A novel integrated long-term generation maintenance coordination and midterm security-constrained unit commitment from ISO's perspective

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In a restructured power system, generation maintenance scheduling makes a significant effect on the operation and planning of the power system. Optimal maintenance schedule would improve power system reliability; as it can reduce unplanned outages and avoid high costs of production losses. Moreover, planned outages may be cut down by avoiding unnecessary maintenance activities. Therefore, it is crucial to study approaches for the generation maintenance schedule. In this paper, a novel approach for the long-term generation maintenance scheduling is proposed which mainly focuses on the ISO's perspective. The approach benefits from the reliability centered maintenance concept by employing criticality indices in the scheduling model. Besides, it founded on new-defined maintenance proposals which would be submitted by generation companies and would make the model more realistic. The coordination between maintenance scheduling and security-constrained unit commitment problem is considered in this study. The model is solved by a mixed integer and real coded genetic algorithm which is combined with a quadratic programming solver. For systematic analysis, the IEEE 30-Bus is employed and the results are presented which emphasize the effectiveness and applicability of the proposed approach.

keywords: *Generation Maintenance coordination, Reliability-centered maintenance coordination, Power system reliability, SCUC, Genetic algorithm.*

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1. INTRODUCTION

Planned and unplanned outages are one of the most significant factors regarding the reliability and profitability of industrial systems. Optimal maintenance schedules not only can reduce stochastic failures and prevents costly production losses, but also can avoid expensive unnecessary maintenance activities. Specifically speaking, high costs in production, outage, and maintenance make this issue one of the challenging ones in power systems. So that generation's maintenance scheduling (GMS) is among the commonly discussed types of studies in power system planning [1]. It is defined as finding the optimal outage time within a specific horizon while considering the economics and reliability of power system participants/equipment [2]. In most recent studies, generation maintenance scheduling has been extensively investigated. However, researches have tended to focus on vertically integrated rather than restructured power systems [3–5]. The studies on maintenance scheduling under restructured power systems falls into two main categories which are summarized in Table 1.

In the first category, researchers have modeled a uni-step maintenance optimization and highlighted adding new features to the problem. One of the most important points of these references is integrating the GMS problem with operation problems; e.g. Unit Commitment (UC). Since maintenance activities of generating units could make them unavailable in the UC problem. On the other hand, operation hours and production levels deteriorate failure rate and affect maintenance intervals. So not coordinating these problems lead to infeasible solution on both sides. It, however, makes the problem more complicated, consequently has been studied in a few researches of past literature.

In [6], authors propose a multi-objective optimization model considers financial returns from selling electricity and the system reserve as the objective functions. A global criterion approach is employed in this paper. References [7, 8] have investigated the coordination of maintenance schedules and operation problem. In these references, long-term equipment maintenance

Table 1. Summery of maintenance shceduling papers

Ref.	Coordination Mechanism	Reliability criteria	Operation	Security	Optimization Method
[6]	-	network reserve	-	-	global criterion approach
[7–10]	-	-	*	*	Lagrangian relaxation
[11]	Iterative Approach	Deterministic criteria	-	-	CPLEX 8.1 under GAMS
[12, 13]	Iterative Approach	EENS	-	-	CPLEX-Cobweb
[14]	Iterative Approach	LOLP	-	-	Modified PSO
[15]	Iterative Approach	EENS	-	-	GA
[16]	Iterative Approach	Reserve	-	-	Game Theory
[17]	Maintenance Bidding	Adequacy	-	-	GA
[18]	Maintenance Bidding	Adequacy	-	-	CLONAL selection algorithm
[19]	Maintenance Bidding	EENS	OPF	N-1 contingency	NSGA-II
[20]	Maintenance Bidding	Deterministic criteria	OPF	N-1 contingency	GA primal-dual interior-point method
[21]	Maintenance Market	EENS	-	-	Game theory- CPLEX
[22]	Maintenance Market	EENS	-	-	GA
[23]	Maintenance Market	EENS	-	-	Dynamic Game Theory
[24]	Maintenance Market	network reserve	-	Network modeling	primal-dual
[25]	Maintenance Market	network reserve	-	-	Game theory-GAMS

and security constraint unit commitment are co-optimized. Following these studies, Ref. [9] considers the uncertainties and Ref. [10] studies the impact of covariates. In these references focus on maintenance and SCUC coordination and no mechanism for maintenance scheduling which highlight the role of different participants is presented. lagrangian relaxation (LR) method is applied in the studies. The second category, however, have focused on introducing new coordination mechanism. Deregulation and introducing new participants in restructured power systems added ambiguity to the GMS problem. Generation companies (GENCOs) tend to optimize their maintenance activity, whereas independent system operator (ISO) is responsible for reliability and security of the power system. This fact makes traditional optimization models impractical and it is the leading cause of several pieces of research to focuses on new coordination mechanisms, instead. Iterative process, maintenance bidding and maintenance market are main investigated mechanism.

Ref. [11] addresses generation maintenance scheduling in a competitive electric energy environment using an iterative approach. In this study power system reliability and profit curve are the objective functions of ISO and GENCOs which are maximized independently. Based on the resultant schedules, ISO would estimate weekly incentives/disincentives to be added to GENCO's objective functions. In this paper a deterministic reliability criteria is employed. Also, network constraints and the security of power system are not considered. In Ref. [12, 13], the iterative process is studied between GENCOs, IMO, and ISO. In this paper, GENCOs schedule their maintenance proposals by maximizing their profit. If the reliability indices of obtained maintenance proposals are under acceptable level, penalties/rewards signals are calculated. GENCOs modify their maintenance proposals based on these signals and the new electricity prices provided by IMO. Although the impact of the power market is studied in this reference, only adequacy reliability indices are calculated, and the security of the power system is not considered. Ref. [14] also focuses on iterative coordination mechanism by maximization of profit and reliability. In these paper LOLP criteria is employed. The coordination mechanism of Ref. [15] is iterative process in which profit is the objective function of GENCOs. In this paper ISO also solves a similar maintenance optimization problem to find a benchmark. The difference of system costs in the two schedules is the base of estimating the corrective signals. Security constraints of the power network are not studied in this reference. Also, only EENS criteria are applied in ISO objective function. In Ref. [16] a non-cooperative game theory is employed by GENCOs to maximize their profit. The ISO calculates the rescheduling signals through reliability assessment.

