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Application of Stochastic Programming to Determine Operating Reserves with Considering Wind and Load Uncertainties

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ABSTRACT

Wind power generation is variable and uncertain. In the power systems with high penetration of wind power, determination of equivalent operating reserve is the main concern of systems operator. In this paper, a model is proposed to determine operating reserves in simultaneous market clearing of energy and reserve by stochastic programming based on scenarios generated via Monte Carlo simulation (MCS). This model considers the wind power, load and network uncertainties and includes the cost of involuntary load shedding and wind spillage. The proposed methodology is examined on an example and a case study to investigate various effects of wind power generation on the system operating reserves and costs.

KEYWORDS: Monte Carlo Simulation, Operating Reserve, Reliability, Stochastic Programming, Wind Power.

1. INTRODUCTION

In recent years, power generation based on renewable energy has received much attention [1]. The electrical power generation based on wind energy has the fastest growth due to its environmental benefits [2]. Wind power is known as an undispatchable source because of its dependence on the atmospheric parameters [3]. The generated wind power is also uncertain quantity due to predictability and variability of wind properties. This uncertainty will face the power system operator with problems [4]. In the power system with high accumulation of wind power, determination of equivalent operating reserve is the main concern of system operator. The more wind power prediction uncertainty, the more reserves are required to be dealt by the operator to meet the real-time system imbalances. Reserve must provide the balance between supply and demand considering forecast error at any time, which is due to imbalance between scheduled generations and the required load. Besides, power system encounters load uncertainty due to inaccurate load forecasting, and generation uncertainty due to egress of the generation units because of equipment failures. Hence, due to difference between the actual and forecasted load, the system should re-dispatch reserves to balance it. Otherwise, load shedding will be in the program of system operator [5].

In the literature, there are different efforts for reserve management in the power systems. A reserve management tool has been introduced in [6]. In this probabilistic model, uncertainties of generation, load and wind power are considered. The presented algorithm of [6] has also been used in [7]. In [7], a probabilistic approach is used to create system generation margin distribution and probability mass functions associated with the generation and load. Finally, upward and downward operational reserve has been calculated by using risk indices. In [5], a method has been presented

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to determine the additional operating costs resulting from the displacement of conventional generation with wind power generating. The impact of wind and load forecast errors and various costs (production costs, startup costs, and the expected cost of interruptions and emission costs) have been included in this paper. In [8], a method has been expressed to determine the requirement reserves in a system considering the accumulation of wind power based on stochastic programming. The load uncertainty has been neglected in this paper. In [9] and [10], the techniques are expressed based on MCS to evaluate the system requirement operating reserves by considering renewable sources (especially wind). In these papers, the load and generation uncertainties are also considered. In [11], the impacts of variable nature of wind power and increasing the wind power installed capacity have been evaluated on the operating reserve requirement and the total cost. Operating reserves include the spinning and non-spinning reserve in this model. Only the wind uncertainty has been considered in this model. Load has been assumed certain, and equipment failures have not been included in the formulation. A method has been introduced to determine the level of requirement spinning and non-spinning reserves in the power system with high penetration of wind power in [12]. Network constraints, load shedding, and wind spillage have been considered in this model. In this paper, the wind power uncertainty has been considered and load uncertainty and equipment failures have not been considered. In [13], an approach has been proposed to determine the optimal spinning reserves requirement using a cost/benefit analysis. The sequential market of energy and reserve has been used in this model. Wind power generation has not considered in this paper. In [14], the wind generation uncertainty has been taken into account in Unit Commitment (UC) and Economic Dispatch (ED) problems. These problems have been solved by dynamic programming, and the demand has assumed as a certain quantity. The systems have been evaluated at first Hierarchical Level (HL1) in [5], [6], [8], [9], [10], [11], [13] and [14]. In [7] and [12] the systems studied at second HL2.

In this paper, the operating reserve requirements are calculated in a simultaneous energy and reserve clearance problem. This problem is solved by stochastic programming based on scenarios generated via MCS. In this problem, the network constraints, the load shedding and wind spillage are modeled. The expected cost is considered as an objective function of a system. The model consists of two stages, which the first stage is system scheduling and the second ones is system operating. Network uncertainty, load and wind power generation uncertainty and equipment failures in transmission lines have also considered for determining the system operation reserve.

This paper is classified into different sections as follows. The proposed model and assumptions are described in Section 2. In Section 3, the proposed model is formulated. Section 4 presents the simulation results. Section 5 provides the conclusions related to the paper.

2. SYSTEM MODEL

Commonly, the reserve levels are determined meeting one of the following two purposes: 1) To determine the maximum acceptable reserve level; 2) To compromise between the risk level and the reserve cost. The system is faced with uncertainties to determine the operating reserve levels. Hence, in this paper, the stochastic programming is used to clear the market accounting for the stochastic behavior of the system into account; where, the stochastic programming process can be formulated as a two-stage problem. At the first stage, the electrical market and its rules is described, and in the second stage, the power system, operation, physical limitations, and its uncertainties are expressed. A two-state Markov model has been used in modeling thermal power plants and UC problem, where the risks occur in the following modes:

$$R_{Operational} < L^S + {P_{WP}}^S + P^S \tag{1}$$

$$R_{Operational} = R^S + R^{NS} \tag{2}$$

See nomenclature A to F for definition of the parameters and variables.

3. PROBLEM FORMULATION

In this section, the problem formulation via stochastic programming will be developed. The objective function which should be minimized is considered as the expected cost of system as in (3). Here, the formulation of [12] has been used for the formulation of the problem. But, we consider the wind power and load uncertainties, and uncertainties of generation and transmission based on scenarios generated by Monte Carlo simulation in this paper. General overview of the market clearing algorithm is shown in Fig. 1.

