Impact of Strategic Behaviors of the Electricity Consumers on Power System Reliability

Amin Shokri Gazafroudi[1], Miadreza Shafie-khah[2], Desta Zahlay Fitiwi[2], Sérgio F. Santos[2], Juan Manuel Corchado[1,3], João P.S. Catalão[2,4,5]

[1]BISITE Research Group, University of Salamanca, Edificio I+D+i, 37008 Salamanca, Spain

[2]C-MAST, University of Beira Interior, Covilhã 6201-001, Portugal

[3]Osaka Institute of Technology, Asahi-ku Ohmiya, Osaka 535-8585, Japan

[4]INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465

[5]INESC-ID, Instituto Superior Técnico, University of Lisbon, Lisbon 1049-001, Portugal

shokri@usal.es; miadreza@ubi.pt; fitiwi@kth.se; sdfsantos@gmail.com; corchado@usal.es; catalao@fe.up.pt

Abstract— **Over the past few decades, electricity markets have created competitive environments for the participation of different players. Electricity consumers (as end-users in power systems) can behave strategically based on their purposes in the markets. Their behaviors induce more uncertainty into the power grid, due to their dynamic load demands. Hence, a power system operator faces more difficulties in maintaining an acceptable level of reliability and security in the system. On the other hand, the strategic behaviors of electricity consumers can be as a double-edged sword in the power grid. There is a group of consumers who are flexible and so, can be interrupted at critical time periods and pursue their economic targets in the electricity markets. However, the second group is concerned with electricity demand being provided to them with the desired reliability level. Hence, the decisions of this group of electrical consumers are in conflict with their corresponding demand response programs. According to the above statement, this chapter aims at investigating the impact of strategic behavior of the electrical consumers on power system reliability. In this way, different agents of electricity markets are defined in this chapter which their behavior can impact on the market-clearing problem. Energy and reserve are assumed as electricity commodities in this chapter. Thus, a two-stage, day-ahead and real-time- stochastic unit commitment problem is solved to clear energy and reserve simultaneously considering the uncertainty of wind power generations and conventional generation units which impacts on the reliability of sustainable power systems.**

Keywords— Simultaneous market clearing; Energy flexibility; Customer behavior; Reliability; Demand response; Energy economy; Stochastic programming; Decision-making under uncertainty; Operating reserve; Wind power integrating; Multi-agent systems.

1. INTRODUCTION

According to the growing awareness about the environment and the demand for a reliable power grid, providing reliable renewable-based systems is a task of future smart grids [1,2]. In recent years, the increased use of renewable energies such as wind power generation has caused some challenges in power systems mainly due to the variable and stochastic nature of these non-dispatchable energy sources [3]-[4]. In connection to this, the extant literature has several related works which present new methods to solve economic dispatch, optimal power flow [5], unit commitment [6], and market-clearing [7] problems considering variability and uncertainty of power generation such technologies. For instance, in [8], the optimal power flow problem is solved considering wind power uncertainty. The stochastic behavior of wind power generation is modeled by a Weibull probability density function. Besides, a heuristic optimization method which is called modified cuckoo search is used to solve the problem. In [9], the economic dispatch problem is solved considering high penetration of wind power generation in the integrated energy storage systems. In the model, wind power is defined as a dispatchable variable. Moreover, dynamic programming is used to solve unit commitment and economic dispatch problems. The impacts of renewable energies on power system are evaluated via a Monte Carlo simulation which accounts for the uncertainty of wind power generation in [10], [11] and [12]. In [5], the renewable power producers are modeled in a multi-agent environment where the uncertainty of these renewable resources is considered by employing a two-stage stochastic framework.

The power system's reliability depends on various factors such as load capacity and customer base, maintenance, as well as age and types of equipment [13]. Providing suitable operating reserves is one of the main duties of power system operator as this allows maintaining the desired reliability level of the power system, which is subjected to high-level uncertainty and stochastic behavior of market agents [14]. Hence, in new approaches, the stochastic and dynamic models are defined to determine operating reserves according to the stochastic nature of wind energy in the power system. Recent studies in this research area can be divided into two groups. The first group focuses on the approaches that allow obtaining operating reserves based on wind power uncertainty, but they do not consider customer's choice of reliability [7, 3-4, 8-12, 15-23]. However, the second group presents algorithms to determine reserves considering the customer's reliability choices and assesses the economic concepts related to the operating reserves [14]. Indeed, the second group follows the necessity of considering the consumers' strategic behavior in future smart grids. In this regard many efforts have been carried out to show the role of consumers' behavior in different aspects of the future interdependent networks [24]. In this context, in [25], decentralized control of responsive consumers is discussed by using a multi-agent method. In addition to these methods that can improve the robustness and security of the future interdependent systems even if a failure occurs in other networks [26], demand side management resources and flexible electric vehicle charging loads can highlight the role of consumers in the future smart grids [27]. On this basis, the role of customers is highlighted in

[28-29], and consequently a framework for determining the reserve is developed by taking the customers' reliability choices into account.

In [17], the energy and spinning reserve market-clearing problem is solved with the aim of minimizing total cost in the considered system and risk level considering wind power and electrical load. Spinning reserves are provided by generators and loads in the model presented in [17]. In [18], a security-constrained unit commitment problem is solved to determine the reserve level linked to transmission stress and increase the reliability of the power system. In [19], a method for determining zonal reserves is presented. This method considers the uncertainty of renewable energies. Authors in [19] present a probabilistic and heuristic optimization technique to solve a similar problem. In [20], operating reserves are determined through a combination of robust optimization and conditional value-at-risk, in order to consider wind power output uncertainty. In [21], a combined dispatch and multi-stages reserve policy optimization problem is solved by using a robust optimization, which models net load uncertainty by applying some decision rules. Such rules are based on forecasting errors in [21]. In [22], an improved interval method is used to solve the unit commitment problem considering network constraints and power output uncertainty of high penetration of wind farms in the power systems. Moreover, authors simulate several cases, where the unit commitment problem is solved using stochastic programming, robust optimization, interval and improved interval methods. The performance of these simulations is assessed on the basis of computational burden and total operating costs. Based on the analysis results, authors highlight the importance of a stochastic unit commitment approach since it best models the uncertainty of wind power generation in the power system.

This chapter first introduces the different agents of the restructured power system. Then, electricity consumers are classified according to their strategic behaviors in the electricity markets. Hence, different examples of the impacts of the behavior and uncertainty of agents are described and evaluated in this chapter. The rest of the chapter is organized as follows. In Section 2, the electricity market model is presented and described in detail. Classes of customers are introduced in Section 3. Section 4 outlines the results of the conducted simulations. Finally, Section 5 concludes this chapter.

2. ELECTRICITY MARKET MODEL

Power system restructuring has led to the appearance of different agents, and these agents have the freedom to participate in Electricity Markets (EMs). In this chapter, the EM model is presented and fully described. Also, details of the agents whose behaviors can impact the problem are included in this section. The EM model aims to solve a Stochastic Unit Commitment (SUC) problem and clear energy and reserve simultaneously. The SUC model consists of two stages. In the first stage, the Day-Ahead Market (DAM) is presented where the uncertainty of decision-making variables is not seen. However, in the second stage the Real-Time Market (RTM) considers the uncertainty of the wind farms' power output other traditional sources of uncertainty in the power grid.