Ref. [17] studies the concept of maintenance in which GENCOs calculate and submit the maintenance bids by making cost-benefit calculations. The ISO makes a balance between the preference of GENCOs for maintenance occasions, and the possibility of load interruptions. According to the outage schedule, a cost settlement is applied. Maintenance bidding is the coordination mechanism of the Ref. [18]. In this paper, GENCOs submit their maintenance bids which represent its willingness to carry out the maintenance. ISO maximizes producer profits and network reliability determine final schedule. Only the adequacy of the system is taken into account and security is not considered. Ref. [19] also investigates bidding mechanism in which GENCO declares its willingness to perform the maintenance at any time interval using bid. ISO solves a three-dimensional optimization problem and propose a set of a candidate solution to be voted by GENCOs. The schedule with most votes is selected as the final maintenance schedules. In this reference, the OPF and the contingency analysis are used to estimate the EENS. In Ref. [20] an ISO-based security constrained maintenance coordination is studied. The approach comprises two main phases, the security-based maintenance scheduling and the bidding based maintenance coordination. Moreover, the N -1 contingency analysis and long-term SCOPF are considered in this study.

Another coordination mechanism is Maintenance market. It is investigated in Ref. [21] which GENCOs maximizes their profits by considering the energy market and the maintenance market. The game theory is used to model the behavior of other participants and to select the best strategy. This will be submitted to ISO for participating in the market. If the schedule is not accepted, a corrective signal is sent for GENCOs. EENS is estimated by ISO using the Monte Carlo method. No security constraint considered in this paper. Ref. [22] also developed this concept in which the genetic algorithm has been used and the energy the market has been seen alongside the maintenance market. It is followed by Ref. [23] which introduces the Lost Opportunity Cost of Market Participants (LOCMP) parameter. The same maintenance market mechanism is employed in this paper and the Nash equilibrium is derived from the dynamic game theory method and by minimizing the LOCMP coefficient. Network security is not considered.

Ref. [24] also models maintenance market which uses a bi-level approach. The upper level represents the revenue the function of GENCO, whereas the lower-level problem represents the market-clearing process by the ISO. The problem is then converted into a single-level MINL optimization using the primal-dual theorem. In [25] a risk-constrained short-term GMS problem in an oligopolistic electricity market is investigated. In this paper the long term maintenance plan is considered which is executed by ISO. This plan would be utilized in Individual scheduling of GenCos which aims to maximizing the profit to obtain the priorities of maintenance intervals. Stochastic parameters include uncertainty in the price and the rivals' behavior of individual GenCos. each GenCo sends its maintenance schedule to the ISO for evaluating the reserve level. The interactions among GenCos in the LT-GMS, is modeled using a game-theoretic approach.

It is thus essential to pay a great deal of attention to potential coordination mechanisms that apply to the restructured power system. Besides, the availability of data in a restructured power system is restricted compared to traditional power systems. Therefore considerable care must be taken when studying the role of participants in the scheduling process. This fact doesn't receive enough attention in the first category. Moreover, security of the power system and integrating with operational problem are two important areas which are almost ignored in the second category.

Moreover, GMS studies have considered cost, reliability or both as the objective function of the problem. Also, a set of constraints includes maintenance-related, power system security and operational limits should be considered in solving this optimization problem. Moreover, integrating GMS and UC problem make it more complicated; as it mostly has a mixed integer non-linear and nonconvex model. Several optimizations methods range from heuristics, meta-heuristics [26] and mathematical programming [27, 28] are employed to overcome the complicity of the problem. Mathematical programming methods are powerful methods in finding the global optimal solution, but they do not apply to non-linear models. Although metaheuristic methods may not be as reliable as the first methods, they could face with the nonlinearity of GMS problems [1]. Since considering probabilistic reliability criteria in the model would make it non-linear, it seems that employing a hybrid of mathematical programming and metaheuristic methods can be a better choice.

This paper outlined a coordination mechanism of long-term generation maintenance scheduling under restructured power systems. To the best of the authors' knowledge, not enough caution is taken to the role of ISO and the limitation of data availability. This may mislead the problem from the optimal solution. So the proposed mechanism focuses on the ISO's perspective in the generation maintenance schedule. To incorporate operational problems and security criteria, mid-term security-constrained unit commitment (SCUC) is also coordinated with the main problem. The problem is a multi-objective model that considers power system reliability and social welfare simultaneously. The power system reliability is related to the ISO's preferred objective and is inspired by the reliability-centered maintenance (RCM) concept. The latter part is the GENCO's preferred objective in which a new maintenance proposal is employed. As a result, the model is defined as a mixed-integer non-linear programming (MINLP) model. Therefore a hybrid of mathematical programming and metaheuristic methods is introduced for solving the problem. Consequently, the significant highlights of this paper are as follows.

1. The approach addresses the role of ISO in the maintenance coordination process.
2. A new coordination mechanism is proposed which also integrates generation maintenance coordination and security-constrained unit commitment.
3. The model is an MINLP multi-objective which makes a tradeoff between reliability and social welfare objective functions.
4. ISO's objective function is based on the reliability of the power system and inspired by the RCM approach. A criticality index is employed in this objective function.
5. Social welfare objective function shows the preferred maintenance time of GENCOs. For this approach, a new model for maintenance proposals is presented which is a mixture of iterative process and maintenance bidding approach.
6. A hybrid solving method of meta-heuristics approach; e.g. genetic algorithms and mathematical programming is introduced in this paper.

The remainder of this paper is organized as follows. Section 2 presents the proposed generation maintenance coordination mechanism. Section 3 describes the mathematical formulation of the coordination mechanism. The proposed solution procedure is described in Sections 4 and 5 presents numerical examples, and the study is summarized in Section 6.

