Co-optimization of Microgrid's bids in Day-ahead Energy and Reserve Markets Considering Stochastic Decisions in a Real-time Market

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Abstract—**High penetration of distributed energy resources in distribution networks is facilitated through the microgrids (MGs) structure. From the technical point of view, the MG operator (MGO) is responsible for the internal operation of the MG regarding which the distribution system operator (DSO) cannot take any decision. From the market viewpoint, the MGO participates in the wholesale markets regarding which the scheduling of the MG's resources is monitored. Therefore, the operation problem of the MGO considering its participation in the wholesale markets under uncertainty has been investigated in many studies. In this paper, a two-stage stochastic optimization approach is developed to model the MGO's bidding strategies in the day-ahead energy and reserve markets considering its stochastic decisions in a real-time market. In this model, the uncertainties of demand, wind speed, and solar radiation are modeled through different scenarios using the probability distribution functions (PDFs) of these parameters. Moreover, the uncertainty of the real-time energy price is modeled using the information gap decision theory (IGDT) method. To show the effectiveness of the model, it is applied on a MG test system.**

Keywords—Microgrid, day-ahead energy and reserve market, two-stage stochastic, distributed energy resources

I. Nomenclature

Acronyms

DA	Day-ahead
DER	Distributed energy resources
DG	Distributed generation
EES	Electrical energy storage
MG	Microgrid
RES	Renewable energy source
RT	Real-time

Indices/sets

e/E	Index/cardinality of EES
f/F	Index/cardinality of RESs
i,j	Indices of buses of MGs
k/K	Index/cardinality of DG
t/T	Index/cardinality of time
ω/W	Index/cardinality of scenarios

Parameters

C_t^{RES}	The bid of RESs to provide energy [$/kWh]
C_t^{DG}	The bid of DGs to provide energy [$/kWh]
$C_t^{ES_c}$	The bid of EES to charge energy [$/kWh]
$C_t^{ES_d}$	The bid of EES to discharge energy [$/kWh]
$C_t^{DG\_Re}$	The bid of DGs to provide reserve [$/kWh]
$C_t^{ES\_Re}$	The bid of EES to provide reserve [$/kWh]
$\overline{\mathrm{E}}_e^{\mathrm{ES}}$	The maximum energy capacity of EES [kWh]
$\underline{\mathrm{E}}_e^{\mathrm{ES}}$	The minimum energy capacity of EES [kWh]
$\overline{\mathrm{I}}_{i,j}^{\mathrm{MGN}}$	The maximum current capacity of feeders [p.u.]
$\widehat{\mathrm{P}}_{l,t}^{\mathrm{MGL\_DA}}$	The forecast amount of MG's load [kW]
$P_{l,t,\omega}^{\mathrm{MGL\_RT}}$	The amount of MG' load in RT [kW]
$\widehat{\mathrm{P}}_{f,t}^{\mathrm{RES}}$	The forecast output power of RES [kW]
$P_{f,t}^{\mathrm{RES}}$	The output power of RES in RT [kW]
$\overline{\mathrm{P}}_k^{\mathrm{DG}}$	The maximum capacity of DG [kW]
$\overline{\mathrm{P}}_e^{\mathrm{ch}}$	The maximum power charging of EES [kW]
$\overline{\mathrm{P}}_e^{\mathrm{dch}}$	The maximum power discharging of EES [kW]
$\overline{\mathrm{P}}^{\mathrm{MG}}$	The maximum trading power with grid [kW]
RU_k	The ramp-up limitation of DG [kW/h]
RD_k	The ramp-down limitation of DG [kW/h]
$\mathrm{R}_{i,j}^{\mathrm{MGN}}$	The resistance of feeders [p.u.]
$\mathrm{S}^{\mathrm{base}}$	Base power for per unit (p.u.) calculations [MVA]
$\overline{\mathrm{V}}_i^{\mathrm{MGN}}$	The maximum voltage limitation of buses [p.u.]
$\underline{\mathrm{V}}_i^{\mathrm{MGN}}$	The minimum voltage limitation of buses [p.u.]
$Z_{i,j}^{\mathrm{MGN}}$	The impedance of feeders [p.u.]
η^{ch}/η^{dch}	The charging/discharging efficiency of EES
$\lambda_t^{\mathrm{DA\_E}}$	The DA energy market price [$/kWh]
$\lambda_t^{\mathrm{RT\_E}}$	The RT energy market price [$/kWh]
λ_t^{Re}	The reserve market price [$/kWh]
ρ_ω	The probability of scenarios
φ^{Re}	The probability of deploying reserve [%]