As previously noted and it’s defined in (3), model is composed of the system scheduling and system operating stages. In the scheduling stage, electric market limitations and its rules are expressed, and the network and wind power uncertainties are not considered. In the operation stage, the physical limitations, operation, and system uncertainties based on scenarios generated by Monte Carlo simulation method are expressed. Equations (4) to (7) express the production constraints.

$$\begin{aligned}
EC = \sum_{t=1}^{N_T} EC(t) = & \sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C^{SU}(i,t) \\
+ \sum_{t=1}^{N_T} d(t)\, EC \Bigg[& \sum_{i=1}^{N_G}\sum_{m=1}^{N_{Oit}} \lambda_G(i,t,m).\, p_G(i,t,m) \\
& - \sum_{j=1}^{N_L} \lambda_L(j,t).\, L^S(j,t,\omega_l) \\
& + \sum_{i=1}^{N_G} \Big(C^{R^U}(i,t).\, R^U(i,t) + C^{R^D}(i,t).\, R^D(i,t) + C^{R^{NS}}(i,t).\, R^{NS}(i,t) \Big) \\
& + \sum_{j=1}^{N_L} \Big(C^{R^U}(j,t).\, R^U(j,t) + C^{R^D}(j,t).\, R^D(j,t) \Big) + \lambda^{WP}(t).\, P_{WP}^S(t) \Bigg] \\
& + \sum_{\omega_N=1}^{\Omega_N} \pi(\omega_N) \Bigg\{ \sum_{\omega_l=1}^{\Omega_l} \pi(\omega_l) \Bigg\{ \sum_{\omega_w=1}^{\Omega_w} \pi(\omega_w) \Bigg\{ \sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C^A(i,t,\omega_w,\omega_l,\omega_N) \\
& + \sum_{t=1}^{N_T} d(t) \Bigg[\sum_{i=1}^{N_G}\sum_{m=1}^{N_{Oit}} \lambda_G(i,t,m).\, r_G(i,t,m,\omega_w,\omega_l,\omega_N)) + \sum_{j=1}^{N_L} \lambda_L(j,t).\, (r^U(j,t,\omega_w,\omega_l,\omega_N) \\
& - r^D(j,t,\omega_w,\omega_l,\omega_N)) + \sum_{j=1}^{N_L} VLOL(j,t).\, L_{shed}(j,t,\omega_w,\omega_l,\omega_N) + V^S(t).\, S(t,\omega_w) \Bigg] \Bigg\} \Bigg\} \Bigg\}
\end{aligned} \tag{3}$$

We allow the wind generation units to submit their offers to the market. However, the marginal costs of the energy offer submitted by the wind producers are equal to zero ($\lambda^{WP}(t) = 0$). In (8) and (9), the wind power limitations, and the load limitations have been expressed, respectively. The system is faced with constraints to determine the reserve. These constraints can be related to up (down)-spinning reserves, non-spinning reserve, and reserves of involuntary interruptible loads. Startup cost in the first stage is described in (15) and (16).

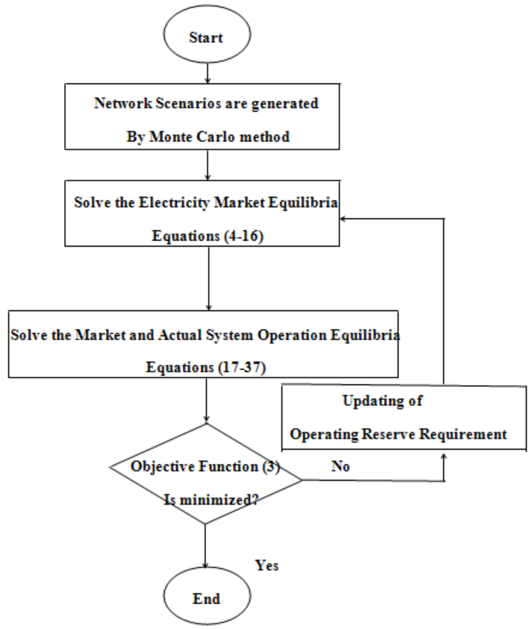

Fig. 1. General Overview of the market clearing algorithm

Market equations and limitations are stated as follows:

$$\sum_{i=1}^{N_G} P^S(i,t) + P^S_{WP}(t) = \sum_{\omega_l=1}^{\Omega_l} \pi(\omega_l)\left\{\sum_{i=1}^{N_L} L^S(j,t,\omega_l)\right\}, \forall t, \omega_l. \tag{4}$$

$$P_{\min}(i).u(i,t) \le P^S(i,t) \le P_{\max}(i).u(i,t), \quad \forall i, \forall t \tag{5}$$

$$0 \le p^G(i,t,m) \le p^G_{max}(i,t,m), \quad \forall m, \forall i, \forall t \tag{6}$$

$$P^S(i,t) = \sum_{m=1}^{N_{Oit}} p^G(i,t,m), \quad \forall i, \forall t. \tag{7}$$

$$P^{min}_{WP}(t) \le P^S_{WP}(t) \le P^{max}_{WP}(t), \quad \forall t \tag{8}$$

$$L^S_{min}(j,t,\omega_l) \le L^S(j,t,\omega_l) \le L^S_{max}(j,t,\omega_l), \quad \forall j, \forall t, \forall \omega_l \tag{9}$$

$$0 \le R^U(i,t) \le R^U_{max}(i,t).u(i,t), \quad \forall i, \forall t \tag{10}$$

$$0 \le R^D(i,t) \le R^D_{max}(i,t).u(i,t), \quad \forall i, \forall t \tag{11}$$

$$0 \le R^{NS}(i,t) \le R^{NS}_{max}(i,t).(1 - u(i,t)), \quad \forall i, \forall t \tag{12}$$

$$0 \le R^U(j,t) \le R^U_{max}(j,t), \quad \forall j, \forall t \tag{13}$$

$$0 \le R^D(j,t) \le R^D_{max}(j,t), \quad \forall j, \forall t \tag{14}$$

$$C^{SU}(i,t) \ge \lambda^{SU}(i,t).\big(u(i,t) - u(i,t-1)\big), \quad \forall i, \forall t \tag{15}$$

$$C^{SU}(i,t) \ge 0, \quad \forall i, \forall t. \tag{16}$$

Constraints related to system operating are stated in (17) and (18), where, the system uncertainties are considered. We use two separate equations for nodes, depending on whether the wind power is generated or not.

Eqeution (19) expresses the power flow through line (*n*, *r*), where *n* and *r* are the system nodes.

