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LONG TERM COORDINATED GENERATION AND TRANSMISSION MAINTENANCE SCHEDULING CONSIDERING NETWORK CONSTRAINTS AND SYSTEM RESERVE

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Abstract- Generation or transmission maintenance scheduling packages provide preventive or corrective maintenance scheduling over a certain period in order to minimize system costs while fulfilling relative requirements. In advanced power systems inclusion of network constraints and increasing rate of electricity demand may result in higher number of generators and transmission lines and hence lower system reserve. In order to avoid this and make the maximum use of power system capacities periodic system maintenance programs should be implemented. This paper proposes a security constrained model for long-term Generation and Transmission Maintenance Scheduling (GTMS) problem. Since generation scheduling and transmission scheduling are in interrelation with each other, here a coordinated GTMS is proposed in which unit and transmission maintenance scheduling are modeled simultaneously. For more study, that is realistic network operation and security constraints as well as power system reserve are taken into account. Impact of load curve on the GTMS problem is investigated by a proposed penalty factor. Unlike some previous studies that consider a fixed period for all unit maintenance windows, here various maintenance windows are considered for the system that is more realistic. Furthermore, a one-year time horizon is considered for the study that is more practical. Considering problem, Mixed Integer Programming (MIP) is employed to obtain most accurate results. An IEEE 24-bus Reliability Test System is utilized for simulation and show the accuracy of results.

Keywords: Generation and Transmission Maintenance Scheduling, Network Constraints, Transmission Security Constraints, Penalty Factor, System Reserve.

I. INTRODUCTION

As of 1980, many countries have made improvements in forming electric power markets. The main aim was breaking the monopoly operation pattern of tradition electric power industry and building a competitive power industry. Additional competition and increasing complexity in power generating systems as well as a necessity for high service reliability and low production costs triggered additional interests in automatic scheduling techniques for maintenance of generators, transmission, and pertinent equipment.

Although in the past decades, several procedures were recommended for the solution of unit and transmission maintenance scheduling, there was no consensus on the most appropriate approach to this problem. However, the literatures show that, among all the possible intelligent techniques genetic algorithm is the most suitable and powerful tool for maintenance scheduling problem [1-5]. On the other hand, there is no doubt that mathematical programming methods supply more reliable and versatile solution to maintenance scheduling [6].

Generally, maintenance scheduling in a raw system may fall into two stages from time horizon perspective, entitled, long-term, and short-term scheduling [7]. Long-Term Maintenance Scheduling (LTMS) considers the schedule of system on a horizon of one or two years in order to minimize system aggregated operation and maintenance costs. The solutions obtained from LTMS then can be used as guidelines and bases for addressing unit commitment and optimal power flow problems [8-11]. The objective of Short-Term Maintenance Scheduling (STMS) is to minimize the cost of operation over hourly, daily, or weekly periods.

Because dynamic economic dispatch is fundamental for real time control of power systems, the STMS causes a commitment strategy for real-time economic dispatch. Some of researches deal with maintenance scheduling problem in both long term and short term scheduling regardless of system security indices [1-3]. M.K.C. Marwali and S.M. Shahidehpour [4, 5, 12] have implemented a long term maintenance scheduling study considering power system reliability and security indices, however impact of consumers loading on maintenance scheduling is not taken into account.

Furthermore, fixed maintenance periods were considered for all participant units that are not necessarily correct. On the other hand, authors in their previous works [13-16] proposed a three months unit maintenance scheduling taking into account system security and reliability indices as well as energy purchase option. This paper proposes a security constrained model for long-term Generation and Transmission Maintenance Scheduling (GTMS) problem.

Since generation scheduling and transmission scheduling are in interrelation with each other, here a coordinated GTMS is proposed in which unit and transmission maintenance scheduling is modeled simultaneously. For study, that is more realistic network operation and security constraints as well as power system reserve are taken into account. Impact of load curve on the GTMS problem is investigated by a proposed penalty factor. Unlike some previous studies that consider a fixed period for all unit maintenance windows, here various maintenance windows are considered for the system that is more realistic.

Furthermore, a one-year time horizon is considered for the study that is more practical. Considering the problem, Mixed Integer Programming (MIP) is employed to obtain the most accurate results. Branch and bound algorithm is employed as the most general algorithm to solve the problem. The paper is organized as follow, sections II and III represent the formulation of proposed maintenance scheduling model and solution methodology, respectively. In section IV case study and simulation results are presented to show the accuracy of the model and finally, section V provides the conclusion.

