A Risk-based Competitive Bi-level Framework for Operation of Active Distribution Networks with Networked Microgrids

Himan Hamedi, Vahid Talavat, Ali Tofighi, and Reza Ghanizadeh

***Abstract*—This paper presents a risk-based competitive bi-level framework for optimal decision-making in energy sales by a distribution company (DISCO) in an active distribution network (ADN). At the upper level of this framework, the DISCO and a rival retailer compete for selling energy. The DISCO intends to maximize its profit in the competitive market. Therefore, it is very important for the DISCO to make a decision and offer an optimal price for attracting customers and winning the competition. Networked microgrids (MGs) at the lower level, as the costumers, intend to purchase energy from less expensive sources in order to minimize costs. There is a bi-level framework with two different targets. The genetic algorithm is used to solve this problem. The DISCO needs to be cautious, so it uses the conditional value at risk (CVaR) to reduce the risk and increase the probability of making the desired profit. The effect of this index on the trade between the two levels is studied. The simulation results show that the proposed method can reduce the cost of MGs as the costumers, and can enable the DISCO as the seller to win the competition with its rivals.**

***Index Terms*—Microgrid, networked operation, bi-level framework, risk, active distribution networks.**

Nomenclature

A. Indices

j	Index of microgrids (MGs)
$Mean_w$	Average value in each scenario
N	Number of scenarios
w	Scenario of price offered by distribution company (DISCO)

B. Parameters

α	Probability of a certain profit
$\rho^{\max}$	The maximum price of exchange between DISCO and MGs
ρ^{M}	Market price
C_{DG}	Generation cost of distributed generation (DG)
C_{IL}	Cost of interruptible load (IL) in MGs
P_{demand}	Power demand in MGs
$P^{j}_{DG,\max}$	The maximum capacity of DG units in the j^{th} MG
$P^{j}_{DG,\min}$	The minimum capacity of DG units in the j^{th} MG
$P^{j}_{IL,\max}$	The maximum IL in the j^{th} MG
$P^{T_{up}}_{\max}$	The maximum power purchased by DISCO from market
$P^{T}_{\max}$	The maximum power exchanged between DISCO and MGs

C. Variables

β	Weighting factor for conditional value at risk in objective function
ζ	Certain amount of profit (value at risk index)
η_w	Surplus of ζ compared with real profit
π_w	Probability of occurrence of each scenario
ρ^{w}_{D}	Price of exchange between DISCO and MGs
ρ^{w}_{RE}	Price of exchange between retailer and MGs
$Benefit^{w}$	Profit of DISCO in each scenario
C_t	Total cost of MGs
$CVaR$	Conditional value at risk for DISCO
OF	Objective function
P^{w}_{D}	Power exchanged between DISCO and MGs
P^{w}_{DG}	Power generated by DG units
P^{w}_{M}	Power exchanged between DISCO and market
P^{w}_{IL}	Amount of IL
P^{w}_{RE}	Power exchanged between retailer and MGs

I. Introduction

In active distribution networks (ADNs), energy retailers purchase energy from the wholesale electricity market and sell it to their customers. Therefore, they deal with wholesale prices and loads of unknown customers. In addition, in this retail environment, the principle of competition must be considered so that each customer has the right to choose. In the case of no competition among retailers, they

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are not cautious and offer prices to the customers with the only intention of increasing their profit. The profit of retailers has an unsustainable nature due to unknown market prices, load demand, and the prices of competitors.

In the past, various strategies were available to reduce the risks of retailers' decisions in the retail electricity market. In [1] and [2], the conditional value at risk (CVaR) method is presented for the problem of risk reduction of retailers' decisions in a competitive market. This method helps the retailer achieve the desired profit with less risk. Some researchers have used a regret model in the decision-making process. The regret in each scenario is calculated as the difference between the objective function value and the optimal value [3]. In [4], a bi-level method of retail pricing is presented based on indirect load control, where the decision-making at one level affects the decision space of the other level [5]. In [6] and [7], a two-stage hierarchical framework is provided for distribution company (DISCO) operators in day-ahead and real-time electricity markets considering the uncertainties of prices in the electricity markets and load demand. Moreover, the participation of DISCO operators in energy and reserve markets is modeled in [8] and [9].

