A Profit-Based Maintenance Scheduling of Thermal Power Units in Electricity Market

Smajo Bisanovic, Mensur Hajro, and Muris Dlakic

***Abstract*—**This paper presents one comprehensive modelling approach for maintenance scheduling problem of thermal power units in competitive market. This problem is formulated as a 0/1 mixed-integer linear programming model. Model incorporates long-term bilateral contracts with defined profiles of power and price, and weekly forecasted market prices for market auction. The effectiveness of the proposed model is demonstrated through case study with detailed discussion.

***Keywords*—**Maintenance scheduling; bilateral contracts; market prices; profit

I. Introduction

THE planning and scheduling of maintenance activities for Generation Company (GenCo) presents one of key tasks that have significant reflections on its profit and efficiency. It is particularly emphasized in decentralized environment where operational readiness of the generating units must not be limiting factor toward challenges of the market, and toward fulfilment of the obligations imposed by regulatory framework. Maintenance scheduling, as critical technical task, requires carefully planning and analysis to guarantee system reliability and economic benefits for the GenCo.

Because all generating units must be maintained and inspected, planners in the GenCo must schedule planned outages during the year. Several factors entering into this scheduling analysis includes: weekly load – demand profile (bilateral contracts), market prices, amount of maintenance to be done on all generating units, capacity of units, elapsed time from the last maintenance, availability of maintenance crews, technical and season limits, obligations toward Independent System Operator (ISO) regarding to ancillary services. All these factors must be included into GenCo's objective for profit maximization.

The maintenance scheduling task for thermal power units is a complex combinatorial optimization problem that has been studied and analyzed widely in past. Traditional optimization techniques such as integer programming [1,2], decomposition methods [2–4], goal programming [5] have been used to solve this problem. Modern evolutionary techniques, as genetic algorithm [6,7], simulated annealing [7,8], memetic algorithm [9], tabu search [7,10,11] and fuzzy sets theory [12,13] have been applied to the problem. The maintenance scheduling of thermal power units should be optimized in terms of the objective function under series of constraints. The selection of objectives and constraints depends on the particular needs of maintenance scheduling problem, the data available, the accuracy to be sought and the chosen methodology for solving the problem. There are generally two categories of objectives in the maintenance scheduling problem: based on costs [1,3,4, 7,14] or profit [11,15–17] and based on reliability [8,10,12]. The most common objective based on costs is to minimize the total operating costs over planning period. This minimization requires many approximations or computationally intensive simulation to yield a solution. It was reported in literature that minimization of the total operating cost (or production cost that is the main part of the operating cost for thermal units) is insensitive objective for maintenance scheduling problem [6,14]. A number of reliability definitions, such as expected lack of reserve, expected energy not supplied and loss of load probability, which are based on power system measures have been used as reliability criteria for formulation of objective function [8,10,14]. The maintenance timetable should satisfy given set of constraints. In recent literature these constraints are related to power units (maintenance window constraints), prevent the simultaneous maintenance of a set of power units (exclusion constraints), restrictions initiation of maintenance on some units after a period of maintenance of some other power units (sequence constraints), power system constraints (balance and transmission constraints), crew constraints, etc. In recent literature maintenance scheduling problem has been oriented toward new relations in electric power sector. In a number of electricity markets, deregulation of the power industry has given the GenCo the independence to maintain generating units in decentralized manner with a minimum regulatory intervention for system security purposes only. The maintenance periods of time for power units are scheduled either by profit-seeking GenCo only, or by coordination between profit-seeking GenCo and reliability-concerned ISO, and the extent of this coordination depends on the market environment and legislative. Although the coordination procedure how ISO adjust the individual GenCos' maintenance schedules and how each GenCo responds to the adjusted schedule is important, it is not a main concern of this paper and one can investigate more about this subject. An applicable procedure that conciliates objective for GenCos, to schedule their units for maintenance in order to maximize their profit, and the ISO requirement that ensures adequate security, is determined through multiple interaction between GenCos and ISO and given in [16,17]. In this paper the maintenance scheduling problem is analyzed from the GenCo point of view. In order to ensure adequate level of security, in this paper we assume simple interaction of the ISO toward the

S. Bisanovic and M. Dlakic are with Public Enterprise Elektroprivreda of Bosnia and Herzegovina, Vilsonovo setaliste 15, 71000 Sarajevo, Bosnia and Herzegovina (corresponding author: phone +387 33 751 371; fax: +387 33 751 361; e-mail: s.bisanovic@elektroprivreda.ba).

M. Hajro is with Faculty of Electrical Engineering, University of Sarajevo, Sarajevo, Bosnia and Herzegovina.

GenCo taking into account minimal level of reserve. This requirement can be a part of ISO's total policy, contained in its plan of ancillary services. For minimal level of reserve the GenCo will have benefits through price of capacity in reserve (this revenue is not considered in this paper).The complexity introduced by planning concepts, associated with the combinatorial nature of the problem, resulting in the fact that the maintenance scheduling is an active research area in power system optimization. This paper presents one comprehensive modeling approach for maintenance scheduling problem of thermal power units in competitive market. Model incorporates long-term bilateral contracts with defined profiles of power and price, and weekly forecasted market prices for market auction.This paper is organized as follows. Section II provides the notation used throughout the paper. In Section III the optimal maintenance scheduling problem is formulated as deterministic programming problem. In Section IV results from a realistic size generation case study are presented and discussed. The conclusions are outlined in Section V.