2. ISO-ORIENTED GENERATION MAINTENANCE COORDINATION MECHANISM

The approach of maintenance schedule in a vertically integrated power system is based on a central optimization of reliability and economy over the whole system. This process is done by the utility who owns the generation and transmission facilities. By introducing the restructured power systems, it is essential to study new maintenance coordination approaches, since each participant, e.g. ISO, GENCOs and TRANSCOs, seeks their independent and specific objective. Fig. 1 shows the proposed ISO-oriented maintenance coordination process.

In this approach, the security of the system, the economy of unit maintenance and fairness among GENCOs are considered in maintenance scheduling. The following twelve steps are included in the presented approach:

1. The required information is gathered from GENCOs.
2. GENCOs submit their maintenance proposals (defined in mathematical model)
3. ISO executes the security-based maintenance scheduling by maximizing the criticality indices and maintenance priority indices subject to a set of network security constraints. if any solution found, the process would go through step 12.
4. If no solution found, the unsatisfied constraints are found and modified.
5. The relaxed ISO-oriented maintenance coordination would be solved by the ISO.
6. If no solution found, the process would go through step 4.

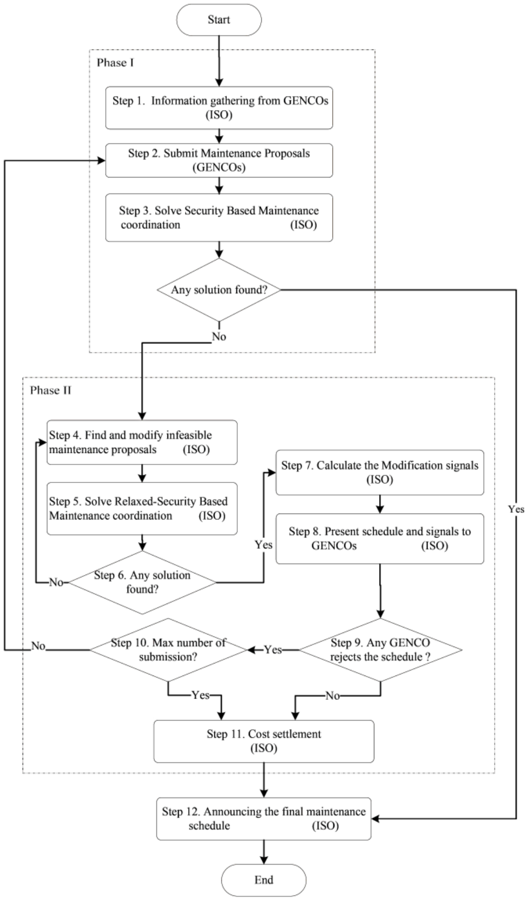


Fig. 1. The proposed ISO-oriented maintenance coordination process.

7. Since some of the maintenance proposals are ignored, the ISO calculates the modification signals.

8. The maintenance schedule and related modification signals would be presented to GENCOs by the ISO.

9. GENCOs evaluate the maintenance plan according to their profit curves, and if it is appropriate, the process would go through step 11.

10. If the limited number of submissions is not exceeded, the process would go through step 2.

11. The cost settlement process is done for the final schedule.

12. The final maintenance schedule is approved by the ISO and announced to GENCOs.

3. MATHEMATICAL MODEL OF ISO-ORIENTED GENERATION MAINTENANCE COORDINATION

The proposed model of this phase is formulated as a Mixed Integer Non-Linear Programming (MINLP) model. In this model the ISO aim to optimize network security and social welfare while satisfying a set of maintenance and operation constraints. The objective is to minimize the ISO's preference Objective (O_{ISO}) and to maximize GENCOs' preference Objective (O_{GENCO}). A weighted coefficient method is employed to handle this multi objective function. Weighting coefficients α and β are used for the objective functions, respectively. It should be noted that $\alpha = 1 - \beta$.

A. ISO's preference objective

The ISO's preference Objective function O_{ISO} is given in Eq. (1). The objective of this section is to find the maintenance occasions with lowest criticality indices. The criticality indices show the effect of generating units maintenance on power system reliability regards to ISO's perspective. In other words, the hierarchy of generation units are estimated using some specific criteria (e.g. reliability, outage cost,...) and expressed by criticality indices.

$$Min \sum_{t=0}^{T} \left[\sum_{g=1}^{N_{gm}} CR_{(g,t)}^{G} \cdot X_{(g,t)} \right] \tag{1}$$

$X_{(g,t)}$ is the decision variable which indicate maintenance occasion for unit g at time t. N_{gm} is the number of maintenance units and $CR_{g,t}^{G}$ is the criticality indices of generation units.

B. GENCOs' preference objective

At the first step, GENCOs submit their maintenance proposal which is their preferred maintenance occasion. Each proposal is an optional maintenance occasion which consists of four different categories: maintenance start time, maintenance duration, allowed offset for start time, priority index. Each company can submit P maintenance proposals for each maintenance activity.

1. Maintenance start time is the day number in which the maintenance would start,$S_{(g,p)}^{pro}$.

2. Maintenance duration is the continues period which maintenance activity would last,$D_{(g,p)}^{pro}$.

3. Allowed offset for start time is an interval which the maintenance start time can be postponed or advanced,$\left[s_{(g,p)}^{pro}, e_{(g,p)}^{pro}\right]$.

4. Priority index is a number in [-1,1] which shows the priority of the proposed maintenance occasion,$PI_{(g,p)}^{G}$.

A sample maintenance proposal is presented in Table 2. In this proposal, the maintenance activity would start at day 20 and last for 3 days. The start time can be postponed for 4 days or maybe advanced by 3 days. It is of high priority by a factor of 0.9. Besides, each company may submit their maintenance proposal in a way that shows their disapproval. This can be done by assigning a negative priority index to the maintenance proposal.

Thus maintenance proposals of GENCOs show the preference or disapproval of them for doing maintenance in each maintenance window by a positive or negative priority index. The positive one represents that the time window is a favorable interval to perform a maintenance activity and vice versa.