The technical, economic and environmental effects of microgrids (MGs) in ADNs have been investigated in previous studies. Three types of demand response programs are considered for the optimal scheduling of electrical and thermal energy consumptions by the customers in [10]. In [11], the effects of MG penetration in ADNs are discussed. In [12], the operation scheduling in MGs via parametric programming is considered. In [13], the day-ahead scheduling problem of a smart MG is modeled as a multi-objective function. To investigate the effectiveness of the proposed model, it is applied to a 24-node MG in four case studies. In [14], the concept of CVaR index and the differences between CVaR and value at risk (VaR) are clearly presented. In [15], the tri-objective scheduling of residential smart electrical distribution networks is modeled with three different targets. Therefore, different Pareto solutions are obtained and the best solution is determined by the decision-making method. In [16], the optimal scheduling problem of an energy hub system is modeled as a tri-objective optimization problem. The proposed model is solved using the augmented ε-constraint method in the system optimization software environment of general algebraic modeling. Reference [17] presents a novel algorithm to solve the problem of day-ahead MG scheduling, considering power flow constraints under normal and emergency conditions of the network and unit commitment. In the operation problem of an ADN in the presence of MGs, [18] and [19] propose bi-level decision-making frameworks for DISCO and MGs. Unlike this paper, in [18] and [19], the DISCO has no rivals that sell energy to MGs. Therefore, the DISCO only looks for the maximum profit without being cautious. As a result, the DISCO freely offers prices to costumers. Additionally, MGs are not in the networked mode and do not cooperate with each other to meet their mutual needs, so they cannot minimize the costs.

Additionally, the operation of MGs and DISCO is studied in [20] and [21] using a system framework.

In [22], the optimal operation of distributed generation (DG) resources is considered with the uncertainties of these resources and loads in networked MGs. To solve the optimization problem in [22], a multi-objective genetic algorithm is used to minimize the operation costs and environmental pollution. Reference [23] presents the optimal scheduling of networked MGs considering resilience constraints in the form of a three-stage framework. In [24], an energy management strategy for day-ahead scheduling is proposed to reduce the operation costs of networked MGs. In [25], the optimal day-ahead scheduling of networked MGs is studied. Two time-based demand response programs and spot pricing are also included to increase the efficiency of solving the problem, so the operation costs of MGs are reduced. In [26], a bi-level multi-objective optimization problem is formulated with an ADN at the upper level and MGs at the lower level. In fact, a multi-grid-connected MG-based ADN is proposed. The optimization problem is solved by using a hierarchical genetic algorithm. In [27], the cooperation and competition among the DISCO, MG, and resource operators are modeled. Four frameworks are proposed to model the decision-making of a DISCO. In [28], for minimizing the energy cost from the grid, a stochastic framework is presented for the energy management of an MG based on pricing.

In [29], an optimal control algorithm is proposed to operate the networked MGs. In [30], the scheduling of energy resources for the networked MGs in an islanded distribution network is presented using multi-factor systems. This scheduling is studied in [31] considering load uncertainties. To solve the optimization problem in some studies, deterministic [32], [33] and stochastic [34], [35] algorithms are used. Reference [36] proposes a game-theory algorithm to evaluate the power exchange in networked MGs, and the economic advantages of these MGs are simulated and analyzed. In [37], a two-stage energy management scheme is studied for networked MGs with high penetration of renewable resources. In [38], the energy as a transaction between three interconnected MGs is studied to improve the economy and reliability of system operation.

The competitive environment in the bi-level framework of power exchange in the presence of DISCO and MGs as the two different levels of trade is ignored in most literature. The presence of a competitor forces the sellers to improve the quality and balance the offered prices. Moreover, customers will have more options. In this paper, MGs are in the networked mode under a unique beneficiary as costumers, and seek to minimize their costs. Additionally, the DISCO and a rival retailer compete with each other for selling energy. Therefore, the DISCO seeks to maximize its profits in competition with the retailer. There are two levels of trade with two different targets. These two different targets depend on the decision-making by the DISCO to offer optimal prices to MGs.

This paper focuses on the important subject of modeling a bi-level framework, in which, despite the inconsistency between the targets of the levels, the trade between them is fully modeled in a competitive space. Technically, it is very important for the DISCO to make a decision and present an optimal price to costumers in the presence of the rival retailer.

Moreover, the objective of the networked MGs as costumers is to minimize the costs. Therefore, the genetic algorithm is used for this problem. The principle of competition in the energy market forces the DISCO to be cautious for winning the competition and sell energy as much as possible. Therefore, by using the genetic algorithm, the DISCO offers the optimal prices to the customers to achieve its goal. In the competition with the retailer, the DISCO employs the CVaR index to include cautiousness in its objective function. The proper selection of a higher weight of cautiousness helps the DISCO make a certain profit with higher probability and less risk. The presented model enables the DISCO to win every competition with rivals. In addition, this case has a considerable impact on reducing the cost of MGs.

The rest of the paper is organized as follows. Section II presents the networked MGs with single management. Section III presents the problem formulation for a competitive bi-level framework for the operation of ADNs. Simulation results are thoroughly discussed in Section IV. Finally, Section V concludes the paper.

