

# Preventive Generation Maintenance Scheduling with Network Constraints, Spinning Reserve, and Forced Outage Rate

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## ABSTRACT:

The completely Electric Power System encompasses three parts: Generation, Transmission, and Distribution that all require maintenance to better system reliability and energy efficiency. Most generation maintenance scheduling (GMS) packages consider preventive maintenance scheduling for generating units over one or two year's time horizon to lessen the total operation costs while fulfilling system energy requirements. In advanced power systems, the inclusion of network limitations, reserve index, forced outage rates of the units, and demand for electricity have highly increased with related expansions in system size, which have led to the higher number of generators and lower reserve margins that making the generator maintenance scheduling problem more complex. This paper proposes a security constrained model for preventive generation maintenance scheduling problem. For more realistic study, system reliability indices such as transmission security, manpower constraint, and forced outage rate of the system as well as amount of system reserve are considered for the proposed maintenance scheduling problem. Impact of the load curve on GMS problem is investigated by a novel proposed penalty factor. General Algebraic Modeling System (GAMS) is utilized for solving optimization problem. An IEEE 24-bus test system is employed for simulation and show the accuracy of results.

**KEYWORDS:** Maintenance Scheduling, Network Constraint, System Reserve, Forced Outage Rate.

## 1. INTRODUCTION

Since 1980, many countries have made the electric power market improvement. The main aim was breaking the monopoly operation pattern of tradition electric power industry and building a competitive power industry. Therefore, it can decrease the electric power production cost and electricity price. Besides, it can improve the power supply quality and promote the healthy development of electric 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. The solution methods can fall into certain categories, which are as follows: integer programming, decomposition methods [1], dynamic programming, simulated annealing method [2], probabilistic approach [3], and artificial intelligence method [4], [5].

In fact, Independent System Operator (ISO) is a

neutral operator responsible for maintaining instantaneous balance of the system. The ISO performs its function by controlling the dispatch of flexible plants and gives the order to adjust or lessen loads to ensure that loads match available generating resources in the system.

Generally, maintenance scheduling in a raw system may fall into three stages of long-term, short-term, and real-time [6]. Long-term maintenance scheduling (LTS) considers the schedule of generating units on a horizon of one or two years in order to minimize the total system operation and maintenance costs. The long-term scheduling problem tackles fuel allocation, emission, budgeting, production, and maintenance costing. The solutions obtained from LTS can then be used as guidelines and bases for addressing unit commitment and optimal power flow problems [7]-[10]. The objective of short-term scheduling (STS) 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

STS causes a commitment strategy for real-time economic dispatch to meet system requirements in an on-line operation. The dynamic economic dispatch is solved for short periods of time in which the system load conditions can be assumed constant.

This paper proposes a security constrained model for preventive generation maintenance scheduling problem. For more realistic study, system reliability indices such as transmission security and manpower constraints as well as amounts of system reserve are considered for the proposed maintenance-scheduling problem. Impact of the load curve on GMS problem is investigated by a novel proposed penalty factor. In addition, a heuristic model is proposed to show the impact of forced outage rates of units while implementing GMS. Due to discrete nature of model, mixed integer programming (MIP) is applied to solve the problem. For this purpose, General Algebraic Modeling System (GAMS) is utilized for solving optimization problem. An IEEE 24-bus test system is employed for simulation and show the accuracy of results.

The paper is organized as follows: Section 2 represents the formulation of proposed maintenance scheduling model and solution methodology. In section 3, a case study is presented to show the accuracy of the results and section 4 and 5 provide the conclusion and suggestions for further research, respectively.

## 2. PROBLEM DESCRIPTION AND SOLUTION METHODOLOGY

While transmission and reliability limitations are taken into account, the proposed long-term maintenance scheduling problem is determining the period for which generating units should be off, over one or two years planning horizon to lessen the total operation cost. Leave out the network in maintenance scheduling, may end in loss of information on scheduling limitations. When network constraints, reserve of the system, and forced outage rates of the units are included, the problem becomes a lot more realistic and complex that could be referred as security constrained maintenance scheduling. The long-term generation maintenance scheduling in the power market environment is a large-scale optimization problem.