Table 2. An example of a maintenance proposal

Proposal number	Start time (day)	Duration (day)	Allowed offset (day)	Priority index
1	20	3	[-3,4]	0.9

$$\text{Maxmize} \quad \{\, O_{GENCO} \} = \sum_{p=1}^{P} \sum_{g=1}^{Ngm} PI_{(g,p)}^{G} \; p_{(g,p)}^{G} \tag{2}$$

where $PI_{(g,p)}^{G}$ is the priority indices of generating units for time t and $P_{(g,p)}^{G}$ is the decision variable which shows the acceptance state of maintenance proposal in the schedule.

C. Constraints

In the proposed model a set of constraints is considered which consists of unit maintenance constraints, network security constraints, and related operating constraints. The maintenance-related constraints ((3)-(7)) are modeled in the body of the main problem and meanwhile, others are considered in the subproblem.

$$\sum_{p=1}^{P} s^{pro}_{(g,p)} * p^{G}_{(g,p)} \leq t^{G}_{g} \leq \sum_{p=1}^{P} e^{pro}_{(g,p)} * p^{G}_{(g,p)} \tag{3}$$

$$t^{start}_{(g)} = \sum_{p=1}^{P} \left(\left(S^{pro}_{(g,p)} + t^{G}_{(g)} \right) * p^{G}_{(g,p)} \right) \tag{4}$$

$$t^{end}_{(g)} = \sum_{p=1}^{P} \left[\left(S^{pro}_{(g,p)} + t^{G}_{(g)} + D^{pro}_{(g,p)} \right) * p^{G}_{(g,p)} \right] \tag{5}$$

$$X_{(g,t)} = \begin{cases} 1, & \text{if } t^{start}_{(g)} \leq t \leq t^{end}_{(g)} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

Eqs. (3)-(6) represent two main maintenance related constraints; maintenance duration constraint and continuous maintenance requirement. In the first constraint, each maintenance occasion should last for a defined duration. This is grantees by setting maintenance start ($t^{start}_{(g)}$) and end time ($t^{end}_{(g)}$) with a distance of $D^{pro}_{(g,p)}$. Besides, continuous maintenance requirement implies that maintenance of a component once started will end without a break in between. This constraint is applied in Eq. (7) which calculates the maintenance state matrix. The matrix shows the maintenance occasion for unit g at time t. Here $t^{G}_{(g)}$ is the deviation of maintenance start time to $S^{pro}_{(g,p)}$.

$$\sum_{g \in (\Lambda gen)} X_{(g,t)} \leq NS^{G}_{gen} \quad gen = 1, \cdots, N_{gen}. \tag{7}$$

Constraint (7) limits the number of simultaneous maintenance units belongs to each GENCO. In this constraint, NS^{G}_{gen} the number of allowable simultaneous maintenance units and lines for a GENCO gen. Λgen is the set of generating maintenance units.

D. Sub problem

To have the state of the generating units the SCUC would be solved in every sub-period t. The SCUC formulation can be expressed as a mixed-integer nonlinear optimization problem. The objective function, Eq. (8), is the summation of generation cost functions, f^{i}_{p} for each generator.

$$\min \sum_{i=1}^{N_g} f^{i}_{p} \left(P_{it} \right) \tag{8}$$

Here f^{i}_{p} is stated as a quadratic cost function as Eq. (9). P_{it} is the decision variable which is generating output power.

$$f^{i}_{p} \left(P_{it} \right) = a_i * P^{2}_{it} + b_i * P_{it} + c_i \tag{9}$$

A set of operations and network constraints is considered in the sub-problem which is outlined in the following.

(a) Power balance constraint:

The constraint is stated in Eq. (10) which is expressed in a matrix form.

$$B_{bus} . \Theta + D_t - C_g P_{ict} = 0 \tag{10}$$

Here Θ is the vector of bus voltage angles, D_t is vector of loads at all buses, B_{bus} is the bus susceptances matrix, C_g is the generator connection matrix.

(b) Transmission flow limit:

Eq. (11) is the transmission flow limit where Fmax is the vector of the maximum flow limit.

$$\left| B_f . \Theta \right| \leq F_{max} \tag{11}$$

(c) Limits on generation output power:

The upper and lower limits on the output power of generating unit i at time t are given in Eq. (12);

$$P_{imin} u_{it} \leq P_{it} \leq P_{imax} u_{it} \tag{12}$$

where Pimin and Pimax are minimum and maximum limits of generating output power. u_{it} is the binary decision variable which experess the commitment status of unit i at time t.

(d) Fixed zonal reserve requirements:

The reserve constraint for each generating unit and zone is considered as Eq. (13)-(15).

$$0 \leq r^{z}_{it} \leq R^{max}_{it} \tag{13}$$

$$r^{z}_{it} + P_{it} \leq u_{it} P^{max}_{i} \tag{14}$$

$$\sum_{i=1}^{N_g} \left(r^{z}_{it} \right) \geq R_{lt} \tag{15}$$

Here r^{z}_{it} is reserve quantity provided by unit i in at time t, R^{max}_{it} is a zonal reserve capacity limits for unit i at time t and R_{lt} is MW reserve requirement for zone l at time t.

(e) Minimum up and downtimes:

$$u_{it} - u_{i(t-1)} \leq v_{ti} - w_{ti} \tag{16}$$

$$0 \leq v_{ti} \leq 1 \tag{17}$$

$$0 \leq w_{ti} \leq 1 \tag{18}$$

$$\sum_{y=t-T^{U}_{i}+1}^{t} \left(v_{yi} \right) \leq u_{it} \tag{19}$$

$$\sum_{y=t-T^{D}_{i}+1}^{t} \left(w_{yi} \right) \leq 1 - u_{it} \tag{20}$$

Here v_{ti} and w_{ti} are binary startup and shutdown states for unit i at time t, 1 if the unit has a startup/shutdown event in period t, 0 otherwise.T^{U}_{i} and T^{D}_{i} are the minimum up- and down-time of unit i, respectively.