II. Networked MGs

The operation of networked MGs means that MGs can interact and access the resources of each other [25]. An individual beneficiary operates multiple MGs simultaneously with access to information of all MGs as shown in Fig. 1. The beneficiary of networked MGs (BNMG) allows the networked MGs to exchange regulation power at an economic optimum and organizes the power flow interactions between the networked MGs. The profits of all MGs are considered as a whole. The required power of all MGs is provided under the operation of a unique beneficiary. The BNMG is allowed to decide on providing the power required by a set of MGs from some MGs it chooses. This decision depends on the operation cost of MGs. The BNMG can use the resources of some MGs to provide the power required by all MGs. The difference between the networked and non-networked MGs is that a non-networked MG has a distinct operator who intends to minimize the operation costs of a single MG, while in networked MGs, the operator intends to minimize the operation costs of all MGs as a whole. For this purpose, the BNMG chooses the cheapest resources by prioritization.

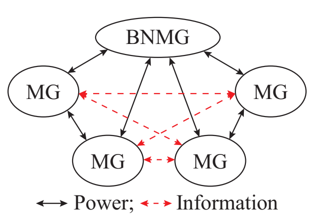

Fig. 1. Networked MGs with single management.

ADNs consist of several DGs and interruptible loads (ILs). These resources are utilized in the form of several MGs so that the management of ADNs is facilitated. The nature of the used resources is the same for all MGs. The components considered in each MG are shown in Fig. 2. The DG in each MG consists of wind turbine (WT), photovoltaic (PV), and micro-turbine (MT) resources.

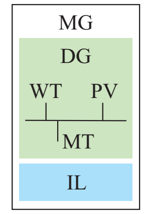

Fig. 2. Components in each MG.

III. Problem Formulation

The operation problem of DISCO and BNMG in the presence of a rival retailer is formulated as a bi-level optimization problem as follows. At the upper level, the DISCO and the rival retailer are introduced as [18]:

$$Benefit^{w} = \sum_{j} \rho_{D}^{w,j} P_{D}^{w,j} - \rho^{M} P_{M}^{w} \tag{1}$$

$$0 \le \rho_{D}^{w} \le \rho^{\max} \tag{2}$$

$$P_{M}^{w} \le P_{\max}^{T_{up}} \tag{3}$$

$$P_{D}^{w} = P_{M}^{w} \tag{4}$$

In the proposed model, the DISCO considers the scenarios of prices offered by the retailer and purchases energy from the wholesale market and sells it to the BNMG. The profit of this trade can be calculated using (1). Accordingly, if $P_D^w >$ 0, the DISCO has sold power to the BNMG; if $P_D^w < 0$, the DISCO has purchased power from the BNMG; and if $P_D^w = 0$, no power has been exchanged between the DISCO and BNMG. Formula (2) gives the limits of transactions (bids and offers) between the DISCO and BNMG in each scenario. The constraint of power that can be purchased in each scenario can be obtained using (3). The power balance constraint of the DISCO in each scenario is expressed in (4). This constraint implies that the power exchanged with the BNMG in each scenario is equal to that exchanged with the energy market. Since the problem in this paper is probabilistic and DISCO needs to obtain a certain amount of profit with a certain probability, the CVaR index is used according to (5) [14]. In fact, CVaR is used to maximize a certain amount of profit which occurs with a probability of 0.7 (α= 0.7) for the DISCO. The reason for using CVaR instead of VaR is that CVaR also tries to bring the amount of profit for DISCO as close to that certain amount of profit as possible with a probability of $1-\alpha$ [14].

$$CVaR = \max\left\{\zeta - \frac{1}{1-\alpha}\sum_{w=1}^{N} \pi_w \eta_w\right\} \quad \forall \alpha \in [0, 1] \tag{5}$$

$$\eta_w = \max\left\{\zeta - Benefit^{w}, 0\right\} \tag{6}$$

Equation (6) calculates η_w properly. The constraints of the risk index function are given as:

$$\zeta - Benefit^{w} \le \eta_w \quad \forall w \tag{7}$$

$$\eta_w \ge 0 \quad \forall w \tag{8}$$

The objective function of the problem, which is the profit function of the DISCO considering the risk, can be written as:

$$OF=\left(1-\beta\right)\left(Mean_w\left(Benefit^w\right)\right)+\beta\cdot CVaR \quad \beta\in[0,1] \tag{9}$$

In (9), β defines the weight of caution for the DISCO and is conventionally between 0 and 1. We consider its minimum, maximum, and middle values for the CVaR index. The risk-averse operators prefer larger values of β to achieve a certain expected profit and win the competition, while risk-lover (seeker) operators prefer smaller values of β expecting higher average profit. If the DISCO considers a larger β, it has in fact more bias towards CVaR in its objective function, and can achieve the minimum profit with high probability. The lower-level problem in the bi-level framework deals with networked MGs with a single management as described in (10). This problem includes the total cost of MGs C_t, i.e., the cost of the power exchanged with the DISCO, the cost of the power exchanged with the retailer, the cost of generating power by the DG units, and the cost of the IL. The parameters in (10) are defined in (11)-(17) [18]. Formula (11) shows the limits of the power that can be exchanged between the networked MGs and the DISCO, and (12) shows the power exchange limits between networked MGs and the retailer in each scenario. Formula (13) describes the power output limits of the DG units in each MG in each scenario. Formula (14) calculates the amount of IL in each MG in each scenario. Equation (15) describes the power balance constraint in MGs, i.e., the values of power exchanged with the DISCO and the retailer plus the amount of IL and the generation of DG units are equal to the amount of energy consumption in the MGs. Equations (16) and (17) give the constraints of the power generated by DG units and IL resources in the networked MGs. In this problem, the MGs minimize their costs by tracking the prices offered by the DISCO and retailer.

