Mixed-Integer Linear Programming based Maintenance Scheduling of Generating Units

Ali Esmaeel Nezhad
Department of Electrical Engineering, School of Energy Systems, LUT University, 53850, Lappeenranta, Finland
Email: ali.esmaeelnezhad@lut.fi

Pedro H.J. Nardelli
Department of Electrical Engineering, School of Energy Systems, LUT University, 53850, Lappeenranta, Finland
Email: pedro.nardelli@lut.fi

Farideh Ghanavati
Department of Industrial Engineering and Management, University of Aveiro, Aveiro, Portugal
Email: Ghanavati@ua.pt

Subham Sahoo
Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark
Email: sssa@energy.aau.dk

Gerardo J. Osório
University Portucalense Infante D. Henrique (UPT), R. Dr. António Bernardino de Almeida, 4200-072 Porto, Portugal
Email: gjosilva@gmail.com

***Abstract*—This paper presents a mixed-integer linear programming model for the maintenance scheduling of generating units in the power system. The proposed model is investigated for weekly scheduling for one year addressing the crew availability constraint. The maintenance scheduling problem is modeled as an optimization problem to determine the optimal timing for handling the technical constraints of the power generation sector. In addition, the technical constraints for optimal scheduling of the tasks, like sequential tasks and rest time of the crews have been addressed in the scheduling management framework. The weekly peak power and spinning reserve have been considered in line with the economic issues for power generation in the whole system. The historical market clearing price (MCP) and mid-term load forecasting have been considered in the developed model.**

Keywords—Maintenance Scheduling, Mixed-Integer Linear Programming, Market Clearing Price, Historical Data, Power Generating Units.

I. INTRODUCTION

The increasing demand for electrical energy has been entering a new stage with new concerns risen regarding climate change and environmental emissions. This issue has already led to starting new investments in the power system to expand the generation and transmission systems, besides employing distributed generation systems and demand response programs. However, much more attempts must be made to promote the operation of the current power system, mitigating the probability of undesired failures, inversely impacting the power system operation and service quality [1]–[3]. Accordingly, it is highly required to regularly carry out maintenance scheduling to keep the secure operation of the system. In this respect, a game theory-oriented maintenance scheduling model has been developed in [4], [5]. The hill climbing technique together with the evolutionary programming (EP) is employed in [6] to tackle the maintenance scheduling problem in the IEEE 30-bus test system. Ref. [7] presented a fuzzy-EP method to tackle the maintenance scheduling problem using a single-objective optimization model aimed at minimizing the cost. The framework was assessed using the IEEE 30-bus test system. The problem of short-term maintenance scheduling problem was studied in [8] using an EP-based algorithm. Ref. [9] used a simulated annealing optimization algorithm to tackle the maintenance scheduling problem. A mathematical method combined with the differential evolution method has been used in Ref. [10] to solve the single-objective optimization generation scheduling problem. The robust optimization theory has also been suggested in Refs. [11], [12] for the generation scheduling problem. The problem of generation maintenance scheduling of virtual power plants has been tackled in [13]. An improved binary particle swarm optimization algorithm was utilized in [14] to solve the generation scheduling problem in power systems. The proposed model was simulated on the IEEE 24-bus test system known as the IEEE reliability test system (RTS), and also, the Kerala power system in India. Ref. [15] introduced a coordination framework for the generation maintenance scheduling in electricity markets. The main contributions of this paper are as follows:

- The maintenance scheduling problem is modeled as a standard mixed-integer linear programming.
- The technical constraints for the maintenance crews have been modeled in this study.
- A Gantt chart interface for the maintenance scheduling and task allocation is provided.

The rest of this paper is organized as follows. Section II presents the problem formulation. Section III includes the simulation results, and lastly, some concluding remarks have been proposed in Section IV.