II. PROBLEM DESCRIPTION

While transmission, generation, and operation constraints are taken into account, the proposed GTMS problem determines the period in which generating units and transmission lines should be under maintenance, over one or two years planning horizon to lessen the total operation and maintenance cost. Leave out the network constraints in maintenance scheduling may end in loss of information on scheduling problems.

When network constraints are included, the problem becomes a lot more realistic and complex that could be referred as a security constrained maintenance scheduling. The long-term generation and transmission maintenance scheduling in the power market environment is a large-scale optimization problem. Mathematically, it can be formulated as follows.

A. Objective Function

The objective function of the proposed model is to minimize the total maintenance and generation costs over the operational planning period. Equation (1) corresponds to a MIP problem since x_{it} and x_{kt} are integer variables and g_{it} is continuous. The first and second terms of the objective function are the maintenance costs of generators and transmission lines, and the third one is the energy generation cost.

$$\min \sum_t \sum_i C_{it} \times \gamma_t \left(1-x_{it}\right) + \sum_t \sum_k C_{kt} \left(1-x_{kt}\right) + \\ + \sum_t \sum_i c_{it} g_{it} \tag{1}$$

A.1. Penalty Factor

In order to consider the impact of the load curve demand on maintenance scheduling problem, a penalty factor is represented as Equation (2). In fact, penalty factor shows importance of loading points on proposed GTMS based on amount of consumptions. In peak periods, the penalty factor is maximum while in off peak period is minimum. Therefore, ISO could employ penalty factor to patronize units and transmission lines not to have maintenance in peak periods. Here, total unit maintenance cost is the maintenance cost of unit multiply by penalty factor. By this strategy, ISO could have more effect on system maintenance scheduling.

$$\forall t \qquad \gamma_t = 2 - \frac{D_{\max} - D_t}{D_{\max} - D_{\min}} \tag{2}$$

B. Maintenance Constraints

In order to make the generation and transmission maintenance scheduling feasible, certain constraints should be fulfilled. Some of basic constraints, which should be set up, are maintenance manpower, maintenance window, maintenance duration, and etc. Maintenance constraints in the current research could be categorized as follows.

B.1. Maintenance Window

Equations (3) to (8) show the maintenance timetable stated in terms of maintenance variables (S_i, S_k). The unit and transmission maintenance may not be scheduled before their earliest period (e_i, e_k), or after latest period allowed for maintenance (l_i+d_i, l_k+d_k).

$$\text{for} \quad t \le e_i \quad \text{or} \quad t \ge l_i + d_i \quad \Rightarrow \quad x_{it} = 1 \tag{3}$$

$$\text{for} \quad S_i \le t \le S_i + d_i \quad \Rightarrow \quad x_{it} = 0 \tag{4}$$

$$\text{for} \quad e_i \le t \le l_i \quad \Rightarrow \quad x_{it} = 0 \quad \text{or} \quad x_{it} = 1 \tag{5}$$

$$\text{for} \quad t \le e_k \quad \text{or} \quad t \ge l_k + d_k \quad \Rightarrow \quad x_{kt} = 1 \tag{6}$$

$$\text{for} \quad S_k \le t \le S_k + d_k \quad \Rightarrow \quad x_{kt} = 0 \tag{7}$$

$$\text{for} \quad e_k \le t \le l_k \quad \Rightarrow \quad x_{kt} = 0 \quad \text{or} \quad x_{kt} = 1 \tag{8}$$

B.2. Maintenance Duration

The maintenance of the unit i or transmission line k lasts a given number of periods d_i and d_k respectively.

$$\sum_{t \in T} \left(1 - x_{it}\right) = d_t \qquad \forall i \in I \tag{9}$$

$$\sum_{t \in T} \left(1 - x_{kt}\right) = d_k \qquad \forall k \in K \tag{10}$$

B.3. Maintenance Number

This constraint determines the maximum number of units and transmission lines that could be under maintenance, simultaneously.

$$\sum_{i \in I} \left(1 - x_{it}\right) = \beta_{it} \qquad \forall t \in T \tag{11}$$

$$\sum_{k \in K} \left(1 - x_{kt}\right) = \beta_{kt} \qquad \forall t \in T \tag{12}$$

B.4. Non-Stop Maintenance

The maintenance of a unit is carried out in consecutive periods.

$$\begin{aligned}&\left(1-x_{it}\right)-\left(1-x_{i,t-1}\right)\le sv_{i,t} \qquad \forall i\in I \ \ \& \ \ t\in T\\ &\text{for} \quad t=1, \quad \text{select} \quad \Rightarrow \quad x_{i,0}=1\end{aligned} \tag{13}$$