2.1. Objective function

In this section, the objective function of the market-clearing model and its constraints are represented.

$$EC = \sum_{t=1}^{N_T} EC_t = \sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C_{it}^{SU} + \sum_{t=1}^{N_T} d_t \left[\sum_{i=1}^{N_G}\sum_{m=1}^{N_{Oit}} \lambda_{itm}^{G}.p_{itm}^{G} - \sum_{j=1}^{N_L} \lambda_{jt}^{L}.L_{jt}^{S} + \sum_{k=1}^{N_W} \lambda^{WP}{}_{kt}.P_{kt}^{S,WP}\right]$$
$$+ \sum_{\omega=1}^{N_\Omega} \pi_\omega . \left\{\sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C^{A}{}_{it\omega}\right.$$
$$+ \sum_{t=1}^{N_T} d_t \left[\sum_{i=1}^{N_G}\sum_{m=1}^{N_{Oit}} \left(C^{R^U}{}_i.r^U{}_{it\omega} + C^{R^D}{}_i.r^D{}_{it\omega} + C^{R^{NS}}{}_i.r^{NS}{}_{it\omega}\right)\right. \tag{1}$$
$$\left.\left. + \sum_{j=1}^{N_L}\left(C^{R^U}{}_j.r^U{}_{jt\omega} + C^{R^D}{}_j.r^D{}_{jt\omega} + VOLL_{jt}.L_{jt\omega}^{shed}\right) + \sum_{k=1}^{N_W} V^S{}_t.S_{kt\omega}\right]\right\}$$

In Eq. (1), the total Expected Cost (EC) of the day-ahead and real-time markets is defined as the objective function. The cost terms from the first to the second line represent the expected costs of DAM that consist of the start-up cost of units, energy cost of units, utility of electricity customers, and the cost of energy produced by wind farms, respectively. The subsequent lines in Eq. (1) gather the expected cost corresponding to the RTM which includes the costs related to the changes in the start-up states of generating units in DAM and RTM, reserve costs related to the generation-side and electricity customer-side, costs of load shedding and wind power spillage, respectively. As mentioned before, EM includes different agents with its corresponding aims and constraints. In the following, some of these agents are introduced on the basis of their limitations.

2.2. Generation Companies (GenCos)

A GenCo is one of the agents in the electricity market; it is in charge of producing electric power in the system. Generally, GenCos are called to the dispatchable electrical energy power plants. The key constraints of GenCos in the DAM and RTM are represented hereinafter:

2.2.1. DAM GenCos' constraints

Eqs. (2a)-(2c) represent power generation limits of GenCos in the DAM. Likewise, the maximum and minimum limitations of GenCos' power scheduling are represented in Eq. (2a). Besides, Eq. (2b) enforces the constraints related to the GenCos' energy blocks. In addition, Eq. (2c) shows that the power scheduling of GenCos in each time period equals the sum of their energy blocks.

$$\underline{P_i}.u_{it} \le P^S{}_{it} \le \bar{P}_{\mathrm{i}}.u_{it}, \quad \forall i, \forall t \tag{2a}$$

$$0 \le p_{itm}^{G} \le \bar{p}_{itm}^{G}, \quad \forall m, \forall i, \forall t \tag{2b}$$

$$P^S{}_{it} = \sum_{m=1}^{N_{Oit}} p_{itm}^{G}, \quad \forall i, \forall t. \tag{2c}$$

Eqs. (2d)-(2f) refer to the list of constraints corresponding to the start-up cost of GenCos:

$$C_{it}^{SU} \geq \lambda_{it}^{SU}.\left(u_{it} - u_{i(t-1)}\right), \quad \forall i, \forall t > 1 \tag{2d}$$

$$C_{i(t=1)}^{SU} \geq \lambda_{i(t=1)}^{SU}.\left(u_{i(t=1)} - u_{i(0)}\right), \quad \forall i, t = 1 \tag{2e}$$

$$C_{it}^{SU} \geq 0, \quad \forall i, \forall t. \tag{2f}$$

2.2.2. RTM GenCos' constraints

The power generation limits of GenCos in the RTM is enforced by Eq. (3a).

$$\underline{P}_i.v_{it\omega} \leq P^G{}_{it\omega} \leq \bar{P}_{\mathrm{i}}.v_{it\omega}, \quad \forall i, \forall t, \forall \omega. \tag{3a}$$

Eq. (3b) represent the relation among the allocated energy of GenCos in the DAM and RTM, and the operating reserves in the RTM. Additionally, the operating reserve constraints of GenCos in the RTM, as in Eqs. (3b)-(3h), need to be included in the model.

$$P^G{}_{it\omega} - P^S{}_{it} = r^U{}_{it\omega} + r^{NS}{}_{it\omega} - r^D{}_{it\omega}, \quad \forall i, \forall t, \forall \omega. \tag{3b}$$

$$0 \leq r^U{}_{it\omega} \leq \overline{R^U}_i.u_{it}, \quad \forall i, \forall t, \forall \omega. \tag{3c}$$

$$0 \leq r^D{}_{it\omega} \leq \overline{R^D}_i.u_{it}, \quad \forall i, \forall t, \forall \omega. \tag{3d}$$

$$0 \leq r^{NS}{}_{it\omega} \leq \overline{R^{NS}}_i.(1 - u_{it}), \quad \forall i, \forall t, \forall \omega. \tag{3e}$$

$$r^U{}_{it\omega} + r^{NS}{}_{it\omega} - r^D{}_{it\omega} = \sum_{m=1}^{N_{Oit}} r_{itm\omega}^G, \quad \forall i, \forall t, \forall \omega. \tag{3f}$$

$$r_{itm\omega}^G \leq \bar{p}_{itm}^G - p_{itm}^G, \quad \forall i, \forall t, \forall \omega. \tag{3g}$$

$$r_{itm\omega}^G \geq -p_{itm}^G, \quad \forall m, \forall i, \forall t, \forall \omega. \tag{3h}$$

The constraints related to the start-up cost due to the new commitment states of GenCos in the RTM are modeled by Eq. (3h)-(3k).

$$C^A{}_{it\omega} = C^{SU}{}_{it\omega} - C^{SU}{}_{it}, \quad \forall i, \forall t, \forall \omega. \tag{3h}$$

$$C^{SU}{}_{it\omega} \geq \lambda_{it}^{SU}.\left(v_{it\omega} - v_{i(t-1)\omega}\right), \quad \forall i, \forall t > 1, \forall \omega. \tag{3i}$$

$$C_{i(t=1)\omega}^{SU} \geq \lambda_{i(t=1)}^{SU}.\left(v_{i(t=1)\omega} - u_{i(0)}\right), \quad \forall i, t = 1 \tag{3j}$$

$$C^{SU}{}_{it\omega} \geq 0, \quad \forall i, \forall t, \forall \omega. \tag{3k}$$