(f) Coordination Constraints for maintenance problem and SCUC:

Eq. (21) expressed the coordination between the decision variable of the main and subproblem, e.g. generation scheduling and unit commitment. According to this constraint, the generation unit cannot be committed if it is under maintenance.

$$u_{it} \leq 1 - X_{it} \tag{21}$$

(g) Integrality constraints:

$$u_{it} \in \{0, 1\} \tag{22}$$

4. A MIXED INTEGER AND REAL CODED GENETIC ALGORITHM

According to the described model in section 3, the proposed coordination problem is a discontinuous and non-linear model and meanwhile, the sub-problem is a mixed-integer quadratic problem.

According to the described model in section 3, the proposed coordination problem is a discontinuous and non-linear model and meanwhile, the sub-problem is a mixed-integer quadratic problem. To have a more effective solving approach, a hybrid problem-specific solver is proposed in this paper which benefits from both mathematical programming and metaheuristic methods. This solver is a combination of the genetic algorithm (GA) as the main optimization method and a quadratic programming method in sub-problem. The latter case is solved using commercial software [29] Based on a high-performance solver. The solver is MOSEK [30] which is a collection of optimization tools that include large-scale linear programming (LP) and quadratic programming (QP) problems.

GA has been widely employed in power system studies such as economic dispatch [31], load modelling [32], unit commitment [33], etc. In this approach, each potential solution is expressed as an individual, mostly known as a chromosome. In this paper, each chromosome is a matrix which consists of an integer (X^I) and a real (X^R) section. A sample chromosome is presented as Eq. (23).

$$\begin{pmatrix} X^I & | & X^R \end{pmatrix} = \begin{pmatrix} x_1^I & x_1^R \\ x_2^I & x_2^R \\ \vdots & \vdots \\ x_{N_{gm}}^I & x_{N_{gm}}^R \end{pmatrix} \tag{23}$$

The first section is an integer in [1, P] and indicates the number of the selected maintenance proposal (Eq. (24)). The second section is a real-coded part which varies in [-100, 100]. This section would be decoded to the percentage that the maintenance start time deviated from the submitted one Spro in the proposal (Eq. (25)).

$$p_{(g,p)}^G = \begin{pmatrix} 1, & if\ x_{(g)}^I = p \\ 0, & otherwise. \end{pmatrix} \tag{24}$$

$$t_{(g)}^G = \begin{pmatrix} s_{(G,p)}^{pro} \cdot x_{(s)}^R/100, & \text{if } x_{(g)}^R \leq 0 \& p_{(g,p)}^Q = 1 \\ e_{(g,p)}^{pro} * x_{(g)}^R/100, & \text{if } x_{(g)}^R \geq 0 \& p_{(g,p)}^G = 1 \end{pmatrix} \tag{25}$$

Fig. 2 presents the proposed solution approach. The following steps are included in the approach:

1. The initial population would be generated randomly and is known as the first generation.

2. Individuals go through a fitness evaluation process:

2.1. Each individual would be decoded and the number of the selected proposal $p_{(g,p)}^G$ and the deviation of the proposed start time,$t_{(g)}^G$, is estimated. This step also grantees constraints 3 to 6.

2.2. Using the decoded parameters the maintenance state of each unit, $X_{(g,t)}$ would be determined.

2.3. The SCUC problem is solved for each period, considering the maintenance states.

2.4. If the SCUS problem is feasible over the maintenance horizon, the ISO's and GENCO's objective functions are calculated. Otherwise, a big value would be allocated to the objective function to make the individual be discarded.

2.5. The fitness value is, finally, estimated by adding penalty factor to the objective function. The penalty factor is calculated based on the deviation from constraint (7).

3. After the estimation of fitness values, the next generation is produced in an iterative process:

3.1. Selection: using this operator individuals are ranked and selected according to the objective values. The selected individuals (parents) are evolved using crossover and mutation operators. In this paper, the roulette wheel method is the selection operator in which high- fitness individuals have more chances to be selected.

3.2. Crossover: this operator is used to combine two individuals and produced two new individuals (offspring).

3.3. Mutation: the offspring are subjected to the mutation operator to form a new individual. In this paper, a problem-specific mutation is presented and implemented.

3.4. Based on comparing the current generation and mutation children, the next generation is selected. A specific percentage of the new generation is selected using elite selection.

4. If the stopping criterion (fixed number of iteration) is satisfied, the process stops and the best individual is decoded to extract the maintenance schedule. Otherwise, the process goes through step 2.

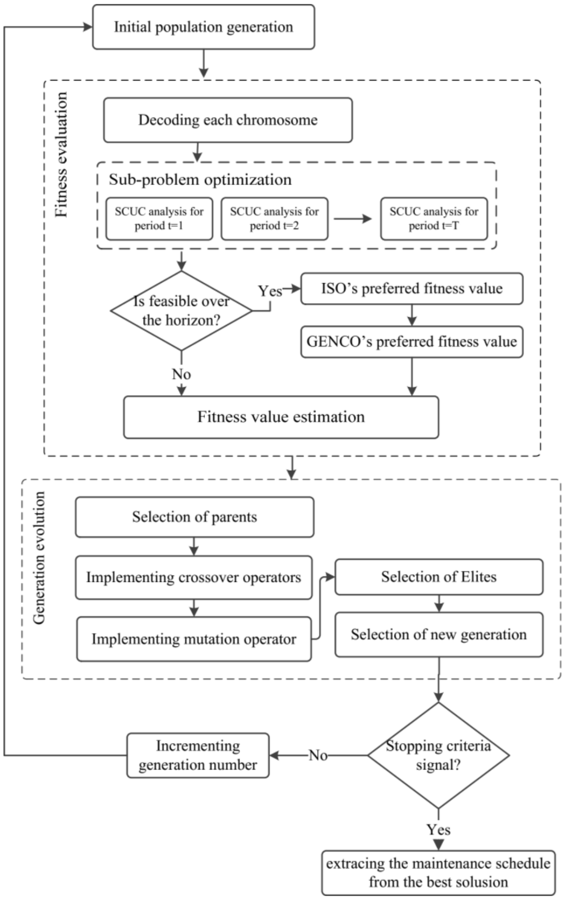


Fig. 2. The proposed genetic algorithm approach.