Variables

$i_{i,j,t,\omega}^{\mathrm{MGN}}$	The current of feeders [p.u.]
$p_{f,t}^{\mathrm{RES}}$	The power generation of RESs in markets* [kW]
$p_{k,t}^{\mathrm{DG}}$	The power generation of DGs in markets [kW]
$p_{k,t}^{\mathrm{DG\_Dep}}$	The reserve deployment by DGs in RT [kW]
$p_{e,t}^{\mathrm{ES_c}}$	The power charging of EES in markets [kW]
$p_{e,t}^{\mathrm{ES_d}}$	The power discharging of EES in markets [kW]
$p_{k,t}^{\mathrm{ES\_Dep}}$	The reserve deployment by EES in RT [kW]
$p_t^{\mathrm{MG\_E_{in}}}$	The purchased power by MG from markets [kW]
$p_t^{\mathrm{MG\_E_{out}}}$	The sold power by MG to markets [kW]
$p_t^{\mathrm{MG\_Dep}}$	The reserve deployment by MG in RT [kW]
$p_{k,t}^{\mathrm{DG\_Re}}$	The reserve provided by DGs [kW]
$p_{e,t}^{\mathrm{ES\_Re}}$	The reserve provided by EES [kW]
$p_t^{\mathrm{MG\_Re}}$	The reserve provided by MG [kW]
$p_{i,j,t,\omega}^{\mathrm{Flow}}$	The power flow in feeders [kW]
$p_{i,j,t,\omega}^{\mathrm{Loss}}$	The power loss of feeders [kW]
$U_{k,t}^{\mathrm{ch}}$	Binary variable used for power charging in markets
$U_{k,t}^{\mathrm{dch}}$	Binary variable used for power discharging in markets
$U_t^{\mathrm{MG\_in}}$	Binary variable used for purchased power from markets
$U_t^{\mathrm{MG\_out}}$	Binary variable used for sold power to markets

$v_{i,t,\omega}^{\text{MGN}}$ The voltage of buses [p.u.]

Functions

$C^{\text{DA\_E}}$ Energy cost of the MGO in the DA market

$C^{\text{DA\_DER\_E}}$ Energy cost of the DER in the DA

$C^{\text{DER\_Re}}$ Reserve cost of the DER in the DA

$R^{\text{DA\_Re}}$ Revenue of the MGO from the reserve market

$C_{\omega}^{\text{RT\_E}}$ Energy cost of the MGO in the RT in each scenario

$C_{\omega}^{\text{RT\_DER\_E}}$ Energy cost of the DER in the RT in each scenario

$C_{\omega}^{\text{DER\_Dep}}$ Cost of reserve deployment of DER in the RT

$R_{\omega}^{\text{RT\_Re}}$ Revenue of the MGO from reserve deployment

TC^{DA} Total cost in the DA operation

TC_{ω}^{RT} Total cost of the MGO in the RT in each scenario

*Remark: For simplification, the indices DA and RT are ignored in some variables. Instead, the term "markets" is mentioned for these variables.

II. Introduction

Although distributed energy resources (DERs) bring several advantages for the power systems, their presence challenges the system operators. The complexity of the operation problem of distribution network increases with the DERs. Also, managing DERs in the wholesale energy markets is a main challenge for the independent system operator (ISO). The microgrids (MGs) are appropriate solutions for handling DERs in the power system [1]. On the one hand, the DERs are integrated in the MG structure to meet the local load, where the MG operator (MGO) is responsible for the operation of this local system. On the other hand, the MGO aggregates the bids of its local DERs to participate in the wholesale energy and reserve markets. Therefore, in the presence of the MGs, the complexity of the ISO and distribution system operator (DSO) problems decreases since they are only cooperating with the MGO instead of several DERs.

The MGO decides to meet the local demand of the MG through participating in the wholesale energy markets and the optimal scheduling of MG's resources. Also, the MGOs have the ability to provide reserve for the market regarding the flexible energy resources of the MGs, i.e., dispatchable distributed generators (DGs) and electrical energy storages (EES). Regarding the low capacity of the MGs in comparison with other energy market players, the MGOs participate in the wholesale markets as the price-taker (self-scheduling) players. In this case, the bids of the MGOs in the markets are the quantity-only one with no price. In fact, the MGOs accept the price of market to trade energy with the market and to provide reserve for it.

The appropriate decision-making models are proposed in the previous studies to model the bidding strategies of the MGO in the wholesale day-ahead (DA) energy and reserve markets. The operation problem of a MG is formulated as a two-level model considering the demand response programs (DRPs) under uncertainty in [2]. The uncertainties of output power of the renewable energy sources (RESs) and demand in a MG are modeled through a two-stage robust optimization approach in [3]. The MGO participates in the wholesale energy market in [4] to meet the required energy of its system including plug-in electric vehicles. For this purpose, a robust optimization model is developed to model the MGO's decisions under the uncertainty of energy market price. The bidding strategies of the MGO in the DA energy market are modeled in [5] considering the uncertainties of demand and outage probabilities of the RESs. The DA scheduling problem of a MG including the RESs and the EESs is modeled as a scenario-based stochastic optimization problem in [6]. The authors of [7] proposed a two-stage robust model for the DA optimal scheduling of a MG considering the uncertainty of real-time (RT) energy market price. The energy management problem of a hybrid AC/DC MG is modeled using a robust optimization approach in [8] considering the DA energy market price. The DA scheduling problem of a MG is modeled in [8], where the machine learning method is used to model the uncertain behavior of demand and RESs.