2.3. Wind farms' constraints

Wind farm is one of the agents in the EM which produces non-dispatchable electrical power. Hence, wind power generation is one of the decision-maker variables that induces uncertainty into the market-clearing problem. As mentioned before, the two-stage stochastic unit commitment problem aims to clear energy and reserve in the DAM and RTM. The uncertainty of wind power generation is not considered in the first stage. Hence, the constraint related to the scheduling of wind power generation in the DAM is represented by Eq. (4a). In the second stage, for instance, a constraint related to the economic and technical concerns of the wind farms may be the real-time spillage of the generated power. Eq. (4b) represents the wind spillage constraint of the wind farm in the RTM.

$$\underline{P}_{kt}^{WP} \leq P_{kt}^{S,WP} \leq \bar{P}_{kt}^{WP}, \quad \forall k, \forall t. \tag{4a}$$

$$0 \leq S_{kt\omega} \leq P^{WP}{}_{kt\omega}, \quad \forall k, \forall t, \forall \omega. \tag{4b}$$

2.4. Customers' constraints

Customers are another group of agents in the electricity market. In the electricity market, these agents have the freedom to behave strategically on the basis of their preferences and desires. Classes of customers consist of economic-followers, reliability-followers, and neutral. Eq. (5) represents the load shedding constraint of the consumers in the RTM. Other equations related to customer classes are described in Section 3.

$$0 \leq L_{jt\omega}^{shed} \leq L^{C}{}_{jt\omega}, \quad \forall j, \forall t, \forall \omega. \tag{5}$$

2.5. Grid operator's constraints

A grid operator is an agent who controls and manages the interactions among various agents in the power grid. The principle role of grid operator is to balance the transacted electrical energy in each bus of the system. The equations below are associated with the constraints of the grid operator in the DAM and RTM. Eq. (6a) represents the balancing equation among GenCos, wind farms, and electrical loads. According to (6a), line capacity limitations and losses are not considered in the DAM. Therefore, the DAM is cleared as a pool-based market without network constraints.

$$\sum_{i=1}^{N_G} P^{S}{}_{it} + \sum_{k=1}^{N_W} P_{t}^{S,WP} = \sum_{i=1}^{N_L} L^{S}{}_{jt}, \forall t. \tag{6a}$$

However, all constraints related to the power flows are included in the RTM. Eq. (6b) represents the power balance equation in the RTM considering line losses. Further network related constraints are presented in (6c). The physical transfer limits i.e. related to the capacity of a transmission line are shown in (6d).

$$\sum_{i:(i,n)} P^{G}{}_{it\omega} - \sum_{j:(j,n)} \left(L^{C}{}_{jt\omega} - L^{shed}_{jt\omega}\right) + \sum_{k:(k,n)} (P^{WP}{}_{kt\omega} - S_{kt\omega}) - \sum_{r:(n,r)} f_{t\omega(n,r)} = 0, \quad \forall n, \forall t, \forall \omega. \tag{6b}$$

$$f_{t\omega(n,r)} = B_{(n,r)}.(\delta_{t\omega n} - \delta_{t\omega r}), \quad \forall (n,r) \in \Lambda, \forall t, \forall \omega. \tag{6c}$$

$$-\bar{f}_{(n,r)} \leq f_{t\omega(n,r)} \leq \bar{f}_{(n,r)}, \quad \forall (n,r) \in \Lambda, \forall \mathrm{t}, \forall \omega. \tag{6d}$$

3. CLASSES OF CUSTOMERS

3.1. Economic-followers

These customers are mainly concerned by their economic situations, and hence show some flexibility in their electrical consumption patterns and quantities. As a result, they play a key role by acting as interruptible loads. This is done by reducing/shifting their loads in some time periods and hence providing an upward and/or downward spinning reserve. It should be noted that economic-driven customers can also provide a downward spinning reserve by increasing their consumptions during periods specified by the system operator.

In return, these customers may receive money as a reward or incentive for their valuable flexibility provisions in the forms of interruptible loads. Besides, the operating reserve that is provided by customers can be different depending on the uncertainty of wind power generation, electrical load or power grid in the system.

Eqs. (7a)-(7b) represent constraints related to the upward and downward operating reserves of economic-follower customers. Also, Eq. (7c) relates the allocated electrical load in the DAM and RTM, and the downward and upward operating reserves. This way, if customers decrease their electrical consumptions, they act as GenCos which increase their generation. Hence, this decrement is called upward operating reserve from the customer-side. On the other hand, customers provide a downward operating reserve when they increase their consumption at the specific periods of time.

$$0 \leq r^{U}{}_{jt\omega} \leq \overline{R^{U}}_{j}, \quad \forall j, \forall t, \forall \omega. \tag{7a}$$

$$0 \leq r^{D}{}_{jt\omega} \leq \overline{R^{D}}_{j}, \quad \forall j, \forall t, \forall \omega. \tag{7b}$$

$$L^{C}{}_{jt\omega} - L^{S}{}_{jt} = r^{D}{}_{jt\omega} - r^{U}{}_{jt\omega}, \quad \forall j, \forall t, \forall \omega. \tag{7c}$$

3.2. Reliability-followers

Getting electricity according to their desired reliability level is the main concern of these customers. Unlike economic-followers who assist the system to provide the electrical demand of the power system, reliability-followers force the system to supply their desired electrical load. It is clear that behavior of reliability-followers increases the operating costs of the system. Hence, they are in charge of paying a portion of this imposed cost. Hence, customers declare their desired reliability according to the Value of loss load (VOLL) that is seen in the last line of Eq. (1).

3.3. Neutral customers

The group of customers whose behavior cannot have any impact on the operating cost and reliability of the system is called neutral. In other words, neutral customers neither provide any operating reserve nor ask for any reliability level that would force the system operator to provide more energy and reserve for the system.

4. SIMULATION RESULTS

In this section, the market-clearing model is assessed using the modified 3-bus test system that is shown in Fig. 1. It should be noticed that only electrical loads connected at buses 2 and 3 of the system are considered in this case study. In other words, the load connected at bus 1 (i.e. L1) is neglected in this study. The data for the generators and the system are given in Tables 1 and 2. Line capacity limits are provided in Table 3. Moreover, wind power generation and its scenarios and their corresponding probabilities are indicated in Tables 4 and 5, respectively. However, in some of the cases discussed here (specifically Case 1 and 2), wind farm is not considered, and wind power generation uncertainty is ignored in Case 3 of this study. The power grid scenarios are generated using Outage Replacement Rate (ORR) which equals 0.02 for generation units and is equal to 0.01 for transmission lines. Besides, the Value Of Loss Load (VOLL) of consumers is supposed to equal 1000 $/MWh. Different examples have been introduced in this section, in order to evaluate the impacts of customers' behavior and wind power uncertainty in the power system. Besides, the mixed integer linear programming model has been implemented in GAMS 24.7.4 [32] that has been linked with MATLAB software [33].