B.5. Exclusion Constraint

Units *i* and *j* cannot be in maintenance at the same time.

$$\left(1-x_{i,t}\right)+\left(1-x_{j,t}\right)\le 1 \qquad \forall t\in T \tag{14}$$

B.6. One-Time Maintenance

Each unit and transmission line has an outage for maintenance just once along the considered time horizon.

$$\sum_{t\in T} sv_{i,t}=1 \qquad \forall i\in I \tag{15}$$

$$\sum_{t\in T} sv_{k,t}=1 \qquad \forall k\in K \tag{16}$$

B.7. Manpower Availability

If one considers that in each maintenance area, there is limited available manpower, the constraints will be stated as follows:

$$\sum_{i\in I}\left(1-x_{i,t}\right)\le M_{it} \qquad \forall t\in T \tag{17}$$

$$\sum_{k\in K}\left(1-x_{k,t}\right)\le M_{kt} \qquad \forall t\in T \tag{18}$$

C. Network Constraints

The network can be considered either as the transportation model or as a linearized power flow model. The network constraints may be considered as below.

C.1. Power System Load Balance

We apply transportation model to exhibit system operation limits such as load balance equation, unit capacities, and power flow limits as below:

$$\forall t \qquad zf+g=D \tag{19}$$

C.2. Unit Capacity Limit

Each unit is designed to work between minimum and maximum power capacity (MW). The following constraint in Equation (20) ensures that unit is within its respective rated minimum and maximum capacities.

$$\forall t \qquad g_{\min,i}\le g_{it}\le g_{\max,i} \tag{20}$$

C.3. Transmission Flow Limit

The power flows on transmission lines are constrained by line capacity. The constraint Equation (21) represents power transmission capacity.

$$\forall t \qquad \left|f_{kt}\right|\le f_{\max,k} \tag{21}$$

C.4. Spinning Reserve

Actually, ISO is in charge of system reserve in all periods. A safety margin usually is given as a demand proportion. Equation (22) represents spinning reserve constraint. This indicates that the total capacity of the units running at each interval should not be less than the specified spinning reserve for that interval.

$$\forall t \qquad \sum_i g_{\max,i}-\sum_i g_{it}\ge \%\ \alpha\times D_t \tag{22}$$

III. SOLUTION METHEDOLOGY

Any determination problem with a purpose to be maximized or minimized in which the determination variables must assume non-fractional or discrete values may be sorted as an integer optimization problem. If all the determination variables are limited to integer values, the problem is called a (pure) integer problem, otherwise a MIP [17-18]. In the context of linear and mixed-integer programming problems, the function that appraises the quality of the solution, named the objective function, should be a linear function of variables.

Actually, all Linear Programming (LP) problems can be transformed into an equivalent minimization problem with nonnegative variables and equality constraints. Therefore, suppose that here, x_1, ..., x_n are our set of determination variables. LP problems are as follows:

$$\text{maximize or minimize} \ \ f(x)=c_1x_1+c_2x_2+\ldots+c_nx_n \tag{23}$$

subject to:

$$a_{11}x_1+a_{12}x_2+\ldots+a_{1n}x_n \ \ (\le,=,\ \text{or}\ \ge)\ b_1 \tag{24}$$

$$a_{21}x_1+a_{22}x_2+\ldots+a_{2n}x_n \ \ (\le,=,\ \text{or}\ \ge)\ b_2 \tag{25}$$

$$\vdots$$

$$a_{m1}x_1+a_{m2}x_2+\ldots+a_{mn}x_n \ \ (\le,=,\ \text{or}\ \ge)\ b_m \tag{26}$$

$$x_i\ge 0 \quad \forall i=1,\ \ldots,n \tag{27}$$

where, the values c_i ($\forall i$ = 1, …, n) are indicated as objective coefficients, and are often connected to the costs associated with their corresponding determinations in minimization problems, or the income generated from the corresponding determinations in maximization problems. The values b_1, …, b_m are the right-hand side values of the constraints and often depict amounts of available resources (especially for '≤' constraints) or requirements (especially for '≥' constraints). The a_{ij} values thus typically indicate how much of requirement or resource *j* is satisfied or consumed by decision *i*.

In this paper in order to find the optimal solution, Branch and Bound [19] is used as the most general algorithm. Branch and bound consists of a systematic enumeration of all candidate solutions, by using upper and lower estimated bounds of the quantity being optimized. Considering above problem assume the goal is to find the minimum value of a function *f*(*x*) where *x* ranges over some set *S* of admissible or candidate solutions. A branch and bound procedure requires two tools.