Equations (20) and (21) express the production constraints; (22) expresses the transmission capacity limitations, (23) describes the interruptible load limitations, and (24) expresses the wind power generation spillage constraints.

$$\sum_{i:(i,n)} P^G(i,t,\omega_w,\omega_l,\omega_N) - \sum_{j:(j,n)} \left(L^C(j,t,\omega_w,\omega_l,\omega_N) - L^{shed}(j,t,\omega_w,\omega_l,\omega_N)\right) - \sum_{r:(n,r)} f\big(t,\omega_w,\omega_l,\omega_N,(n,r)\big) = 0, \quad \forall n \ne r, \forall t, \forall\omega_w, \forall\omega_l, \forall\omega_N. \tag{17}$$

$$\sum_{i:(i,n)} P^G(i,t,\omega_w,\omega_l,\omega_N) - \sum_{j:(j,n)} \left(L^C(j,t,\omega_w,\omega_l,\omega_N) - L^{shed}(j,t,\omega_w,\omega_l,\omega_N)\right) + P^{WP}(t,\omega_w) - S(t,\omega_w) - \sum_{r:(n,r)} f\big(t,\omega_w,\omega_l,\omega_N,(n,r)\big) = 0, \quad \forall n = r, \forall t, \forall\omega_w, \forall\omega_l, \forall\omega_N. \tag{18}$$

$$f\big(t,\omega_w,\omega_l,\omega_N,(n,r)\big) = \frac{P^{loss}\big(t,\omega_w,\omega_l,\omega_N,(n,r)\big)}{2} + B(n,r).\big(\delta(n,t,\omega_w,\omega_l,\omega_N) - \delta(r,t,\omega_w,\omega_l,\omega_N)\big), \quad \forall (n,r) \in \Lambda, \forall t, \forall\omega_w, \forall\omega_l, \forall\omega_N. \tag{19}$$

$$P^G(i,t,\omega_w,\omega_l,\omega_N) \ge P_{\min}(i).v(i,t,\omega_w,\omega_l,\omega_N), \quad \forall i, \forall t, \forall\omega_w, \forall\omega_l, \forall\omega_N \tag{20}$$

$$P^G(i,t,\omega_w,\omega_l,\omega_N) \le P_{\max}(i).v(i,t,\omega_w,\omega_l,\omega_N), \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{21}$$

$$-f_{max}(n,r) \le f\big(t,\omega_w,\omega_l,\omega_N,(n,r)\big) \le f_{max}(n,r), \quad \forall(n,r) \in \Lambda, \forall \mathrm{t}, \forall\omega_w,\forall\omega_l,\forall\omega_N. \tag{22}$$

$$0 \le L_{shed}(j,t,\omega_w,\omega_l,\omega_N) \le L^C(j,t,\omega_w,\omega_l,\omega_N), \forall j,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N. \tag{23}$$

$$0 \le S(t,\omega_w) \le P_{WP}(t,\omega_w), \quad \forall t,\forall\omega_w. \tag{24}$$

Equations (25) to (31) describe the relation between market and the actual system operating [12]. Equation (32) is analogous to (7) and states the decomposition of the reserve deployment by blocks through variables $r_G(i,t,\omega_w,\omega_l,\omega_N,m)$. Equations (33) and (34) enforce that the blocks of reserve are added (or subtracted in case of down-spinning reserve) to the blocks of energy. Startup cost in the second stage is described as in (35) to (37):

$$P^G(i,t,\omega_w,\omega_l,\omega_N) = P^S(i,t) + r^U(i,t,\omega_w,\omega_l,\omega_N) + r^{NS}(i,t,\omega_w,\omega_l,\omega_N) - r^D(i,t,\omega_w,\omega_l,\omega_N), \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N. \tag{25}$$

$$L^C(j,t,\omega_w,\omega_l,\omega_N) = L^S(j,t,\omega_l) - r^U(j,t,\omega_w,\omega_l,\omega_N) + r^D(j,t,\omega_w,\omega_l,\omega_N), \forall j,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N. \tag{26}$$

$$0 \le r^U(i,t,\omega_w,\omega_l,\omega_N) \le R^U(i,t), \quad \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{27}$$

$$0 \le r^D(i,t,\omega_w,\omega_l,\omega_N) \le R^D(i,t), \quad \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{28}$$

$$0 \le r^{NS}(i,t,\omega_w,\omega_l,\omega_N) \le R^{NS}(i,t), \quad \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{29}$$

$$0 \le r^U(j,t,\omega_w,\omega_l,\omega_N) \le R^U(j,t), \quad \forall j,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{30}$$

$$0 \le r^D(j,t,\omega_w,\omega_l,\omega_N) \le R^D(j,t), \quad \forall j,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{31}$$

$$r^U(i,t,\omega_w,\omega_l,\omega_N) + r^{NS}(i,t,\omega_w,\omega_l,\omega_N) - r^D(i,t,\omega_w,\omega_l,\omega_N) = \sum_{m=1}^{N_{Oit}} r_G(i,t,\omega_w,\omega_l,\omega_N,m), \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{32}$$

$$r_G(i,t,\omega_w,\omega_l,\omega_N,m) \le P^G_{max}(i,t,m) - p^G(i,t,m), \quad \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{33}$$

$$r_G(i,t,\omega_w,\omega_l,\omega_N,m) \ge -p^G(i,t,m), \quad \forall m,\forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall \tag{34}$$

$$C^A(i,t,\omega_w,\omega_l,\omega_N) = C^{SU}(i,t,\omega_w,\omega_l,\omega_N) - C^{SU}(i,t), \quad \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N \tag{35}$$

$$C^{SU}(i,t,\omega_w,\omega_l,\omega_N) \ge \lambda^{SU}(i,t).\big(v(i,t,\omega_w,\omega_l,\omega_N) - v(i,t-1,\omega_w,\omega_l,\omega_N)\big), \quad \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega \tag{36}$$

$$C^{SU}(i,t,\omega_w,\omega_l,\omega_N) \ge 0, \quad \forall i,\forall t,\forall\omega_w,\forall\omega_l,\forall\omega_N. \tag{37}$$

4. SIMULATION RESULTS

In this paper, the proposed approach has been evaluated via applying to the test system used in [12]. It is a 3-buses system that consists of three units, three lines and one load. The test system has been shown in Fig. 2.