II. PROBLEM FORMULATION

A. Objective Function

The objective function of the maintenance scheduling is represented as the maximization of the profits of generation companies (GenCos). The profit of the generating units is represented as the historical MCP and the weekly peak loads. There is a logical relationship between the MCP and the load demand. The objective function includes three main parts, the first term is related to the operating profit of generating units; the second term addresses the maintenance cost of generating

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units and the last term deals with the interruption in the maintenance period to guarantee the continuous time interval. The objective function is as follows:

$$
\begin{aligned}
&Max\\
&Z=\underbrace{\sum_{\omega=1}^{N_\omega}\sum_{u=1}^{N_u}\left[MCP(\omega)PG(u,\omega)-\beta(u)PG(u,\omega)\right]}_{Operational\ Profit}\\
&-\underbrace{\sum_{\omega=1}^{N_\omega}\sum_{u=1}^{N_u}\left[IM(u,\omega)\left[Fix(u)+Var(u)PG^{\max}(u)\right]\right]}_{Maintenance\ Cost}\\
&-\underbrace{\sum_{\omega=1}^{N_\omega}\sum_{u=1}^{N_u}M(u)\left[SC(u,\omega)+SD(u,\omega)\right]-2\sum_{u=1}^{N_u}M(u)}_{Interruption\ Cost}
\end{aligned}
\tag{1}
$$

The operational profit is modeled as the difference between revenue of participating in the market and the cost of power generation during the whole year. The scheduling is performed for one year by a weekly resolution. Therefore, the number of time slots is 52 weeks, i.e. $\omega = 52$. In this study, the historical weekly MCP is considered for the revenue calculation. In addition, the linear operating cost function is considered.

The second term is related to the maintenance cost of generating units. The maintenance cost of each unit is expressed by the fix and variable cost terms, while the $IM(u,\omega)$ is the maintenance binary decision variable. In the case of planned maintenance, this binary variable is 1; otherwise, it will be 0.

To guarantee continuous maintenance scheduling, an extra term has been added to the model as the last term in the objective function. This term ensures that the outage duration of each generating unit would be continuous and there is no interruption during the maintenance period to accomplish the tasks during the predefined time interval. The corresponding constraints are as follows:

B. General Constraints

Techno-economic constraints of the maintenance scheduling problem are as follows:

$$\sum_{u=1}^{N_u}PG(u,\omega)=PL(\omega) \tag{2}$$

$$IG(u,\omega)PG^{\min}(u)\le PG(u,\omega)\le IG(u,\omega)PG^{\max}(u) \tag{3}$$

$$SR(u,\omega)=IG(u,\omega)PG^{\max}(u)-PG(u,\omega) \tag{4}$$

$$SR(u,\omega)\ge SR^{\min}(\omega) \tag{5}$$

$$IG(u,\omega)\le\left(1-IM(u,\omega)\right) \tag{6}$$

$$\sum_{\omega=1}^{N\omega}IM(u,\omega)=MT(u) \tag{7}$$

$$SC(u,\omega)-SD(u,\omega)=IM(u,\omega)-IM(u,\omega-1)\quad\forall\omega>1 \tag{8}$$

$$\omega\times SC(u,\omega)=Start(u) \tag{9}$$

$$\omega\times SD(u,\omega)=Finish(u) \tag{10}$$

$$\sum_{u=1}^{N_u}Lbr(u)\times IM(u,\omega)\le Crew(\omega) \tag{11}$$

The constraints of the generating units maintenance scheduling are as follows. Constraint 2 indicates the power balance equation at each time interval of the scheduling period. The maintenance team must be assured that the operable units are adequate to supply the load demand in each week. The operating constraint of available units is stated in constraint (3). The binary variable *IG* shows the operation status of the available units while the unit is operating within its permitted operating bounds if *IG* is "1". Constraint (4) shows the spinning reserve of committed units, while constraint (5) is the limitation of the spinning reserve of committed units. As constraint (6) indicates, the unit cannot be operated if it is decommitted for maintenance. In other words, the unit would not be absent in the generation scheduling if the binary variable *IM* is equal to "1". The maintenance time of each generating unit is stated in constraint (7) where *MT* is applied to the constraint on a weekly basis. Constraint (8) emphasizes that the maintenance time should be continuous and for any interruption occurring, a penalty would be applied to the third part of the objective function. All binary variables of Eq. (8) are binary variables and accordingly, the starting and ending time of each generating unit maintenance should conform to constraint (7). Constraints (9) and (10) show the starting and ending weeks of the maintenance scheduling, respectively. The limitation of the crews is applied to the problem through constraint (11) in which *Lbr(u)* is the number of crews for the maintenance of a generating unit. *Lbr(u)* is determined by the maintenance scheduling entity as a parameter for each generating unit.