The first one is a splitting procedure that, given a set *S* of candidates, returns two or more smaller sets S_1, S_2,...whose union covers *S*. Note that the minimum of the *f*(*x*) over *S* is min(v_1, v_2, ...), where each v_i is the minimum of the *f*(*x*) within S_i. This step is called branching, since its recursive application defines a tree structure whose nodes are the subsets of *S*. The second tool is a procedure that computes upper and lower bounds for the minimum value of *f*(*x*) within a given subset of *S*.

This step is called bounding. The key idea of the branch and bound algorithm is, if the lower bound for some tree node (set of candidates) *A* is greater than the upper bound for some other node *B*, then *A* may be safely discarded from the search. This step is called pruning, and is usually implemented by maintaining a global variable *m* that records the minimum upper bound seen among all sub regions examined so far. Any node whose lower bound is greater than *m* can be discarded. The recursion stops when the current candidate set *S* is reduced to a single element or when the upper bound for set *S* matches the lower bound. Either way, any element of Swill is a minimum of the function within *S*.

Problems of the Equations (23) to (27) are called linear programming since the objective function and constraint functions are all linear. A MIP is a linear program with the added limitation that some, but not necessarily all, of the variables must be integer-valued. Several studies also replace the term integer with binary (0-1 variables) when variables are limited to take on either 0 or 1 values.

IV. CASE STUDY

In order to have global maintenance scheduling, this paper proposes an annual security constrained model for preventive long generation and transmission maintenance scheduling problem in which system security and operation indices such as transmission line limits, penalty factor, and system reserve are taken into account. Here, the proposed method is applied to the IEEE 24-bus reliability test system [12]. The system has 32 units, 20 consumers, 24-buses and 38 transmission lines. Some units and transmission lines in a special area require maintenance within the study period.

The maintenance area coverage is from buses 1 through 10. Accordingly, Table 1 gives generation unit data. Operating and maintenance characteristics of the units are given in Table 2. Also corresponding transmission line data are provided in Table 3. In addition, a constant transmission maintenance cost is assumed for all available lines that is 0.72×10^4 \$/mile with one week maintenance duration for each line [12].

Table 1. Unit data

Unit	10, 11	12, 13	14	15, 16	6, 7
Capacity (MW)	2×76	2×76	1×100	2×100	2×20
Bus	1	2	7	7	1

Figure 1 depicts weekly peak load curve as the percent of the annual peak load. As shown the maximum peak loads are in weeks 50-52. Subsequently, weekly penalty factors are illustrated in Figure 2. As indicated the highest penalty factors are applied in peak-loaded weeks to avoid unit maintenance during peak periods, hence shifting maintenance periods towards off peak times. It is assumed that during a year, manpower constraint is up to three groups for generation maintenance and two groups for transmission maintenance.

