Turkish Journal of Electrical Engineering & Computer Sciences
http://journals.tubitak.gov.tr/elektrik/
Research Article

Turk J Elec Eng & Comp Sci
(2014) 22: 529 – 545

doi:10.3906/elk-1207-69

Competitive unit maintenance scheduling in a deregulated environment based on preventing market power

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Received: 20.07.2012 • **Accepted:** 21.11.2012 • **Published Online:** 21.03.2014 • **Printed:** 18.04.2014

Abstract: With the advent of electricity markets, the traditional approach to unit maintenance scheduling (UMS) needs to undergo major changes in order to be compatible with competitive environment structures. The transition from a vertical power system to a competitive structure makes many challenges for policymakers and market designers. In this paper, a new approach to UMS in competitive electricity markets is presented. The main part of this study involves both how to treat generating companies (GENCOs) fairly and how to guarantee power system security during the maintenance scheduling. This paper advances the UMS in the electricity market so that one can determine which maintenance plans are to be selected while guaranteeing power system security and ensuring fair competition among GENCOs. The main contribution of this study is the constructing of a new kind of UMS to prevent market power and economic withholding. In order to guarantee power system security, a probabilistic approach of reliability analysis is presented. This probabilistic methodology is designed based on the health levelization and well-being analysis technique. The optimal strategy profile is defined by a genetic algorithm, so it can strike the right balance between profit and security with fair competition. In the end, maintenance scheduling as numerical results for 9 GENCOs of a large-scale IEEE reliability test system is applied to show the applicability of the proposed framework.

Key words: Competitive market, compensation, fairness, reliability, maintenance scheduling

1. Introduction

Power system operations planning has been so challenged with the changing market environments that most privatized generating companies (GENCOs) are pressured to more efficiently schedule and commit their generators in order to maximize their profit [1]. In such a structure, competition among GENCOs in order to maximize the profit is essential and inevitable. The authors in [2] intended the unit maintenance scheduling (UMS) as game theory, where all GENCOs have to participate in the game with strong competition to earn the maximum profit. In the game, GENCOs are the players and the independent system operator (ISO) is intended as the play manager. It is anticipated that each GENCO prefers the maintenance durations corresponding to its own desired conditions.

Therefore, all GENCOs arrange their maintenance plans as a priority list of maintenance durations and submit them. It is most evident that some of the plans may exceed the predefined power system security and therefore will be inapplicable. In fact, the key to the UMS problem is both how to treat GENCOs equally and how to guarantee power system security during the UMS. Therefore, the ISO, as the market operator, has 2 main duties:

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1) coordinating a market-based mechanism for UMS to ensure fair competition among the GENCOs and 2) guaranteeing power system security during the maintenance scheduling.

In such a situation, what plans should be accepted and what plans must be denied? This is one of the most important challenges and allocates the main contribution of recent studies on the grounds of UMS in the power market. Many studies have been done in recent years about this problem. Different papers proposed widespread methods for UMS in the electricity market, some of them based on market-based mechanisms and others not. For instance, the market-based method was adopted in the Spanish [3], Nordic, and British markets [4], whereas the central arrangement is accepted in China currently [5]. As mentioned above, a GENCO's interests as the competition factor and power system security as the reliable operation factor need to be considered simultaneously in the UMS, which is called maintenance coordination. The authors in [5] surveyed some papers and classified the coordination mechanism into the following 3 categories:

1. The ISO coordinated the UMS based on both the GENCO's interest and system security.
2. The ISO negotiated the UMS with GENCOs on behalf of customers and obtained improved system security by paying for GENCOs who would adjust their plans; the cost burden would go to the customers.
3. The ISO coordinated the UMS according to some forms of expression about maintenance desire announced by GENCOs.

Recently, the third category was extended in many papers. In this method, GENCOs bid for all maintenance durations, which are called maintenance windows, and the ISO arranges them according to the maximal bid collected from the GENCOs [6]. If one or more of the GENCOs' maintenance plans are denied due to security considerations, the economic losses are imposed on the corresponding GENCOs. On the other hand, a privatized GENCO is faced with financial losses in order to guarantee power system security and this is against fair competition. Hence, this type of loss should be compensated somehow. There are many disputes about 'How are the losses compensated?' or 'What financial resources must be allocated to compensation?' In this method, the GENCOs face 2 types of losses: 1) losses due to power system security criteria and 2) losses due to buying maintenance windows. The first cost is a negative expense in order to prevent GENCOs from choosing the windows that correspond to the high-risk area of power system security and the latter cost is a positive expense that is paid to the GENCOs in order to encourage them to participate in fair competition [7].

According to the market structure, the ISO is a nonprofit entity; therefore, it has to allocate all of income from selling maintenance windows. Some parts of the incomes should be allocated to GENCOs so that their plans are adjusted or denied. This part of the income compensates the losses of GENCOs due to power system security considerations. After that, residual incomes must be allocated to all GENCOs that participated in the UMS. However, there still exist many disputes about the income allocation mechanism, so different studies have presented various approaches [8]. Some studies allocated the incomes to all GENCOs who participated in the UMS competition [8–10] or allocated them to GENCOs whose plans were revised or denied only.

Many studies have been done on the grounds of UMS in the power market [11], but they have not made a completely fair environment for competition; hence, the concept of the ISO's income allocation still remains unsolved. Table 1 describes the complete qualities of the studied UMS [12–22] models in the 2 last decades.