II. Notation

The notation used throughout the paper is stated below:

Indexes:

i thermal unit index

k thermal power plant index

m bilateral contract index

t time period (week) index

Constants:

θ number of hours in week ($\theta = 168$)

$\pi_m^c(t)$ price of bilateral contract m in period t [\$/MWh]

$\pi^s(t)$ market price of energy in period t [\$/MWh]

$a_{i,k}$ fixed operating cost of unit i in plant k [\$/h]

$b_{i,k}$ linear cost term in cost characteristic of unit i in plant k [\$/MWh]

$c_{i,k}$ quadratic cost term in cost characteristic of unit i in plant k [\$/MW^{2}h]

$d_{i,k}$ variable O&M cost of unit i in plant k [\$/MWh]

$C_{i,k}^M$ maintenance cost of unit i in plant k [\$/MW]

$ET_{i,k}$ earliest maintenance start time of unit i in plant k

$LT_{i,k}$ latest maintenance start time of unit i in plant k

$M_{i,k}$ duration of maintenance for unit i in plant k

N_k number of units in plant k that can be maintained simultaneously

$O_{a,b}$ number of periods during that the maintenance of units a and b should overlap

$p_m^c(t)$ power from bilateral contract m in period t [MW]

$\overline{P}_{i,k}$ capacity of unit i in plant k [MW]

$\underline{P}_{i,k}$ minimum output of unit i in plant k [MW]

$R_0(t)$ minimum reserve level assigned to GENCO from ISO in period t [MW]

$S_{a,b}$ number of periods required between the end of the maintenance of unit a and the beginning of the maintenance of unit b

Variables:

$P_{i,k}(t)$ power generated by unit i in plant k in period t [MW]

$p^s(t)$ power for bid on market in period t [MW]

$v_{i,k}(t)$ 0/1 variable, equal to one if unit i in plant k is online in period t , otherwise zero

$y_{i,k}(t)$ 0/1 variable, equal to one if unit i in plant k is being maintained in period t , otherwise zero

Numbers:

I_k number of thermal units in plant k

K number of thermal power plants

M number of bilateral contracts

T number of periods of the planning horizon.

III. Problem Formulation

A. Objective Function

Important point in maintenance scheduling of thermal generating units presents selection of objective function. It depends of GenCo's strategic parameters, its obligations toward the ISO, regulatory framework and etc. Because of that, the maintenance scheduling is essentially multi-objective task with conflicting objectives. This paper considers the GenCo objective that maximizes profit. The expected profit for the GenCo is calculated as a difference between expected revenues and operating costs. Operating costs include costs of energy production and maintenance costs. The bilateral sales contracts with particular power patterns and price profiles are included in this objective, and the market clearing prices for each period are known. The objective function for the GenCo is expressed as profit maximization and formulated as follows:

$$\max \sum_{t=1}^{T} \left\{ \theta \sum_{m=1}^{M} \pi_m^c(t) p_m^c(t) + \theta \pi^s(t) p^s(t) - C_o(t) \right\} \tag{1}$$

$$\begin{aligned} C_o(t) = {} & \theta \sum_{k=1}^{K} \sum_{i=1}^{I_k} a_{i,k} v_{i,k}(t) + b_{i,k} P_{i,k}(t) + c_{i,k} P_{i,k}^2(t) + \\ & + \theta \sum_{k=1}^{K} \sum_{i=1}^{I_k} d_{i,k} P_{i,k}(t) + \sum_{k=1}^{K} \sum_{i=1}^{I_k} C_{i,k}^M \overline{P}_{i,k} y_{i,k}(t) \end{aligned} \tag{2}$$

In equation (1) the first term is related to revenue from contracts between the GenCo and other market players (load serving entities, distribution companies, traders). The amount of power that the GenCo has agreed to serve in period t as result of bilateral contract m is $p_m^c(t)$ and the price that the GenCo will be paid is $\pi_m^c(t)$. With this contract, the GenCo's revenue increases for $\pi_m^c(t) p_m^c(t)$. The second term in (2) represents expected revenue from selling power $p^s(t)$ on market with forecasted price $\pi^s(t)$ in period t. The third term represents the total costs $C_o(t)$ consist of production (fuel) costs $FC_{i,k}(t)$, variable O&M costs $d_{i,k}$ and maintenance costs $C_{i,k}^{M}$, as stated in (2). The fuel costs are represented by quadratic function.

$$FC_{i,k}(t) = a_{i,k} + b_{i,k} P_{i,k}(t) + c_{i,k} P_{i,k}^{2}(t) \tag{3}$$

In order to use advanced techniques for linear programming, quadratic fuel cost function will be given by piecewise linear approximation. This ensures formulation of problem as mixed-integer linear programming model that guarantees convergence to the optimal solution and computational efficiency in large-scale case studies. The representation of this approximation is stated in Section 4.