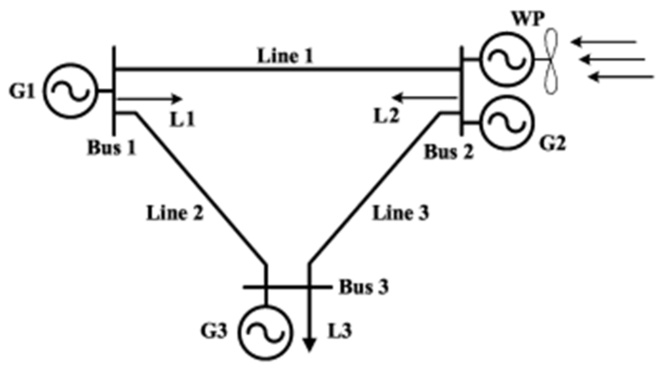

Figure 1 A 3-bus test system [14] and [30].

Table 1 Generator data for the 3-bus test system [14] and [31].

	Unit 1	Unit 2	Unit 3
$\underline{P}_i$ (MW)	10	10	10
$\overline{P}_i$ (MW)	100	100	50
λ_{it}^{SU} ($)	100	100	100
λ_{itm}^{G} ($/MWh)	30	40	20
${C^{R^U}}_{it}$ ($/MWh)	5	7	8
${C^{R^D}}_{it}$ ($/MWh)	5	7	8
${C^{R^{NS}}}_{it}$ ($/MWh)	4.5	5.5	7
Ramping Capabilities (MW/h)	100	100	50
$\overline{R^U}_{it}$	90	90	40
$\overline{R^D}_{it}$	90	90	40
$\overline{R^{NS}}_{it}$	100	100	50

Table 2 Other system data for the 3-bus test system [14] and [31].

${C^{R^U}}_{jt}$ ($/MWh)	70
${C^{R^D}}_{jt}$ ($/MWh)	70
$VOLL_{base}$ ($/MWh)	1000
Lines reactance (p.u.)	0.13
Lines capacity (MW)	55
P_{base} (MW)	41
V_{base} (kV)	120

Table 3 Loads scenarios at bus 3 and wind power in the 3-bus test system [14] and [31].

Transmission lines	Capacity (MW)
Line (1,2)	10
Line (1,3)	28
Line (2,3)	24

Table 4 Loads scenarios at bus 3 and wind power in the 3-bus test system [14], [30], and [31].

Period t	${P^{WP}}_{t\omega}$ (MW)		
	As forecasted	High	Low
1	6	9	2
2	20	30	13
3	35	50	25
4	8	12	6

Table 5 Probabilities of load scenarios at bus 3 and wind power in the 3-bus test system [14], [30], and [31].

	${P^{WP}}_{t\omega}$ (MW)		
	As forecast	High	Low
Probability	0.6	0.2	0.2

4.1. Case 1

In this case, customers at nodes 2 and 3 are not economic-followers. Hence, they do not provide upward and downward spinning reserves in the system. According to Eq. (7c), the real-time electrical demands of consumers 2 and 3 are equal to that of the day-ahead because their corresponding upward and downward spinning reserves are equal to zero. Table 6 shows the day-ahead electrical load of consumers and their expected real-time demand. Also, the expected load shedding of consumers is shown in Table 7. Moreover, power scheduling of GenCos in the day-ahead market and their expected real-time power generation are presented in Table 8. The difference between the dispatched power of GenCos in the DAM and the RTM is deployed as the operating reserves of GenCos in the RAM, as represented in (3b).

Table 6 Day-ahead electrical demand of consumers and their expected load in the real-time market in Case 1.

Consumer (MW)		Time (Hour) t 1	t 2	t 3	t 4
L2	$L^S{}_{jt}$	20	60	90	30
	$L^C{}_{jt}$	20	60	90	30
L3	$L^S{}_{jt}$	30	80	110	40
	$L^C{}_{jt}$	30	80	110	40

Table 7 Expected load shedding of consumers in Case 1.

L_{jt}^{shed} (MW)	Time (Hour) t 1	t 2	t 3	t 4
L2	0	0	0.012	0
L3	0	0.123	13.367	0

As it can be seen in Table 9, G2 provides both upward and downward spinning reserves in the 2nd time period. At first, it seems that these results are not true because GenCos can only provide upward or downward spinning reserves. However, the results are expected reserves that are generated in different scenarios. This means that G1 produces only upward spinning reserve in one scenario, and it provides the downward spinning reserve in another one.

Table 8 Dispatched power of GenCos in the day-ahead market and their expected real-time power generation in Case 1.

GenCo (MW)		Time (Hour) t 1	t 2	t 3	t 4
G1	$P^S{}_{it}$	0	30	50	10
	$P^G{}_{it}$	0	29.968	36.92	10.199
G2	$P^S{}_{it}$	0	60	100	10
	$P^G{}_{it}$	0.1	60.107	100	10.199

G3	$P^S{}_{it}$	50	50	50	50
	$P^G{}_{it}$	49.9	49.801	49.701	49.602

Table 9 Expected allocated operating reserves of GenCos in Case 1.

		Time (Hour)			
GenCo (MW)		t 1	t 2	t 3	t 4
G1	$r^U{}_{it}$	0	0.008	0	0.199
	$r^D{}_{it}$	0	0.04	13.08	0
	$r^{NS}{}_{it}$	0	0	0	0
G2	$r^U{}_{it}$	0	0.107	0	0.199
	$r^D{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0.1	0	0	0
G3	$r^U{}_{it}$	0	0	0	0
	$r^D{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0	0	0	0

4.2. Case 2

In Case 2, customers can join the reserve market as economic-followers in the electricity market. Hence, there is no doubt that if they provide upward and downward spinning reserves, their electrical demand in the DAM and RTM are different. Table 10 shows the electrical demand of consumers in the DAM and RTM. Table 11 presents the expected load shedding. As shown in Tables 7 and 11, the expected load shedding in Case 2 is less than that of Case 1 because of the higher reliability level that is provided by economic-followers. Additionally, power scheduling of GenCos in the DAM and the RTM is represented in Table 12. Operating reserves that are provided by GenCos and consumers are presented in Tables 13 and 14, respectively.

As summarized in Table 12, the amounts of dispatched power of G3 in the DAM and RTM are not the same. According to Eq. (3b), it seems that G3 should provide the operating reserves. However, G3 does not provide any operating reserve for the system as shown in Table 13. This is because of grid uncertainty. In other words, G3 is in a shut-down mode in some scenarios, so its expected power generated in the RTM is less than 50 MW. However, G3 generates 50 MW when it is ON. Moreover, L3 provides both upward and downward spinning reserves in the 2nd time period, which has been explained in Case 1. Table 15 compares the expected cost of the system in Cases 1 and 2. As shown in this table, economic-followers decrease the expected cost of the system due to their participation in the reserve market to provide the electrical demand of the system.

Table 10 Demand of consumers in the day-ahead market and their expected load in real-time market in Case 2.

Consumer (MW)		Time (Hour) t 1	t 2	t 3	t 4
L2	$L^S{}_{jt}$	20	60	90	30
	$L^C{}_{jt}$	18	54	81.015	27.988
L3	$L^S{}_{jt}$	30	80	110	40
	$L^C{}_{jt}$	32	87.909	101.478	44

Table 11 Expected load shedding of consumers in Case 2.

