different GENCOs in a competitive environment is not considered in these papers.

To illustrate industrial practice for maintenance coordination by an ISO in a competitive environment, let us consider the GMS procedure implemented by NYISO as an example [15]. First, GENCOs submit their initial maintenance schedules to NYISO. NYISO then executes a reliability validation process. If this process determines that these maintenance schedules would lead to periods of insufficient reserve, the proposed maintenance schedules are rejected and the GENCO must submit revised maintenance schedules. This process is repeated until the combination of the maintenance schedules submitted by the GENCOs achieves an acceptable level of reliability.

This mechanism may require complex iterative negotiations between the GENCOs and the ISO. Sometimes, the ISO has to invoke forced rescheduling of the maintenance schedules to maintain the reliability of the system, which obviously conflicts with the interests of at least some of the GENCOs.

Extensive research has therefore been conducted on the development of a more effective coordination mechanism. Wang and Handschin [16] proposed a coordination model which minimizes the fluctuation in system reserve rate as well as the fluctuations in the variance of the scheduling window of all the units to be maintained. However, how this could be coordinated among competing GENCOs was not discussed. Wu *et al.* [17] formulated a stochastic model that combines generation maintenance scheduling with hourly price-based unit commitment. The model aims at developing maintenance schedules for GENCOs before submitting them to the ISO. Conejo *et al.* [18] presented a coordination mechanism with incentives and disincentives for generators. In [18], a maximum-reliability maintenance schedule is computed by the ISO, while the GENCOs develop maximum-profit maintenance schedules. The ISO then sets up incentives/disincentives for each period to encourage GENCOs to modify their maintenance schedules and negotiates with the GENCOs until the two plans are sufficiently close in terms of reliability. Feng and Wang [19] designed a similar coordination mechanism but in this case the maintenance bidding cost was determined by the GENCOs themselves. Lu *et al.* [20] derived a coordination mechanism that attempts to solve the two main issues: which schedule should be adjusted and how should it be adjusted. Security constraints, such as transmission flow limits and random transmission line outages are also incorporated. Min *et al.* [21] proposed a game-theory-based generation maintenance scheduling coordination procedure. The optimal maintenance strategies of GENCOs are determined by the Nash equilibrium of the non-cooperative dynamic game. The ISO then conducts a reliability assessment to determine whether to authorize, reject or adjust the submitted GMS.

To solve the GMS models efficiently, several methods are proposed. The GMS can be modelled and solved as a Mixed Integer Programming (MIP) [12]. To solve the large MIP model, Benders Decomposition is commonly used [4], [5], [11], which decomposes the problem into a master problem and several subproblems. Besides, Heuristic Method such as Tabu Search (TS) [25], Genetic Algorithm (GA) [26], Particle Swarm Optimization (PSO) [27], Simulated Annealing (SA) [28], differential evolution [29] and the combination of GA, SA, TS [13] and

Dynamic Programming [14] are also commonly employed in solving the GMS models.

C. Proposed Methodology and Contributions

The main contributions of this paper are as follows:

1) A novel coordination mechanism is proposed, which aims at maximizing the maintenance preference of GENCOs while maintain the operational reliability of the system. Compared with the mechanism addressed in existing literature, the mechanism proposed in this paper is more concise and straightforward.
2) A new form of reliability index is proposed, which aims at equalizing the system spinning reserve over the entire planning horizon.
3) According to the mechanism, a reliability based maintenance scheduling model and a coordination model of ISO are proposed. With the reliability index proposed, the reliability based maintenance scheduling model can be recast as a mixed-integer linear programming model which is tractable with currently available branch-and-cut techniques and much more applicable for realistic power systems.

Besides, in order to further improve the computational efficiency, an algorithm recently proposed by the authors, termed as the relaxation induced algorithm [22], is utilized to solve the resulting large MIP problem. This technique is based on the solution of the linear relaxed problem. Case studies show that this algorithm improves the computational efficiency by more than an order of magnitude.

D. Paper Organization

The remainder of the paper is organized as follows. Section II presents the coordination mechanism for generation maintenance scheduling between GENCOs. Section III provides the formulation of the GMS according to the proposed coordination mechanism. Section IV describes the relaxation induced algorithm used to solve the MIP problem. Section V details the tests that have been conducted on a modified version of the IEEE 118-bus test system case and a provincial power system in China. Section VI concludes.

II. Design of Coordination Mechanism

A. Reliability Index

Several reliability indexes for generation maintenance scheduling are listed in [24], including maximizing the minimum reserve, minimizing the sum of the squares of the reserves, levelling the risk over the entire period and so on. All of these objective functions lead to a levelling of reserve or the risk over the entire period. However, all the listed objective functions in [24] is non-linear, and it is computational burdensome, especially for large-scale realistic power systems. The reliability index (RI) in this paper is expressed as follows:

$$RI = \frac{T-1}{\sum_{t=2}^{T} |S_t - S_{t-1}|} \tag{1}$$

Equation (1) is also aiming at a levelling of reserve over the entire period and it can be easily converted into the linear formulation, which will be illustrated in Section III. Thus, it is easier to solve the model and much more applicable for large-scale realistic power systems.