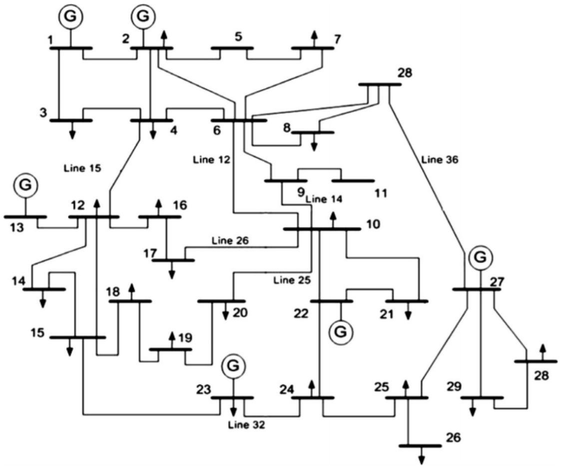


Fig. 3. The IEEE 30-bus test system.

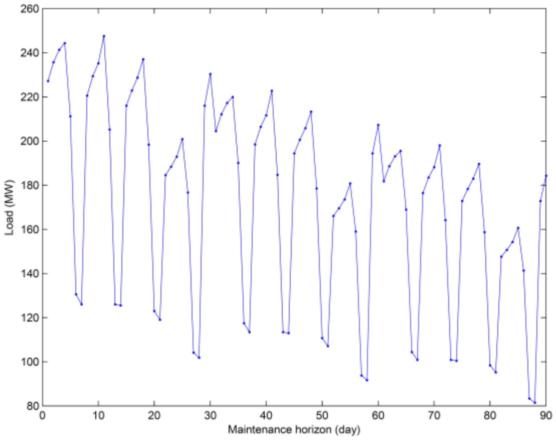


Fig. 4. System load profile for IEEE 30-bus test system.

5. NUMERICAL RESULTS

The effectiveness of the proposed coordination approach is tested by employing several cases on the IEEE 30-bus test system. The maintenance scheduling horizon is a season which is divided into 90 days. The presented results in this section are carried out using Matlab 2013b on an Intel (R) Core (TM Duo CPU@ 2.66 GHz).

The modified IEEE 30-bus system includes six generation units and 41 transmission lines which are illustrated in Fig. 3. The maintenance schedule is considered for two-generation units whose data are presented in Table 3. The system load profile over the maintenance horizon (90 days) is shown in Fig. 4.

Table 3. Generator maintenance related data

unit	At bus	Maintenance window (week)	Duration (day)	GENCO
3	22	1-52	6	1
6	13	1-52	4	2

The following cases are studied to examine the effectiveness of the proposed approach.

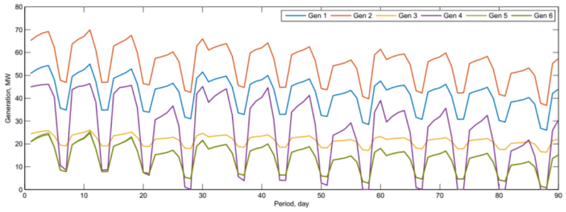


Fig. 5. Generation power for case A.

Table 5. Summary of results in Scenario B-1

Scenario	ISO objective	Genco objective	Total objective	
B-1	3.104	0.7	1.202	Best
	3.478	0.74	1.369	Average
	3.914	0.8	1.557	Worst

- Case A: SCUC without any maintenance
- Case B: coordination of maintenance scheduling and SCUC
- Case C: maintenance scheduling with considering the effect of weighting factor

Case A: In this case, the SCUC problem is solved without considering maintenance activities.

The expected power generation and commitment schedule of case A are shown in Fig. 5. This case is considered as a base case in which only the SCUC problem is solved without considering the maintenance scheduling problem.

Case B: in this case, coordination of generation maintenance scheduling and SCUC problem is studied. As explained before, the proposed approach includes two phases and each phase starts if the previous phase couldn't find any feasible solution. To benchmark both phases, two different scenarios are defined for Case B, as follows:

- Scenario B-1: Maintenance proposals are feasible (Phase I)
- Scenario B-2: A set of maintenance proposals are infeasible (Phase II)

Scenario B-1: In this scenario, GENCOs submit their maintenance proposals based on which the ISO schedules the outage times. The maintenance proposals of this scenario are shown in Table 4.

According to the stochastic characteristic of GA solutions, it is essential to have enough simulations to find the optimum solution. The result is summarized in Table 5. The final maintenance schedule is the best among ten GA runs. The average simulation time of this case is about 105 seconds.

The resultant maintenance schedule of scenario B-1 is presented in Table 6. In this schedule, the first and third proposals of GENCO 1 and 2 are selected, respectively. The maintenance schedule of unit 3 starts on day 16. It is its first maintenance proposal which advances for 2 days. On the other hand, Unit is on maintenance outage on day 51 to 57 and the third maintenance proposal has been selected with a 1-day delay.

The maintenance statue of units 3 and 6 are also shown in Fig. 6. The schedule is aligned with the maintenance proposals in Fig. 7.

The resulting expected dispatch is presented in Fig. 8. It is found that on the outage time of unit 3 (days 16 to 20) almost all generating units have an equal portion in compensating the decreased power since all units are similar in operation cost.

Table 4. Maintenance proposals in Scenario B-1

Genco	unit	proposal number	start time (day)	Duration (day)	allowed offset for start time (day)	Priority index
		1	18	5	[-4,3]	0.4
1	3	2	26	5	[-3,3]	0.5
		3	46	7	[-3,3]	0.1
		1	14	6	[-5,2]	0.4
2	6	2	33	7	[-4,2]	0.3
		3	50	7	[-4,2]	0.3

Table 6. Final results of scenario B-1

Unit	Proposal number	Maintenance start time (day)	Maintenance duration (day)	Priority index
3	1	16	5	0.4
6	3	51	6	0.3

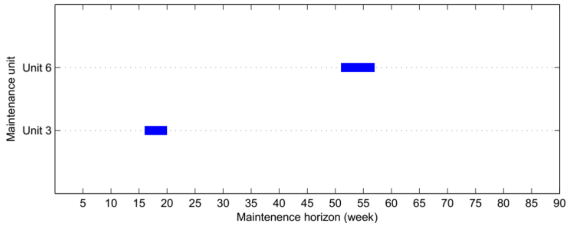


Fig. 6. Maintenance schedule for Scenario B-1.