L_{jt}^{shed} (MW)	Time (Hour) t 1	t 2	t 3	t 4
L2	0	0	0	0
L3	0	0.08	0.358	0

Table 12 Dispatched power of GenCos in the day-ahead market and their real-time expected power generation in Case 2.

GenCo (MW)		Time (Hour) t 1	t 2	t 3	t 4
G1	$P^S{}_{it}$	0	34	50	20
	$P^G{}_{it}$	0.063	33.944	32.433	12.991
G2	$P^S{}_{it}$	0	56	100	0
	$P^G{}_{it}$	0.039	58.084	100	10.195
G3	$P^S{}_{it}$	50	50	50	50
	$P^G{}_{it}$	49.9	49.801	49.701	49.6

Table 13 Expected allocated operating reserves of GenCos in Case 2.

GenCo (MW)		Time (Hour) t 1	t 2	t 3	t 4
G1	$r^{U}{}_{it}$	0	0	0	0.135
	$r^{D}{}_{it}$	0	0.056	17.567	7.944
	$r^{NS}{}_{it}$	0.063	0	0	0
G2	$r^{U}{}_{it}$	0	2.84	0	0
	$r^{D}{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0.039	0	0	10.195
G3	$r^{U}{}_{it}$	0	0	0	0
	$r^{D}{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0	0	0	0

Table 14 Expected allocated operating reserves of consumers in Case 2.

Consumer (MW)		Time (Hour) t 1	t 2	t 3	t 4
L2	$r^{U}{}_{jt}$	2	6	8.985	2.012
	$r^{D}{}_{jt}$	0	0	0	0
L3	$r^{U}{}_{jt}$	0	0.044	8.522	0
	$r^{D}{}_{jt}$	2.002	7.952	0	4

Table 15 Expected Costs (ECs) in Cases 1 and 2.

	Example 1	Example 2
EC ($)	27371.713	13920.459

4.3. Case 3

The impact of wind power generation on the system is assessed in Case 3. It should be noted that wind power uncertainty is not considered in this case. In other words, it is assumed that wind power prediction is out of any error, and the probability of Scenario "As forecast" is equal to 1, and probabilities of Scenarios "high" and "low" are both equal to 0. Tables 16 and 17 present the electrical loads and expected load shedding, respectively. As shown in Tables 11 and 17, load shedding in Case 3 in the 3rd time period is less than that of Case 2 because of the higher reliability level that is provided by the wind farm like a power producer agent without uncertainty. The dispatched power of the GenCos in the DAM and RTM is shown in Table 19. As shown in Tables 12 and 18, the total amount of GenCos' dispatched power in Case 3 is less than any of the previous cases (i.e. Cases 1 and 2) because the wind farm's offered energy cost is assumed to equal zero in the electricity market. Hence, the wind farm 's power generation is first cleared in the electricity market, and it decreases the dispatched power of GenCos in the DAM and the RTM. Moreover, wind power generation uncertainty is disregarded. Therefore, operating reserves that are provided by GenCos and consumers in Case 3 are less than any of those provided in Cases 1 and 2 (see in Tables 19 and 20).

Table 16 Day-ahead demand of consumers and their real-time expected load in Case 3.

		Time (Hour)			
Consumer (MW)		t 1	t 2	t 3	t 4
L2	${L^S}_{jt}$	20	60	90	30
	${L^C}_{jt}$	18	54	81.018	32.944
L3	${L^S}_{jt}$	30	80	110	40
	${L^C}_{jt}$	33	87.909	101.973	44

Table 17 Expected load shedding of consumers in Case 3.

	Time (Hour)			
L_{jt}^{shed} (MW)	t 1	t 2	t 3	t 4
L2	0	0	0	0
L3	0	0.08	0.355	0

Table 18 Dispatched power of GenCos in the day-ahead market and their real-time expected power generation in Case 3.

GenCo (MW)		Time (Hour) t 1	t 2	t 3	t 4
G1	$P^{S}{}_{it}$	0	34	49	12
	$P^{G}{}_{it}$	0.063	33.944	31.935	12.191
G2	$P^{S}{}_{it}$	0	36	66	0
	$P^{G}{}_{it}$	0.027	38.084	66	10.151
G3	$P^{S}{}_{it}$	44	50	50	50
	$P^{G}{}_{it}$	44.91	49.801	49.701	49.602

Table 19 Expected allocated operating reserves of GenCos in Case 3.

GenCo (MW)		Time (Hour) t 1	t 2	t 3	t 4
G1	$r^{U}{}_{it}$	0	0	0	0.199
	$r^{D}{}_{it}$	0	0.056	17.065	0.008
	$r^{NS}{}_{it}$	0.063	0	0	0
G2	$r^{U}{}_{it}$	0	2.084	0	0
	$r^{D}{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0	0.027	0	10.151
G3	$r^{U}{}_{it}$	0.998	0	0	0
	$r^{D}{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0	0	0	0

Table 20 Expected allocated operating reserves of consumers in Case 3.

Consumer (MW)		Time (Hour) t 1	t 2	t 3	t 4
L2	${r^U}_{jt}$	2	6	8.982	0.024
	${r^D}_{jt}$	0	0	0	2.968
L3	${r^U}_{jt}$	0	0.0244	8.072	0
	${r^D}_{jt}$	3	7.952	0	4

4.4. Case 4

In this case, wind power generation uncertainty is considered. Therefore, the maximum amount of wind power that can be committed to the DAM is the forecasted amount of the wind farm. However, three scenarios are defined for wind power generation with their corresponding probabilities as seen in Tables 4 and 5. Tables 21 and 22 show the DAM and RTM electrical loads and expected load shedding, respectively. Likewise, the dispatched power of the GenCos in the DAM and the RTM is shown in Table 23. Also, the expected allocated reserves for GenCos and consumers are shown in Tables 24 and 25, respectively.

Table 21 Electrical demand of consumers in the day-ahead and real-time markets in Case 4.

Consumer (MW)		Time (Hour) t 1	t 2	t 3	t 4
L2	${L^S}_{jt}$	20	60	90	30
	${L^C}_{jt}$	18.399	55.59	81.014	32.349
L3	${L^S}_{jt}$	30	80	110	40
	${L^C}_{jt}$	33	87.909	101.973	44

Table 22 Expected load shedding of consumers in Example 4.

L_{jt}^{shed} (MW)	Time (Hour) t 1	t 2	t 3	t 4
L2	0	0	0	0
L3	0	0.08	0.355	0

Table 23 Day-ahead dispatched power of GenCos and their real-time expected power generation in Case 4.

GenCo (MW)		Time (Hour) t 1	t 2	t 3	t 4
G1	${P^S}_{it}$	0	34	49	12
	${P^G}_{it}$	0.063	33.944	31.935	12.191
G2	${P^S}_{it}$	0	36	66	0
	${P^G}_{it}$	0.027	39.074	67.996	8.156
G3	${P^S}_{it}$	44	50	50	50
	${P^G}_{it}$	45.509	49.801	49.701	49.602

Table 24 Expected allocated operating reserves of GenCos in Case 4.