### 2.1. Objective Function

The objective function of the proposed model is to minimize the total maintenance and production costs over the operational planning period. Equation (1) corresponds to a mixed integer-programming problem since  $x_{it}$  is integer variables and  $g_{it}$  is continuous. The first term of the objective function is the maintenance cost of generators, and the second is the energy production cost. Mathematically, it can be formulated as follows:

$$\text{Min} \sum_t \sum_i C_{it} \times \gamma_t \times (1 - x_{it}) + \sum_t \sum_i C_{it} \times g_{it} \quad (1)$$

#### 2.1.1. Penalty Factor

In order to consider the impact of the load curve demand on generation maintenance scheduling problem a novel penalty factor is represented as Equation (2). In fact, penalty factor depicts importance of loading points based on the amount of consumptions. ISO could employ penalty factor to patronize unit not to have maintenance in peak loads. Here, the total unit maintenance cost is the maintenance cost of a unit multiply by the penalty factor. By this strategy, ISO could have more effect on unit maintenance schedules.

$$\forall t \quad \gamma_t = 2 - \frac{D_{max} - D_t}{D_{max} - D_{min}} \quad (2)$$

## 2.2. Maintenance Constraints

In this paper, maintenance constraints are considered as follows:

### 2.2.1. Maintenance Window

Here, constraints (3-5) show the maintenance window stated in terms of maintenance variables ( $S_i$ ). The unit maintenance may not be scheduled before their earliest length of time ( $e_i$ ), or after the latest length of time allowed for maintenance ( $l_i + d_i$ ).

$$\text{for } t \leq e_i \text{ or } t \geq l_i + d_i \Rightarrow x_{it} = 1 \quad (3)$$

$$\text{for } S_i \leq t \leq S_i + d_i \Rightarrow x_{it} = 0 \quad (4)$$

$$\text{for } e_i \leq t \leq l_i \Rightarrow x_{it} = 0 \text{ or } 1 \quad (5)$$

### 2.2.2. Maintenance Duration

The maintenance of the unit  $i$  lasts a given number of periods  $d_i$ .

$$\sum_{t \in T} (1 - x_{i,t}) = d_i \quad \forall i \in I \quad (6)$$

### 2.2.3. Maintenance Period

A maximum number of maintenance  $\beta_t$  is imposed in the period  $t$ .

$$\sum_{i \in I} (1 - x_{i,t}) \leq \beta_t \quad \forall t \in T \quad (7)$$

### 2.2.4. Non-Stop Maintenance

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

$$(1 - x_{i,t}) - (1 - x_{i,t-1}) \leq sv_{i,t} \quad , \quad \forall i \in I \ \& \ \forall t \in T \quad (8)$$

for  $t = 1$  select,  $x_{i,0} = 1$

### 2.2.5. Exclusion Constraint

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

$$(1 - x_{i,t}) + (1 - x_{j,t}) \leq 1 \quad \forall t \in T \quad (9)$$

2.2.6. One-Time Maintenance

Each unit has an outage for maintenance only once along the time horizon considered.

$$\sum_{t \in T} sv_{i,t} = 1 \quad \forall i \in I \quad (10)$$

2.2.7. Manpower Availability

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

$$\sum_{i \in I} (1 - x_{i,t}) \leq M_{i,t} \quad (11)$$

Here,  $M_{i,t}$  would be the number of maintenance team in area for maintenance of unit  $i$ .

2.3. Network Constraints

The network can be modeled as either the transportation model or a linearized power flow model.