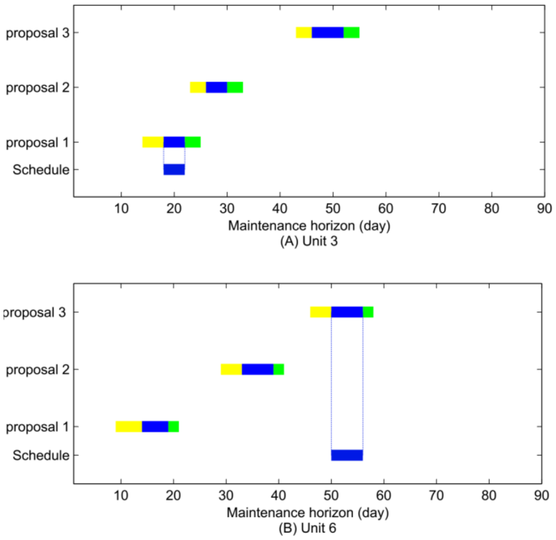


Fig. 7. Maintenance schedule and proposals for Scenario B-1 (blue bar is proposal outage interval, yellow bar shows allowed offset to advance start time, green bar is allowed offset to postpone start time, the dark blue bar is the final maintenance schedule).

Maintenance of unit 6 starts on day 51 and lasts for 6 days. During this maintenance interval Unit, 3 has the lowest power increase compared to other economical units, since it is the most expensive unit.

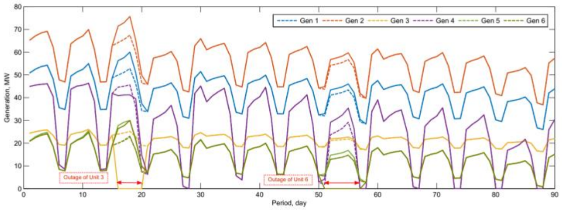


Fig. 8. Generation power for Scenario B-1 (solid lines is the dispatched power in scenario B-1 and dashed lines denote the generation power in base case A).

Table 9. Summary of results in Scenario B-2

Scenario	ISO objective	Genco objective	Total objective	
B-2	4.855	0.586	2.1345	Best
	5.013	0.586	2.2135	Average
	5.314	0.586	2.364	Worst

Table 10. Final results of scenario B-2

Unit	Proposal number	Maintenance start time (day)	Maintenance duration (day)	Priority index
3	2	19	5	0.29
6	2	31	7	0.3

Scenario B-2: In this scenario, not all maintenance proposals are feasible, from the network security view, so the Phase I scheduling wouldn't come out with any feasible result. To solve the problem, the ISO should first distinguish ad discard infeasible proposals and then optimize the modified maintenance proposals (Phase II).

GENCO's maintenance proposals in this scenario are shown in Table 7. Analyzing these maintenance proposals shows that all proposals of Unit 3 and the first proposal of Unit 6 are infeasible and there is no optimal maintenance schedule for the submitted proposals. To have a maintenance schedule, the ISO would execute the second step of the proposed scheduling process; Phase II. In this phase, the infeasible proposals are firstly modified by the ISO which is presented in Table 7. For performing this modification, the interval of allowed offset for start time is extended by 10 days. The priority indices are also changed to increase the chance of finding a feasible maintenance schedule.

The summary of results in Scenario B-2 is presented in Table 9 which is an average of ten GA runs.

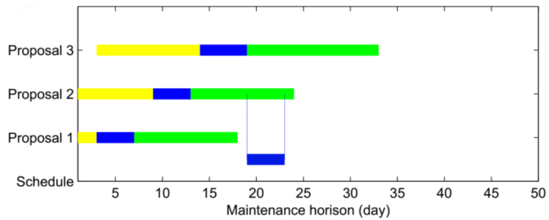
The final results are shown in Table 10 which indicates the proposal number, start time and duration of the maintenance schedule of each unit. Unit 3 is schedule to be on outage on day 19 and for 5 days which is the second one of modified maintenance proposals. Besides, the days 31 to 38 are the maintenance outage days of unit 6.

Table 7. Maintenance proposals in Scenario B-2

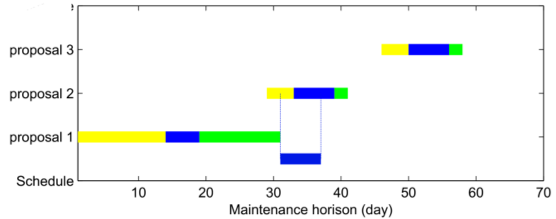
Genco	unit	proposal number	start time (day)	Duration (day)	allowed offset for start time (day)	Priority index
1	3	1	3	5	[-2,1]	0.4
		2	9	5	[-3,1]	0.5
		3	14	6	[-1,4]	0.1
2	6	1	14	6	[-5,2]	0.4
		2	33	7	[-4,2]	0.3
		3	50	7	[-4,2]	0.3

Table 8. Modified maintenance proposals in Scenario B-2

Genco	unit	proposal number	start time (day)	Duration (day)	allowed offset for start time (day)	Priority index
1	3	1	3	5	[-2,11]	0
		2	9	5	[-8,11]	0.29
		3	14	6	[-11,14]	0.71
2	6	1	14	6	[-13,12]	0.4
		2	33	7	[-4,2]	0.3
		3	50	7	[-4,2]	0.3



(A) Unit 3



(B) Unit 6

Fig. 9. Maintenance schedule and proposals for Scenario B-2 (blue bar is proposal outage interval, yellow bar shows allowed offset to advance start time, green bar is allowed offset to postpone start time, the dark blue bar is the final maintenance schedule).