In this paper, therefore, a novel approach to the UMS problem applicable to fair competition in competitive markets is presented, and it can prevent the exercising of market power by large-capacity GENCOs. The complete maintenance scheduling for the generating units is done according to a market-based mechanism. The numerical results for a 9-GENCO power system are obtained to demonstrate the basic ideas of the proposed

Table 1. A complex of UMS in different studies.

Reference No.	Generation	Transmission	Electrical loss	Cost	Reliability	Fuel limit	Crew availability	Market-based	Optimization method
12	×	×		×	×		×		Benders decomposition
13	×			×	×				Ant colony algorithm
14	×		×	×	×				Heuristic algorithm-tabu search
15	×			×	×	×			Commercial software
16	×			×	×		×		Linear programming & GA
17	×	×		×	×	×	×		Mixed integer programming
18	×	×		×	×	×	×	×	Benders′ decomposition
19	×	×		×	×	×	×		Benders′ decomposition
20	×			×	×	×	×		Duality theory
21	×			×	×			×	GA
22	×				×				Hybrid PSO

method and, at the end, a large-scale IEEE reliability test system (IEEE-RTS) is also considered to show the applicability of the proposed method.

2. UMS in the competitive electricity market

2.1. GENCOs adjust their desired maintenance plans

In the deregulated structure of a power system, a privatized GENCO is pressured toward more efficient schedule maintenance in order to maximize their profit. Therefore, in the maintenance horizon, which is usually supposed to be 1 year, GENCOs try to schedule maintenance in the highly efficient windows while corresponding to the maximum profit. The maintenance request plans that are submitted by GENCOs may contain the following objects:

- Maintenance capacity (MW),
- Maintenance duration (weeks),
- Priority list of maintenance plans.

Willingness-to-pay (WTP) curves are the most common way to express the priority of plans. In these curves, GENCOs determine their desired maintenance duration through a proposed price that will be paid for buying the windows. GENCOs arrange the WTP curves according to their own conditions, which may be different or the same for some GENCOs. Many parameters and constraints may be intended by the companies. Some of them are numerated below.

1. Maintenance history data and the experiences of the maintenance crew and engineers.

2. Spare equipment, expected failure cost model (EFC), and unit failure cost usually used for equipment cost analysis [23]:

$$EFC = \sum_{i=1}^{M} C_i P_i t_c, \tag{1}$$

$$C_i = \frac{R}{N} \sum_{k=1}^{N} S_k, \tag{2}$$

where C_i is the average of the failure cost for failure state i (\$/h), P_i is the probability of state i, t_c is the total duration of the imposed failure cost (h), R is the fixed electricity rate, N is the number of hours during t$_c$, S_k is the loss of load in hour k, and M is the total number of system failure states.

3. Crew availability: the number of people to perform the maintenance schedule cannot exceed the available crew:

$$\sum_i c_i^w x_i^w \leq c_{i,w}^{av}, \tag{3}$$

where c^{av} is the available crew for maintenance; i is the GENCO's number, i = 1,..,G; w is the available windows of the maintenance horizon, w = 1,..,N; and x_i is the decision variable of the UMS (1/0) where 1 means maintenance.

4. Seasonal limitation.

5. Resource availability: the amount of available resource k for maintenance by GENCO i:

$$\sum_w \sum_i r_{ik} x_i^w \leq r_{kt}^{av}, \tag{4}$$

where r_{kt}^{av} is the available resource k for maintenance in time t.

6. Forecasting electricity price in the future: the game theory can forecast the electricity price properly in the power market using dynamic programming, especially for forecasting the electricity price in a spot market or forward markets.

7. Operational plans: such as sale contracts in the power market as future contracts or contracts for difference.

8. Load level: it is most evident that lower load level durations (lower electricity price durations) are more economically effective in order to perform maintenance. Therefore, it would be expected that there is an inverse relation between the electricity price in the power market and the worth of the maintenance durations, such as the following:

$$P^w = F(\frac{1}{MCP^w}), \tag{5}$$

where P^w is the sale price of the maintenance window for week w($), MCP^w is the market clearing price in the power market ($/MWh); and F is the mathematical function.

9. Fuel network constraints: the fuel allocated to units at each time duration is limited and can change some operation plans:

$$f_i^w \leq f_{i,w}^{\max} x_i^w, \tag{6}$$

where $f^{\max}$ is the maximum fuel allocated to GENCOs (MBtu).

10. System emission limits: in recent years due to extensive concerns about pollutants of generating units, emission control is as an important parameter aside from the fuel constraints:

$$\sum_w \sum_i e_i({P_{g_i}}^w) \leq E^{cap}, \tag{7}$$

where e_i is the emission function of GENCO i, P_{g_i} is the active power generation for GENCO i (MW), and E^{cap} is the emission cap for the system emission.

Although the electricity price plays an important role in how to determine the WTP curve (in order to reduce the financial loss of not selling energy), other constraints, as mentioned above, can restrict the maintenance plans; hence, each term of the mentioned constraint complex plays its own role with a different degree of importance. All of these constraints will form the WTP curve, as shown in Figure 1.

2.2. ISO investigates the submitted plans and determines the final schedule

The ISO, as the market manager, has 2 main duties: 1) coordinating the maintenance plans according to market-based mechanisms, which could guarantee fair competition among GENCOs and ensure the power system security; and 2) allocating the ISO's income to improve the UMS program.