C. Maintenance Scheduling Specific Constraints

Some constraints are particularly significant to the maintenance team, including the time limitation, available crews' limitations, rest time, and also geographical limitations of a unit. Constraint (12) models the crews' limitation for the case that the simultaneous maintenance of two units is not possible. In this respect, the units in the set $\{k,l,\ldots,m\}$ cannot enter the maintenance scheduling, concurrently.

$$IM(k,\omega)+IM(l,\omega)+\ldots+IM(m,\omega)\le 1\quad\{k,l,\ldots,m\}\in u \tag{12}$$

Furthermore, the maintenance scheduling of similar units in a plant should be done in a way that the crews do not have to move to another plant until finished with such units in one plant. This limitation is addressed in constraint (13). Accordingly, the maintenance of unit *l* would be exactly after the maintenance of unit *k*, where the maintenance of the unit *k* is indicated on the right-hand side of Eq. (13).

$$Start(l)=Start(k)+MT(k)\quad\{k,l,\}\in u \tag{13}$$

In case the crews need rest or an interruption after finishing with the maintenance of a unit, the *rest* would be used as (14).

$$Start(m)=Start(l)+MT(l)+rest(l)\quad\{l,m\}\in u \tag{14}$$

For those generating units their maintenance periods are pre-determined due to the environmental, economic, or fuel limitations, the binary variables corresponding to the maintenance of the unit would be assigned to the model as parameters. Accordingly, they are not included in the maintenance scheduling. If the time limit is longer than *MT*, it can be modeled by using constraint (15), where *Initial* and *End* specify the permitted time interval for the maintenance of the unit.

$$IM(u,\omega)\le\begin{cases}0 & if\ \omega<Initial\\ 1 & if\ Initial\le\omega\le End\\ 0 & if\ \omega>End\end{cases} \tag{15}$$

TABLE I. UNIT MAINTENANCE DATA

Unit	PGmax	PGmin	MT	Fix	Var	*β*	*Lbr*
U01	12	2.4	1	10	5	25.5472	2
U02	12	2.4	1	10	5	25.6753	2
U03	12	2.4	1	10	5	25.8027	2
U04	12	2.4	1	10	5	25.9318	2
U05	12	2.4	1	0.3	5	26.0611	2
U06	20	4	1	0.3	5	37.9637	2
U07	20	4	1	0.3	5	37.7770	2
U08	20	4	1	0.3	5	37.9637	2
U09	20	4	3	10	0.9	38.7770	2
U10	76	15.2	3	10	0.9	13.5073	2
U11	76	15.2	3	10	0.9	13.3272	2
U12	76	15.2	3	10	0.9	13.3538	2
U13	76	15.2	4	8.5	0.8	13.4073	2
U14	100	25	4	8.5	0.8	18.0000	3
U15	100	25	4	8.5	0.8	18.6000	3
U16	100	25	4	8.5	0.8	18.1000	3
U17	100	25	4	8.5	0.8	18.2800	3
U18	100	25	4	8.5	0.8	18.2000	3
U19	100	25	5	7	0.8	17.2800	3
U20	155	54.25	5	7	0.8	10.7367	4
U21	155	54.25	5	7	0.8	10.7154	4
U22	155	54.25	5	7	0.8	10.7367	4
U23	155	54.25	5	5	0.7	10.7583	4
U24	197	68.95	6	5	0.7	23.0000	4
U25	197	68.95	6	5	0.7	23.1000	4
U26	197	68.95	6	5	0.7	23.2000	4
U27	197	68.95	6	5	0.7	23.4000	4
U28	197	68.95	6	5	0.7	23.5000	4
U29	197	68.95	6	5	0.7	23.0400	4
U30	350	140	8	4.5	0.3	10.8416	5
U31	400	100	8	5	0.3	7.49210	6
U32	400	100	8	5	0.3	7.50310	6