However, this maintenance is selected from GENCO's maintenance proposals, since it is not infeasible. The result is also shown in Fig. 9. The dispatched power of all generating units is also presented in Fig. 10. It can be seen that changes in generated power during maintenance interval follows the same pattern in scenario B-1, based on the fact that economical units have more effective cooperation in power increase.

Case C: in this case, the effect of weighting coefficients, α, on coordination of generation maintenance scheduling and SCUC problem is studied. The maintenance proposal of this case is similar to Case B-1 but the criticality indices are modified. Three different scenarios are defined for this case, as follows:

- Scenario C-1: $\alpha = 0$
- Scenario C-2: $\alpha = 1$
- Scenario C-3: $\alpha = 1/2$

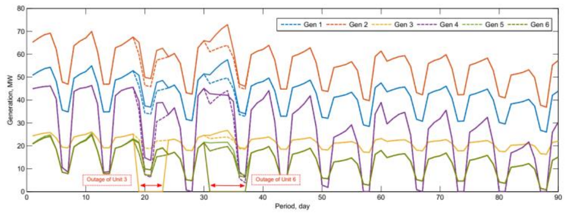


Fig. 10. Generation power for Scenario B-2 (solid lines is the dispatched power in scenario B-1 and dashed lines denote the generation power in base case A).

Table 11. Summary of results in Case C

Scenario	ISO objective	Genco objective	Total objective	
C-1	2.52	0.9	-0.9	Best
	3.943	0.9	-0.9	Average
	5.78	0.9	-0.9	Worst
C-2	1.15	0.4	1.15	Best
	1.2606	0.41	1.2606	Average
	1.536	0.5	1.536	Worst
C-3	1.266	0.5	0.383	Best
	1.363	0.43	0.4665	Average
	1.636	0.4	0.618	Worst

The result of Case C is summarized in Table 11 and Table 12. The final maintenance schedule is the best among ten GA runs. The average simulation time of this case is about 100 seconds.

By applying the $\alpha = 0$ in the objective function, the GENCO's objective receives more weights compared to the ISO's objective. In this scenario, the maintenance occasions of units 3 and 6 are due in days 28 and 16, respectively. As expected, the final results are the most preferred schedule from GENCOs' perspective which means proposals with the highest priority indices are selected.

In the scenario C-2 with $\alpha = 1$, the Genco's objective function is ignored, and only ISO's objective is considered in the optimization process. In the final result, Unit 3 and 6 are maintained

Table 12. The final schedule of Case C

Scenario	Unit	Proposal number	Maintenance start time (day)	Priority index
C-1	3	2	28	0.5
	6	1	16	0.4
C-2	3	3	46	0.1
	6	2	33	0.3
C-3	3	3	45	0.1
	6	1	16	0.4

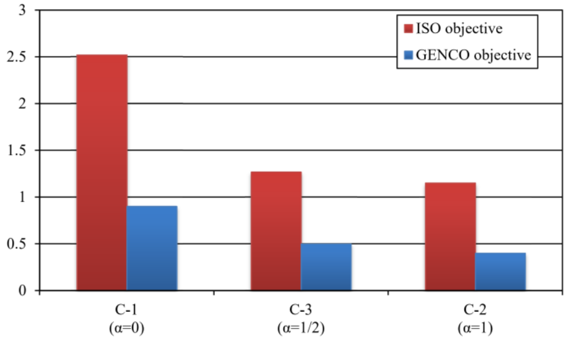


Fig. 11. Comparison of result of Case C.

in days 46 and 33, respectively. Since the GENCO objective function is discarded in the objective value, these days have the minimum values of criticality index over the maintenance horizon.

Scenario C-3 confirms an equal trade-off between two objective functions. In the final result, Unit 3 and 6 are maintained in days 46 and 16, respectively. This scenario is a more realistic case in which led to a balance between two objectives.

The comparison of results is summarized in Fig. 11. As expected decreasing the value of α affects both objectives. It is shown that higher values of α would close the schedule to the GENCOs' preferred days, while the ISO objective would receive less weights. The ISO and GENCO objective values in scenario C-3 are 1.27 and 0.5, which have decreased by 49.7% and 44.4% compared to scenario C-1, respectively. Comparing the same results with scenario C-2 indicates an increase of 10% and 25%, respectively.

These results would confirm the ability of proposed coordination mechanism to find the best solution by making a well balance between the ISO and GENCO objective functions.

6. CONCLUSION

Generation maintenance scheduling in a restructured power system is one of the controversial issues in the power system. It involves two independent participants with contrast benefits; e.g. ISO and GENCOs. While GENCOs seek power market profit and product availability, the ISO concern about the reliability of whole power system. In the literature, the maintenance schedule has been widely studied. These studies vary in different aspects, such as responsible organization, coordination approach, integrating with operation problem, mathematical model and optimizing method. This fact makes the maintenance scheduling a complicated problem that still needs a comprehensive coordination approach to solve the surrounding controversies.

In this paper, a novel generation maintenance coordination approach is proposed which focuses on the ISO's perspective. To have a realistic outcome, it is integrated with the unit commitment problem. This results in a mixed-integer non-linear problem that falls into main and sub problem. The main problem is the multi-objective maintenance scheduling problem which, in turn, includes ISO and GENCO related objective functions. The preference of ISO is considered by employing a set of criticality indices which is inspired by the RCM methodology. Besides a new maintenance proposal scheme is proposed which shows GENCO's preferred maintenance intervals. The approach may be performed in two phases, based on the feasibility of maintenance proposals.

The proposed model is solved using a combination of heuristic and mathematical methods. The genetic algorithm is used for solving the main problem which is a mixed-integer nonlinear problem. Moreover, the sub problem is a mixed-integer quadratic problem and commercial software is employed as its solver. A modified version of the IEEE 30-bus system is used for solving several cases to demonstrate the performance of the proposed method. The model also examined by applying different values of weighting coefficients. Results have shown that with a realistic weighting factor the ISO's objective indicates an average increase of 10% compared to minimum achievable value. Moreover, the GENCO's objective has decreased by 44% compared to maximum possible value. Research into improving the proposed model is already underway. Future work will concentrate on investigating transmission maintenance coordination as well.

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