$$\min_{P_D^w,P_{IL}^w,P_{DG}^w,P_{RE}^w}\left(Mean_w,\rho_D^wP_D^w+\rho_{RE}^wP_{RE}^w+C_{DG}P_{DG}^w+C_{IL}P_{IL}^w\right) \tag{10}$$

$$-P_{\max}^T\le P_D^w\le P_{\max}^T \tag{11}$$

$$-P_{\max}^T\le P_{RE}^w\le P_{\max}^T \tag{12}$$

$$-P_{DG,\min}^j\le P_{DG}^{w,j}\le P_{DG,\max}^j \tag{13}$$

$$0\le P_{IL}^{w,j}\le P_{IL,\max}^j \tag{14}$$

$$P_{DG}^w+P_D^w+P_{RE}^w+P_{IL}^w=P_{demand} \tag{15}$$

$$P_{DG}^w=\sum_{j=1}^{n}P_{DG}^{w,j} \tag{16}$$

$$P_{IL}^w=\sum_{j=1}^{n}P_{IL}^{w,j} \tag{17}$$

Figure 3 shows the competitive bi-level framework of energy trade between the wholesale and retail markets [18]. The DISCO and the retailer are at the upper level, and four MGs are networked under single management at the lower level. In this paper, MGs have DG units and ILs that are exploited by the BNMG to minimize costs. The bi-level decision-making leader-follower structure is shown in Fig. 4 [18]. The DISCO intends to maximize its profit, so it uses a genetic algorithm to offer the optimal prices considering the scenarios of prices offered by the retailer to the MGs and the amount of energy required by the MGs. However, at the lower level, the BNMG intends to procure energy with lower prices considering the needs of MGs, the amount of energy produced by local resources and IL resources, and the prices offered by the DISCO and retailer. Once again, the DISCO aims to maximize its profit, so it changes the offered prices to make more profits from the outcome of transactions with the networked MGs and retailer. Figure 5 shows the flowchart of DISCO profit problem in a competitive market.

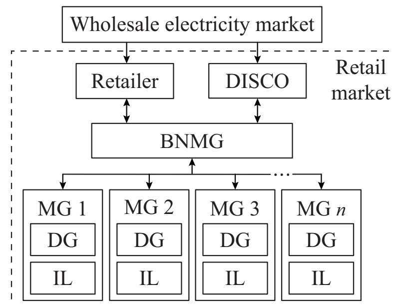

Fig. 3. Competitive bi-level framework of energy trade between wholesale and retail markets.

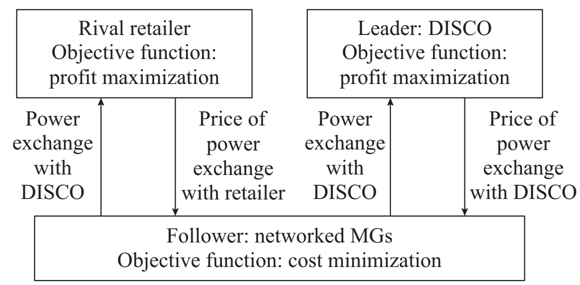

Fig. 4. Bi-level decision-making leader-follower structure in problem of transactions (bids and offers) among DISCO, retailer, and networked MG.

The assumptions of the problem are presented as follows.

1) The model presented in this paper is intended for one hour and will be solved for this period.

2) Power losses in the problem are ignored.

3) DG and IL are considered as the sources of each MG.

IV. Simulation Results

In the presented bi-level framework, four MGs are studied as shown in Table I. The simulations are based on changes in energy prices in the wholesale market. The energy prices in the wholesale market change from 35 to 46 \$/MWh. Each MG is allowed to shed up to 10% of its load. The cost of the IL for the MGs is 41 \$/MWh. Moreover, the maximum price offered by the DISCO is 50 \$/MWh. The scenarios of the prices offered by retailer are shown in Table II. The value of parameter α is hypothetically considered to be 0.7.

In this section, the transactions among DISCO, retailer, and BNMG are simulated. The results of the simulations are presented in Tables III. The first column presents the wholesale prices. These prices are the input of the problem, and affect the transaction among all sides. The second column gives the risk-seeking value of the DISCO (β coefficient).