B. Long-term bilateral contracts and energy for market

In the newly restructured electricity market, the GenCo and other market players (load serving entities, distribution companies) can sign long-term bilateral contracts to cover players needs, which are derived from the demand of their customers. These bilateral contracts cover the real physical delivery of electrical energy. The actors agree on different prices, quantities, or different qualities of electrical energy. Also, duration of the contracts may differ, from medium-term (weekly, monthly) to long-term (yearly, few years). How much of their capacity and demand the GenCo and players will contract through bilateral contracts, and how much they will leave open for market transactions, is their strategic and fundamental question. Basically, their reasons for contracting bilateral contracts are follows. Because of price volatility, market power risks and possible constraints in transmission network, the GenCo will estimate how much of its capacity will be contracted through bilateral contracts, and how much of capacity will be offered on the market. Bilateral contracts reduce risk for the GenCo because its capacities may go unused as a result of not finding buyers or transportation capacity on the market. Load-serving entities and distribution companies, as other party in bilateral contracts with the GenCo, face with risk on market because of price volatility. Additionally, for the large consumers whose load needs high reliable electric energy, the bilateral contracts give guarantee that their load will be always supplied. The bilateral contracts define that certain amount of energy during number of hours will be delivered at given time in the future, at agreed prices and at defined locations. The GenCo must take these bilateral contracts into consideration when scheduling its units [18].

Usually, bilateral contracts have a discrete power pattern during certain number of periods and corresponding price pattern. Power $p_m^c(t)$ and price $\pi_m^c(t)$ in period t are constant. This implies that revenue from bilateral contracts is constant. According to forecasted hourly prices on the market, the GenCo has possibility to sell a part of its remaining production on the market. Level of power for bid on the market in period t, $p^s(t)$, depends of market price in period t, $\pi^s(t)$. The revenue from selling power on the market is $\pi^s(t)p^s(t)$. The variables $p^s(t)$ are optimization variables.

Prices and power quantities relevant for the bilateral contract can be obtained by systematic negotiation scheme [19] throughout the GenCo and its contract partners can reach a mutually benefit and tolerable risk. Negotiation for prices and power quantities will converge only if both sides can find price mix that provides an acceptable compromise between the risks and benefit (part of the portfolio management).

C. Maintenance constraints

The following relations represent set of constraints that must be satisfied in maintenance scheduling problem. Minimal request on reserve level determined by the ISO is here taken in consideration as obligation for the GenCo.

A) Minimum and maximum power output: The power output for each online unit must be within declared range represented by its minimum and maximum power output:

$$\underline{P}_{i,k} v_{i,k}(t) \le P_{i,k}(t) \le \overline{P}_{i,k} v_{i,k}(t) \quad \forall i,\ \forall k,\ \forall t \tag{4}$$

The unit cannot be online if it is in maintenance that ensured by constraint:

$$v_{i,k}(t) + y_{i,k}(t) \le 1 \quad \forall i,\ \forall k,\ \forall t \tag{5}$$

If the unit undergo maintenance in period t, $y_{i,k}(t) = 1$, constraint (5) ensures that $v_{i,k}(t) = 0$, because of that constraint (4) ensures the output of the unit is set to zero during maintenance. The power output of the unit can be equal to zero if the unit is not online and is not undergo maintenance.

B) Covering of contracted arrangements and power for market: The total power generated in thermal units must be enough to covers the contracted load patterns and power determined for electricity market for each period:

$$\sum_{k=1}^{K} \sum_{i=1}^{I_k} P_{i,k}(t) = \sum_{m=1}^{M} p_m^c(t) + p^s(t) \quad \forall t \tag{6}$$

C) Requirement on minimal level of reserve: Available capacity of units must satisfied requirement on minimal level of reserve imposed by ISO for each period:

$$\sum_{k=1}^{K} \sum_{i=1}^{I_k} \overline{P}_{i,k}(1 - y_{i,k}(t)) - \sum_{m=1}^{M} p_m^c(t) - p^s(t) \ge R_0(t) \tag{7}$$

D) Continuous maintenance period: The next constraint ensures that the maintenance for each unit must be finished once when begins:

$$y_{i,k}(t) - y_{i,k}(t-1) \le y_{i,k}(t + M_{i,k} - 1) \quad \forall i,\ \forall k,\ \forall t \tag{8}$$

E) Maintenance duration: For each unit must be ensured the necessary number of time periods for its maintenance during the horizon. The constraint (9) ensures this request:

$$\sum_{t=1}^{T} y_{i,k}(t) = M_{i,k} \quad \forall i,\ \forall k \tag{9}$$

F) Earliest and latest maintenance start time: Planner in GENCO determines earliest and latest maintenance start time for each thermal unit taking into consideration specific unit maintenance requirements, appropriate season limits (heating, working feasibility, crew availability).Suppose $T_{i,k} \subset T$ is the set of periods when maintenance unit i in plant k may start, so:

$$T_{i,k} = \left\{ t \in T \ : \ ET_{i,k} \le t \le LT_{i,k} \right\} \quad \forall i,\ \forall k \tag{10}$$

G) Number of units in the plant that can be maintain simultaneously: The next constraint limits the number of units in one plant that can be maintained at the same time:

$$\sum_{i=1}^{Ik} y_{i,k}(t) \le N_k(t) \quad \forall k,\ \forall t \tag{11}$$

H) Incompatible pairs of units: The requirement that some units cannot be maintained at the same time is easily stated by binary constraints (12). If units a and b (in the same plant or in other plants) cannot undergo maintenance during the same period, this is stated as follows:

$$y_{a,k}(t) + y_{b,k}(t) \le 1 \quad \forall t \tag{12}$$

I) Maintenance priority: If unit a must be maintained before unit b, following constraint must be satisfied:

$$\sum_{\tau=1}^{t} y_{a,k}(\tau - 1) \ge y_{b,k}(t) \qquad \forall t,\ \left\{ y_{a,k}(t) = 0, \text{for } (\tau - 1) \le 0 \right\} \tag{13}$$