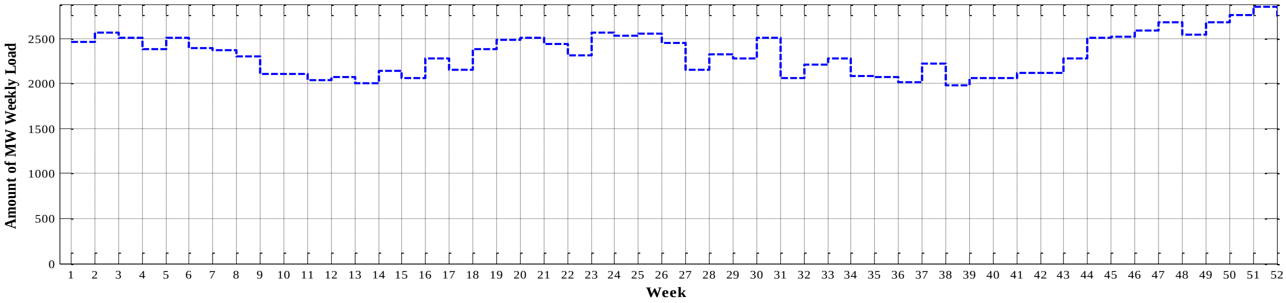

Figure 1. Weekly peak load in percent of annual peak

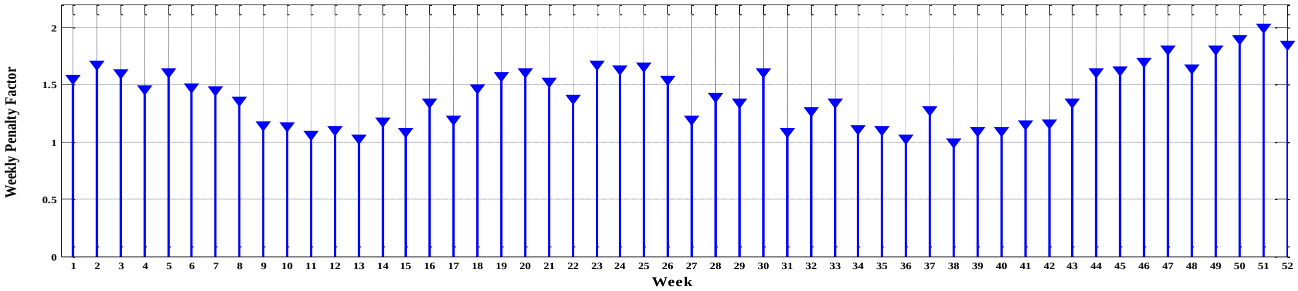

Figure 2. Penalty factor for unit maintenance cost

Table 2. Unit operating and maintenance data

Size (MW)	Fuel	Fuel Price (US\$/MBtu)	Maintenance Cost (\$/kW/Yr)	Heat rate (Btu/KWh)	Maintenance	
					Window (Week)	Duration (Week)
20	Oil #2	3.00	0.3	14500	1-52	2
76	Coal	1.20	10	12000	1-52	3
100	Oil #6	2.30	8.5	10000	1-52	4

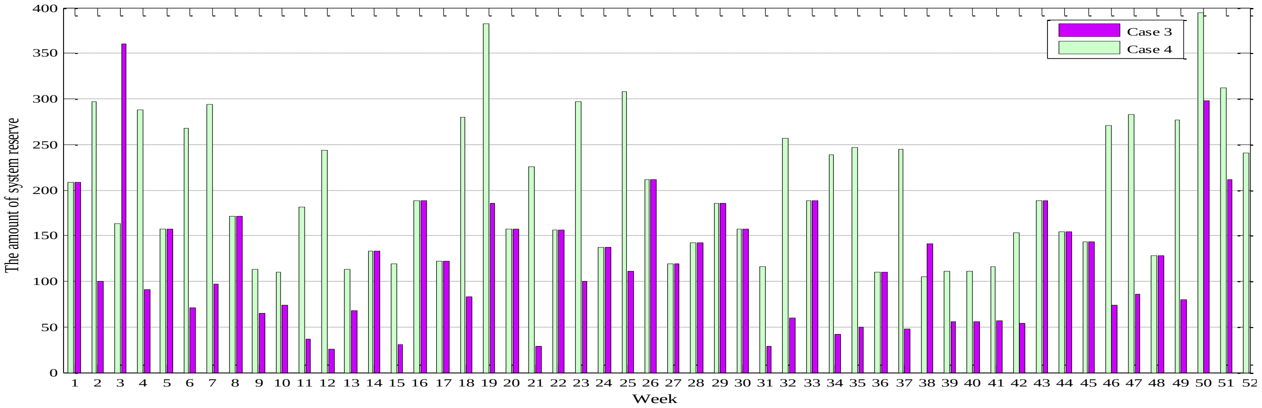

Figure 3. Comparison of the amount of system reserve in case study

As the first scenario, Table 4 represents total operation and maintenance costs while system reserve is not taken into account. To show the accuracy of the results first and second cases show the results of [12] and [13] for three months GMS considering network constraints regardless of penalty factor that are comparable. Subsequently, third and fourth cases represent the results of proposed GTMS for three months duration with and without penalty factor, respectively. As shown considering transmission maintenance results in an excessive cost causing an increase in aggregated operation and maintenance costs.

Since penalty factor is more than unity it leads to increases in unit maintenance costs, however, ISO may employ penalty factor to patronize units not to be maintained within peak periods. Case 5 shows the results of annual GTMS study excluding penalty factor. As shown the total cost is drastically increased due to increased unit operation costs. Note that here unit maintenance cost is the same as cases two and three in which penalty factor was neglected. This is because maintaining units and corresponding maintaining periods are fix in all cases. In order to study the impact of penalty factor case six illustrates the results of annual GTMS while network constraints and penalty factors are taken into account.