B. Coordination Mechanism for GENCOs

Fig. 1 illustrates the main part of the proposed coordination mechanism:

a) GENCOs submit their initial generating units' outage requests to the ISO, including maintenance windows, maintenance duration, maintenance capacity.
b) Based on these requests, the ISO develops a reliability-based maintenance schedule (R-MS). This schedule aims to maximize the reliability index that will be discussed in Section III. If this reliability index is less than the minimum reliability requirement defined by the ISO, all GENCOs must accept the R-MS and the process concludes. In this case, the ISO would seek other means, such as utilizing inter-regional power exchange, to ensure the reliability of the system.
c) If the R-MS is greater than the minimum reliability requirement, which means there is still room for maintenance re-scheduling, the maintenance schedules are then fed back to the GENCOs.
d) If all the GENCOs accept the schedules, the process concludes; otherwise, the GENCOs that are not satisfied with the maintenance slots which they have been allocated can submit a bid for other slots to the ISO.
e) Several times of bidding simulation is allowed. ISO will set up the maximum times of bidding simulation. ISO will schedule the maintenance slots based on the simulated bidding of GENCOs, considering the effects of these changes on the reliability index. Those generation units which are not willing to participate in the process of bidding simulation are considered to accept the reliability-based maintenance schedules. ISO will release the maintenance slots, but the results of bidding simulation is not the final results, which is only used to help GENCOs formulate more appropriate final bid.
f) When the bidding simulation ends, GENCOs will submit the final bid to the ISO. Then the ISO re-schedules the maintenance slots based on the bidding of GENCOs, considering the effects of these changes on the reliability index.
g) Due to the nonprofit characteristic, the revenue collected from the GENCOs is used to improve operational reliability such as utilizing inter-regional power exchange, encouraging the users to participate in the demand response.
h) The final maintenance schedule is released by the ISO.

C. Bidding for Alternate Maintenance Slots

GENCOs are mostly concerned about how maintenance schedules will affect their profits. They can decide whether or not to accept the R-MS. If a GENCO doesn't accept the R-MS, it can bid for another maintenance slot. Each bid reflects the preference of the GENCO for a different maintenance slot for

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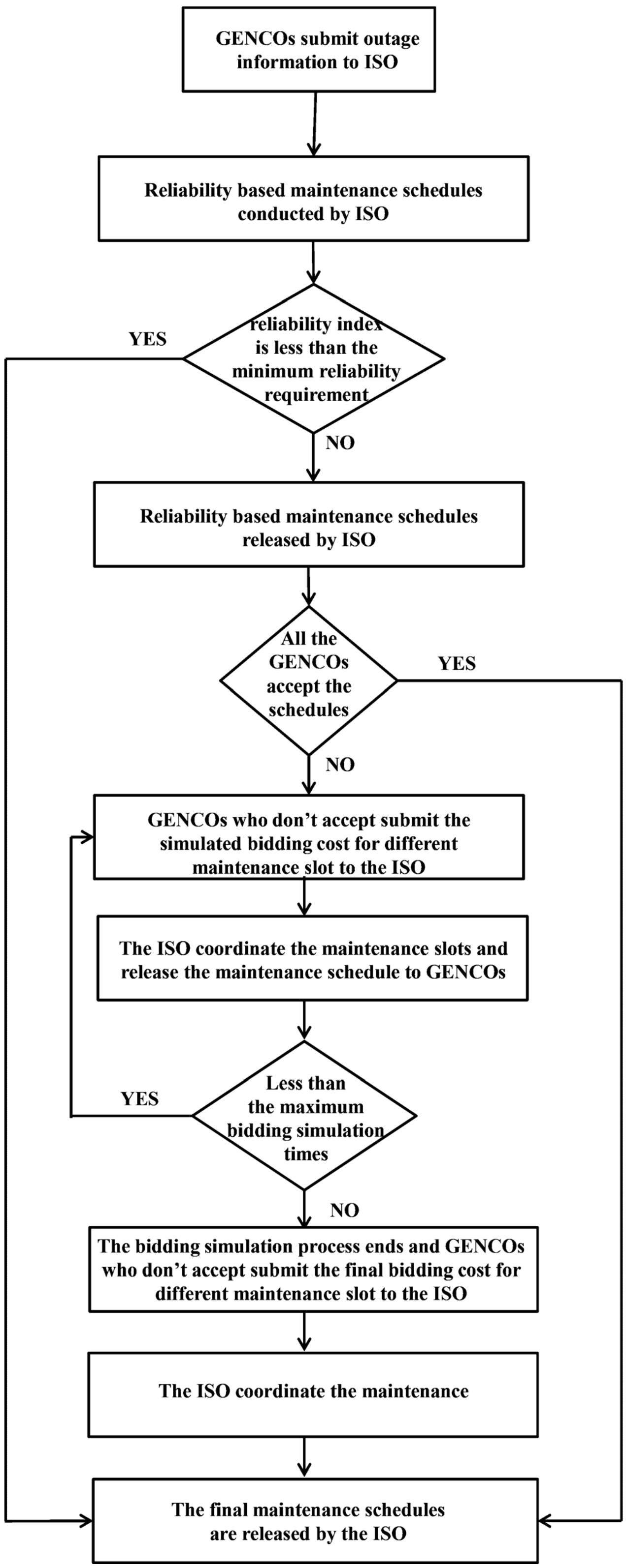

Fig. 1. Flowchart of the coordination mechanism for GENCOs.

a given generating unit and how much the GENCO is willing to pay for the maintenance slot. A GENCO's bdding depends on its operating plan, its business strategy and the strategies of other GENCOs [19].

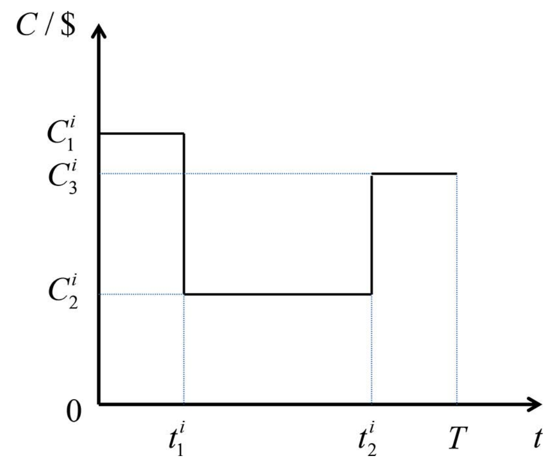

Fig. 2. Bid for other maintenance slots for unit i.