J) Separation among consecutive maintenance outages: If between finish of maintenance of unit a and begin of maintenance of unit b (in the same plant or in other plants) is needed time separation of $S_{a,b}$ periods, than following constraints must be satisfied [16]:

$$\sum_{\tau=1}^{t} y_{a,k}(\tau - M_{a,k} - S_{a,b}) \ge y_{b,k}(t) \quad \forall t \tag{14}$$

$$\sum_{\tau=1}^{t} M_{a,b,k}^{\min} y_{a,k}(\tau - M_{a,k} - S_{a,b}) \le \sum_{\tau=1}^{t} M_{a,b,k}^{\max} y_{b,k}(\tau) \qquad \forall t,\ \left\{ y_{a,k}(t) = 0, \text{for } (\tau - M_{a,k} - S_{a,b}) \le 0 \right\} \tag{15}$$

$$M_{a,b,k}^{\min} = \min\left\{ M_{a,k}, M_{b,k} \right\},\ M_{a,b,k}^{\max} = \max\left\{ M_{a,k}, M_{b,k} \right\}$$

K) Overlap in maintenance outages: If during period in that unit a finishes the maintenance before unit b and if duration the maintenance of unit b must overlap specified number of periods $O_{a,b}$, than following constraints must be satisfied [16]:

$$\sum_{\tau=1}^{t} y_{a,k}(\tau - M_{a,k} + O_{a,b}) \ge y_{b,k}(t) \quad \forall t \tag{16}$$

$$\sum_{\tau=1}^{t} M_{a,b,k}^{\min} y_{a,k}(\tau - M_{a,k} + O_{a,b}) \le \sum_{\tau=1}^{t} M_{a,b,k}^{\max} y_{b,k}(\tau) \qquad \forall t,\ \left\{ y_{a,k}(t) = 0, \text{for } (\tau - M_{a,k} + O_{a,b}) \le 0 \right\} \tag{17}$$

The unit a and unit b can be in the same power plant, or in different plants. Specially, if is $O_{a,b} = M_{b,k}$, that unit a and unit b finish maintenance simultaneously. One important parameter is the company human resources involved. Sometimes for the maintenance program a shared company maintenance team is used and their availability can influence the maintenance schedule itself. Another important parameter is the spare parts availability; also this variable can be considered a constraint for the maintenance schedule. In this paper assumed that the resource availability (manpower availability, spare parts, and special tools) is not crucial factor for maintenance activity. Taking into account these parameters in maintenance scheduling model is given in [6,10].

IV. Case Study

To illustrate the effectiveness of the proposed model we have presented an illustrative case study. The model has been implemented and solved using the homogeneous and self dual interior point method for linear programming [20] with branch and bound optimizer for binary part of the problem (using MATLAB) on PC based platform with GenuineIntel processor at 3.20 GHz with 3 GB of RAM. The algorithmic parameter, as relative gap tolerance, is set to 1.0e–6. The required CPU time is about 38 s.

A. Input data

The GenCo generation system consists of five thermal power plants with total 22 power units. Table I and Table II show list of thermal units with its capacities, maintenance parameters, fuel cost coefficients, O&M and maintenance costs. The length of the planning horizon is 52 weeks. It is necessary to note that maintenance schedule for each unit will occur just once during the planning horizon.

The request on minimal reserve level determined by the ISO, that GenCo must satisfy as an obligation, assumed to be constant value of 250 (MW) for each week.

TABLE I

CAPACITIES AND MAINTENANCE PARAMETERS OF THE THERMAL UNITS

plant *k*	unit *i*	unit *mark*	Pmin	Pmax	*M*	*ET*	*LT*
TPP #1	1	1	265	310	5	23	32
	2	2	265	310	6	18	26
	3	3	120	220	6	1	20
	4	4	115	180	4	1	44
	5	5	65	90	4	1	44
TPP #2	1	6	100	155	3	1	50
	2	7	120	180	5	1	36
	3	8	120	180	5	1	36
TPP #3	1	9	360	450	7	24	38
	2	10	255	330	4	22	29
	3	11	215	270	4	18	42
	4	12	160	240	6	16	29
TPP #4	1	13	420	450	3	34	40
	2	14	265	320	5	20	28
	3	15	220	340	6	20	35
	4	16	210	255	5	1	45
TPP #5	1	17	155	230	5	1	45
	2	18	130	180	4	18	29
	3	19	120	160	5	12	40
	4	20	120	160	5	18	36
	5	21	60	95	3	1	50
	6	22	65	80	3	1	50