Similarly, in comparison to case five unit maintenance cost is increased due to penalty factor inclusion (Figure 3). However, unit maintenance cost is reduced with respect to three months GTMS study (case four). The reason is that in annual GTMS the operator has more time intervals for unit maintenance. This in turn could shift unit maintenance time toward off peak periods that results in mitigations in unit maintenance cost. Furthermore, having more choice to select unit maintenance time and considering the cheap units that are not forced anymore to be maintained within a short period of time (three months), here unit operation cost is reduced from 57.54128×10^6 \$ (in case 4) to 56.29061×10^6 \$ during summer.

Finally in the last case to study the effect of transmission line congestion on the proposed maintenance problem it is assumed that transmissions capacity of the lines, between buses (15 to 21) are reduced to 1/3 while penalty factor is considered as well. As seen the maintenance costs are unchanged while the operation costs are increased. This is due to the fact that, applying limits on transmission line capacities may result in contributions by more expensive units that leads to higher operation costs. It should be noted that due to constant transmission maintenance cost for all transmission lines and taking into account that all transmission lines should be maintained within a year, the aggregated transmission costs would be the same for all cases.

Note that transmission maintenance is considered regardless of penalty factor. Subsequently, Tables 5 to 13 shows corresponding units and transmissions maintenance scheduling in cases 2-6. Comparison results of Table 5 with Tables 6 and 7, it can be seen that including transmission maintenance may affect unit maintenance scheduling, hence shifting efficient unit maintenance scheduling toward peak periods. This could increase unit operation costs. Tables 8 and 9 indicate results of annual unit maintenance scheduling in different cases. As indicated unit maintenance scheduling has been spread over a wider period of time (weeks 10 to 40).

Table 3. Transmission line data

Line No.	From bus	To bus	No. of lines	Length (miles)	Rating (MVA)
1	1	2	1	3	193
2	1	3	1	55	208
3	1	5	1	22	208
4	2	4	1	33	208
5	2	6	1	50	208
6	3	9	1	31	208
8	4	9	1	27	208
9	5	10	1	23	208
10	6	10	1	16	193
11	7	8	1	16	208
12	8	9	1	43	208
13	8	10	1	43	208

Here, having more choice to select the time of maintenance and considering that efficient units are not forced to be in maintenance in just three months, the unit operation cost during summer is reduced (with respect to Tables 6 and 7). Furthermore, unit maintenance cost is reduced when penalty factor is taken into account (Tables 7 and 9). The impact of penalty factor is illustrated in Tables 8 and 9. Comparing the results, one can conclude that applying penalty factor leads to some shifting in unit maintenance scheduling toward off peak periods.

As shown in Table 9, unit maintenance periods have been occurred in weeks 10-15 and 34-36 and 38-40 (that are normally off peak periods, while they used to be in heavy loaded weeks like 16 and 37 when penalty factor was not considered (Tables 8). In fact due to more request for energy in peak periods (weeks 50-52), all units especially cheaper ones (i.e. 12 and 13) must be available within these periods. This in turn improves system reliability.

However, due to penalty factor coefficients that are normally more than unity, aggregated maintenance cost will increase. Subsequently, Tables 10 to 13 represent corresponding transmission maintenance scheduling in cases 3-6. In the second scenario, in order to investigate the impact of power system operation indices on proposed maintenance scheduling problem, system reserve is taken into account as one of the significant factors from system operator point of view. Here four cases are provided and it is assumed that network constraints and penalty factor are considered for all cases.

Furthermore, system reserve in each week is limited to 1% and 5% of total weekly load, respectively. Similarly, for more clarification, case 1 presents results of authors' previous study in [16] for three months GMS considering 1% of weekly load as system reserve. Case 2 represents an annual GMS considering 1% of weekly load reserve.

Finally, cases 3 and 4 provide results of annual GTMS with 1% and 5% of weekly load reserve, respectively. Table 14 represents corresponding unit operation and maintenance costs in all above mentioned cases. For more clarifications, Tables 15 and 16 show corresponding unit and transmission maintenance scheduling in case 3.

Table 4. Total operation and maintenance cost (Scenario 1)

Case	Total Operation & Maintenance cost ($\times 10^6$) $	Unit maintenance cost ($\times 10^6$) $	Transmission maintenance cost ($\times 10^6$) $	Unit operation cost ($\times 10^6$) $
1. Three months GMS with network constraints and excluding penalty factor [12]	63.52694	5.7205	-------	57.80644
2. Three months GMS with network constraints and excluding penalty factor [13]	63.07048	5.6020	-------	57.46848
3. Three months GTMS with network constraints and excluding penalty factor	65.74968	5.6020	2.60640	57.54128
4. Three months GTMS with network constraints and considering penalty factor	68.84316	8.6954	2.60640	57.54128
5. Annual GTMS with network constraints and excluding penalty factor	237.7135	5.6020	2.60640	229.5051
6. Annual GTMS with network constraints and considering penalty factor	238.2099	6.0398	2.60640	229.5637
7. Annual GTMS with network constraints, considering penalty factor and limit on transmission capacity	238.3305	6.0398	2.60640	229.6843