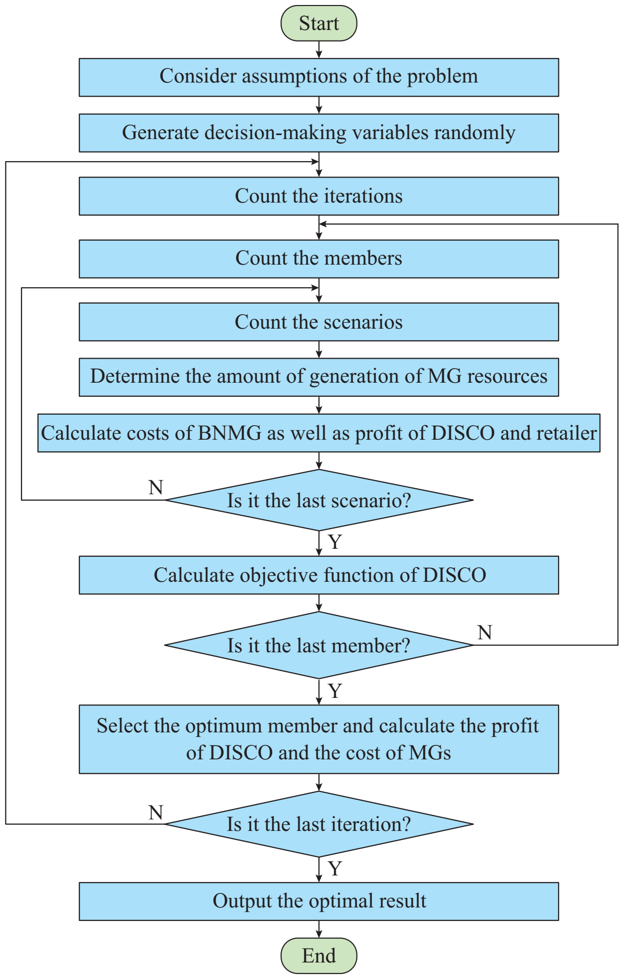

Fig. 5. Flowchart of DISCO profit problem in a competitive market.

TABLE I
SPECIFICATIONS OF STUDIED MGs

MG	The minimum power of DGs (MW)	The maximum power of DGs (MW)	Generation cost ($/MWh)	Load (MW)
1	0	4.0	37	5.0
2	0	5.0	40	5.0
3	0	5.5	35	6.0
4	0	7.0	45	5.5

TABLE II
SCENARIOS OF PRICES OFFERED BY RETAILER

Scenario	Offered price	Probability of scenario
1	3% higher than wholesale price	0.03
2	5% higher than wholesale price	0.05
3	7% higher than wholesale price	0.05
4	9% higher than wholesale price	0.09
5	11% higher than wholesale price	0.13
6	13% higher than wholesale price	0.22
7	15% higher than wholesale price	0.25
8	17% higher than wholesale price	0.10
9	19% higher than wholesale price	0.05
10	21% higher than wholesale price	0.03

Since we intend to solve the problem with more details, three different values are considered for β. β equal to unity indicates a fully risk-averse DISCO; β equal to zero indicates a full risk-seeking behavior; and β equal to 0.5 indicates 50% risk-seeking behavior. This coefficient is another input of the optimization problem in this paper. The third column gives the value of the decision-making variable of the DISCO. In fact, the purpose of solving the problem is to obtain the optimal value of this variable. The decision-making variable, which is the optimal price agreed upon by the DISCO and BNMG, is given in the tables for every wholesale price and β. For this optimal price, the amount of power purchased by the BNMG from the DISCO, the amount of power purchased from the retailer, the power generated by DGs, and the power from IL resources of the networked MGs are calculated. Moreover, the value of the objective function of the DISCO, profit of the operator, CVaR index, profit of retailer, and MG costs are calculated and presented in these tables.

The simulation results in Table III imply the following points. It can be found that the BNMG firstly uses less expensive resources of MGs to provide energy and avoid more expensive energy from the DISCO and retailer. With an increase in the wholesale price, BNMG uses DG3, DG1, DG2, IL resources, and DG4, respectively. In general, as the wholesale price increases from 35 to 46 $/MWh, the average price offered by the DISCO and retailer has also increased, because they have bought energy from the wholesale market at higher prices. As a result of this case, the total energy purchased by the BNMG from the DISCO and retailer becomes less or equal, and the MGs tend to use their resources more. Figures 6-8 show the effect of change in β on the generation of the local resources of MGs with different wholesale prices.

The DISCO intends to maximize the average expected profit, so it trades with MGs at lower prices to compete with the retailer and achieve the guaranteed minimum profit. Based on the results of Table III, Fig. 9 shows that by increasing β, the retail market prices presented by the DISCO to BNMG are mostly reduced. It is clear that this reduction is approximately between 0 and 2.35 $/MWh. Accordingly, the total cost of the MGs is mostly reduced. This reduction is approximately between 0 and 22.5 $/MWh. As shown in Fig. 10, by increasing β, the power sold by the DISCO to the BNMG mostly increases (approximately between 0 and 6 MW). Moreover, the power sold by the retailer mostly decreases (approximately between 0 and 2.5 MW). The DISCO wins the competition with the retailer. This is a great achievement for the DISCO, because the scenarios of prices offered by the retailer are assumed to be known by the DISCO, and using this complete information, the DISCO adopts a cautious approach by increasing β and offering a lower price than before.