TABLE II

FUEL COST COEFFICIENTS, O&M COSTS AND MAINTENANCE COSTS OF THE THERMAL UNITS

plant	unit	*a*	*b*	*c*	*d*	C^M
TPP #1	1	90	9.64	0.0395	0.76	126
	2	90	9.64	0.0395	0.76	126
	3	122	11.04	0.0673	0.44	117
	4	104	12.60	0.0883	0.43	104
	5	130	16.02	0.0831	0.36	93
TPP #2	6	210	10.44	0.0639	0.30	104
	7	156	13.09	0.0761	0.34	104
	8	156	13.09	0.0761	0.34	104
TPP #3	9	555	4.77	0.0234	0.82	137
	10	287	7.34	0.0493	0.77	126
	11	135	9.93	0.0534	0.53	117
	12	255	11.04	0.0678	0.48	117
TPP #4	13	540	5.91	0.0263	0.79	137
	14	297	10.05	0.0471	0.72	126
	15	303	11.13	0.0398	0.81	117
	16	167	16.04	0.0477	0.69	117
TPP #5	17	136	12.18	0.0701	0.51	117
	18	144	14.01	0.0826	0.49	104
	19	202	13.89	0.0931	0.52	104
	20	202	13.89	0.0931	0.52	104
	21	77	18.09	0.1493	0.29	93
	22	76	12.33	0.2012	0.27	93

Primal-dual interior point method for mixed-integer linear programming approach guarantees convergence to the optimal solution and computational efficiency in large-scale case studies. Using of piecewise linear approximation for quadratic fuel cost characteristics given in Eq. (3), complete model is presented as 0/1 mixed-integer linear programming formulation of the maintenance scheduling problem that allows an efficient solution using interior point method with branch and bound optimizer. The piecewise linear approximation of fuel cost characteristics is formulated as follows:

$$VC_{i,k}(t) = \sum_{n=1}^{N} F_n(i,k) d_n(i,k,t), \quad \forall i,\ \forall k,\ \forall t$$

$$P_{i,k}(t) = \underline{P}_{i,k} v_{i,k}(t) + \sum_{n=1}^{N} d_n(i,k,t), \quad \forall i,\ \forall k,\ \forall t$$

$$0 \le d_n(i,k,t) \le d_n^s(i,k), \quad \forall i,\ \forall k,\ \forall t,\ n = 1,2,\dots,N$$

where N is the number of blocks of the piecewise linear variable cost function, $F_n(i,k)$ represents the slope of block n of the variable cost of thermal unit i , $d_n(i,k,t)$ represents the power produced by unit i in period t using nth power block, $d_n^s(i,k)$ is size of the nth power block for unit i .Variable costs have been modelled using the piecewise linear approximation with three blocks as shown in Table III.

TABLE III

PIECEWISE LINEAR APPROXIMATION OF QUADRATIC FUEL COST CHARACTERISTICS

plant	unit	T_1 (MW)	T_2 (MW)	F_1 ($/MWh)	F_2 ($/MWh)	F_3 ($/MWh)
TPP #1	1	280	295	31.168	32.353	33.538
	2	280	295	31.168	32.353	33.538
	3	153.3	186.7	29.435	33.922	38.409
	4	136.7	158.3	34.822	38.649	42.475
	5	73.3	81.7	27.516	28.901	30.286
TPP #2	6	118.3	136.7	24.392	26.735	29.078
	7	140	160	32.876	35.920	38.964
	8	140	160	32.876	35.920	38.964
TPP #3	9	390	420	22.320	23.724	25.128
	10	280	305	33.716	36.181	38.646
	11	233.3	251.7	33.871	35.829	37.787
	12	186.7	213.3	34.544	38.160	41.776
TPP #4	13	430	440	28.265	28.791	29.317
	14	283.3	301.7	35.877	37.603	39.330
	15	260	300	30.234	33.418	36.602
	16	225	240	36.790	38.221	39.652
TPP #5	17	180	205	35.664	39.169	42.674
	18	146.7	163.3	36.863	39.616	42.369
	19	133.3	146.7	37.475	39.958	42.441
	20	133.3	146.7	37.475	39.958	42.441
	21	71.7	83.3	37.748	41.232	44.715
	22	70	75	39.492	41.504	43.516

In Table III constants T_1 and T_2 mean upper limit of blocks 1 and 2 of thermal unit variable (fuel) cost.Table IV shows forecasted weekly prices on the market. It should be noted that the price profile should be obtained by appropriate forecasting procedures.

TABLE IV
WEEKLY FORECASTED MARKET PRICES

t	$\pi^S(t)$	t	$\pi^S(t)$	t	$\pi^S(t)$	t	$\pi^S(t)$
1	40.4	14	34.4	27	36.9	40	32.9
2	41.7	15	34.2	28	36.6	41	31.7
3	40.9	16	37.8	29	38.8	42	33.3
4	40.4	17	33.4	30	37.7	43	37.8
5	42.8	18	37.7	31	31.6	44	43.6
6	40.1	19	41.9	32	32.8	45	43.5
7	41.9	20	41.5	33	34.4	46	47.6
8	39.0	21	38.6	34	32.7	47	48.3
9	37.4	22	42.6	35	31.5	48	46.6
10	36.3	23	42.5	36	32.4	49	49.9
11	36.5	24	44.7	37	35.3	50	53.3
12	35.6	25	42.8	38	31.7	51	60.2
13	36.7	26	39.1	39	30.6	52	51.2

The GENCO has two long-term bilateral contracts with market participants, for example, with large consumers. These are yearly bilateral contracts with precise power and price patterns that change weekly. First contract has power pattern that is constant during certain number of weeks and corresponding price pattern. Second contract represents delivery with constant power during year with fixed price. The contracted power profiles and prices for weekly bases in the year are presented in Table V.