Fig. 2 illustrates the bids that the owner of generating unit i can submit. In Fig. 2, C means the bid. This company is willing to pay C_1^i to be allowed to be on maintenance during interval $[0, t_1^i]$, C_2^i for interval $[t_1^i, t_2^i]$, and C_3^i for interval $[t_2^i, T]$. Since $C_1^i > C_3^i > C_2^i$, interval $[0, t_1^i]$ is its most preferred maintenance window for generating unit i.

D. Settlement Mechanism

In this paper, generating units that don't accept the initial maintenance schedule are termed as "bidding units", while generating units that accept the initial maintenance schedules are termed as "non bidding units". Adjusting the maintenance schedules of the bidding units, will usually worsen the reliability index for some periods. The ISO should therefore use the revenue collected from the bidding units to improve the operational reliability of the system [23].

In conclusions, according to the three procedures above, the proposed mechanism not only ensures the profits of the GENCOs, but also maintains the operational reliability of the system.

III. Problem Formulation

A. Reliability-Based Maintenance Scheduling

The objective function of the Reliability-Based Maintenance Scheduling model is to maximize the Reliability Index as follows:

$$\max RI = \max \frac{T-1}{\sum_{t=2}^{T} |S_t - S_{t-1}|} = \max \frac{T-1}{\sum_{t=2}^{T} S_t^{abs}} = \min \frac{\sum_{t=2}^{T} S_t^{abs}}{T-1} \quad (2)$$

where:

$$S_t = \sum_{i-1}^{NG} (1 - X_{i,t}) G_{i,max} - D_t \quad (3)$$

S_t^{abs} is linearized as follows:

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$$S_t^{abs} \geq S_t - S_{t-1} \tag{4a}$$
$$S_t^{abs} \geq S_{t-1} - S_t \tag{4b}$$

B. Constraints

For each maintenance window of generating unit i the maintenance outage duration constraint is:

$$\sum_{t=1}^{T} X_{i_j,t} = MD_{i_j}, \quad i = 1, \ldots, NG_m, \quad j = 1, \ldots, MT_i \tag{5}$$

The maintenance must be completed once it begins, the maintenance continuity constraint of generating unit i is:

$$X_{i_j,t} - X_{i_j,t-1} \leq X_{i_j,t+MD_{i_j}-1}, \quad \forall i, \forall j, \forall t \tag{6}$$

where $X_{i_j,t} = 0, \forall t \leq 0, \forall t > T$.

Since different windows of the same generating units cannot be overlapped, then:

$$\sum_{j=1}^{MT_i} X_{i_j,t} \leq 1, \quad \forall i, \forall t \tag{7}$$

Generating units located in the same power plant typically cannot be on maintenance simultaneously. This introduces maintenance exclusive constraints:

$$\sum_{i_j \in \Phi_e} X_{i_j,t} \leq 1, \quad \forall t \tag{8}$$

Since the number of units on maintenance for GENCO c is limited at each time period, maintenance simultaneity constraints must be introduced:

$$\sum_{i_j \in \Phi_s} X_{i_j,t} \leq N_{s,t} \tag{9}$$

Maintenance priority constraints are introduced if unit i_j^1 must be maintained prior to unit i_j^2:

$$\sum_{\tau=1}^{t} X_{i_j^1,\tau-1} - X_{i_j^2,t} \geq 0, \quad i_j^1, i_j^2 \in \Phi_p, \quad \forall t \tag{10}$$

From a system perspective, the following constraints must also be observed:

Positive spinning reserve:

$$S_t \geq D_t \cdot R, \forall t \tag{11}$$

System power balance:

$$\sum_{i=1}^{NG} P_{i,t} = D_t, \forall t \tag{12}$$

For the sake of simplicity, unit commitment is not considered. Minimum and maximum power generation limits of maintenance generation unit i:

$$\left(1 - \sum_{j=1}^{MT_i} X_{i_j,t}\right) G_{i,\min} \leq P_{i,t} \leq \left(1 - \sum_{j=1}^{MT_i} X_{i_j,t}\right) G_{i,\max} \tag{13}$$

Minimum and maximum power generation limits of generation unit i which doesn't request to be on maintenance:

$$G_{i,\min} \leq P_{i,t} \leq G_{i,\max} \tag{14}$$

Transmission flow constraints for some main interfaces of the network:

$$P_{l,\min} \leq \sum_{i=1}^{NG} G_{l-i} P_{i,t} - \sum_{n=1}^{NN} G_{l-n} D_{n,t} \leq P_{l,\max} \tag{15}$$

Finally, the decision variables associated with the maintenance status of the generating units are binary:

$$X_{i_j,t} \in \{0, 1\}, \quad i = 1, \ldots, NG_m, \quad j = 1, \ldots, MT_i, \quad \forall t \tag{16}$$

C. Coordination Problem

If GENCOs are not satisfied with the reliability-based maintenance schedule, they provide bids to the ISO that indicate their preferred maintenance periods for each of their units. For those units who have more than one maintenance windows, they can submit different bids for different maintenance window. The ISO must then develop a maintenance schedule that maximizes these preferences. This can be formulated as an optimization problem whose objective is to maximize the bid of GENCOs, i.e., maximize the social welfare:

$$\max \left\{ \sum_{t=1}^{T} \sum_{i=1}^{N_b} \sum_{j=1}^{MT_i^b} C_{i_j,t}^b X_{i_j,t} \right\} \tag{17}$$

Constraints in this model $(\mathrm{Prob}_{\mathrm{C-MS}})$ include (5)–(16) and (18), (19):

$$RI \geq RI_{R-MS}(1 - \lambda) \tag{18}$$
$$0 < \lambda < 1 \tag{19}$$

where λ is a parameter that indicates by how much the reliability index of this modified schedule is allowed to decrease compared to the index of the reliability-based maintenance schedule (RI_{R-MS}). This parameter thus encapsulates the tradeoff between economy and reliability.