Figure 11 shows the effect of increasing β by the DISCO on the profits of the DISCO and retailer. It is clear that the profits of both rivals are reduced with increasing β, but the reduction in the profit of DISCO is much less than that in the profit of retailer.

TABLE III
SIMULATION RESULTS OF NETWORKED MGS

ρ^M (\$/MWh)	β	ρ_D^w (\$/MWh)	P_{DG1}^w (MW)	P_{DG2}^w (MW)	P_{DG3}^w (MW)	P_{DG4}^w (MW)	P_{IL}^w (MW)	P_D^w (MW)	P_{RE}^w (MW)	C_t (\$)	$Benefit^w$ (\$)	Profit of retailer (\$)	$CVaR$ (\$)	Objective function (\$)
35	0.0	38.80	3.68	0	5.5	0	0	9.36	2.96	802.27	35.63	6.77	12.18	35.63
	0.5	38.12	3.68	0	5.5	0	0	10.44	1.88	795.83	32.60	3.37	21.23	26.92
	1.0	36.70	0	0	5.5	0	0	15.52	0.48	779.47	26.47	0.50	24.56	24.56
36	0.0	39.93	4.00	0	5.5	0	0	9.36	2.64	815.77	36.79	6.48	12.58	36.79
	0.5	39.19	4.00	0	5.5	0	0	10.44	1.56	808.87	33.39	2.98	21.74	27.57
	1.0	38.51	4.00	0	5.5	0	0	11.04	0.96	801.72	27.75	1.46	22.11	22.12
37	0.0	39.98	4.00	0	5.5	0	0	10.44	1.56	818.67	31.11	3.06	20.26	31.11
	0.5	39.98	4.00	0	5.5	0	0	10.44	1.56	818.67	31.11	3.06	20.26	25.69
	1.0	39.58	4.00	0	5.5	0	0	11.04	0.96	814.59	28.58	1.50	22.78	22.78
38	0.0	39.88	4.00	0	5.5	0	0	11.64	0.36	818.82	21.91	0.41	20.33	21.91
	0.5	39.88	4.00	0	5.5	0	0	11.64	0.36	818.82	21.91	0.41	20.33	21.12
	1.0	39.88	4.00	0	5.5	0	0	11.64	0.36	818.82	21.91	0.41	20.33	20.33
39	0.0	43.25	4.00	5	5.5	0	1.97	3.78	1.23	836.67	16.09	3.12	5.50	16.09
	0.5	40.90	4.00	5	5.5	0	0	6.79	0.21	826.70	12.96	0.24	12.02	12.49
	1.0	40.90	4.00	5	5.5	0	0	6.79	0.21	826.70	12.96	0.24	12.02	12.02
40	0.0	44.37	4.00	5	5.5	0	2.15	3.78	1.06	842.12	16.56	2.91	5.66	16.56
	0.5	43.59	4.00	5	5.5	0	2.15	4.21	0.63	839.16	15.17	1.33	9.88	12.53
	1.0	43.59	4.00	5	5.5	0	2.15	4.21	0.63	839.16	15.17	1.33	9.88	9.88
41	0.0	44.67	4.00	5	5.5	0	2.15	4.21	0.63	844.36	15.49	1.37	10.09	15.49
	0.5	44.67	4.00	5	5.5	0	2.15	4.21	0.63	844.36	15.49	1.37	10.09	12.79
	1.0	43.84	4.00	5	5.5	0	2.15	4.46	0.38	840.85	12.67	0.67	10.10	10.10
42	0.0	44.91	4.00	5	5.5	0	2.15	4.46	0.38	846.05	13.01	0.69	10.37	13.01
	0.5	44.91	4.00	5	5.5	0	2.15	4.46	0.38	846.05	13.01	0.69	10.37	11.69
	1.0	44.91	4.00	5	5.5	0	2.15	4.46	0.38	846.05	13.01	0.69	10.37	10.37
43	0.0	44.96	4.00	5	5.5	0	2.15	4.70	0.14	846.63	9.24	0.18	8.58	9.24
	0.5	44.96	4.00	5	5.5	0	2.15	4.70	0.14	846.63	9.24	0.18	8.58	8.91
	1.0	44.96	4.00	5	5.5	0	2.15	4.70	0.14	846.63	9.24	0.18	8.58	8.58
44	0.0	44.96	4.00	5	5.5	0	2.15	4.85	0	846.73	4.68	0	4.68	4.68
	0.5	44.96	4.00	5	5.5	0	2.15	4.85	0	846.73	4.68	0	4.68	4.68
	1.0	44.96	4.00	5	5.5	0	2.15	4.85	0	846.73	4.68	0	4.68	4.68
45	0.0		4.00	5	5.5	4.85	2.15	0	0	846.90	0	0	0	0
	0.5		4.00	5	5.5	4.85	2.15	0	0	846.90	0	0	0	0
	1.0		4.00	5	5.5	4.85	2.15	0	0	846.90	0	0	0	0
46	0.0		4.00	5	5.5	4.85	2.15	0	0	846.90	0	0	0	0
	0.5		4.00	5	5.5	4.85	2.15	0	0	846.90	0	0	0	0
	1.0		4.00	5	5.5	4.85	2.15	0	0	846.90	0	0	0	0