TABLE V
BILATERAL CONTRACTS WITH WEEKLY POWER PROFILE AND PRICES

CONTRACT #1							
t	1-8	9-24	25-28	29-32	33-40	41-49	50-52
$p_1^c(t)$	2300	2150	2000	1700	1750	2200	2300
$\pi_1^c(t)$	41.4	35.3	34.5	34.9	33.5	38.6	48.1
CONTRACT #2: $p_2^c(t)$ = 1250 (BASE LOAD); $\pi_2^c(t)$ = 41.6							

The results of the following test cases are included in order to illustrate the effect of constraints assigned in maintenance scheduling problem:

- **case #1**: only constraints (1) – (11);
- **case #2**: case #1 plus incompatible pairs of units (units 4 and 5 in TPP#1 and units 7 and 8 in TPP#2 cannot be maintained at the same time);
- **case #3**: case #2 plus maintenance priority (in TPP#5, unit 19 must be maintained before unit 20);
- **case #4**: case #3 plus separation among consecutive maintenance outages (after finishing maintenance of unit 16 in TPP#4 and beginning maintenance of unit 22 in TPP#5, separation of 5 weeks is needed);
- **case #5:** case #4 plus overlap in maintenance outages (maintenance of unit 14 in TPP#4 must begin 3 weeks before unit 9 in TPP#3 finish its maintenance).

B. Test results and analysis

For specified test cases, Table VI shows total costs, profit and total energy for market. Maximum profit and the biggest energy amount for market are offered in test case #1 that considers only basic constraints (1) – (11). The lowest costs and the smallest energy amount for market are offered in test case #5 characterized with the smallest value of profit compared with other cases. It can be concluded, from Table VI, how different set of constraints assigned to maintenance scheduling problem affects total costs of the GenCo's generation system, and how affects its profit. Although test cases #2 and #3 have the equal total energy amount for market (equal power patterns in both scenarios), because of additional constraint related to maintenance priority total costs are increased in test case #3 for $1,774.6 and its profit is decreased for exact amount compared these differences with test case #2.

TABLE VI
THE GLOBAL RESULTS FOR DIFFERENT TEST CASES

test case	total costs ($)	profit ($)	total energy for market (MWh)
#1	909,946,708.8	577,565,280.2	8,350,776
#2	910,193,927.4	577,538,901.0	8,358,790
#3	910,195,702.0	577,537,126.4	8,358,790
#4	909,868,384.9	577,451,667.5	8,347,870
#5	904,518,373.3	574,901,608.5	8,193,192

To illustrate the results obtained, test cases #1 and #5 are selected, and maintenance schedule of the thermal power units can be seen in Tables VII and VIII, respectively.

Tables VII and VIII show total production of thermal units $P^T(t)$, power for market $p^S(t)$, total reserve $R(t)$ and power in maintenance $P^M(t)$ for each week t. Shown in Tables VII and VIII, resulting schedule during the horizon satisfied all specified constraints and ensured profit maximization for the GenCo. Schedules for test cases #2, #3 and #4 are obtained in similar manner, where given constraints are satisfied for each case. In analyzed test cases maintenance constraints, weekly power profile from bilateral contracts and weekly forecasted prices are basic factors for high number of contemporaneous plants in maintenance condition.

Figs. 1–2 show the evolution of the total power production, the power in maintenance, and the market prices over the time span. As it can be seen, maintenance powers are allocated mainly in weeks when market prices are lowest, so profit is maximized. GenCo's obligations resulting from bilateral contracts for physical delivery of electrical energy and requirement on minimal reserve level, additionally affect on schedule results. Also, effect of constraints assigned in maintenance scheduling problem significantly change power in maintenance and therefore change total production, i.e. power that will be offered on the market.

TABLE VII

WEEKLY MAINTENANCE SCHEDULE OF THE THERMAL UNITS FOR CASE #1

week	units in maintenance	$P^T(t)$ (MW)	$p^S(t)$ (MW)	R(t) (MW)	$P^M(t)$ (MW)
1	–	4935	1385	250	0
2	–	4935	1385	250	0
3	–	4935	1385	250	0
4	–	4935	1385	250	0
5	–	4935	1385	250	0
6	–	4935	1385	250	0
7	–	4935	1385	250	0
8	–	4842	1292	343	0
9	–	4637	1237	548	0
10	–	4558	1158	627	0
11	–	4577	1177	608	0
12	3	4307	907	658	220
13	3	4408	1008	557	220
14	3,5	4125	725	750	310
15	3,5,6,22	3835	435	805	545
16	3,5,6,22	4195	795	445	545
17	3,5,6,22	3835	435	805	545
18	–	4692	1292	493	0
19	–	4935	1535	250	0
20	–	4935	1535	250	0
21	–	4767	1367	418	0
22	–	4935	1535	250	0
23	–	4935	1535	250	0
24	–	4935	1535	250	0
25	–	4935	1685	250	0
26	2	4553	1303	322	310
27	2	4285	1035	590	310
28	2,14	4002	752	553	630
29	2,10,12,14,18	3517	567	288	1380
30	2,10,12,14,18	3460	510	345	1380
31	2,10,12,14,17,18,20,21	2950	0	370	1865
32	1,10,12,14,17,18,20,21	2950	0	370	1865
33	1,7,9,12,17,20,21	3007	7	513	1665
34	1,7,9,12,17,19,20	3000	0	455	1730
35	1,7,9,15,17,19,20	3000	0	355	1830
36	1,7,8,9,15,19	3000	0	565	1620
37	7,8,9,15,19	3343	343	532	1310
38	4,8,9,15,16,19	3000	0	620	1565
39	4,8,9,11,15,16	3000	0	510	1675
40	4,8,11,13,15,16	3000	0	510	1675
41	4,11,13,16	3450	0	580	1155
42	11,13,16	3450	0	760	975
43	–	4692	1242	493	0
44	–	4935	1485	250	0
45	–	4935	1485	250	0
46	–	4935	1485	250	0
47	–	4935	1485	250	0
48	–	4935	1485	250	0
49	–	4935	1485	250	0
50	–	4935	1385	250	0
51	–	4935	1385	250	0
52	–	4935	1385	250	0