2.3.1. Power System Load Balance

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

$$\forall t \quad zf + g = D \quad (12)$$

2.3.2. Unit Capacity Limit

Each unit is designed to work between the minimum and the maximum power capacity (MW). The following constraint in equation (13) ensures that the unit is within their respective rated minimum and maximum capacities.

$$\forall t \quad g_{min,i} \leq g_{it} \leq g_{max,i} \quad (13)$$

2.3.3. Transmission Flow Limit

The power flows on transmission lines are constrained by line. The constraint (14) represents power transmission capacity.

$$\forall t \quad |f| \leq f_{max} \times N \quad (14)$$

2.3.4. Spinning Reserve

The reserve is the power provided if a unit fails. It is a safety margin. Usually, it is given as a demand proportion. Equation (15) represents spinning reserve constraint. This specifies that the total capacity of the units running at any interval should not be less than predicted load and the specified spinning reserve for that interval.

$$\forall t \quad \sum_i g_{max,i} - \sum_i g_{it} \geq \% \alpha \times D_t \quad (15)$$

2.4. Forced Outage rates of the Units

For the sake of simplicity, most of the time, no uncertainty is considered, which means that appropriate units are provided. Nevertheless, unit forced outage rates can be approximately taken into account derating their corresponding capacity [13]-[15]. In order to model forced outage rates of the units, a model is proposed that considers forced outage rates option while implementing GMS, as follows:

$$g_{max,i}^+ = (1 - for(i)) \times x_{it} \times g_{max,i} \quad (16)$$

$$\forall t \quad \sum_i g_{Max,i} \times (1 - for(i)) - \sum_i g_{i,t} \geq \% \alpha \times d_t \quad (17)$$

Here, we should replace equation (16) instead of the maximum level of power generation in equation (13). Accordingly, one can replace equation (17) instead of equation (15) in order to model forced outage rates in spinning reserve.

As we know, the set of network constraints (12)-(17), which depict the peak load balance, transmission flow limits, allowable system reserve, etc, will be verified by the ISO.

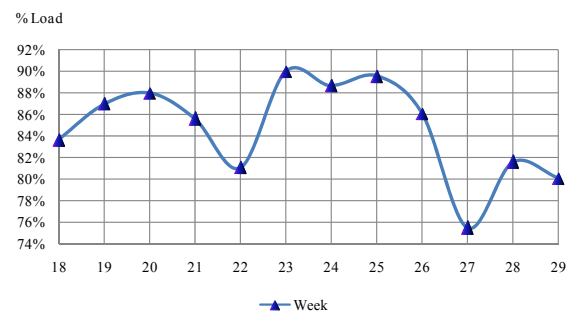


Fig. 1. Weekly peak load in percent of annual peak

To solve the problem, the mixed integer problem solver of GAMS optimization software is employed. The GAMS is a high-level algebraic modeling system for large-scale optimization. The modeling and optimization framework is based on an open architecture, which allows seamless communication with build-in components (e.g. optimization solvers) and external systems. The GAMS provides an one-of-a-kind solver portfolio with all major commercial and academic state-of-the-art solvers and also special solvers for stochastic and global optimization. It opens architecture and assures a smooth integration of optimization models of all kinds of application environments and provides all the tools a modeler needs for fast and reliable development and deployment. It is also dedicated to performance and reliability.

3. CASE STUDY

The proposed method is applied to the 24-Bus IEEE-RTS. This system has made of 32 generating

units, 20 consumers, 24 buses, and 38 transmission lines. A three months study period of summer weeks, weeks 18-29, is taken into account. Some generations facilities in a particular area need maintenance within the study period. The maintenance area coverage is from buses 1 through 10. Table 1 gives the generators' placement and capacity data. Operating characteristics of the generating units are illustrated in Table 2. Fig. 1 depicts weekly peak loads as the percent of the annual peak load. As shown, the maximum peak load is in the week 23. Subsequently, weekly penalty factors considered for generators are provided in Fig. 2. It is assumed that during three months, manpower constraint is up to two groups for unit maintenance, and the maintenance windows are two weeks for all generations. Detailed system data for transmission lines, units, and loads can be found in [11].

In the last paper [12], we considered unit maintenance scheduling with network constraint and unserved energy as reliability indices. To improve the reliability of the system, in this paper, we consider reserve of the system and forced outage rates of units as reliability indices instead of unserved energy.