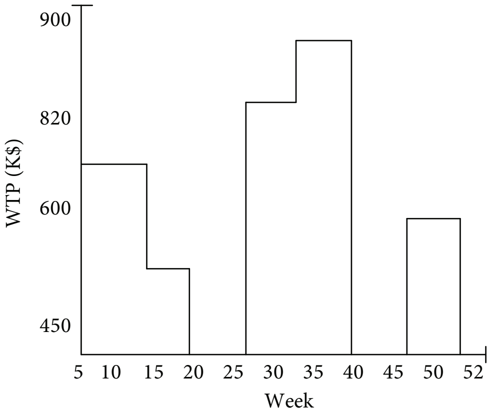


Figure 1. GENCO's maintenance plans as a WTP curve.

First, all of the GENCOs submit their own maintenance plans and present them to the ISO. After that, the ISO forms a virtual auction sale and each maintenance window is sold according to the highest proposed price of the WTP curves. Meanwhile, the ISO calculates the power system security corresponding to each plan and does not permit it to be scheduled for the plans that have exceeded the predefined power system security criteria. Windows such as these are called infeasible windows. Therefore, the UMS process has 3 main steps that are explained in the following sections.

2.2.1. ISO calculates the security level of each plan

In the first step, the ISO calculates the security of the submitted maintenance plans, determines the plans that exceed the predefined reliability criteria, and does not permit these plans (infeasible plans) to be included in the final competitive procedure.

Considering the appropriate index for security analysis is one the main contributions of UMS studies. The oldest reliability criterion is the loss of load probability [24], but nowadays, the most common approach is to utilize the loss of load expectation method [25]. There is, however, considerable appeal in utilizing a deterministic technique rather than more complicated probabilistic methodologies. A technique was developed recently that embeds an accepted deterministic criterion within a probabilistic framework. This is known as the well-being approach [26]. System well-being analysis utilizes 3 well-being analysis indices: 1) the probability of health P (H), 2) the probability of margin P (M), and 3) the probability of risk P (R). The probability of health, P (H), is the probability of the system being in the healthy state, where the available reserve is equal to or greater than the required reserve. The P (H) associated with this state is the probability of being in this capacity condition multiplied by the probability of being at the current load level [26].

The proposed method uses the mentioned probabilistic approach and the well-being analysis in order to evaluate the power system reliability. In this method, the weekly load levels are divided into some probabilistic load levels with corresponding probabilities. It is anticipated that the total sum of the probabilities in each week is equal to 1.

$$\sum_{i=1,i\neq j}^{NG} P_{g,i}^{w} - R^{w} - L^{w} \geq 0 \tag{8}$$

Therefore, the P (H) as the reliability criterion is as follows:

$$PH^w = \sum_{i=1}^{NG}\sum_{k=1}^{NL} P_{l,k}^w \times P_{c,i}^w \times I_{i,j}, \tag{9}$$

$$PH^w \geq \lambda, \tag{10}$$

where $P_{g,i}^w$ is the power generation of GENCO i in week w (MW), R^w is the reserve capacity of the power system (MW), L^w is the load level of the power system (MW), NG is the number of states in the capacity outage probability table (COPT), NL is the number of probabilistic load levels in each week, PH^w is the reliability criterion for week w, $P_{l,k}^w$ is the probability of load level k in week w, $P_{c,i}^w$ is the probability of available capacity i in week w, and $I_{i,j}$ is the healthy mode indicator (1/0) with 1 being the healthy mode. If Eq. (8) is satisfied, $\mathrm{I}_{i,j}$ is 1; otherwise, it is 0. j is the GENCO that is taken offline for maintenance and λ is the permitted level of reliability.

In this method, 2 basic models are required to perform the well-being analysis: 1) a generation model and 2) a load model. The load model can be in the form of the load duration curve or the daily peak load variation curve. Moreover, the generation model can be presented by a COPT. The COPT is an array of capacity levels or corresponding capacity out of service and the associated probabilities of existence. The associated probability of existence is the probability of exactly the indicated amount of capacity being out of service. For the capacity model, the cumulative probability of existence is used and it is equal to the sum of probabilities corresponding to the capacity on an outage equal to or greater than the indicated amount. This paper uses a convolution algorithm to create the COPT.

2.2.2. ISO prepares the virtual auction sale

In the second step, the ISO prepares a virtual auction sale and permits GENCOs to buy their desired maintenance plans according to the highest proposed price. The ISO sells the windows in such a way that it does bring in more revenue; hence, an optimization solution should economically find the maximum point of the UMS. Similar to any optimization problem, the following should be observed:

- The objective function,
- The constraint,
- The optimization algorithm.

2.2.3. Objective function and constraints

In this paper, the ISO considers a virtual auction sale and permits GENCOs to participate in a competition in order to buy the desired maintenance windows; hence, each window will be bought at the highest price satisfying the power system security criteria. Mathematically, the objective function of the UMS problem can be stated as follows:

$$Max : \sum_{i=1}^{G}\sum_{w=1}^{W} P_i^w x_i^w. \tag{11}$$

Maximizing the mentioned objective function has 2 important results:

- Making a perfect market,
- Maximizing the global welfare.