TABLE VIII

WEEKLY MAINTENANCE SCHEDULE OF THE THERMAL UNITS FOR CASE #5

week	units in maintenance	$P^T(t)$ (MW)	$p^S(t)$ (MW)	R(t) (MW)	$P^M(t)$ (MW)
1	–	4935	1385	250	0
2	–	4935	1385	250	0
3	–	4935	1385	250	0
4	–	4935	1385	250	0
5	–	4935	1385	250	0
6	–	4935	1385	250	0
7	–	4935	1385	250	0
8	–	4842	1292	343	0
9	–	4637	1237	548	0
10	–	4558	1158	627	0
11	–	4577	1177	608	0
12	3	4307	907	658	220
13	3	4408	1008	557	220
14	3	4215	815	750	220
15	3	4145	745	820	220
16	3	4505	1105	460	220
17	3	4145	745	820	220
18	–	4692	1292	493	0
19	–	4935	1535	250	0
20	–	4935	1535	250	0
21	–	4767	1367	418	0
22	–	4935	1535	250	0
23	–	4935	1535	250	0
24	9	4485	1085	250	450
25	9	4485	1235	250	450
26	2,9	4103	853	322	760
27	2,9	3835	585	590	760
28	2,9,14	3552	302	553	1080
29	2,9,10,12,14,18	3067	117	288	1830
30	2,9,10,12,14,18	3010	60	345	1830
31	2,7,10,12,14,16,18	2950	0	420	1815
32	1,7,10,12,14,16,18	2950	0	420	1815
33	1,5,7,12,16	3492	492	618	1075
34	1,5,7,12,15,16,21	3048	48	627	1510
35	1,5,7,15,16,17,19,21	3000	0	525	1660
36	1,5,8,15,17,19,20,21	3023	23	597	1565
37	8,15,17,19,20	3658	658	457	1070
38	4,6,8,11,15,17,19,20	3000	0	510	1675
39	4,6,8,11,15,17,19,20	3000	0	510	1675
40	4,6,8,11,13,20	3053	53	737	1395
41	4,11,13,22	3450	0	755	980
42	13,22	3783	333	872	530
43	22	4627	1177	478	80
44	–	4935	1485	250	0
45	–	4935	1485	250	0
46	–	4935	1485	250	0
47	–	4935	1485	250	0
48	–	4935	1485	250	0
49	–	4935	1485	250	0
50	–	4935	1385	250	0
51	–	4935	1385	250	0
52	–	4935	1385	250	0

Fig. 1 Evolution of total production, power in maintenance and market prices for test case #1

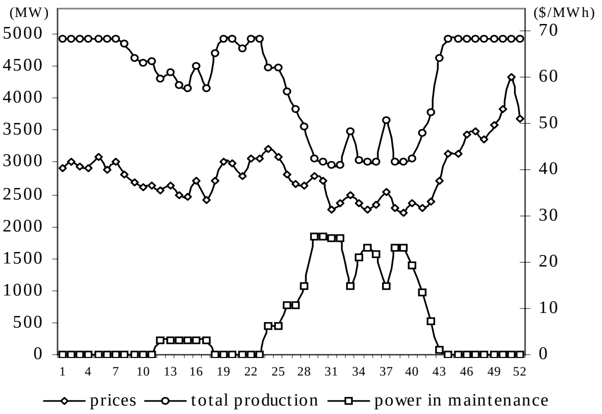

Fig. 2 Evolution of total production, power in maintenance and market prices for test case #5

V. Conclusion

In restructured power systems and liberalized market, maintenance scheduling problem has new characteristics quite different from those in traditional environment. In the proposed maintenance scheduling formulation, GenCo's aim is to maximize profit, combining energy sales through bilateral contracts and energy sales on the market. The GenCo is responsible for performing necessary maintenance of its power units in order to sustain its position on competitive energy market. The maintenance periods of time for power units are scheduled either by profit-seeking GenCos only, or by coordination between profit-seeking GenCos and reliability-concerned ISO, and the extent of this coordination depends on market environment. Although the coordination procedure how the ISO adjust the individual GenCos' maintenance schedules and how each GenCo responds to the adjusted schedule is important, it is not a main concern of this paper and one can investigate more about this subject. In this paper the maintenance scheduling problem is analyzed from the GenCo point of view.