IV. Problem Solution

Solving the generation maintenance scheduling problem becomes computationally challenging for large power systems. This section therefore introduces a new solution technique termed relaxation induced method [22] to solve generation maintenance scheduling problems more efficiently. This method can be applied to the solution of the reliability-based maintenance scheduling problem. It proceeds as follows:

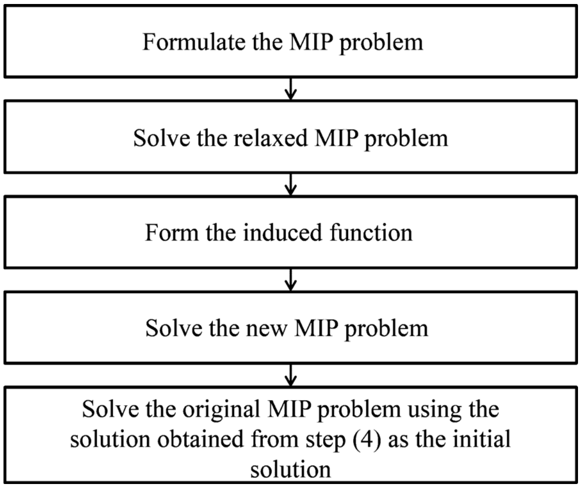

Fig. 3. Flowchart of the proposed relaxation induced method.

Step 1: Let $X'_{i_j,t}$ be the optimal solution of the relaxed problem where constraints (16) are not included.

Step 2: The inducement function is as:

$$\mu_{i_j,t} = [(1/X'_{i_j,t}) - 1]A_{i_j} \tag{20}$$

When $X'_{i_j,t} < \xi, \mu_{i_j,t} = M$, where ξ is a small positive number and M is a large positive number. A_{i_j} is a positive number.

Step 3: The inducement function as second part of (21) is included in the original objective function as (2), then the objective function of the new MIP problem is:

$$\min \left\{ \frac{\sum_{t=2}^{T} S_t^{abs}}{T-1} + \sum_i \sum_j \sum_t \mu_{i_j,t} X_{i_j,t} \right\} \tag{21}$$

Besides the relaxation of the binary variables, this problem is subject to the same constraints as the original problem;

Step 4: Find the optimal solution of this new MIP problem;

Step 5: Solve the original problem using the solution of the relaxed problem as a starting point.

The procedure can be found in Fig. 3.

V. Case Studies

In this section, the performance of the proposed mechanism and model is tested using the IEEE 118-bus system and a model of the power system of a Chinese province over a time horizon of one year (divided into 52 weeks). The testing was carried out using CPLEX 12.4 on an Intel Core® i5-3210 at 2.50 GHz with 8 GB of RAM.

A. IEEE 118-Bus Test System

The IEEE 118-bus system test data can be found in http://motor.ece.iit.edu/data/maintscuc. The system load profile is obtained from a provincial power system in China and is depicted in Fig. 4. Table I summarizes the relevant maintenance characteristics of the generating units.

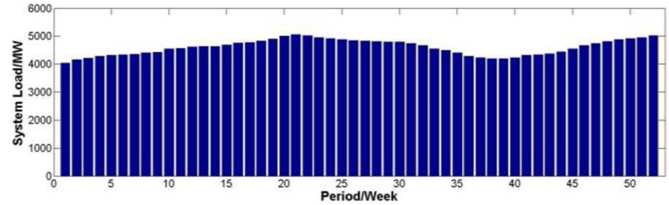

Fig. 4. System load profile.

TABLE I
Unit Maintenance Duration

Unit	1	4	14	21	24	25	26
Duration	2	8	3	4	4	4	4
GENCO	1	1	1	2	2	2	2
Unit	27	39	40	51	52	53	54
Duration	4	8	8	8	3	3	3
GENCO	2	3	3	3	4	4	4

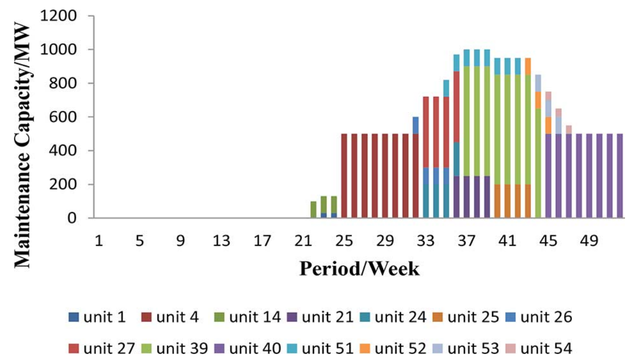

Fig. 5. Maintenance capacity in every period.

1) Reliability Based Maintenance Schedule: The reliability based maintenance schedule is conducted via solving the $\text{Prob}_{\text{R-MS}}$. Fig. 5 shows the maintenance schedule of every generating units and the resulting capacity on maintenance. The reliability index is 0.022. Assuming that the minimum reliability requirement defined by the ISO is 0.0022, then this reliability index is greater than the minimum reliability requirement defined by the ISO, the maintenance schedules are then fed back to the GENCOs. The GENCOs that are not satisfied with the maintenance slots which they have been allocated can submit a bid for other slots to the ISO.

2) Maintenance Coordination: To demonstrate the effectiveness of the proposed mechanism and model, three scenarios are considered as follows:

Scenario A: All the maintenance generating units accept the reliability-based maintenance schedules. The maintenance schedules of every generating units are shown in Table II, which is the same as the reliability based maintenance schedules.