The related constraints are as follows:

1. The length of the maintenance period:

$$\sum_{w=1}^{W} x_i^w = d_i. \tag{12}$$

2. The maintenance of a unit must be started, once the maintenance of another unit is already finished:

$$x_i^w(t) - x_i^w(t-1) + x_{i_1}^{w_1}(t) \geq 0, \tag{13}$$

where $x_{i_1}^{w_1}$ shows the maintenance for GENCO i_1 in week $w_{1,}$ while it is performed after the maintenance for GENCO i in week w.

3. The system reserve at any time should be greater than a prespecified level:

$$R^w \geq R^{low}, \tag{14}$$

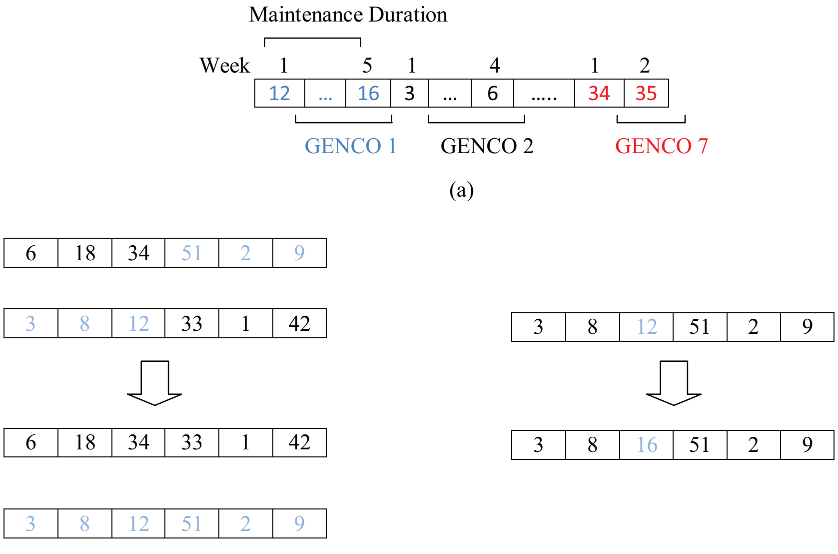
where $x_i^w = \left\{ \begin{array}{c} 1 \\ 0 \end{array} \right.$ is the decision variable of the UMS (1/0) with 1 meaning maintenance; i is the GENCO's number, $i = 1,..,G$; w is the available windows of the maintenance horizon, $w = 1,..,W$; P_i^w is the price of the WTP curves for GENCO i in week $w(K\$)$; d_i is the maintenance duration of GENCO i (weeks); and R^{low} is the prespecified level of the reserve capacity (MW).

2.2.4. Genetic algorithm optimization solution

In recent years, many optimal techniques, such as the genetic algorithm (GA), particle swarm optimization (PSO), and ant colony, have been applied to solve the UMS problem. All of these optimization models may solve the UMS problem, but the solution process may be streamlined. The GA is an applicable and effective optimization solution for solving maintenance schedule problems [27], and therefore it is used in this paper to strike the right balance between profit and power system security with fair competition. Figure 2 shows the GA coding.

As seen in Figure 2, each GENCO allocates some genes in each chromosome that are equal to the maintenance duration. Therefore, the number of genes in one chromosome is equal to the total number of all of the GENCOs' maintenance durations. A gene in the mentioned chromosome indicates a maintenance week.

In order to solve an optimization problem using the GA, first the possible solutions of the problem have to be coded in chromosomes. Next, a fitness function to compare the chromosomes has to be defined. The period of maintenance scheduling is usually 1 year and it is divided into weekly stages. In solving the generation maintenance scheduling problem, the main variables to be identified are maintenance states of the generating units. The maintenance schedule corresponding to each GENCO is considered as a gene and the chromosomes are built by these genes. Therefore, a single chromosome will completely describe the maintenance schedules for the power generating units. The GA evaluates the fitness of each string to guide its search instead of the explicit optimization function. There is no need for computations of derivatives or other auxiliary knowledge. Crossover cuts parent chromosomes at a point between 2 genes (called single-point crossover) and exchanges the parent genes after the cut. Mutation randomly changes the values of some bits (genes) in each selected chromosome. Figure 2 shows the chromosome, crossover, and mutation operators.



(a)

(b)

(c)

Figure 2. a) Structure of the UMS' chromosome, b) cross-over operator, and c) mutation.

2.2.5. ISO allocates the income to the UMS in order to prevent market power

As mentioned above, the ISO is a nonprofit entity and has to allocate the income from maintenance scheduling in the auction sale. The main part of the income is allocated to GENCOs whose maintenance plans are adjusted due to power system security limitations and hence are not permitted to buy the plans with the highest satisfaction degree. Financial losses are imposed on such GENCOs in order to maintain power system security. Therefore, the first contribution of the ISO's income should be allocated to these GENCOs. However, this sort of income allocation, if it is according to the proposed price of the GENCOs, can be a strong reason for exercising market power by strategic players (large-capacity GENCOs) whose plans are adjusted, because they can propose a high price for infeasible windows and receive an illegal income from this mechanism. Hence, the income allocation mechanism must have some controllers that could detect market power states and prevent those GENCOs from doing that. The proposed method uses the following mechanism to compensate the losses. The mechanism has intelligent parameters that can detect market power states and penalize the GENCOs by reducing their loss compensation costs. Hence, the compensation cost for GENCO i is formulated as follows:

$$C_1^i = I_i \times \sum_{w=1}^{M} \frac{P_i^{Inf_1}(w)}{M_i} \times \frac{\left(\sum\limits_{w=1}^{N} \frac{P_i^{sc}(w)}{d_i} \right)}{Max\left(Max\left\{ P_i^{Inf}(w) \right\}, \sum\limits_{w=1}^{N} \frac{P_i^{sc}(w)}{d_i} + \left| \sum\limits_{w=1}^{N} \frac{P_i^{sc}(w)}{d_i} - \sum\limits_{w=1}^{K} \frac{P_i^{Inf_2}(w)}{K_i} \right| \right)}. \tag{15}$$