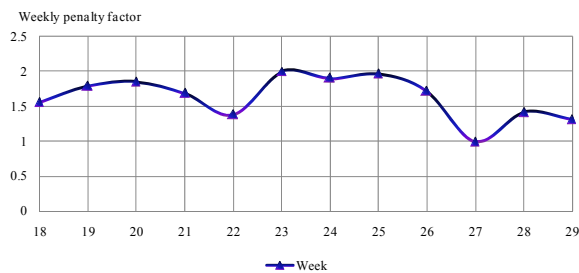


Fig. 2. Penalty Factor for generator unit maintenance cost

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

Here, two cases are studied for GMS problem considering transmission reliability, reserve of the system, security constraints, and forced outage rates of the units as follows:

Case 1: Study on generator maintenance scheduling problem considering the reserve index for each week.

Case 2: Study on generator maintenance scheduling problem considering forced outage rates of the units and transmission security constraint.

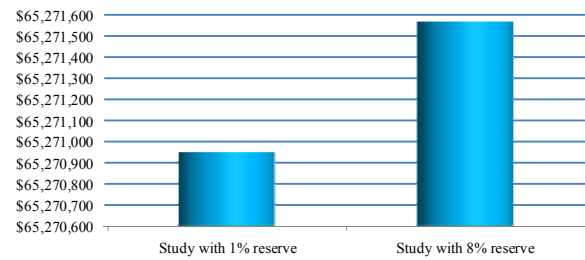


Fig. 3. Comparison of total operation & maintenance cost for case 1

In case 1, the reserve index is regarded as the significant factor from the system operator while implementing maintenance scheduling. For this purpose, system reserve in each week is limited to the minimum of 1% and 8%, of the total weekly load. Fig. 3 illustrates the comparison of total operation and maintenance cost. Detailed cost for operation and maintenance can be seen in Table 3. Subsequently, Tables 4 and 5 show corresponding unit maintenance scheduling during the specified 12 weeks. As shown, increase in the minimum reserve level results in changes in Maintenance scheduling. It can change the loading points of units and may increase the generation of expensive and inefficient units, resulting also in increase of the overall cost of operation. Fig. 4 illustrates the comparison of the amount of spinning reserve.

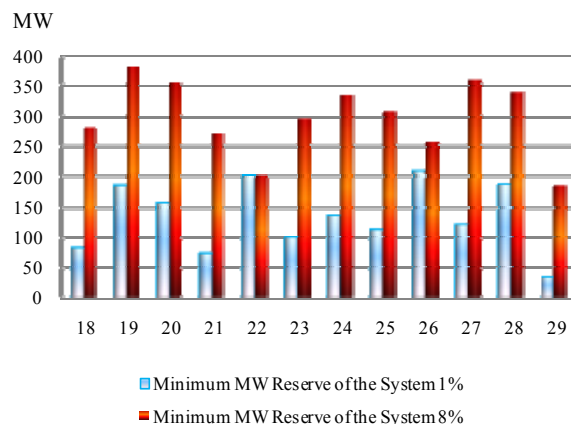


Fig. 4. Comparison of the amount of spinning reserve in case study

In this case, units maintenance scheduling is shifted, i.e. maintenance of units 12, 13 is shifted from weeks 28 and 29 to weeks 26 and 27. Furthermore, maintenance of units 15 and 16 is shifted from weeks 26 and 27 to weeks 28 and 29.

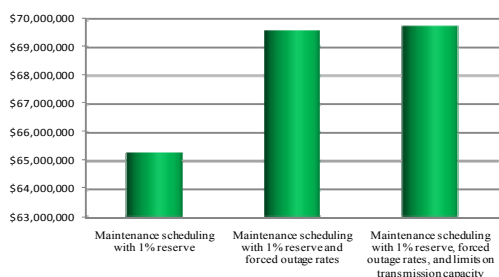


Fig. 5. Comparison of total operation & maintenance cost for case 2

Case 2 studies the effect of transmission security, reserve of the system, and forced outage rates of the units on the maintenance scheduling problem. Here, system reserve in each week is limited to the minimum of 1% of the total weekly load. Two cases are considered in this study.