Scenario B: Let us assume that Units 1, 4, 21, 26, 27 and 40 are satisfied with this maintenance schedule while Units 14, 24, 25, 39, 51, 52, 53 and 54 are not. The latter set of units therefore submit the bids shown in Fig. 6 to change their allocated maintenance slot. Given these bids, the ISO performs the maintenance coordination optimization. Different λ encapsulates the tradeoff between economy and reliability, two different cases are considered as follows:

Case 1: $\lambda = 0.4$

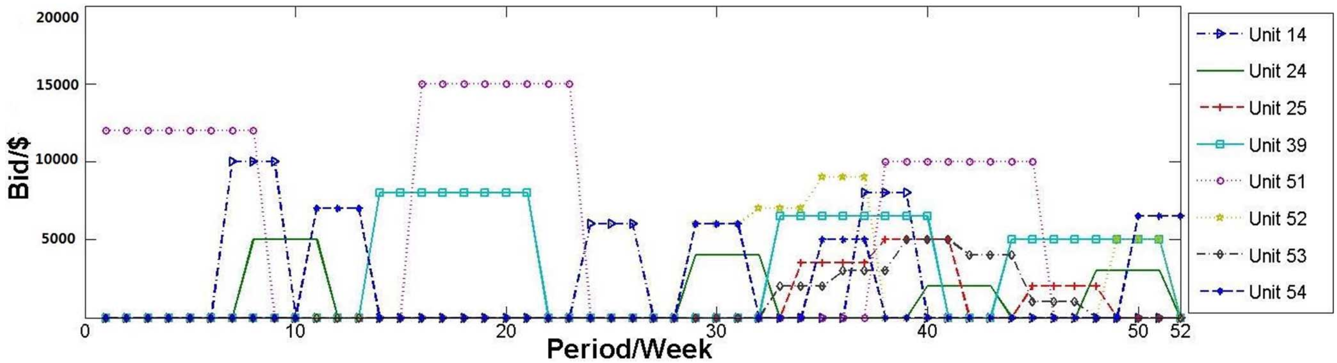

Fig. 6. Bids submitted by the units that are not satisfied with the maintenance slot that they have been allocated in the reliability-based maintenance schedule in Scenario B.

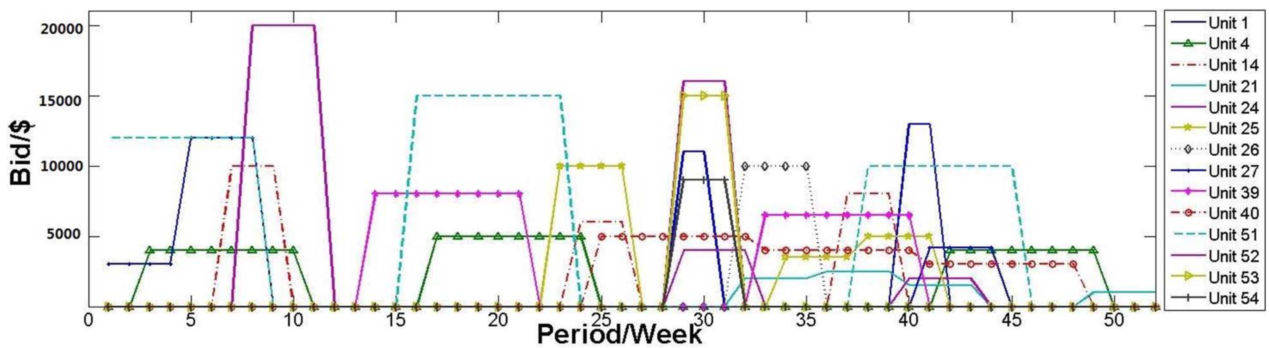

Fig. 7. System reserve of every period in Scenario A, Case 1 in Scenario B and Case 2 in Scenario B.

TABLE II
MAINTENANCE STARTING PERIOD OF EVERY GENERATING UNIT OF SCENARIO A, CASE 1 OF SCENARIO B AND CASE 2 OF SCENARIO B

Maintenance Unit	Scenario A	Case 1 of Scenario B	Case 2 of Scenario B
1	40	40	40
4	17	17	17
14	7	7	7
21	36	36	36
24	8	33	8
25	23	37	38
26	32	32	32
27	5	5	5
39	14	9	14
40	25	25	25
51	16	16	16
52	29	33	35
53	29	41	39
54	29	29	11

The coordinated maintenance schedule of every generating unit is shown in Table II. In this case, not all the bidding units can be maintained during their most preferred slots (e.g., units 25,52,53 and 54), while units 14, 24, 39, 51 can be maintained during their most preferred slots.

Case 2: $\lambda = 0.8$ The coordinated maintenance schedule of every generating unit is shown in Table II. In this case, all the bidding units can be on maintenance during their most preferred slots.

And the system reserve of every period in these two cases and Scenario A is depicted in Fig. 7. The reliability indices of Scenario A, Case 1 in Scenario B, Case 2 in Scenario B are 0.022, 0.013, and 0.008, respectively. It can be concluded that more generating units can be accommodated in their preferred maintenance slots in Case 2. However, this is accompanied by a decrease in the reliability index, i.e., a decrease in the operational reliability of the system.