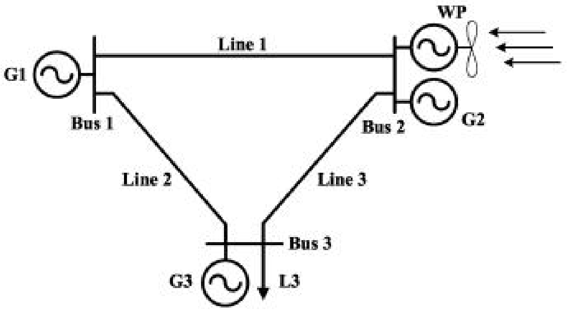

Fig. 2. Three-bus test system

In this model, line resistances are ignored and minimum up (down)-time are not considered. The UC program has been implemented using mixed integer linear programming (MILP) in Gams [15]. Network scenarios are generated by Monte Carlo simulation (MCS) method which have been implemented in MATLAB [16].

Operating reserves and expected cost are studied for 24 hours.

The generators and the system data are brought in Tables 1 and 2, respectively. Load's up-spinning reserve is provided via curtailing up to 10% of the hourly load [12]. Besides, the wind and load uncertainties based on their scenarios are shown in Table 3. Table 4 expresses the probabilities of wind and load scenarios. Networks scenarios generated based on outage replacement rate (ORR) equal to 0.02 for units and 0.01 for transmission lines.

Table 1. Generator data

	Unit 1	Unit 2	Unit 3
$P_{min}(i)$ (MW)	10	10	10
$P_{max}(i)$ (MW)	100	100	50
$\lambda^{SU}(i,t)$ ($)	100	100	100
$\lambda_G(i,t)$ ($/MWh)	30	40	20
$C^{R^U}(i,t)$ ($/MWh)	5	7	8
$C^{R^D}(i,t)$ ($/MWh)	5	7	8
$C^{R^{NS}}(i,t)$ ($/MWh)	4.5	5.5	7
Ramping Capabilities (MW/h)	100	100	50
$R^U_{max}(i,t)$	90	90	40
$R^D_{max}(i,t)$	90	90	40
$R^{NS}_{max}(i,t)$	100	100	50

Table. 2. Test system data.

System Property	Value
$C^{R^U}(j,t)$ ($/MWh)	70
$C^{R^D}(j,t)$ ($/MWh)	70
VOLL ($/MWh)	1000
Lines Reactance (p.u.)	013
Lines capacities (MW)	55
P_{base} (MW)	41
V_{base} (kV)	120
P^{WP}_{max}(MW)	60

The total system uncertainty will be different; depending on how the variables are dependent on each other. In this paper, network, load and wind uncertainties are considered without any correlation with each other, which is a reasonable assumption. Hence, these three variables will create an orthogonal three-dimensional space. In such a space, system scenarios are achieved via multiplication of the corresponding variable probabilities. The network uncertainty has been considered as a major system nature in analyses of this study. So, all analyses will be discussed concentrating on this object.

Table. 3. Scenarios of load at bus 3 and wind power

Period t	$P_{WP}(t,\omega_w)$ (MW)			$L^S(t,\omega_l)$ (MW)		
	As forecast	High	Low	As forecast	High	Low
1	11	13	10	40	43	39
2	14	17	13	35	37	34
3	16	20	14	32	33	30
4	13	16	11	30	31	29
5	10	13	8	37	40	35
6	6	9	2	40	42	38
7	10	12	8	55	57	54
8	12	14	10	62	65	61
9	13	15	11	69	70	68
10	15	17	13	75	76	74
11	17	20	15	81	83	80
12	19	21	18	86	88	84
13	20	23	19	92	95	91
14	25	35	20	94	96	93
15	20	30	13	94	96	93
16	20	25	18	98	99	97
17	17	19	16	100	101	98
18	15	17	13	110	115	107
19	13	15	12	110	112	108
20	12	14	11	95	100	93
21	35	50	25	83	87	80
22	9	11	8	69	71	68
23	7	8	6	55	58	54
24	8	12	6	40	42	39

Table. 4. Scenarios for load probabilities at bus 3 and the underlying wind power

	$P_{WP}(t,\omega_w)$ (MW)			$L^S(t,\omega_l)$ (MW)		
	As forecast	High	Low	As forecast	High	Low
Probability	0.6	0.2	0.2	0.8	0.1	0.1

4.1. Effect of the wind and load uncertainties

As stated earlier, the power system is faced with various types of uncertainties. These uncertainties challenge the system performance in real time. Here, we consider the wind power and the load uncertainties as two independent variables. The impacts of uncertainties are studied via four cases.

Case1: The system is analyzed without considering uncertainties.

Case2: Only load uncertainty is considered.

Case3: Only wind power uncertainty is considered.

Case4: Wind power and load uncertainties are considered, simultaneously.

Figures 3 to 6 show the impact of the wind power and the load uncertainties on the 24-hours operating reserves. As shown in these figures, the results of cases 1 and 3, in which the load uncertainty is not included, are very close to each other. On the other hand, cases 2 and 4 are very similar to each other, because the load uncertainty is considered in both cases. Besides, it can be seen that the simultaneous impact of the wind and the load uncertainties is not in direction of uncertainty of wind or load in the determination of all parameters; and this is the other reason that wind power uncertainty is independent of load uncertainty.

In Tables 5 and 6 the impact of wind power and load uncertainties on total amount of operating reserves and operating costs are assessed. These Tables express that load uncertainty has higher effect on determining the operating reserves. This effect is, however, more evident in the load's up-spinning reserve. The same behavior is observed for the operating costs, as well. It should be noted that the uncertainty of wind power doesn't affect the start-up cost of units. Because, in the system scheduling stage, wind producers just offer their wind power generating capacity into the market and don't reflect their uncertainty. Since their offer cost is equal to zero and the wind farm is at bus 2, the unit 2 doesn't turn on and the start-up cost of unit 2 is zero.