The bidding strategies of the MGO in the DA energy and reserve markets are modeled considering the uncertainties of the RESs in [9]. The DA energy and reserve scheduling of the MGs in the presence of electric vehicles is modeled as a robust optimization approach in [10]. The MGO's bids in the DA energy and reserve markets are determined using a risk-based approach in [11]. The information gap decision theory (IGDT) approach is used in [12] to model the uncertainties of MGO's bid acceptance in the DA reserve market.

The uncertain behavior of demand and output power of the RESs in the MG may lead to deviation in the power balance of the MG in the RT operation. The MGOs manage these deviations through the RT energy market. Therefore, the behavior of the MGO in the RT market needs to be modeled in the bidding strategy problem of the MGO in the DA energy and reserve markets which it is not addressed in the literature. Since the timeline of participating in the DA and RT markets is different, a decision-making framework is needed to model the bids of the MGOs in the DA markets considering their stochastic behavior in the RT. For this purpose, a two-stage stochastic optimization model is developed in this paper to model the bidding strategy of the MGO in the DA markets considering its stochastic decisions in the RT markets. Moreover, the IGDT approach is used to model the uncertainty of the RT energy market price. Therefore, the main contributions of this paper are as follows:

- Modeling the MGO's bids in the DA energy and reserve markets considering stochastic decisions in the RT markets.
- Modeling the uncertain behavior of the RT energy market price using the IGDT approach.

The rest of the paper is organized as follows. The problem description is presented in Section III. This problem is mathematically formulated in the Section IV. Numerical results are described in Section V. The conclusions are given in the last section.

III. Problem Description

The cyber-physical structure of the bidding strategy problem of the MGO in the DA energy and reserve markets is described in Fig. 1. The DERs' owners send their bids and technical constraints of resources to the MGO. Moreover, the forecast data related to output power of the RESs, demand of the MG, and energy and reserve market prices are sent to the MGO through a service provider. Regarding this data, the MGO solves its optimization problem (which is described in the next section) in the energy management system (EMS) center. The output results of the optimization problem are the optimal bids of the MGO in the DA energy and reserve markets. The MGO sends its bids with technical constraints of trading power with the main grid to the ISO, which is responsible of the wholesale energy and reserve markets. The clearing process of the wholesale markets is beyond the scope of this paper. After clearing the wholesale markets, the market results are announced regarding which the optimal scheduling of the DERs is determined. The control signals are sent from the MG central control (MGCC) to the local controllers (LCs) of the MG's resources. Regarding these signals, the DERs trade energy with the distribution network.

A. *Modeling uncertainties*

The bidding strategies of the MGO is the DA energy and reserve markets are modeled in the presence of uncertainties. The uncertainties of demand and output power of the RESs are modeled using the appropriate probability distribution functions (PDFs). For this purpose, the normal, Weibull, and irradiance PDFs are used to model the uncertain behavior of demand, wind speed, and solar radiation, respectively. To model these uncertainties in the decision-making problem of the MGO, these PDFs are discretized into some intervals. Details of determining the value of uncertain parameters in each interval and their probabilities are described in [13]. Regarding the probability of each interval of the uncertain parameters, the high number of samples are generated. Then, the scenarios are obtained through the scenario tree construction method. In this method, the scenario tree stages are the time steps of the problem and the generated samples are considered as the nodes. In this method, 1000 scenarios are generated, which are then reduced to 15 using the fast-forward scenario reduction technique.

B. *Two-stage stochastic formulation*

Regarding the obtained scenarios in the previous sub-section, the decision-making problem of the MGO is modeled as a two-stage stochastic optimization model. In this model, there are two sets of decision variables: before and after the occurrence of the scenarios. The first-stage decisions are bids of the MGO in the DA energy and reserve markets, which are determined before the occurrence of scenarios. The MGO's bids in the RT market are considered as the second-stage decisions determined after the occurrence of the scenarios. The MGO's decisions on the optimal scheduling of the DERs are considered in both stages.