The correlation between unit bid and maintenance capacity of bidding units is depicted in Fig. 8. In Case 1 of Scenario B, it is shown that from period 8 to 16, although the aggregated bid per MW is very low, the maintenance capacity is large since the load demand during this period is low. On the other hand, from period 34 to 40, because of the higher aggregated bid per MW, some generation units are on maintenance during this period. In Case 2 of Scenario B ($\lambda = 0.8$), the correlation between aggregated unit bid and maintenance capacity of bidding uints is much higher than that of case 1 of Scenario B ($\lambda = 0.4$). For example, for those periods in which the bid is high, the maintenance capacity is relatively large. Thus, it can be concluded that in the proposed maintenance mechanism, the ultimate maintenance schedules not only rely on the bid but also the load demand in each period. Therefore, in order to obtain the most preferred maintenance schedules, the GENCOs have to choose appropriate bid for each unit according to the combination of the forecasted system load and λ that released by ISO.

Scenario C: Let us assume that all the generating units are not satisfied with the reliability-based maintenance schedules. All the maintenance generating units therefore submit the bids shown on Fig. 9 to change their allocated maintenance slot. Given these bids, the ISO performs the maintenance coordination optimization. Likewise, two cases are considered as follows:

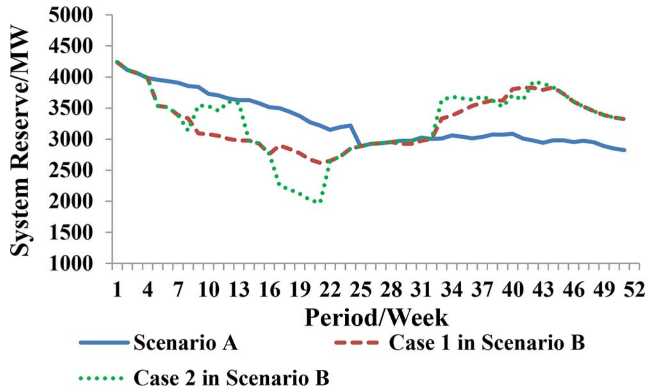

Fig. 8. Aggregated bid per MW and maintenance capacity of bidding units in every period of Case 1 of Scenario B.

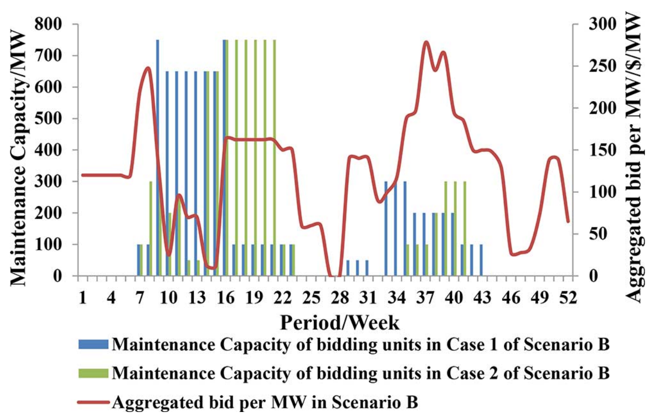

Fig. 9. Bids submitted by the units that are not satisfied with the maintenance slot that they have been allocated in the reliability-based maintenance schedule in Scenario C.

Case 1: $\lambda = 0.4$ The coordinated maintenance schedule of every generating unit is shown in Table III. In this case, not all the bidding units can be maintained during their most preferred slots (e.g., units 4, 25, 27,39 and 54). However, if unit 54 raises the bid (for example: \$19,00) during period 29 to 31, unit 54 can be maintained during its most preferred slots, while units 4, 25,27,39,53 cannot be maintained during their most preferred slots. It can be concluded that submitting an appropriate bids has an impact on the slots that the unit can obtain. How a unit determines how to bid depends on its operating plan, its business strategy and the strategies of other units.

Case 2: $\lambda = 0.8$

The coordinated maintenance schedule of every generating unit is shown in Table III. In this case, the preferences of all bidding units can be accommodated.

It can be concluded that the final maintenance schedules depend on not only the submitted bids of "bidding units" but also the λ that ISO set up.

To illustrate the proposed mechanism further, more cases of different values of λ in Scenario C are tested. Fig. 10 illustrates how the system reserve varies over the maintenance horizon for different values of λ. Fig. 11 shows how the objective function of the coordination model and the reliability index vary with λ. C-ISO in this figure means the coordination model of ISO. As λ increases, more generating units can be accommodated in their preferred maintenance slots and the objective function increases, which represents the total preferences of all the bidding units. However, this is accompanied by a decrease in the reliability index, i.e., a decrease in the operational reliability of the system. Therefore, ISO can choose an appropriate λ to encapsulate the tradeoff between economy and reliability. And to obtain the satisfied maintenance slots, GENCOs have to submit an appropriate bid for themselves.

TABLE III
MAINTENANCE STARTING PERIOD OF EVERY GENERATING UNIT OF CASE 1 OF SCENARIO C AND CASE 2 OF SCENARIO C

Maintenance Unit	Case 1 of Scenario C	Case 2 of Scenario C
1	40	40
4	41	17
14	7	7
21	36	36
24	8	8
25	24	23
26	32	32
27	49	5
39	33	14
40	25	25
51	16	16
52	29	29
53	29	29
54	28	29

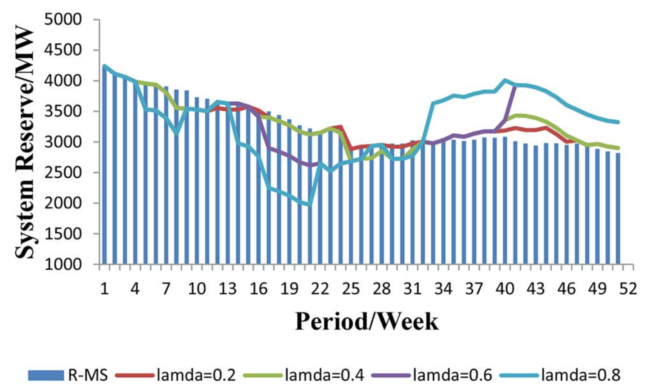

Fig. 10. System reserve over the maintenance horizon for different values of λ.