4.2. Effect of the wind farm location

In addition to the wind power uncertainty, the wind farm location can affect the operating reserves and costs, as well. In a power system, generating units must be placed at the suitable possession to provide the requirements of the power consumption in the lowest costs. We assess the impact of wind farm at buses 1, 2 and 3, individually. Once again, the impacts of wind power and load uncertainties are considered, here. Figures 7 to 10 show the impact of wind farm location on the 24-hours operating reserves. As shown in these figures, the results of locating the wind farm at bus 1 and wind farm at bus 2 are very close to each other. But, the results of wind farm at bus 3 are different. As mentioned before, the offer cost of wind generation is equal to zero. So, the conventional generating units and wind generation should supply the demand at bus 3. At first, the wind generation is cleared. Second, other units are cleared to hold (4). Then, the model (25) should solve to link the market and actual system operation. The purpose is solving the problem with lowest expected cost. So, the total start-up costs should be zero, and down-spinning reserve deployed by units is equivalent to power output scheduled for units and other operating reserves are equal to zero.

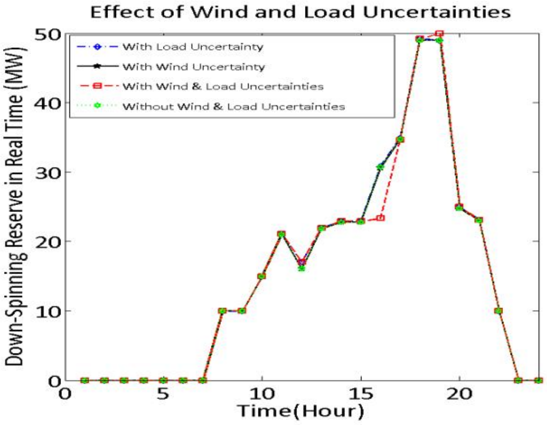

Fig. 3. The impact of the wind power and load uncertainties on down-spinning reserve.

Table 5. Assessment of the impact of wind power and load uncertainties on operating reserves.

Reserve in real time (MWh)	Down-spinning reserve	Up-spinning reserve	Non-spinning reserve	Load's up-spinning reserve
Case 1	360.458	0.4006	54.9203	0.5
Case 2	362.688	0.3753	54.432	3.0267
Case 3	360.340	5.8927	54.9203	0.5
Case 4	355.957	3.3346	54.432	3.0267

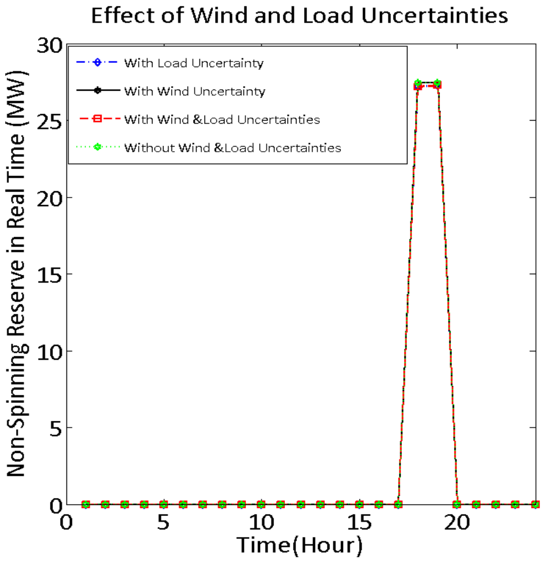

Fig. 4. The impact of the wind power and load uncertainties on non-spinning reserve.

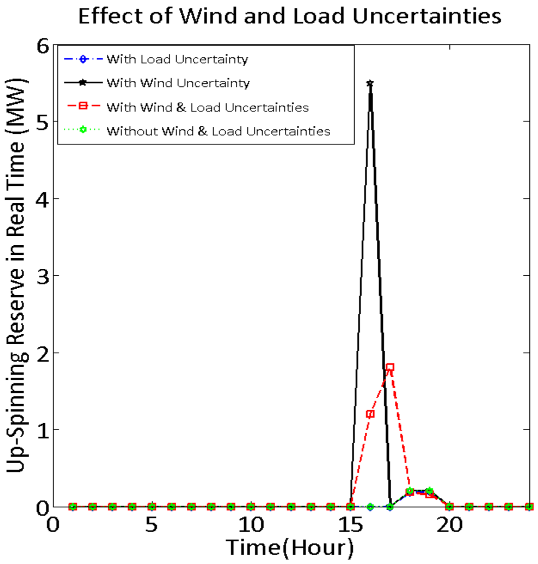

Fig. 5. The impact of the wind power and load uncertainties on Up-spinning reserve.

Table 6. Assessment of the impact of wind power and load uncertainties on operating costs.

	Start-up cost ($)				Expected cost($)
	Unit 1	Unit 2	Unit 3	Total	
Case 1	2.01	0	97.855	99.865	7702.01
Case 2	2.01	0	97.855	99.865	7835.138
Case 3	2.01	0	97.855	99.865	7702.01
Case 4	2.01	0	97.855	99.865	7835.138

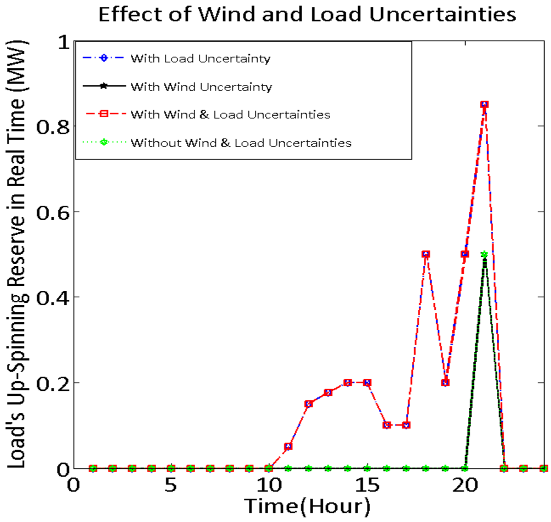

Fig. 6. The impact of the wind power and load uncertainties on load's up-spinning reserve.