GenCo (MW)		Time (Hour) t 1	t 2	t 3	t 4
G1	${r^U}_{it}$	0	0	0	0.199
	${r^D}_{it}$	0	0.056	17.065	0.008
	${r^{NS}}_{it}$	0.063	0	0	0
G2	${r^U}_{it}$	0	3.074	1.996	0
	${r^D}_{it}$	0	0	0	0
	${r^{NS}}_{it}$	0.027	0	0	8.156
G3	${r^U}_{it}$	1.597	0	0	0
	${r^D}_{it}$	0	0	0	0
	${r^{NS}}_{it}$	0	0	0	0

Table 25 Expected allocation of operating reserves of consumers in Case 4.

		Time (Hour)			
Consumer (MW)		t 1	t 2	t 3	t 4
L2	$r^U{}_{jt}$	1.601	4.807	8.986	0.025
	$r^D{}_{jt}$	0	0.398	0	2.375
L3	$r^U{}_{jt}$	0	0.044	8.027	0
	$r^D{}_{jt}$	3	7.952	0	4

Table 26 Expected Costs (ECs) in Cases 3 and 4.

	Example 3	Example 4
EC ($)	11228.733	11243.46

As shown in Tables 24-25 and 19-20, wind power uncertainty has different impacts on the operating reserves that are provided by different agents in the electricity market. However, in Table 26, we can see that the expected cost in Case 4 is greater than that of Case 3. In other words, this study demonstrates that wind power uncertainty increases the system's expected cost. Fig. 2 shows the impact of different examples on the reliability of the power system. In this chapter, Expected Energy Not Supplied (EENS) is chosen as reliability criteria of the system. As seen in Fig. 2, EENS in case 2 is less than case 1. In other words, joining consumers in the reserve market, as economic-follower agents, improves reliability level of the sustainable power systems. Also, considering wind farms in cases 3 and 4 increases the reliability level of the system. Fig. 3 demonstrates the impact of our studies on the total expected cost of the system. As shown in Fig. 3, economic-followers decrease the expected cost of the system due to their flexible behavior of consumers to provide reserve and improve the sustainability of the power system. Moreover, the total expected cost of the system is minimum in case 3 where wind farm is considered in the system, and we ignore uncertainty of wind power generation. However, the total expected cost in case 4 is higher than case 3 due to the negative effect of wind power generation uncertainty. Furthermore, it should be noticed that the EM has been cleared based on a centralized approach in this chapter. Hence, energy management system has not developed as a Multi-Agent System (MAS). However, MASs could be one of the solutions for the sustainable power system to manage energy in a decentralized manner [34-36].

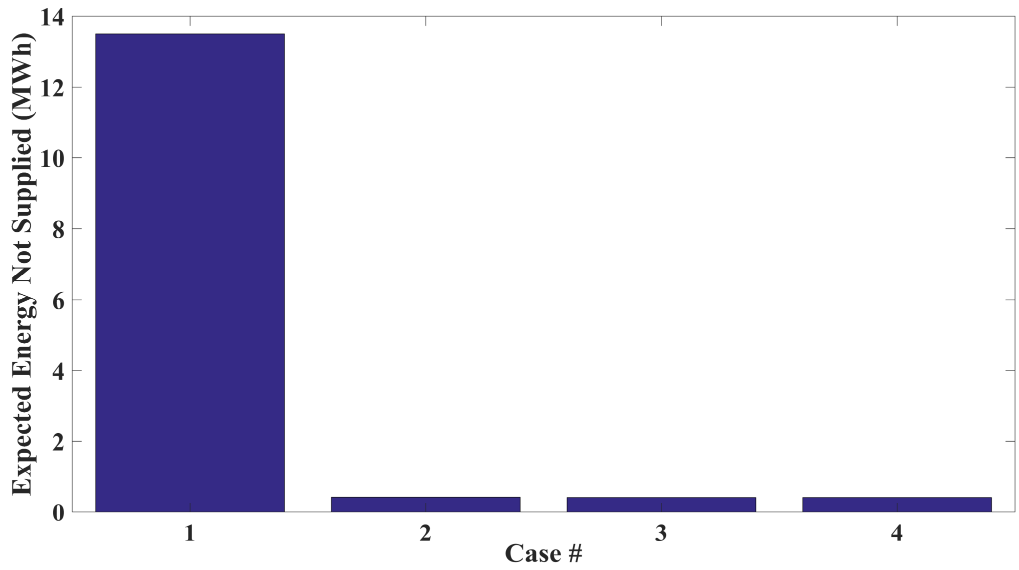

Figure 2 Assessment of Expected Energy Not Supplied (EENS) in examples 1 to 4.

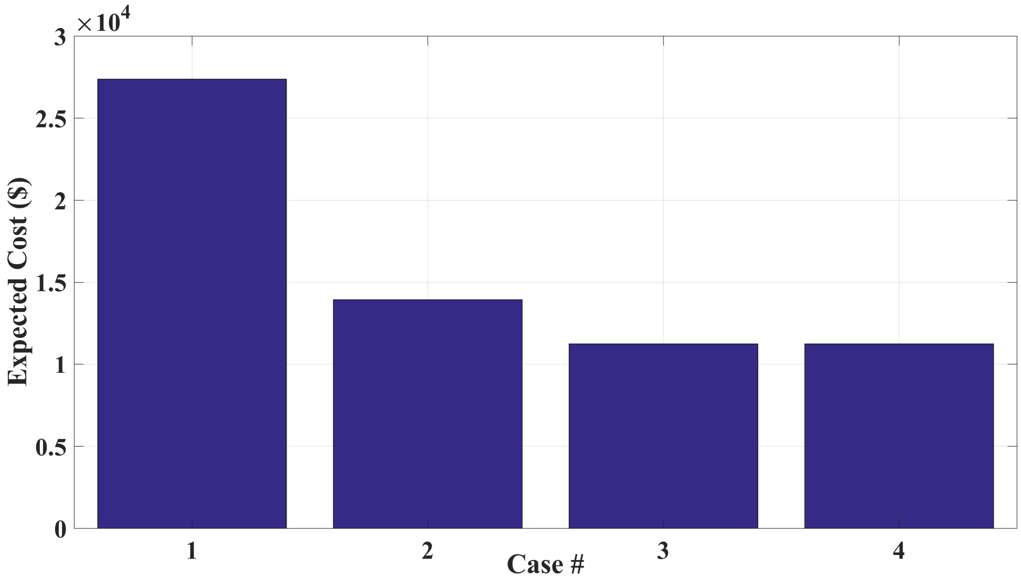

Figure 3 Assessment of Expected Cost (EC) in examples 1 to 4.