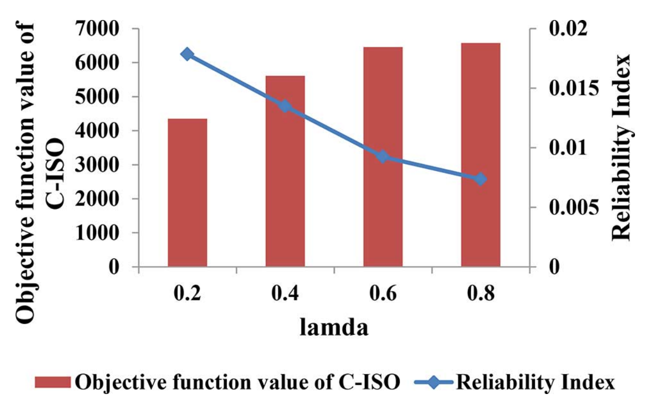

Fig. 11. Objective function and reliability index as a function of λ.

3) Computational Performance: Fig. 12 illustrates the improvement in computation time achieved through the implementation of the relaxation induced algorithm over a direct application of CPLEX for various values of the duality gap when

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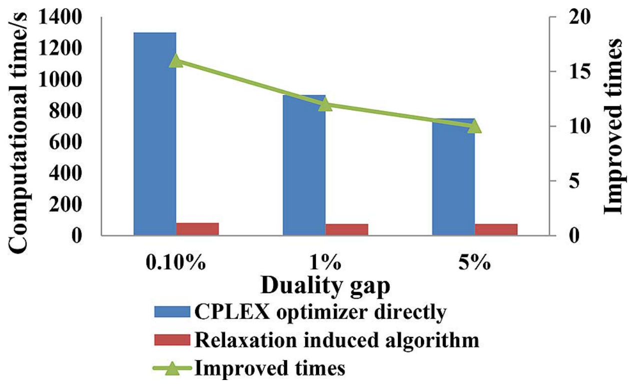


Fig. 12. Comparison of the computation time.

solving the $\text{Prob}_{\text{R-MS}}$. The relaxation induced algorithm reduces the computing time by a factor of 16, 12, 10 as compared with the direct application of the CPLEX optimizer in different values of the duality gap, respectively It can be concluded that the algorithm is quite efficient at solving the optimization problem.

B. A Provincial Power System in China

To validate the effectiveness of the proposed mechanism, model and algorithm further, a provincial power system in China is employed. The system consists of 215 generation units, 480 buses and 963 transmission lines. 50 of all the generation units have two maintenance windows over the year, the rest has only one maintenance window over the year. The minimum reliability requirement defined by the ISO is 0.0005.

1) Maintenance Scheduling Process: The reliability based maintenance schedule is conducted via solving the $\text{Prob}_{\text{R-MS}}$. The reliability index is 0.0062. This reliability index is larger than the minimum reliability requirement defined by the ISO. The maintenance schedules are then fed back to the GENCOs.

100 of the generation units are not satisfied with the maintenance slots which they have been allocated, they submit a bid for other slots to the ISO.

The ISO re-schedules the maintenance slots considering the effects of these changes on the reliability index. λ is set to 0.4. All the generation units obtain the most preferred maintenance schedules. Then the process concludes.

In conclusions, the proposed mechanism works well for large scale realistic power systems.

2) Computational Performance: The value of the duality gap is set to 1% in this case. And computational time of the relaxation induced algorithm in this case is 570s, while the computational time of the direct application of the CPLEX optimizer is 7300s. The relaxation induced algorithm reduces the computing time by a factor of 12.8 as compared with the direct application of the CPLEX optimizer. It can be concluded that the algorithm is quite efficient at solving the large scale optimization problem.

Therefore, the proposed mechanism, model and algorithm can be applied on large scale realistic power systems.

VI. Conclusion

This paper proposes a novel coordination mechanism for generation maintenance scheduling in a competitive market environment. The mechanism mainly involves three steps: 1) The ISO develops a maintenance schedule that maximizes the operational reliability of the system; 2) Generating units that are not satisfied with the maintenance slot that they have been allocated under this schedule can submit bids to obtain better slots; 3) Based on these bids, the ISO develops a coordinated maintenance schedule that maximizes the revenue collected from the bids while performing a trade-off with the inevitable decline in operational reliability.

Test cases demonstrate that the proposed models and algorithm can not only improve the satisfaction of the GENCOs with the final maintenance schedule but also maintain the operational reliability of the system.

A relaxation induced algorithm is utilized to efficiently solve the resulting large MIP problems. This algorithm improves the computational efficiency by more than an order of magnitude.

Future work may include transmission maintenance scheduling, stochastic modeling considering the wind power or load forecasting errors, and the bidding strategy of a GENCO.

References

[1] M. Shahidehpour and M. K. C. Marwali, *Maintenance Scheduling in Restructured Power Systems*. Norwell, MA, USA: Kluwer, 2000.

[2] M. K. C. Marwali and M. Shahidehpour, “Integrated generation and transmission maintenance scheduling with network constraints,” *IEEE Trans. Power Syst.*, vol. 13, no. 3, pp. 1063–1068, Aug. 1998.

[3] R. Billinton and R. Mo, “Composite system maintenance coordination in a deregulated environment,” *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 485–492, Feb. 2005.

[4] Y. Fu, M. Shahidehpour, and L. Zuyi, “Security-constrained optimal coordination of generation and transmission maintenance outage scheduling,” *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1302–1313, Aug. 2007.

[5] Y. Fu, Z. Li, M. Shahidehpour, T. Zheng, and E. Litvinov, “Coordination of midterm outage scheduling with short-term security-constrained unit commitment,” *IEEE Trans. Power Syst.*, vol. 24, no. 4, pp. 1818–1830, Nov. 2009.