Considering the results in cases 1 and 2, one can deduce that as the units are not forced to be maintained within 12 weeks, the unit maintenance cost is decreased in case 2 and a better distribution of the risk can be obtained. Comparing the result represented in Table 15 and 16 and taking into account, minimum level of the system reserve, it is deduced that units with more capacity and more efficiency have arranged their maintenance timetable in minimum weekly load to satisfy requirement of the ISO.

Table 5. Unit maintenance scheduling (Scenario 1, Case 2)

Unit/Week	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29
6				▨	▨							
7				▨	▨							
10						▨	▨	▨				
11						▨	▨	▨				
12	▨	▨	▨									
13	▨	▨	▨									
14							▨	▨	▨	▨		
15									▨	▨	▨	▨
16									▨	▨	▨	▨

Table 6. Unit maintenance scheduling (Scenario 1, Case 3)

Unit/Week	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29
6	▨	▨										
7	▨	▨										
10										▨	▨	▨
11										▨	▨	▨
12			▨	▨	▨							
13			▨	▨	▨							
14			▨	▨	▨	▨						
15						▨	▨	▨	▨			
16						▨	▨	▨	▨			

Table 7. Unit maintenance scheduling (Scenario 1, Case 4)

Transmission/Week	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29
6								▨	▨			
7								▨	▨			
10										▨	▨	▨
11										▨	▨	▨
12	▨	▨	▨									
13	▨	▨	▨									
14									▨	▨	▨	▨
15				▨	▨	▨	▨					
16				▨	▨	▨	▨					

Table 8. Unit maintenance scheduling (Scenario 1, Case 5)

Unit/Week	T11	T12	T13	T14	T15	T16	T17	T20	T21	T34	T35	T36	T37	T38
6								▨	▨					
7								▨	▨					
10	▨	▨	▨											
11	▨	▨	▨											
12												▨	▨	▨
13												▨	▨	▨
14										▨	▨	▨	▨	
15				▨	▨	▨	▨							
16				▨	▨	▨	▨							

Table 9. Unit maintenance scheduling (Scenario 1, Case 6)

Unit/Week	T10	T11	T12	T13	T14	T15	T34	T35	T36	T38	T39	T40
6					▨	▨						
7					▨	▨						
10										▨	▨	▨
11										▨	▨	▨
12							▨	▨	▨			
13							▨	▨	▨			
14	▨	▨	▨	▨								
15	▨	▨	▨	▨								
16	▨	▨	▨	▨								

Table 10. Transmission maintenance scheduling (Scenario 1, Case 3)

Transmission/Week	T18	T19	T21	T22	T23	T24	T25	T27	T28
1									■
2							■		
3									■
4						■			
5				■					
6		■							
8					■				
9			■						
10								■	
11					■				
12	■								
13			■						

Table 11. Transmission maintenance scheduling (Scenario 1, Case 4)

Transmission/Week	T19	T20	T21	T22	T23	T24	T25	T26	T28
1						■			
2			■						
3			■						
4								■	
5	■								
6							■		
8				■					
9									■
10		■							
11					■				
12						■			
13		■							

Table 12. Transmission maintenance scheduling (Scenario 1, Case 5)

Transmission/Week	T1	T3	T5	T20	T22	T26	T31	T34	T45	T46	T49
1		■									
2			■								
3				■							
4							■				
5											■
6	■										
8									■		
9								■			
10					■						
11										■	
12						■					
13											■

Table 13. Transmission maintenance scheduling (Scenario 1, Case 6)

Transmission/Week	T1	T4	T13	T17	T19	T31	T32	T49	T50	T52
1							■			
2				■						
3						■				
4					■					
5		■								
6									■	
8	■									
9								■		
10										■
11			■							
12										■
13	■									

Table 14. Total operation and maintenance cost (Scenario 2)

Case	Total Operation & Maintenance cost $(\times 10^{6})\,\$$	Unit maintenance cost $(\times 10^{6})\,\$$	Transmission maintenance cost $(\times 10^{6})\,\$$	Unit operation cost $(\times 10^{6})\,\$$
1. Three months GMS for 1% of weekly load as system reserve [16]	66.41019	9.335050	---	57.07514
2. Annual GMS for 1% of weekly load as system reserve	235.1143	5.978600	---	229.1357
3. Annual GTMS for 1% of weekly load as system reserve	238.2312	6.0398	2.6064	229.5850
4. Annual GTMS for 5% of weekly load as system reserve	238.4113	6.0489	2.6064	229.7560