For each WTP curve, the ISO measures the deviation from normal bidding using a smoothing factor as follows:

$$\eta_i = \frac{P_{tot,i}^{ave}}{P_{\mathrm{inf},i}^{ave}}, \tag{16}$$

where $P_{tot,i}^{ave}$ is the average cost of the total proposed price in the WTP curve for GENCO i; $P_{\inf,i}^{ave}$ is the average cost of the total infeasible windows, which is greater than the scheduled windows' price, for GENCO i; $P_i^{Inf_1}$ is the price of the total infeasible windows due to system security limitations; $P_i^{Inf_2}$ is the price of the infeasible windows due to system security limitations that are greater than the scheduled windows' prices (K\$); P_i^{sc} is the price of the scheduled windows for GENCO i (K\$); I is the ISO's income (K\$); K_i is the number of infeasible windows, and their prices are greater than the scheduled windows' prices, for GENCO i; M_i is the total number of infeasible windows for GENCO i; and I_i is the compensation indicator with 1 meaning compensation mode and 0 meaning that no compensation cost is allocated to GENCO i, as follows:

$$I_i = \begin{cases} 1 & \text{if} \quad P_{i\max}^{\inf} \geq P_{i\max}^{sc} \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

The lower η means that the probability of exercising the market power is higher. In fact, this means that the GENCO bid a high price for special windows in order to earn a high compensation cost; hence, the ISO fines such GENCOs through the penalty factor if the smoothing factor is less than the predefined amount. The penalty factor is calculated with the following equation:

$$PF = 1 - \eta. \tag{18}$$

The ISO reduces the compensation cost (C_1) of the target GENCO as the penalty factor percent and dedicates its residual amount to the GENCO as the final compensation cost. This mechanism can prevent the bidding of a high price for infeasible windows, hence preventing market power by strategic players.

The above equations compensate the first part of the losses due to power system security considerations, and after that, if there still exists any amount, the residual income is allocated to compensate the latter financial losses due to buying the maintenance windows. Hence, the following mechanism represents the compensation cost for GENCO i:

$$C_2^i = \frac{\sum_{w=1}^{N} P_i^{sc}(w)}{I} \times \left(I - \sum_{i=1}^{G} C_1^i \right). \tag{19}$$

In Eq. (15), the compensation cost does not depend on the proposed price only; rather, it depends on the average of the feasible and infeasible windows prices, and it can prevent the market power of some GENCOs. According to the mechanism, if a GENCO bids a high price for infeasible windows, it may not necessarily earn much money from the market, because the limiting parameters of Eqs. (15)–(18) detect the unfair states and prevent them. This approach can be summarized with the flowchart shown in Figure 3.

3. Numerical examples

3.1. The IEEE-RTS as a test system

A 9-GENCO IEEE-RTS is used as a test system to demonstrate the applicability of the proposed method [28]. The total installed capacity is 3405 MW and the scheduling horizon is supposed to be 1 year, though it can be greater or less than that if necessary. Two of the GENCOs in the IEEE-RTS are hydro and nuclear GENCOs; hence, because of special conditions in the operation of such GENCOs, the mentioned GENCOs are not considered in the maintenance scheduling process. Therefore, the maintenance scheduling is performed for the remaining 7 GENCOs only. Table 2 shows the generator data of the test system. The forced outage rate (FOR) is one of the most important parameters used in the well-being analysis. The weekly load profile from the IEEE-RTS is used as the total system load, which is shown in Figure 4.

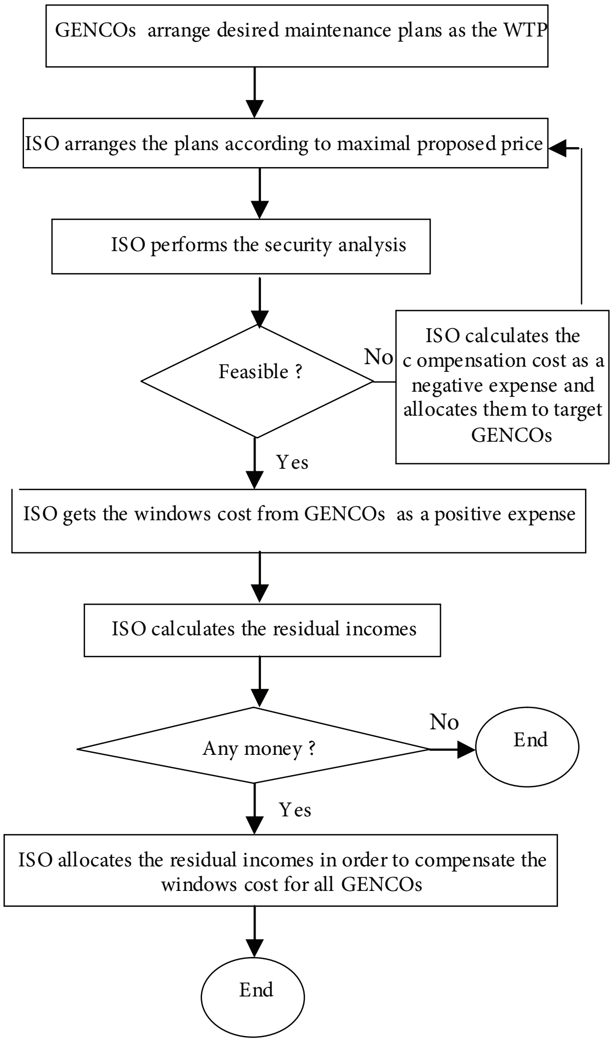


Figure 3. Flowchart of the fair market-based UMS.