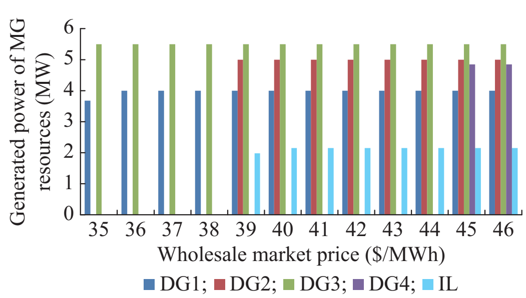

Fig. 6. Generated power of MG resources with different prices in wholesale market for $\beta=0$.

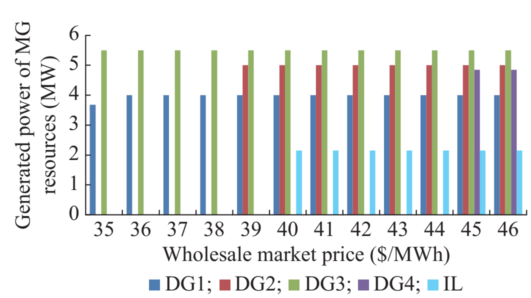

Fig. 7. Generated power of MG resources with different prices in wholesale market for $\beta=0.5$.

Accordingly, the probability of making the minimum expected profit for the DISCO increases, as shown in Fig. 12.

It is important to note that if the DISCO takes a risk and does not increase β (not being risk-averse), its profit may be reduced considerably and it may not be able to compete with the retailer. Based on (9), an increase in β makes the minimum expected profit of DISCO (CVaR) more important than the average expected profit in the objective function. In (9), the objective function of the problem is equal to the weighted sum of the minimum and average profits expected by the DISCO. The risk-averse operators tend to increase β and make a minimum profit with less risk, while the risk-seeker operators prefer to decrease β and make a higher profit.

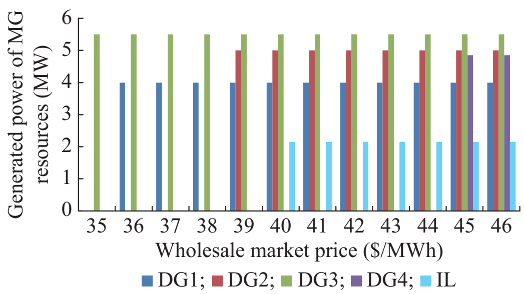

Fig. 8. Generated power of MG resources with different prices in wholesale market for $\beta = 1$.

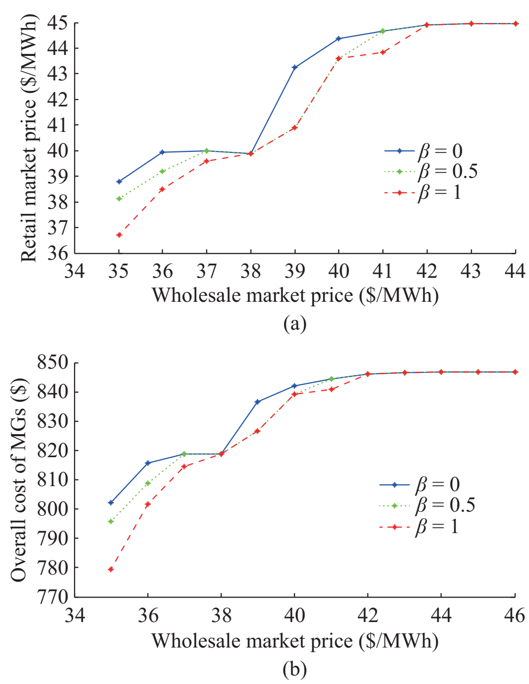

Fig. 9. Effect of increasing β on retail market prices and overall cost of MGs. (a) Retail market prices presented by DISCO to BNMG. (b) Overall cost of MGs.