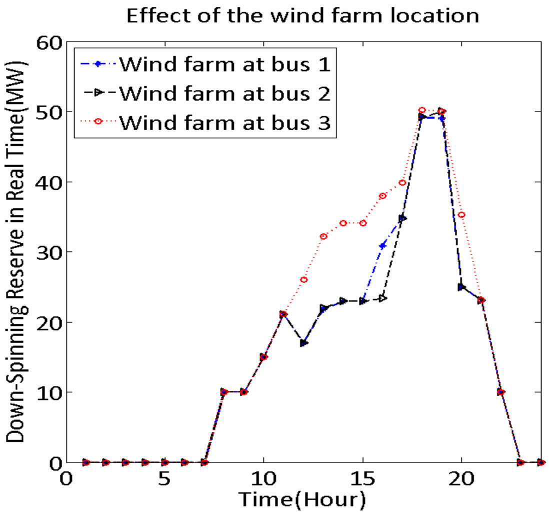

Fig. 7. The impact of the wind farm location on down-spinning reserve.

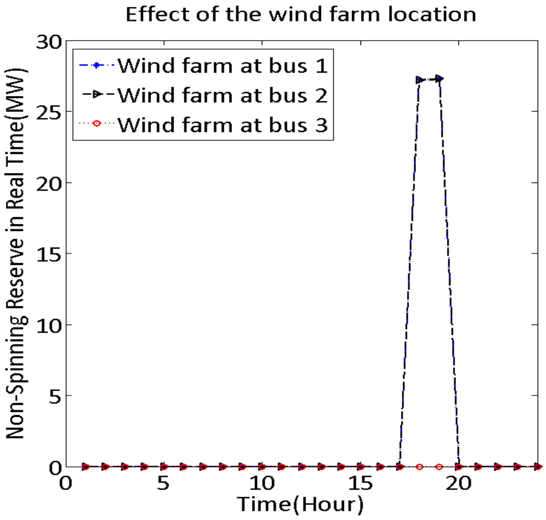

Fig. 8. The impact of the wind farm location on non-spinning reserve.

Table 7. Assessment of the impact of wind farm location on the operating reserves.

Reserve in real time (MWh)	Down-spinning reserve	Up-spinning reserve	Non-spinning reserve	Load's up-spinning reserve
Wind farm at bus 1	362.601	0.375	54.432	2.85
Wind farm at bus 2	362.687	0.373	54.432	3.0267
Wind farm at bus 3	429	0	0	0

Table 8. Assessment of the impact of wind farm location on the operating costs.

	Start-up Cost ($)				Expected Cost ($)
	Unit 1	Unit 2	Unit 3	Total	
Wind farm at bus 1	0	2.011	97.85	99.86	8534.68
Wind farm at bus 2	2.01	0	97.855	99.86	7835.13
Wind farm at bus 3	0	0	0	0	2145

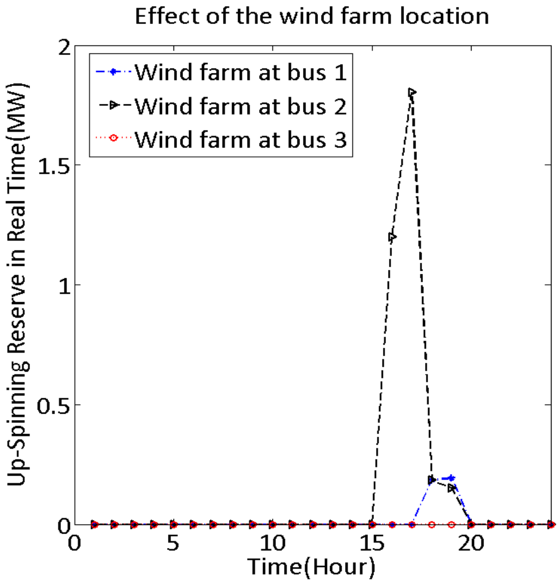

Fig. 9. The impact of the wind farm location on up-spinning reserve.

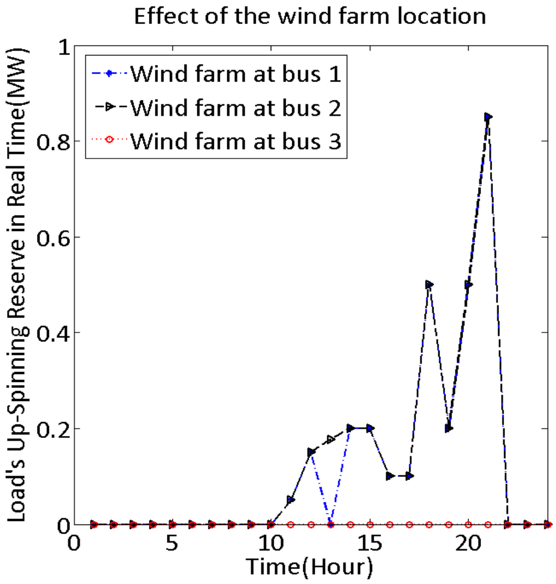

Fig. 10. The impact of the wind farm location on load's up-spinning reserve.

In Tables 7 and 8, the impact of wind farm location on total amount of operating reserves and operating costs are assessed. These tables express that locating the wind farm at bus 3, results in the lowest expected costs and the zero start-up costs of generating units. It should be noted that when the wind farm is located at bus 3. We have only the down-spinning reserve in real time and other operating reserves are equivalent to zero.

4.3. Effect of the wind power penetration

It is well known that the wind power penetration is increased via distributed wind generation units at network buses. In order to investigate the effect of wind power penetration, in this section two scenarios are compared. In the first scenario, a 60 MW wind farm is distributed uniformly among the three buses. That is, a 20 MW wind farm is located at each bus of the system. In the second scenario, the three 20 MW wind farms are integrated as a 60MW wind farm at bus 2.

In Figs. 11 to 14 the 24-hours operating reserves impact of wind farm penetration are shown. In Tables 9 and 10 the impact of wind power penetration on total amount of operating reserves and operating costs are assessed.