Table 15. Unit maintenance scheduling (Scenario 2, Case 3)

Unit/Week	T10	T11	T12	T13	T14	T15	T34	T35	T36	T38	T39	T40
6					■	■						
7					■	■						
10							■	■	■			
11							■	■	■			
12										■	■	■
13										■	■	■
14	■	■	■	■								
15	■	■	■	■								
16	■	■	■	■								

Furthermore, comparing Tables 4 and 14, shows that system reserve may increase unit operation costs. It is due to contribution of more expensive units. As shown the more demand for reserve results in increases in unit maintenance cost as shown in cases 3 and 4. This is because demanding more reserve is equal to providing more standby units that require maintenance costs.

Finally, Figure 3 illustrates variation of system reserve within all maintenance periods in proposed GTMS. As the amount of the reserve is directly dependent on the amount of the weekly load the contributions of the units to satisfying the system requirement are proportion to corresponding load levels.

Table 16. Transmission maintenance scheduling (Scenario 2, Case 3)

Transmission/Week	T1	T8	T13	T20	T24	T35	T44	T46	T47	T48	T49
1								■			
2		■									
3										■	
4						■					
5							■				
6								■			
8											■
9									■		
10				■							
11			■								
12					■						
13	■										

As shown, increasing in minimum reserve levels results in changes in the amount of actual weekly reserves. This in turn will improve the system security and reliability although it may increase system aggregated costs by increasing unit operation and maintenance costs as well.

V. CONCLUSIONS

This paper presents a model for long-term generation and transmission maintenance scheduling in which network security constraints as well as system reserve are taken into account. Transmission maintenance has profound effects on generation maintenance programs in terms of varying unit maintenance scheduling and raising system maintenance costs. On the other hand, security and operational constraints like transmission capacity limits and power system reserve may affect maintenance scheduling and altering system aggregated costs.

In order to consider effect of system loading on proposed GTMS problem, a heuristic penalty factor coefficient was introduced. Applying penalty factor could enable system operator to patronize units not to have maintenance in peak periods. As demonstrated extending maintenance window will alleviate unit maintenance and operation costs.

Nevertheless, it may increase system aggregated costs. Including system reserve in proposed GTMS would increase system reliability during unit outages, although it entails some costs. As shown increasing system reserve may affect transmission and unit maintenance scheduling and corresponding costs as well. However, it is up to operator to make a right decision between system security and reliability and corresponding costs.

NOMENCLATURES

I: The number of gas and heat units

x_{it}: Unit maintenance status, 0 if unit is off for maintenance, 1 otherwise

x_{kt}: Transmission maintenance status, 0 if transmission line is off for maintenance, 1 otherwise

S_i: Period in which maintenance of unit i starts

S_k: Period in which maintenance of transmission line k starts

e_i: Earliest period for the beginning of unit i maintenance

e_k: Earliest period for the beginning of transmission line k maintenance

l_i: Latest period for the beginning of unit i maintenance

l_k: Latest period for the beginning of transmission line k maintenance

sv_{it}: Maintenance start-up variable of unit i at time t

sv_{kt}: Maintenance start-up variable of transmission k at time t

C_{it}: Maintenance cost of unit i at time t

C_{kt}: Maintenance cost of transmission line k at time t

c_{it}: Operation cost of unit i at time t

γ_t: Weekly penalty factor

d_i: Duration of maintenance for unit i

d_k: Duration of maintenance for transmission line k

$g_{\max,i}$: Maximum power generation for unit i

$g_{\min,i}$: Minimum power generation for unit i

g_{it}: Vector of power generation for unit i at time t

D_t: Vector of the demand at time t

$D_{\max}$: Maximum demand at study period

$D_{\min}$: Minimum demand at study period

Z: Node-branch incidence matrix

α: Percentage of load for system reserve

α_t: Maximum number of units under maintenance at time t

β_t: Maximum number of transmission lines under maintenance at time t

$f_{\max,k}$: Maximum line flow capacity for transmission line k

$f_{k,t}$: Active line flow

N: Maximum number of transmission lines

M_{it}: Maximum number of maintenance crew for maintenance of unit i at time t

M_{kt}: Maximum number of maintenance crew for maintenance of transmission line k at time t

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