Table 2. Unit operating & 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	14000	18-29	2
76	Coal	1,20	10	12000	18-29	2
100	Oil #6	2,20	8.5	10000	18-29	2

Table 3. Total operation & maintenance cost for generating unit (case 1)

Amount of reserve	Total Operation & Maintenance cost	Maintenance cost	Operation cost
1% of weekly load	6.527095×10 <sup>7</sup> \$	8195813.793 \$	5.707514×10 <sup>7</sup> \$
6% of weekly load	6.527157×10 <sup>7</sup> \$	8196434.482 \$	5.707514×10 <sup>7</sup> \$

Table 4. Maintenance scheduling of generating unit for 1% of System Reserve (case 1)

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

Table 5. Maintenance scheduling of generating unit for 6% of System Reserve (case 1)

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. Total operation & maintenance cost for generating unit (case 2)

Condition	Total operation & maintenance cost	Maintenance cost	Operation cost
Maintenance scheduling with 1% reserve index and forced outage rates	6.9587484×10 <sup>7</sup> \$	8195813.793 \$	6.139159×10 <sup>7</sup> \$
Maintenance scheduling with 1% reserve index, forced outage rates, and limits on transmission capacity	6.9763470×10 <sup>7</sup> \$	8195813.793 \$	6.156766×10 <sup>7</sup> \$

**Table 7.** Maintenance scheduling with 1% reserve index and forced outage rates (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 8.** Maintenance scheduling with 1% reserve index, forced outage rates, & limits on transmission capacity (case2)

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

In the first case, the effect of units' forced outage rate on GMS problem is investigated. In the latter case, transmission security limits are imposed on the maintenance scheduling problem. It is assumed that transmission capacity between two buses (15 to 21) are reduced to quarter.

Fig. 5 illustrates the comparison of total operation and maintenance cost for both case 1 and 2. Detailed cost for operation and maintenance can be seen in Table 6. Further, Tables 7 and 8 show corresponding unit maintenance scheduling during specified 12 weeks.

The imposed transmission constraints and forced outage rates of the units increase the cost of operation. The cost of operation demonstrates the change in operating cost over the study period, indicating a shift from units that use inexpensive fuel to those with more expensive fuels and inefficient units. With transmission limitations, available units in one time period may become less attractive in compare with those in some other time periods, when availability is even more crucial.

#### 4. CONCLUSIONS

This paper presents generation maintenance scheduling considering reserve of the system, network constraints, and transmission constraints as well as forced outage rates of the units. As we know, the penalty factor depicts importance of loading points based on the amount of consumption. The ISO could employ penalty factor to patronize units not to have

maintenance in peak loads. Using the proposed method, additional complex constraints can be imposed on the maintenance scheduling problem and will have a significant effect on the secure and reliable operation, especially in those systems with very low reserve margin. The test results demonstrate that limits on system reserve, transmission line capacity and forced outage rates of the units affect the loading points of units and may increase the generation of expensive and inefficient units, resulting in the increase in the overall cost of operation and maintenance.

#### 5. SUGGESTIONS FOR FURTHER RESEARCH

In a universal unit maintenance-scheduling problem, we suggest to take into account transmission maintenance scheduling problem, fuel consumption, and environmental pollution as well as generation maintenance scheduling problem.

#### REFERENCES

- [1] Salvador Perez Canto. "Application of benders' decomposition to power plant preventive maintenance scheduling," *European Journal of Operational Research (Science direct)*, pp. 759-777, 2007.
- [2] K. Suresh, N. Kumarappan, "Combined genetic algorithm and simulated annealing for preventive unit maintenance scheduling in power system," *IEEE*, 2006.
- [3] M.K.C. Marwali, S.M. Shahidehpour, "A probabilistic approach to generation maintenance scheduler with network constraints," *Elsevier*