III. SIMULATION RESULTS

The proposed MILP maintenance scheduling model has been simulated on the modified IEEE 24-bus test system. Table I represents the maintenance data of generating units including the generation capacity, cost of energy generation, and also maintenance costs, besides the number of weeks and crews required for the annual maintenance [16].

The weekly maintenance data for one year including the peak power and MCP based on the average annual cost are given in Table II. It is noteworthy that a year is comprised of 52 weeks and the energy price of a week is the average energy price. The data represented in Tables I and II are used for the maintenance scheduling in the base case [17]. Furthermore, the assumptions made with respect to constraints (12)-(15) are as follows:

- The 197-MW units, i.e. U24-U29 have fixed maintenance crews. Hence, the maintenance of these units cannot be carried out concurrently.

TABLE II. WEEKLY MAINTENANCE DATA

Week	MCP	Demand	Week	MCP	Demand
W01	36.7	86.2	**W27**	29.2	75.5
W02	39.3	90.0	**W28**	34.1	81.6
W03	37.2	87.8	**W29**	33.2	80.1
W04	35.6	83.4	**W30**	38.1	88.0
W05	37.9	88.0	**W31**	25.2	72.2
W06	35.9	84.1	**W32**	30.9	77.6
W07	35.4	83.2	**W33**	33.1	80.0
W08	33.5	80.6	**W34**	26.0	72.9
W09	27.2	74.0	**W35**	25.8	72.6
W10	26.7	73.7	**W36**	25.0	70.5
W11	25.1	71.5	**W37**	31.1	78.0
W12	25.9	72.7	**W38**	23.8	69.5
W13	24.9	70.4	**W39**	25.6	72.4
W14	28.8	75.0	**W40**	25.5	72.4
W15	25.2	72.1	**W41**	27.7	74.3
W16	33.2	80.0	**W42**	27.9	74.4
W17	29.1	75.4	**W43**	33.1	80.0
W18	35.7	83.7	**W44**	38.1	88.1
W19	37.0	87.0	**W45**	38.2	88.5
W20	37.8	88.0	**W46**	40.3	90.9
W21	36.4	85.6	**W47**	42.2	94.0
W22	33.7	81.1	**W48**	38.7	89.0
W23	39.7	90.0	**W49**	42.8	94.2
W24	38.3	88.7	**W50**	45.0	97.0
W25	39.0	89.6	**W51**	58.0	100.0
W26	36.6	86.1	**W52**	43.4	95.5

- After the maintenance of the two 197-MW units is finished, i.e. after 8 weeks, an obligatory rest period is considered for the crews.
- The 400-MW units have also the same maintenance crews and the rest is considered two weeks after the overhaul of the first unit.
- The number of crews is 18.

The proposed problem has been modeled as a single-objective optimization problem, aimed at maximizing the profit of GenCos from selling energy in the market taking into account the fuel cost of units, besides the variable and fixed costs of units. The simulation has been done in GAMS by using the CPLEX solver installed on an Intel Corei7 Laptop with 32 GB RAM. The simulation results have been plotted in Microsoft Excel by using an interface where the maintenance scheduling would be shown to the user within a Gantt chart interface. Fig. 1 depicts the maintenance scheduling of all generating units of the modified IEEE 24-bus system. As mentioned in the specific constraints of the problem, the maintenance of 19-MW units are carried out pairwise and continuously in the maintenance scheduling.