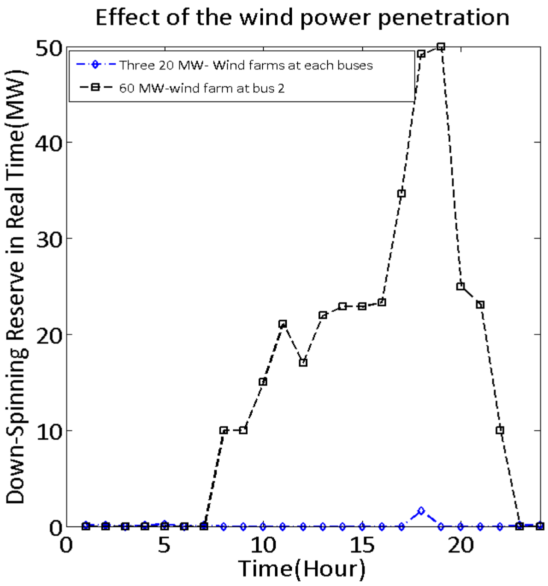

Fig. 11. The impact of wind power penetration on down-spinning reserve.

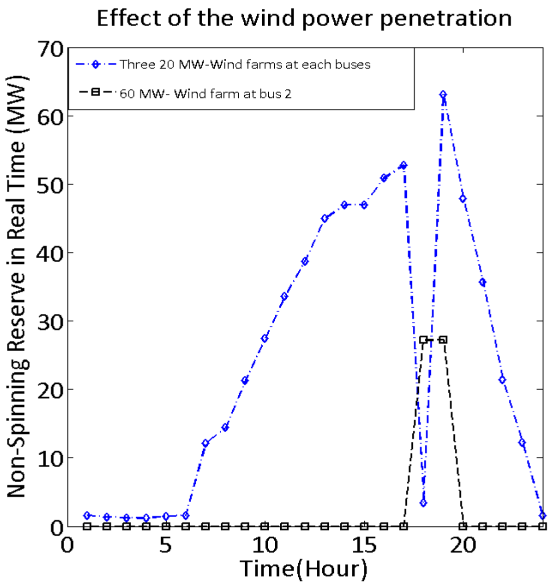

Fig. 12. The impact of wind power penetration on non-spinning reserve.

Table 9. Assessing the impact of wind power penetration on operating reserves.

Reserve in real time(MWh)	Down-spinning reserve	Up-spinning reserve	Non-spinning reserve	Load's up-spinning reserve
Scenario 1	2.5402	3.608	583.8661	3.0267
Scenario 2	362.6878	0.3753	54.432	3.0267

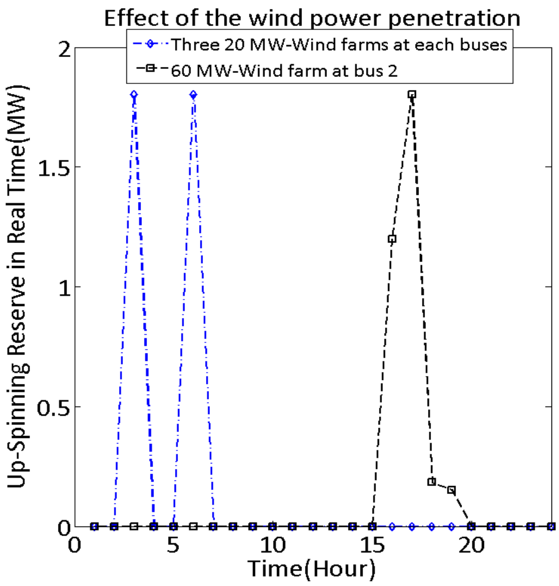

Fig. 13. The impact of wind power penetration on up-spinning reserve.

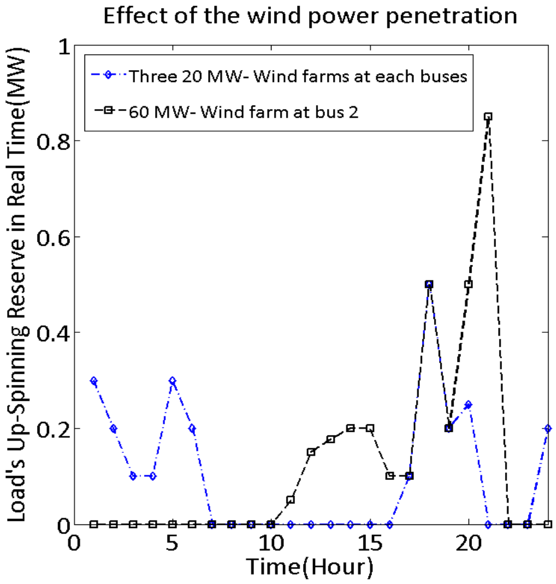

Fig. 14. The impact of wind power penetration on load's up-spinning reserve.

Table 10. Assessing the impact of wind power penetration on operating costs.

	Start-up Cost ($)				Expected Cost ($)
	Unit 1	Unit 2	Unit 3	Total	
Scenario 1	97.9	3.86	98	199.8	52747.2
Scenario 2	2.01	0	97.8	99.8	7835.13

In order to make the results in Tables 9 and 10 clearer, one should note that as stated before, the units which are committed in first stage of commitment, can offer energy and up (down)-spinning reserves, and the units which are not committed in the first stage, just can offer non-spinning reserve. So, in the first scenario with respect to the second one, the total amount of spinning reserves ((up-spinning reserve) plus (down-spinning reserve)) has been decreased due to decrease in the number of states that unit 1 is committed by adding the 20 MW- wind farm at bus 1. On the other hand, the total amount of non-spinning reserve has been increased due to increase in the number of states that unit 1 has not been committed by adding the 20 MW wind farm at bus 1.

Besides, in the first scenario, the total amount of start-up cost and start-up cost of unit 2 are increased (with respect to the second scenario) due to increase in the number of states that have been started up; by replacing the 60 MW wind farm at bus 2 with 20 MW wind farm at buses 1, 2 and 3.

5. CONCLUSIONS

In this paper, a two-stage stochastic programming model has been proposed to evaluate the impact of wind power generation on the system operating reserves and costs in a simultaneous energy and reserve market clearing problem. We allow the wind producers to submit offers to the market. The impact of wind power and load uncertainties, wind farm location and wind power penetration was assessed on operating reserve and cost.

It was shown that, the load uncertainty has higher effect to determine the operating reserves in this system. However, the amount of uncertainty is important and high forecast errors do not have desirable results. Besides, it was shown that the wind farm location has the high impact on the operating and start-up costs, and the expected costs can be decreased by installing the wind generation at the suitable places. Finally, the effect of the wind power penetration was analyzed. It was shown that the wind power penetration doesn’t have the positive effect on the amount of expected costs. It reduces the system spinning reserves and increases the non-spinning reserves in this system.