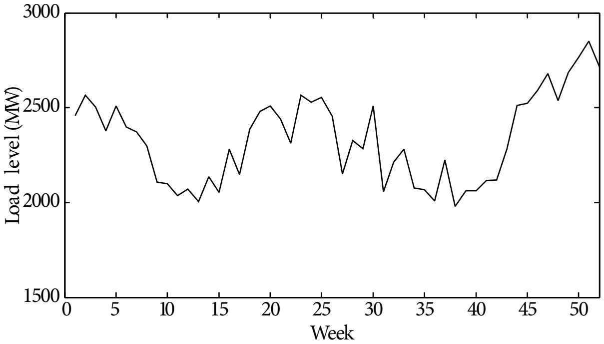


Figure 4. IEEE-RTS weekly load profile.

Table 2. Generators data of the IEEE-RTS.

Unit size (MW)	Number of units	Unit type	FOR	Scheduled maintenance weeks/year	Unit ID
400	2	Nuclear	0.12	No schedule	-
350	1	Coal/steam	0.06	5	1
197	3	Oil/steam	0.05	4	2
155	4	Coal/steam	0.04	4	3
100	3	Oil/steam	0.04	3	4
76	4	Coal/steam	0.02	3	5
50	6	Hydro	0.01	No schedule	-
20	4	Oil/CT	0.1	2	6
12	5	Oil/steam	0.02	2	7

3.2. GENCOs submit their desired maintenance plans

As mentioned above, GENCOs arrange maintenance plans according to the desired conditions and present them to the ISO as WTP curves. For case study, 7 GENCOs present their plans as the WTP curves that are shown in Figure 5 and 6, where it is seen that there exist many overlaps in the maintenance plans for the GENCOs; hence, severe competition will exist among the GENCOs in order to maximize the profit. In this situation, all of the GENCOs fight one another in order to allocate the best desired maintenance plans for themselves. In fact, the WTP curve is a kind of in-fighting cost for making a fair competitive environment.

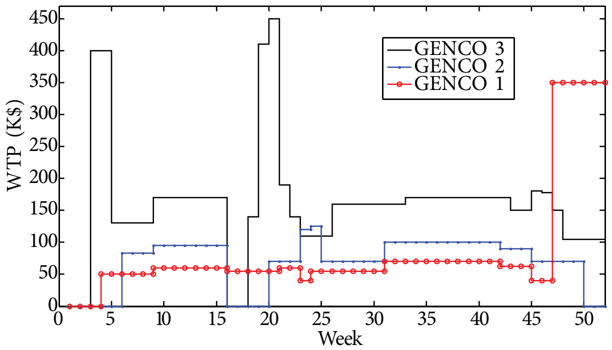


Figure 5. WTP curves for GENCOs 1–3.

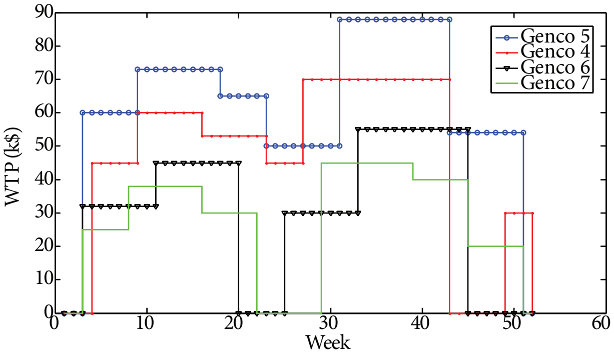


Figure 6. WTP curves for GENCOs 4–7.

In order to show the applicability of the proposed method on the grounds of preventing market power, 3 case studies are considered, as follows:

- Case study 1: All GENCOs submit their maintenance plans, shown in Figures 5 and 6, and no preventing mechanism is considered by the market operator.
- Case study 2: All GENCOs submit their maintenance plans, shown in Figures 5 and 6, and a preventive mechanism is considered as in Eqs. (15)–(18).
- Case study 3: GENCOs 1 and 3 adjust their maintenance plans moderately through the reduction of the proposed price for the infeasible weeks, according to Figure 7.
- Case study 4: GENCOs 1 and 3 adjust their maintenance plans noticeably through the reduction of the proposed price for the infeasible weeks, according to Figure 7.