[6] M. K. C. Marwali and M. Shahidehpour, “Coordination between long-term and short-term generation scheduling with network constraints,” *IEEE Trans. Power Syst.*, vol. 15, no. 3, pp. 1161–1167, Aug. 2000.

[7] L. Wu, M. Shahidehpour, and Y. Fu, “Security-constrained generation and transmission outage scheduling with uncertainties,” *IEEE Trans. Power Syst.*, vol. 25, no. 3, pp. 1674–1685, Aug. 2010.

[8] H. Pandzic, A. J. Conejo, and I. Kuzle, “An EPEC approach to the yearly maintenance scheduling of generating units,” *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 922–930, May 2013.

[9] Y. Yare and G. K. Venayagamoorthy, “GMS considering uncertainty in wind power in a wind-hydrothermal power system,” in *Proc. IEEE PES General Meeting*, 2010.

[10] Y. Wang, H. Zhong, Q. Xia, Q. Chen, and Y. Bai, “Generation maintenance scheduling considering shiftable loads,” in *Proc. 2014 Int. Conf. Power System Technology (POWERCON 2014)*.

[11] J. Yellen, T. M. Al-Khamis, S. Vermuri, and L. Lemonidis, “A decomposition approach to unit maintenance scheduling,” *IEEE Trans. Power Syst.*, vol. 7, no. 2, pp. 726–733, May 1992.

[12] R. C. Leou, “A flexible unit maintenance scheduling considering uncertainties,” *IEEE Trans. Power Syst.*, vol. 16, no. 3, pp. 552–559, Aug. 2001.

[13] H. Kim, Y. Hayashi, and K. Nara, “An algorithm for thermal unit maintenance scheduling through combined use of GA, SA and TS,” *IEEE Trans. Power Syst.*, vol. 12, no. 1, pp. 329–335, Feb. 1997.

[14] H. H. Zurn and V. H. Quintana, “Generator maintenance scheduling via successive approximations dynamic programming,” *IEEE Trans. Power App. Syst.*, vol. PAS-94, no. 1, pp. 665–671, Mar./Apr. 1975.

[15] New York ISO, Outage Scheduling Manual [Online]. Available: http://www.nyiso.com

[16] Y. Wang and E. Handschin, "Unit maintenance scheduling in open systems using genetic algorithm," in *Proc. IEEE Transmission and Distribution Conf.*, 1999, vol. 1, pp. 334–339.

[17] L. Wu, M. Shahidehpour, and Z. Li, "GENCO's risk-constrained hydrothermal scheduling," *IEEE Trans. Power Syst.*, vol. 23, no. 4, pp. 1847–1858, Nov. 2008.

[18] A. J. Conejo, R. Garcia-Bertrand, and M. Diaz-Salazar, "Generation maintenance scheduling in restructured power systems," *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 984–992, May 2005.

[19] C. Feng and X. Wang, "A competitive mechanism of unit maintenance scheduling in a deregulated environment," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 351–359, Feb. 2010.

[20] G. Lu, C. Y. Chuang, K. P. Wong, and F. Wen, "Unit maintenance scheduling coordination mechanism in electricity market environment," *Proc. IET Gener., Transm., Distrib.*, vol. 5, no. 24, pp. 646–654, Mar. 2008.

[21] C. G. Min, M. K. Kim, J. K. Park, and Y. T. Yoon, "Game-theory-based generation maintenance scheduling in electricity markets," *Energy*, vol. 55, pp. 310–318, 2013.

[22] Y. Wang, H. Zhong, Q. Xia, D. Kirschen, and C. Kang, "An approach for integrated generation and transmission maintenance scheduling considering N-1 contingencies," *IEEE Trans. Power Syst.*, to be published.

[23] PJM Manuals [Online]. Available: http://www.pjm.com/documents/manuals.aspx

[24] G. T. Egan, T. S. Dillon, and K. Morsztyn, "An experimental method of determination of optimal maintenance schedules in power systems using the branch-and-bound technique," *IEEE Trans. Syst., Man, Cybern.*, vol. 8, pp. 538–547, 1976.

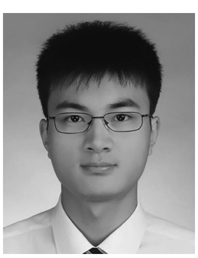
[25] I. El-Amin, S. Duffuaa, and M. Abbas, "A tabu search algorithm for maintenance scheduling of generating units," *Electr. Power Syst. Res.*, vol. 54, no. 2, pp. 91–99, 2000.

[26] R. C. Leou, "A new method for unit maintenance scheduling considering reliability and operation expense," *Int. J. Elect. Power Energy Syst.*, vol. 28, no. 7, pp. 471–481, 2006.

[27] Y. Yare, G. K. Venayagamoorthy, and U. O. Aliyu, "Optimal generator maintenance scheduling using a modified discrete PSO," *IET Gener., Transm., Distrib.*, vol. 2, no. 6, pp. 834–846, 2008.

[28] T. Satoh and K. Nara, "Maintenance scheduling by using simulated annealing method [for power plants]," *IEEE Trans. Power Syst.*, vol. 6, no. 2, pp. 850–857, May 1991.

[29] A. Mishra and G. V. N. Kumar, "Congestion management of power system with interline power flow controller using disparity line utilization factor and multi-objective differential evolution," *CSEE J. Power Energy Syst.*, vol. 1, no. 3, pp. 76–85, 2015.



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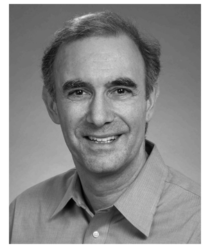

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