5. CONCLUSIONS

This chapter has introduced the agents of the restructured electricity market. The impacts of these agents' behavior on the power system have been assessed by setting up different cases. A two-stage Stochastic Unit Commitment (SUC) model of a MILP nature is developed in this chapter, which is then solved to clear energy and reserve simultaneously. The Day-Ahead Market (DAM) is presented in the first stage without the uncertainty of decision-making variables. However, the Real-Time Market (RTM) is represented in the second stage considering the uncertainty of wind power generation and other traditional sources of uncertainty in the power grid. Moreover, electricity consumers have been classified into different groups of agents based on their strategic behaviors: economic-followers, reliability-followers, and neutral. Besides, examples of different cases have been studied to assess the influence of customer behavior and wind power uncertainty on the power system. Based on the analysis results in this chapter, key findings of this chapter are highlighted in the following:

- Economic-followers improve the reliability level of the system and decrease load shedding.
- Economic-followers decrease the total expected cost of the system due
- Considering wind farms in the power system optimizes the total expected cost of the system due to reducing the total amount of GenCos' dispatched power.
- However, wind power uncertainty has a negative effect on the expected cost of the system.

Although different agents have been introduced in this chapter in the sustainable power systems, the market-clearing problem has been solved in centralized from. However, central energy management systems are not good strategies for forthcoming self-organized power systems. Therefore, decentralized electricity markets based on multi-agent energy management approach could be one of the solutions to increase energy efficiency and customers' choice of reliability in the sustainable power systems.

6. ACKNOWLEDGMENT

Amin Shokri Gazafroudi and Juan Manuel Corchado acknowledge the support by the European Commission H2020 MSCA-RISE-2014: Marie Sklodowska-Curie project DREAM-GO Enabling Demand Response for short and real-time Efficient And Market Based Smart Grid Operation - An intelligent and real-time simulation approach ref. 641794. Amin Shokri Gazafroudi acknowledge the support by the Ministry of Education of the Junta de Castilla y León and the European Social Fund through a grant from predoctoral recruitment of research personnel associated with the research project "Arquitectura multiagente para la gestión eficaz de redes de energía a través del uso de técnicas de intelligencia artificial" of the University of Salamanca. The work of Miadreza Shafie-khah and João P.S. Catalão was supported by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, and UID/EMS/00151/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

7. REFERENCES

[1] M.H. Amini, et al, Load management using multi-agent systems in smart distribution network, IEEE Power and Energy Society General Meeting, 2013.

[2] Boroojeni, Kianoosh G., et al. "Reliability in Smart Grids." Smart Grids: Security and Privacy Issues. Springer, Cham, 2017. 19-29.

[3] A. Ahmadi-Khatir, A. J. Conejo, R. Cherkaoui, "Multi-area unit scheduling and reserve allocation under wind power uncertainty", IEEE Trans. on power systems, Vol. 29, No. 4, PP. 1701-1710, Dec. 2013.

[4] J. Morales, A. Conejo, J. Perez- Ruiz, “Economic valuation of reserves in power systems with high penetration of wind power”, IEEE Trans. on Power Systems, Vol. 24, No. 2, pp. 900-910, May 2009.

[5] Ali Mohammadi, et al, Diagonal Quadratic Approximation for Decentralized Collaborative TSO+DSO Optimal Power Flow, IEEE Transactions on Smart Grid, 2018, DOI: 10.1109/TSG.2018.279603.

[6] Shafie-khah, Miadreza, and JPS Catalao. "A stochastic multi-layer agent-based model to study electricity market participants behavior." IEEE Transactions on Power Systems30.2 (2015): 867-881.

[7] Wang, F., Xu, H., Xu, T., Li, K., Shafie-Khah, M., & Catalao, J. P. (2017). The values of market-based demand response on improving power system reliability under extreme circumstances. Applied Energy, 193, 220-231.

[8] Ch. Mishra, Sh. P. Singh, J. Rokadia, “Optimal power flow in the presence of wind power using modified cuckoo search”, IET Gener. Transm. Distrib., 2015, Vol. 9, Iss. 7, pp. 615–626.

[9] H. Chen, R. Zhang, G. Li, L. Bai, F. Li, “Economic dispatch of wind integrated power systems with energy storage considering composite operating costs”, IET Gener. Transm. Distrib., 2016, Vol. 10, Iss. 5, pp. 1294–1303.

[10] A. L. Silva, W. Sales, L. Manso and R. Billinton, “Long-Term Probabilistic Evaluation of Operating Reserve Requirements With Renewable Sources”, IEEE Transactions on power systems, Vol. 25, No.1, Feb. 2010.

[11] M. Mastos, J. Lopes, M. Rosa, R. Ferreira, A. Silva, W. Sales, L. Resend, L. Manso, P. Cabral, M. Ferreira, N. Martins, C. Artiaz, F. Soto, R. Lopez, “Probabilistic evaluation of reserve requirements of generation systems with renewable power sources: The Portuguese and Spanish cases”, Electrical Power and Energy Systems 31 (2009) : 562- 569.

[12] A. M. Leite da Silva, M. A. Rosa, W. S. Sales, M. Matos, “Long Term Evaluation of Operating Reserve with High Penetration of Renewable Energy Sources”, IEEE Conference, Power and Energy Society General Meeting, July 2011.

[13] Sarwat, Arif I., et al. "Weather-based interruption prediction in the smart grid utilizing

chronological data." Journal of Modern Power Systems and Clean Energy 4.2 (2016): 308-315.

[14] A. Shokri Gazafroudi, K. Afshar, N. Bigdeli, "Assessing the operating reserves and costs with considering customer choice and wind power uncertainty in pool-based power market", International Journal of Electrical Power & Energy Systems, Vol. 67, May 2015, Pages 202-215.

[15] M. Ortega- Vazquez, D. Kirschen, "Assessing the Impact of Wind Power Generation on Operating Costs", IEEE Transactions on Smart Grid, Vol. 1 , No. 3, Dec. 2010.

[16] M. Ortega-Vazquez, D. Kirschen, "Optimizing the Spinning Reserve Requirements Using a Cost/Benefit Analysis", IEEE Transaction on Power Systems, Vol. 22, No.1, Feb. 2007.

[17] S. S. Reddy, P. R. Bijwe, and A. R. Abhyankar, "Joint Energy and Spinning Reserve Market Clearing Incorporating Wind Power and Load Forecast Uncertainties", IEEE Systems Journal, Vol. 9, No. 1, March 2015.

[18] Joshua D. Lyon, Kory W. Hedman, and Muhong Zhang, "Reserve Requirements to Efficiently Manage Intra-Zonal Congestion", IEEE Transactions on Power Systems, Vol. 29, No. 1, Jan. 2014.

[19] F. Wang, and Kory W. Hedman, "Dynamic Reserve Zones for Day-Ahead Unit Commitment With Renewable Resources", IEEE Transactions on Power Systems, Vol. 30, No. 2, March 2015.

[20] Zh. Wang, Q. Bian, H. Xin, and D. Gan, "A Distributionally Robust Co-Ordinated Reserve Scheduling Model Considering CVaR-Based Wind Power Reserve Requirements", IEEE Transactions on Sustainable Energy, Vol. 7, No. 2, April 2016.