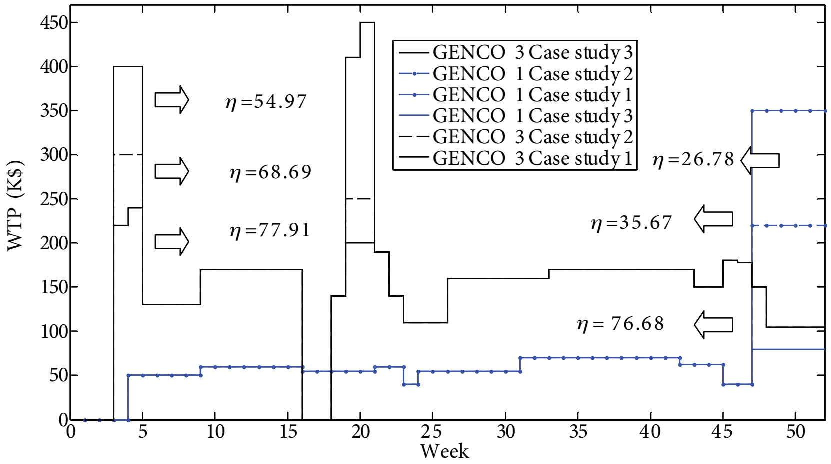


Figure 7. WTP curves of GENCOs 1 and 3 for case studies 1–3.

In the mentioned case studies, in order to concentrate on the power market concept, we suppose that all GENCOs bid properly, except for GENCOs 1 and 3, which try to disturb the perfect market and exercise market power through the allocation of high compensation costs to themselves.

3.3. Output results

As mentioned above, 4 case studies are considered in order to show the applicability of the proposed method on the grounds of preventing market power. In case study 1, all GENCOs bid the desired price for maintenance windows and no control mechanism is considered by the market operator. In fact, whenever a GENCO bids a higher price for infeasible windows, it can earn a lot of money from the income allocation process because the market operator allocates the compensation cost according to the proposed price only, with no controlling mechanism. In this case study, the compensation cost is calculated according to the difference between the infeasible windows' price and the scheduled windows' price. The result is shown in Tables 3 and 4 for GENCOs 1 and 3, respectively. As seen in case study 1, GENCOs 1 and 3 allocated very high compensation costs and this state can be expressed as an economic withholding state. This state obviously disturbs the perfect market. In figures 5 and 6, all of the GENCOs have a moderate proposed price with no noticeable jump in the bidding, except for GENCOs 1 and 3, which have enormous jumps in the prices of weeks 47–52 for GENCO 1 and weeks 3, 4, 19, and 20 for GENCO 3.

Table 3. Compensation costs for GENCOs 1 and 3 in different case studies: GENCO 1.

Case study	Smoothing factor (%)	Penalty factor (%)	Compensation cost (K$)	Market status
1	No market mechanism	No market mechanism	1820	Imperfect market
2	26.78	73.22	21.31	Try to exercise market power
3	35.67	64.33	28.44	Try to exercise market power
4	76.68	0	56	Fair market

In case study 2, the market mechanism is activated and limits the compensation cost by penalizing the corresponding transgressor GENCOs using a penalty factor. In the other 2 case studies, cases 3 and 4, GENCOs 1 and 3 reduced the proposed price for infeasible windows. As seen, the penalty factor is reduced and GENCOs 1 and 3 can earn a higher real compensation cost in case studies 3 and 4, respectively. It is anticipated that whenever a GENCO bids a moderate price for windows, it may have a greater smoothing factor (lower penalty factor) and, hence, earn more real compensation cost. Figure 8 shows the market power states on the WTP curves of GENCOs 1 and 3, where it is seen that the proposed prices, corresponding to a higher amount of 0.75 (as the predefined smoothing factor), are detected as market power states.

Table 4. Compensation costs for GENCOs 1 and 3 in different case studies: GENCO 3.

Case study	Smoothing factor (%)	Penalty factor (%)	Compensation cost (K$)	Market status
1	No market mechanism	No market mechanism	980	Imperfect market
2	54.97	45.02	65.5	Try to exercise market power
3	68.69	31.3	91.63	Try to exercise market power
4	77.91	0	142.47	Fair market

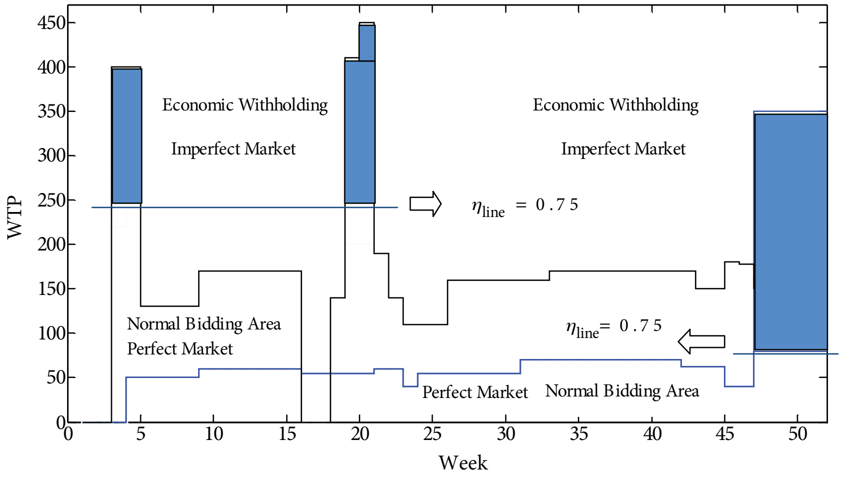


Figure 8. Market power states of the WTP curves for GENCOs 1 and 3.