The proposed model has been successfully tested on the realistic size case study. Numerical results have revealed the accuracy and computationally efficient performance of the proposed formulation.

References

[1] K. W. Edwin and F. Curtius, "New maintenance scheduling method with production cost minimization via integer linear programming ", *International Journal of Electric Power and Energy Systems*, Vol. 12, pp. 165-170, 1990.

[2] L. Chen and J. Toyoda, "Optimal generating unit maintenance scheduling for multi-area system with network constraints", *IEEE Transactions on Power Systems*, Vol. 6, No. 3, pp. 1168-1174, August 1991.

[3] M. K. C. Marwali and S. M. Shahidehpour, "Long-term transmission and generation maintenance scheduling with network, fuel and emission constraints", *IEEE Transactions on Power Systems*, Vol. 14, No. 3, pp. 1160-1165, August 1999.

[4] M. K. C. Marwali and S. M. Shahidehpour, "Integrated generation and transmission maintenance scheduling with network constraints", *IEEE Transactions on Power Systems*, Vol. 13, No. 3, pp. 1063-1068, August 1998.

[5] L. M. Moro and A. Ramos, "Goal programming approach to maintenance scheduling of generating units in large scale power systems", *IEEE Transactions on Power Systems*, Vol. 14, No. 3, pp. 1021-1028, August 1999.

[6] K. P. Dahal, C. J. Aldridge and J. R. McDonald, "Generator maintenance scheduling using genetic algorithm with a fuzzy evaluation function", ELSEVIER, *Fuzzy Sets and Systems*, No. 102, pp. 21-29, 1999.

[7] E. K. Burke, J. A. Clarke and A. J. Smith, "Four methods for maintenance scheduling", in G. D. Smith, N. C. Steele and R. Albrecht (eds.) *Proceedings of Third International Conference Artifical Neural Nets and Genetic Algorithms* (ICANNGA '97), Springer-Varlag, pp. 265-270, Vienna, 1998.

[8] K. P. Dahal, G. M. Burt, J. R. McDonald and S. J. Galloway, "GA/SA based hybrid techniques for the scheduling of generator maintenance in power systems", *Proceedings of Congress of Evolutionary Computation* (CEC2000), pp. 567-574, San Diego, USA, 2000.

[9] E. K. Burke and A. J. Smith, "Hybrid Evolutionary Techniques for the Maintenance. Scheduling Problem", *IEEE Transactions on Power Systems*, Vol. 15, No. 1, pp. 122-128, February 2000.

[10] I. El-Amin, S. Duffuaa and M. Abbas, "A tabu search algorithm for maintenance scheduling of generating units", ELSEVIER, *Electric Power Systems Research*, Vol. 54, No. 2, pp. 91-99, 2000.

[11] J. Sugimoto, H. Tajima, S. Machi, R. Yokoyama and V. V. R. Silva, "Profit-based thermal unit maintenance scheduling under price volatility in competitive environment", *International Conference on Intelligent Systems and Control – ISC*, Cambridge, USA, October-November, 2005.

[12] H. S. Kim, S. P. Moon, J. S. Choi, S. Y. Lee, D. H. Do and M. M. Gupta, "Generator maintenance scheduling considering air pollution based on the fuzzy theory", *IEEE International Fuzzy Systems Conference Proceedings*, Vol. III, pp. 1759-1764, Seoul, Korea, August 1999.

[13] H. S. Kim and J. S. Choi, "Development of a method for flexibile generator maintenance scheduling using the fuzzy theory", *Proceedings of Asia Fuzzy System Symposium* (AFSS2000), Tsukuba, Japan, May-June, 2000.

[14] H. H. Zurn and V. H. Quintana, "Several objective criteria for optimal generator preventive maintenance", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-96, No. 3, pp. 984-992, May/June 1977.

[15] M. Shahidehpour, H. Yamin and Z. Li, *Market operations in electric power systems: Forecasting, scheduling and risk management*, First ed., New York, NY: John Wiley & Sons, 2002.

[16] A. J. Conejo, R. Bertrand and M. D. Salazar, "Generation maintenance scheduling in restructured power systems", *IEEE Transactions on Power Systems*, Vol. 20, No. 2, pp. 984-992, May 2005.

[17] R. Eshraghnia, M. H. M. Shanechi and H. R. Mashhadi, "A new approach for maintenance scheduling of generating units in power market", 9th *International Conference on Probabilistic Methods Applied to Power Systems, KTH*, Stockholm, Sweden, June 2006.

[18] S. Bisanovic, M. Hajro, M. Dlakic, "Hydrothermal self-scheduling problem in a day-ahead electricity market", *Electric Power Systems Research*, Vol. 78, No. 9, pp 1579-1596.

[19] S. El Khatib and F. D. Galiana, "Negotiating bilateral contracts in electricity markets", *IEEE Transactions on Power Systems*, Vol. 22, No. 2, pp. 553-562, May 2007.
[20] E. D. Andersen and K. D. Andersen, "The MOSEK interior point optimizer for linear programming: An implementation of the homogeneous algorithm", in H. Frenk, K. Roos, T. Terlaky, and S. Zhang, editors, *High Performance Optimization*, pp 197-232, Kluwer Academic Publishers, 2000.