NOMENCLATURE

A. *Indices and Numbers*

n	Index of system buses, from 1 to N_B.
i	Index of conventional generating units, from 1 to N_G.
j	Index of loads, from 1 to N_L.
t	Index of time periods, from 1 to N_T.
m	Index of energy blocks offered by conventional generating units, from 1 to N_{Oit}.
ω_w	Index of wind power scenarios, from 1 to Ω_w.
ω_l	Index of load scenarios, from 1 to Ω_l.
ω_N	Index of network scenarios, from 1 to Ω_N.

B. *Continuous Variables*

$C^{SU}(i,t)$	Cost due to the scheduled start-up of unit i in period t[\$]. $C^{SU}(i,t,\omega_w,\omega_l,\omega_N)$ is the start-up cost in real time by unit i in period t and scenarios ω_w, ω_l and ω_N.
$P^S(i,t)$	Power output scheduled for unit i in period t[MW].
$p^G(i,t,m)$	Power output scheduled from the m-th block of energy offered by unit i in period t [MW]. Limited to $P^G_{max}(i,t,m)$.
$L^S(j,t,\omega_l)$	Power scheduled for load j in period t and scenario ω_l [MW].
$R^U(i,t)$	Up-spinning reserve scheduled for unit i in

	period t[MW]. Limited to$R^{U}_{max}(i,t)$.
$R^{D}(i,t)$	Down-spinning reserve scheduled for unit i in period t[MW]. Limited to$R^{D}_{max}(i,t)$.
$R^{NS}(i,t)$	Non-spinning reserve scheduled for unit i in period t[MW]. Limited to$R^{NS}_{max}(i,t)$.
$R^{U}(j,t)$	Up-spinning reserve scheduled for load j in period t[MW]. Limited to$R^{U}_{max}(j,t)$.
$R^{D}(j,t)$	Down-spinning reserve scheduled for load j in period t[MW]. Limited to$R^{D}_{max}(j,t)$.
$P^{S}_{WP}(t)$	Scheduled wind power in period t [MW].
$C^{A}(i,t,\omega_w,\omega_l,\omega_N)$	Cost due to the change in the start-up plan of unit i in period t and scenariosω_w, ω_l andω_N.
$P^{G}(i,t,\omega_w,\omega_l,\omega_N)$	Power output of unit i in period t and scenariosω_w, ω_l and ω_N [MW].
$L^{C}(j,t,w)$	Power consumed by load j in period t and scenariosω_w, ω_l and ω_N [MW].
$r^{U}(i,t,\omega_w,\omega_l,\omega_N)$	Up-spinning reserve deployed by unit i in period t and scenariosω_w, ω_l and ω_N [MW].
$r^{D}(i,t,\omega_w,\omega_l,\omega_N)$	Down-spinning reserve deployed by unit i in period t and scenariosω_w, ω_l and

	ω_N [MW].
$r^{NS}(i,t,\omega_w,\omega_l,\omega_N)$	Non-spinning reserve deployed by unit i in period t and scenariosω_w, ω_l and ω_N [MW].
$r^{U}(j,t,\omega_w,\omega_l,\omega_N)$	Up-spinning reserve deployed by load j in period t and scenariosω_w, ω_l and ω_N [MW].
$r^{D}(j,t,\omega_w,\omega_l,\omega_N)$	Down-spinning reserve deployed by load j in period t and scenariosω_w, ω_l and ω_N [MW].
$r_{G}(i,t,m,\omega_w,\omega_l,\omega_N)$	Reserve deployed from the m-th block of energy offered by unit i in period t and scenariosω_w, ω_l and ω_N [MW].
$L_{shed}(j,t,\omega_w,\omega_l,\omega_N)$	Load shedding of load j in period t and scenariosω_w, ω_l and ω_N [MW].
$S(t,\omega_w)$	Wind power generation spillage in period t and scenario ω_w [MW].
$f(t,\omega_w,\omega_l,\omega_N,(n,r))$	Power flow through line (n,r) in period t and scenariosω_w, ω_l and ω_N [MW].
$P^{loss}(t,\omega_w,\omega_l,\omega_N,(n,r))$	Power loss in line (n,r) in period t and scenariosω_w, ω_l and ω_N [MW].
$\delta(n,t,\omega_w,\omega_l,\omega_N)$	Voltage angle at node n in period t and scenariosω_w, ω_l and ω_N [MW].

C. Binary Variables

$u(i,t)$	0/1 variable that is equal to

	1 if unit i is committed in period t at scheduled stage.
$v(i,t,\omega_w,\omega_l,\omega_N)$	0/1 variable that is equal to 1 if unit i is committed in period t and scenariosω_w, ω_l and ω_N in real time.

D. Random Variables

$P_{WP}(t)$	Random variable modeling the wind power generation in period t [MW]. $P_{WP}(t,\omega_w)$ represents the amount of this random variable in scenario ω_w in real time [MW].

E. Constants

$d(t)$	Duration of time period t [h].
$\lambda^{SU}(i,t)$	Start-up offer cost of unit i in period t [\$].
$\lambda_G(i,t,m)$	Marginal cost of the m-th block of energy offered by unit i in period t [\$/MWh].
$\lambda_L(j,t)$	Utility of load j in period t [\$/MWh].
$\lambda^{WP}(t)$	Marginal cost of the energy offer submitted by the wind producer in period t [\$/MWh].
$VLOL(j,t)$	Value of loss load for load j in period t [\$/MWh].
$V^S(t)$	Cost of wind power spillage in period t [\$/MWh].
$d(t)$	Probability of wind power generation scenarioω_w.
$\pi(\omega_l)$	Probability of load scenarioω_l.
$\pi(\omega_N)$	Probability of Network scenarioω_N.
$P_{\max}(i)$	Capacity of unit i [MW].
$P_{\min}(i)$	Minimum power output of unit i [MW].
$B(n,r)$	Absolute value of the imaginary part of the admittance of line (n,r) [p.u.].
$f_{max}(n,r)$	Maximum capacity of line (n,r) [MW].

F. Sets

Λ	Set of transmission lines.

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