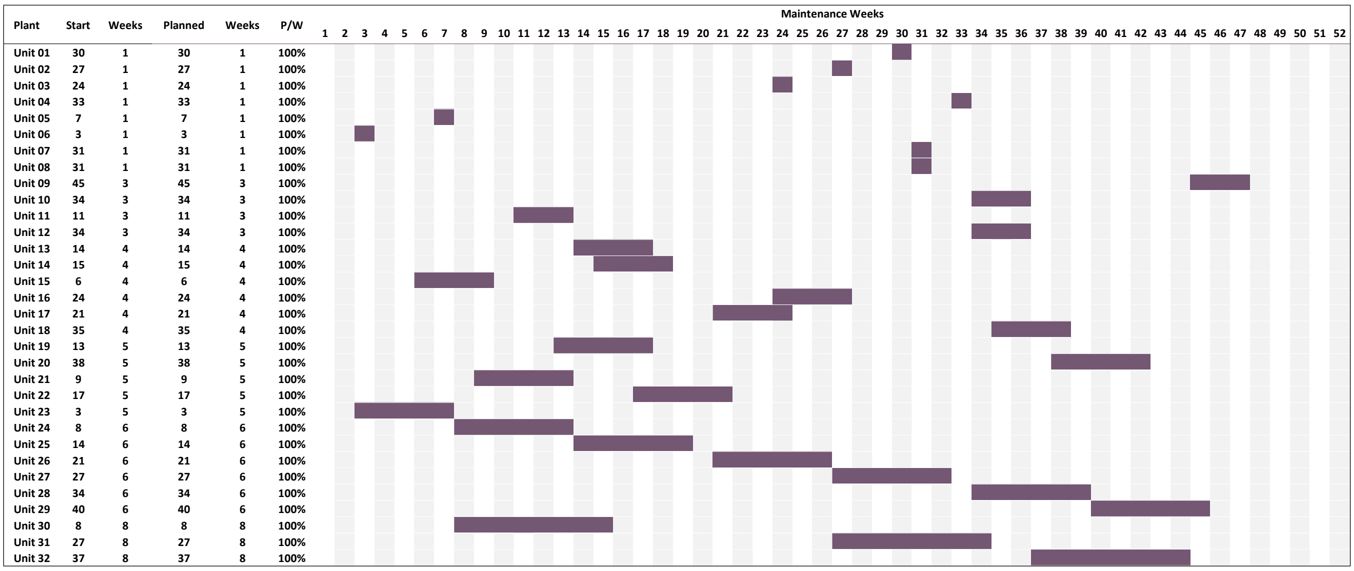

Fig. 1. Optimal Maintenace Scheduling of Power Generating Units in IEEE RTS

As can be shown, the rest time of crews after the overhaul of the two units, i.e. one week, has well been addressed. Moreover, the two-week rest time of the 400-MW units has also been satisfied. The largest number of units decommitted for maintenance occurs during weeks 9-15 when the load demand is relatively low, which is quite economically justified due to the low energy prices as well. The same thing happens during weeks 38-42, during which one of the 400-MW units is decommitted for maintenance. This would not cause any difficulty to the power system reliability considering the reserve requirements. In addition, there would not be any maintenance during the initial and final weeks of the year due to the high load demand and high energy prices. Fig. 2 illustrates the weekly maintenance scheduling of generating units and the number of crews for the maintenance each week. The total maintenance cost of the system for the studied year is M$ 2.723.

IV. Conclusion

The maintenance scheduling problem of generating units is known as one of the most vital problems of the power system. The aim beyond carrying out maintenance scheduling is to manage available resources to supply the load demand addressing the overhaul of generating units and mitigating the units' trips. Accordingly, this paper presented an efficient MILP maintenance scheduling model, aimed at maximizing the profit of GenCos from selling energy in the market. In this respect, the objective function included revenues of the units, the maintenance costs of units, and also a term addressing the continuity of the maintenance period. Furthermore, the techno-economic constraints, besides the maintenance scheduling specific constraints relating to the time limitations and crews' rest, were all modeled and satisfied. The developed model was simulated using the modified IEEE 24-bus system. The simulation results indicated that the presented maintenance scheduling model could effectively address the requirements of the problem and provided the user with a Gantt chart interface.