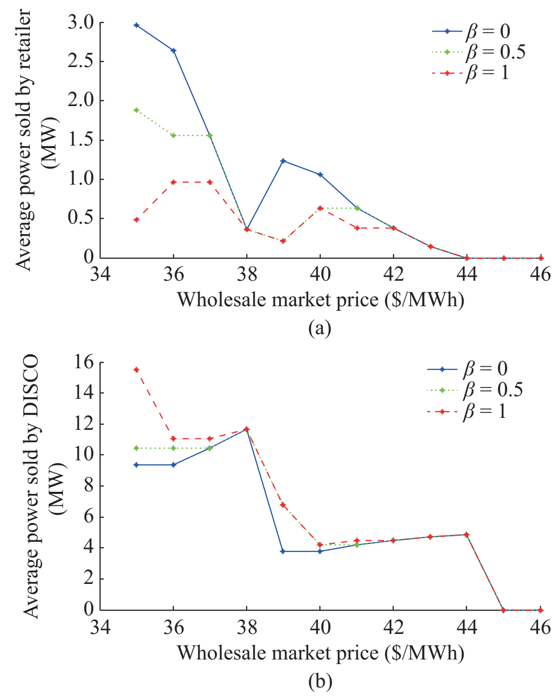

Fig. 10. Effect of increasing β on average power sold by retailer and DISCO. (a) Sold by retailer. (b) Sold by DISCO.

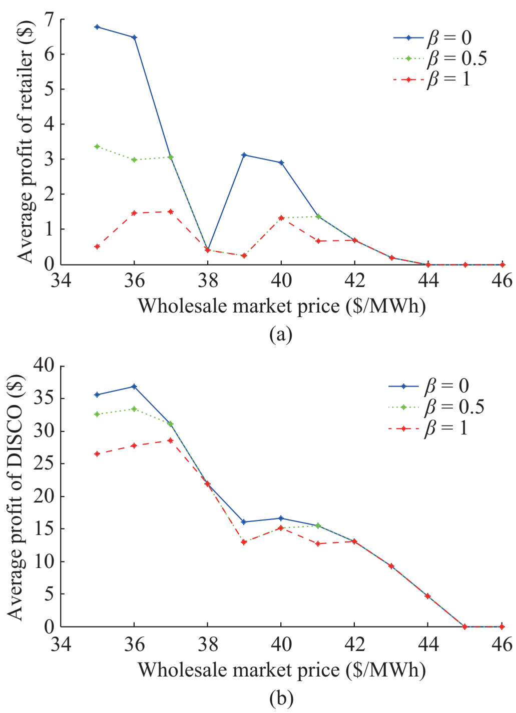

Fig. 11. Effect of increasing β on average profits. (a) Average profit of retailer. (b) Average profit of DISCO.

V. Conclusion

In this paper, a risk-based competitive bi-level framework has been modeled for the optimal decision-making in energy sales by the DISCO in an ADN. The ADN including four MGs is considered as the case study. The decision of the DISCO to sell energy in a competitive environment is very important and needs to be taken with caution. As the competitive nature of the energy market urges, the DISCO has to offer the optimal price to the customers to win the competition. Accordingly, the optimal prices are determined by a genetic algorithm, and the DISCO offer them to the MGs. The existence of competition in selling power in market causes risk for sellers, so the CVaR index is used to reduce the risk in the objective function of the DISCO. This index in the objective function of the problem corresponds to the weighted cautiousness of the DISCO.

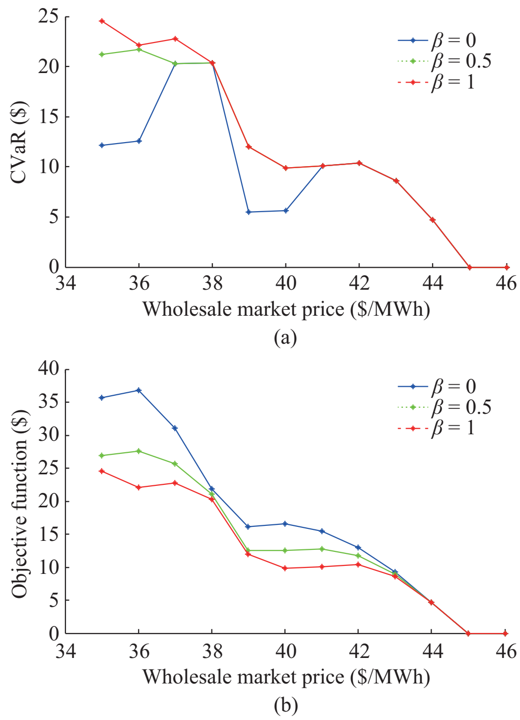

Fig. 12. Effect of increasing β on CVaR and objective function. (a) CVaR. (b) Objective function.

Simulation results show that by increasing the weight of CVaR, the power sold by the DISCO increases, while the power sold by the retailer decreases. Therefore, the DISCO is satisfied with a certain amount of profit (rather than with high profit) and keeps offering lower prices to the customers to compete with the retailer. However, the profit of the retailer as the rival of the DISCO falls sharply, and the DISCO wins the competition. Another achievement is the reduction of the overall cost of MGs by increasing the weight of CVaR in the objective function. Consequently, the impacts of market price and CVaR on the decision-making at both levels of the proposed model are clearly investigated. The results reveal that the proposed bi-level optimization enables the DISCO to win the competition with rivals and achieve its expected profit in any situation.

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