It is evident that case studies of 1–3 do not represent a fair state of the UMS, because in case study 1, no preventing mechanism is considered and it leads to high bidding in order to earn an illegal compensation cost by GENCOs 1 and 3. In case studies 2 and 3, GENCOs 1 and 3 bid high prices for infeasible windows; hence, they are faced with heavy penalty factors, such that they lose the opportunity for earning the real compensation cost. In fact, in case study 1, the market operator is responsible for the imperfect market, and in case studies 2 and 3, GENCOs 1 and 3 are responsible for their losses in the compensation cost allocation mechanism. Therefore, it is anticipated that whenever a GENCO bids a price with an enormous jump in infeasible windows, it faces heavy fines and this mechanism encourages the GENCOs to bid a moderate price for maintenance windows. In this mechanism, for a smoothing factor with a higher amount of 0.75, no penalty cost is considered; therefore, case study 4 has no reduction in the compensation cost and it is expressed as the fairest state. The amount of the smoothing factor is an empirical number and can be changed according to the market requirements. Therefore, the policymakers of power markets should define its amount according to economic conditions, which can be varied in different markets. It is anticipated that a higher smoothing factor sets more serious conditions in preventing market power.

Table 5 shows the complete UMS for the fairest state, case study 4. Moreover, the third column of this table describes the infeasible windows that are not permitted to be scheduled. The permitted level of reliability is considered as 0.7 (PH = 0.7); therefore, the infeasible windows that are introduced in Table 5 exceed the mentioned security level. Table 5 also shows the complete UMS for the fairest state, case study 4. The final UMS for all of the case studies is the same as in Table 5, except for the amount of the compensation cost. In other words, all of the mentioned case studies have the maintenance schedule shown in Table 5, but their compensation costs are different according to Tables 3 and 4.

Table 5. Infeasible windows of maintenance plans and final UMS results.

Unit ID	Unit size (MW)	Infeasible weeks	Scheduled weeks	Paid cost-WTP (K$)	Real loss (K$)	Compensation C_1 (K$)	Compensation (K$) C_2
1	350	47–52	15–19	280	56	56	243.62
2	197	1–6, 20, 21, 23–26, 45, 46	32–35	400	66.48	66.48	348.03
3	155	1–6, 19–21, 23–26, 30, 44–46	11–14	680	142.47	142.47	591.65
4	100	51, 52	28–30	210	0	0	182.7
5	76	50–52	40–42	264	0	0	229.69
6	20	No infeasible weeks	36, 37	110	0	0	95.71
7	12	No infeasible weeks	38, 39	95	0	0	82.65

As seen in Table 5, compensation cost C_1 is allocated to GENCOs 1, 2, and 3 only, because no losses are imposed for the other GENCOs according to Eqs. (15)–(18). The mechanism first compensates the losses of C_1, and after that, it allocates the residual income in order to compensate the losses of C_2. In Table 5, the fifth column, 'paid cost', shows the money that is paid by each GENCO to buy the scheduled maintenance windows (fourth column).

As mentioned above, the proposed mechanism could prevent market power through financial fines. Figure 9 shows the reliability levels of the proposed UMS for 52 weeks, and as is seen, all of the windows have an acceptable reliability amount. Therefore, the proposed mechanism can ensure fair competition among the GENCOs and guarantee power system security.

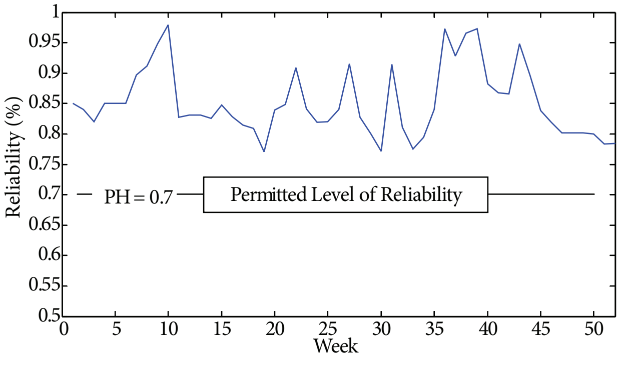


Figure 9. Reliability levels of the maintenance horizon for 52 weeks.

4. Conclusion

A novel approach of UMS in the competitive electricity market is presented in this paper. It can ensure fairness among GENCOs and guarantee power system security during maintenance scheduling. The main contribution of the method is concentrated on the market power concept, while it plans some controlling parameters that help market designers and policymakers detect the market power states and prevent them. In this mechanism, GENCOs can present their willingness in the form of WTP curves and then participate in a competition according to their desire in the bidding process in an auction sale, and finally buy the desired maintenance duration. The ISO, as a market manager, should make a fair environment where all GENCOs can participate in a safe competition.

Some plans are adjusted by the market operator and the ISO compensates their financial losses so as to prevent market power and make a perfect market. The mechanism can reduce the financial losses that are imposed on the GENCOs due to system security limitations. The income allocation's mechanism is planned in order to prevent the exercising of market power by large-capacity GENCOs. The numerical result demonstrates that the proposed method makes a good opportunity for GENCOs and a safe environment for power system operators, while it can ensure the reliable operation of the system. A fair UMS mechanism can prevent economic withholding and lead to a perfect market. Although this paper presents the whole UMS process, some problems could still be extended in future research, such as the preventing of market power, UMS coordination mechanism, and the mechanism of performing the auction sale.

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