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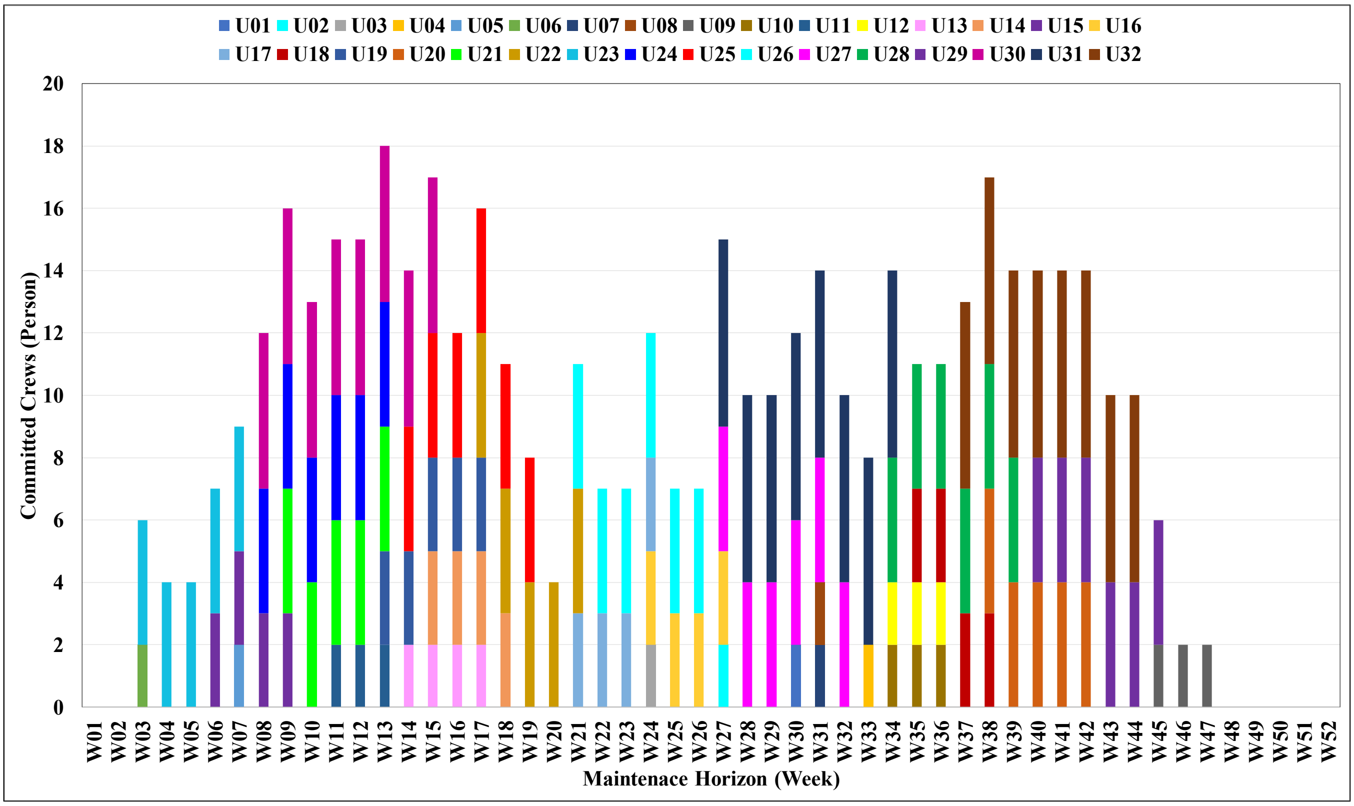

Fig. 2. Committed Crews for Optimal Maintenace Scheduling of Generating Units in the IEEE RTS.