- Science, Electrical Power and Energy Systems*, pp. 533-545, May 1999.
- [4] R. Eshraghnia, M.H. Modir Shanechi, H. Rajabi Mashhadil. "A new approach for maintenance scheduling of generating units in power market," presented at the 9th Int. Conf. Probabilistic Methods Applied to Power Systems, KTH, Stockholm, Sweden, June 2006.
- [5] A.M. Leite Da Silva, L.A.F. Mansob, G.J. Anders, "Evaluation of generation and transmission maintenance strategies based on reliability worth," *Science direct, Electric Power Systems Research* 71, pp. 99-107, 2004.
- [6] Y. Yare, G. K. Venayagamoorthy. "A differential evolution approach to optimal generator maintenance scheduling of the nigerian pwr system," *IEEE*, pp. 1-8, 2008.
- [7] M. Manbachi, A.H. Parsaeifard, M.R. Haghifam, "A new solution for maintenance scheduling using maintenance market simulation based on game theory," presented at the IEEE Int. Conf. Electrical Power & Energy, 2009.
- [8] Hemantkumar Barot, Kankar Bhattacharya, "Security coordinated maintenance scheduling in deregulation based on genco contribution to unserved energy," *IEEE Trans, Power Systems*, VOL. 23, NO. 4, pp. 1302-1313, NOV 2008.
- [9] Dushmantha Kumar Mohantaa, Pradip Kumar Sadhub, R. Chakrabartiac, "Deterministic and stochastic approach for safety and reliability optimization of captive power plant maintenance scheduling using ga/sa-based hybrid techniques," *Science direct, Reliability Engineering and System Safety*, pp. 187-199.
- [10] Zhang Shuangmei, Ge Ju, "Study on generation and transmission maintenance scheduling under electricity market," *IEEE*, 2010.
- [11] IEEE Reliability Test System, *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No.6 Nov./Dec. 1979 IEEE 197.
- [12] A.Badri, A.Norozpour and S.M.Hosseini, "Long Term Preventive Generation Maintenance Scheduling with Network Constraints," *Science direct, Energy Procedia*, pp 1889-1895, 2011.
- [13] J. T. Saraiva, M. L. Pereira, V. T. Mendes, and J. C. Sousa, "Preventive Generation Maintenance Scheduling – a Simulated Annealing Approach to use in Competitive Markets," *IEEE, presented at 7th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion, 7-10 November Paper No. MED10/105*, 2010.
- [14] Antonio J. Conejo, Raquel García-Bertrand, and Manuel Díaz-Salazar, "Generation Maintenance Scheduling in Restructured Power Systems," *IEEE Transactions On Power Systems*, VOL. 20, NO. 2, MAY 2005
- [15] Joao Tomé Saraiva, Marcelo Leandro Pereira, Virgilio Torrado Mendes, José Carlos Sousa, "A Simulated Annealing based approach to solve the generator maintenance scheduling problem," *Electric Power Systems Research* 81 (2011) 1283-1291.

## NOMENCLATURE

$C_{it}$	Maintenance cost of unit $i$ at time $t$
$c_{it}$	Generation cost of unit $i$ at time $t$
$\gamma_t$	Weekly penalty factor
$d_i$	Duration of maintenance for unit $i$
$D_t$	Vector of the demand for bus $i$ at time $t$
$z$	Node-branch incidence matrix
$\alpha$	Percentage of load for system reserve
$\beta_t$	Maintenance period
$f_{max}$	Maximum line flow capacity
$f$	Active line flow
$N$	Maximum number of transmission line
$for$	Forced outage rates of the units
$g_{max,i}$	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 $t$
$x_{it}$	Unit maintenance status, 0 if unit is off for maintenance, otherwise 1
$S_i$	Period in which maintenance of generating unit $i$ starts
$e_i$	Earliest period for maintenance of generating unit $i$ to begin
$l_i$	Latest period for maintenance of generating unit $i$ to begin
$sv_{i,t}$	Maintenance start-up variable of unit $i$ at time $t$
$M_{i,t}$	Maximum number of maintenance crew in area for maintenance of unit $i$ at time $t$