[21] P. N. Beuchat, J. Warrington, T. H. Summers, and M. Morari, "Performance Bounds for Look-Ahead Power System Dispatch Using Generalized Multistage Policies", IEEE Transactions on Power Systems, Vol. 31, No. 1, Jan. 2016.

[22] H. Pandžić, Y. Dvorkin, T. Qiu, Y. Wang, and D. S. Kirschen, "Toward Cost-Efficient and Reliable Unit Commitment Under Uncertainty", IEEE Transactions on Power Systems, Vol. 31, No. 2, March 2016.

[23] M. Yousefi Ramandi, K. Afshar, A. Shokri Gazafroudi, N. Bigdeli, "Reliability and Economic Valuation of Demand Side Management Programming in Wind Integrated Power Systems", International Journal of Electrical Power & Energy Systems, Vol. 78, Jan. 2016, Pages 258-268.

[24] M.H. Amini, K.G. Boroojeni, S.S. Iyengar, P.M. Pardalos, F. Blaabjerg, and A.M. Madni, Sustainable Interdependent Networks, Springer, Cham, 2018.

[25] Najafi, Soroush, et al. "Decentralized Control of DR Using a Multi-agent Method." Sustainable Interdependent Networks. Springer, Cham, 2018. 233-249.

[26] Buldyrev, Sergey V., et al. "Catastrophic cascade of failures in interdependent networks." Nature 464.7291 (2010): 1025.

[27] M.H. Amini, et al. "A Panorama of Future Interdependent Networks: From Intelligent Infrastructures to Smart Cities." Sustainable Interdependent Networks. Springer, Cham, 2018. 1-10.

[28] M. Najafi, M. Ehsan, M. Fotuhi-Firuzabad, A. Akhavein, K. Afshar. “Optimal reserve capacity allocation with consideration of customer reliability requirements”, Energy 35 (2010): 3883-3890.

[29] A. Ahmadi-Khatir, M. Fotuhi-Firuzabad, L. Goel, “Customer choice of reliability in spinning reserve procurement and cost allocation using well-being analysis”, Electric Power Systems Research 79 (2009): 1431-1440.

[30] A. Shokri Gazafroudi, M. Shafie-khah, M. Abedi, S. H. Hosseinian, Gh. H. R. Dehkordi, L. Goel, P. Karimyan, J. M. Corchado, J. P.S. Catalão, “A Novel Stochastic Reserve Cost Allocation Approach of Electricity Market Agents in the Restructured Power Systems”, Electric Power Systems Research, 152(C):223–236, July 2017.

[31] Antonio J. Conejo, Miguel Carrion, Juan M. Morales, “Decision making under uncertainty in electricity markets”, International series in operations research & management science, Springer, 2010.

[32] GAMS Release 2.50. A User’s Guide; GAMS Development Corporation: 1999. Available online: http://www.gams.com (Accessed 20 September 2017).

[33] The MathWorks, MATLAB. Available online: http://www.mathworks.com (Accessed 20 September 2017).

[34] A. Shokri Gazafroudi, F. Prieto-Castrillo, T. Pinto, J. M. Corchado, “Organization-Based Multi-Agent System of Local Electricity Market: Bottom-Up Approach”, 15th International Conference on Practical Applications of Agents and Multi-Agent Systems (PAAMS), June 2017.

[35] A. Shokri Gazafroudi, T. Pinto, F. Prieto-Castrillo, J. Prieto, J. M. Corchado, A. Jozi, Z. Vale, G. K. Venayagamoorthy, “Organization-based Multi-Agent Structure of the Smart Home Electricity System”, IEEE Congress on Evolutionary Computation (CEC), June 2017.

[36] A. Shokri Gazafroudi, J. F. De Paz, F. Prieto-Castrillo, G. Villarrubia, S. Talari, M. Shafie-khah, J. P. S. Catalão, “A Review of Multi-Agent Based Energy Management Systems”, 8th International Symposium on Ambient Intelligence (ISAmI), June 2017.

1. Appendix

1.1. Appendix 1: 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	Index of wind power, electrical load and power grid scenarios, from 1 to Ω.

B. Continuous Variables

C_{it}^{SU}	Scheduled start-up cost ($).
${P^S}_{it}$	Power output of units in the DAM (MW).
p_{itm}^G	Power output from the m-th block of energy offered by the unit in DAM (MW).
${L^S}_{jt}$	Power consumed of load in DAM (MW).
${R^U}_{it}$	Up-spinning reserve in DAM (MW).
${R^D}_{it}$	Down-spinning reserve in DAM (MW).
${R^{NS}}_{it}$	Non-spinning reserve in DAM (MW).
${R^U}_{jt}$	Up-spinning reserve from demand-side in DAM (MW).
${R^D}_{jt}$	Down-spinning reserve from demand-side in DAM (MW).
$P_t^{S,WP}$	Wind power in DAM (MW).
${C^A}_{it\omega}$	Start-up cost due to change in commitment status of units in DAM and RTM ($).
${P^G}_{it\omega}$	Power output of unit in RTM (MW).
${L^C}_{jt\omega}$	Electrical consumed in RTM (MW).
${r^U}_{it\omega}$	Up-spinning reserve in RTM (MW).
${r^D}_{it\omega}$	Down-spinning reserve in RTM (MW).
${r^{NS}}_{it\omega}$	Non-spinning reserve in RTM (MW).
${r^U}_{jt\omega}$	Up-spinning reserve from demand-side in RTM (MW).
${r^U}_{jt\omega}$	Down-spinning reserve from demand-side in RTM (MW).

$r^G_{itm\omega}$	Reserve deployed from the m-th block of energy offered in RTM (MW).
$L^{shed}_{jt\omega}$	Load shedding (MW).
$S_{t\omega}$	Wind power generation spillage (MW).
$f_{t\omega(n,r)}$	Power flow through line (n,r) (MW).
${P^{loss}}_{t\omega(n,r)}$	Power loss in line (n,r) (MW).
$\delta_{t\omega n}$	Voltage angle at node .

C. Binary Variables

u_{it}	Commitment status of units in DAM.
$v_{it\omega}$	Commitment status of units in RTM.

D. Random Variables

${P^{WP}}_{t\omega}$	Wind power generation in RTM (MW).

E. Constants

d_t	Duration of time period (h).
λ^{SU}_{it}	Start-up offer cost of unit (\$).
λ^G_{itm}	Marginal cost of the m-th block of energy offered (\$/MWh).
λ^L_{jt}	Utility of electrical load (\$/MWh).
${\lambda^{WP}}_t$	Marginal cost of the energy offer submitted by the wind producer (\$/MWh).
$VOLL_{jt}$	Value of loss load for load (\$/MWh).
${V^S}_t$	Wind spillage cost (\$/MWh).
π_ω	Probability of scenarios.
$\bar{P}_{\mathrm{i}}$	Maximum capacity of units (MW).
$\underline{P_i}$	Minimum power output of generation units (MW).
$B_{(n,r)}$	Absolute value of the imaginary part of the admittance of line (n,r) (p.u.).
$\bar{f}_{(n,r)}$	Maximum capacity of line (n,r) (MW).