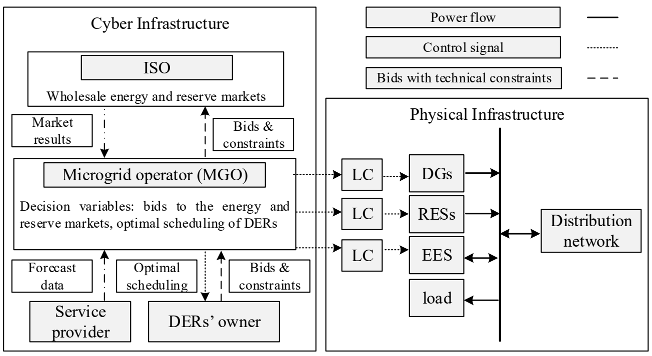

Fig.1. The cyber-physical infrastructure of the problem.

C. *Timeline*

The deadline of submitting bids for the DA energy and reserve markets is usually before noon at the day before the real operation (e.g., 10 a.m. in the California ISO (CAISO)). The deadline for submitting the bids to the RT energy market starts after publishing the DA market results until a short time before the real operation (i.e., 75 min before the real operation in the CAISO). Therefore, the proposed model in this paper is used by the MGO before the deadline of the submitting bids in the DA markets. For the RT market, the MGO waits to see the amount of forecast data, regarding which it submits the bids to this market. These bids can be considered as the same obtained from the proposed model in this paper, or the MGO can use the new models for participating in the RT market considering the obtained results of the DA markets and the values of the uncertain parameters.

IV. Mathematical Modeling

The bidding strategy of the MGO in the markets is modeled as (1)-(53). The objective function of the problem is modeled as (1) consisting of the total cost of the MGO in the DA and RT which are described in the next two sub-sections.

$$ETC = \sum_{\omega=1}^{W} \rho_{\omega} \left(TC^{\mathrm{DA}} + TC_{\omega}^{\mathrm{RT}}\right) \qquad (1)$$

A. *MG's DA problem*

The total cost of the MGO in the DA is modeled as (2) consisting of four terms. The first one is the cost of trading power with the DA energy market as described in (3). The revenue of the MGO from providing the reserve capacity to the market as the second term is modeled in (4). The cost of MG's resources to provide energy and reserve for the system is considered as the third and fourth terms which are modeled in (5) and (6), respectively.

$$TC^{\mathrm{DA}} = C^{\mathrm{DA\_E}} - R^{\mathrm{DA\_Re}} + C^{\mathrm{DA\_DER\_E}} + C^{\mathrm{DER\_Re}} \qquad (2)$$

$$C^{\mathrm{DA\_E}} = \sum_{t=1}^{T} \lambda_t^{\mathrm{DA\_E}} \left(p_t^{\mathrm{MG\_DA\_E_{in}}} - p_t^{\mathrm{MG\_DA\_E_{out}}}\right) \qquad (3)$$

$$R^{\mathrm{DA\_Re}} = \sum_{t=1}^{T} \lambda_t^{\mathrm{Re}} p_t^{\mathrm{MG\_Re}} \qquad (4)$$

$$C^{\mathrm{DA\_DER}} = \sum_{t=1}^{T} \begin{bmatrix} \sum_{f=1}^{F} \mathrm{C}_t^{\mathrm{RES}} p_{f,t}^{\mathrm{RES\_DA}} + \sum_{k=1}^{K} \mathrm{C}_t^{\mathrm{DG}} p_{k,t}^{\mathrm{DG\_DA}} + \\ \sum_{e=1}^{E} \mathrm{C}_t^{\mathrm{ES}_d} p_{e,t}^{\mathrm{ES}_d\mathrm{\_DA}} - \sum_{e=1}^{E} \mathrm{C}_t^{\mathrm{ES}_c} p_{e,t}^{\mathrm{ES}_c\mathrm{\_DA}} \end{bmatrix} \qquad (5)$$

$$C^{\mathrm{DER\_Re}} = \sum_{t=1}^{T} \left[\sum_{k=1}^{K} C_t^{\mathrm{DG\_Re}} p_{k,t}^{\mathrm{DG\_Re}} + \sum_{e=1}^{E} C_t^{\mathrm{ES\_Re}} p_{e,t}^{\mathrm{ES\_Re}} \right] \qquad (6)$$

The technical constraints of the DA's problem are as follows:

- DA power balance constraint: Equation (7) shows the power balance of the system in the DA operation.

$$\sum_{f=1}^{F} p_{f,t}^{\mathrm{RES\_DA}} + \sum_{k=1}^{K} p_{k,t}^{\mathrm{DG\_DA}} + \sum_{e=1}^{E} p_{e,t}^{\mathrm{ES}_d\mathrm{\_DA}} + p_t^{\mathrm{MG\_DA\_E_{in}}} = \sum_{l=1}^{L} \hat{\mathrm{P}}_{l,t}^{\mathrm{MGL\_DA}} + \sum_{e=1}^{E} p_{e,t}^{\mathrm{ES}_c\mathrm{\_DA}} + p_t^{\mathrm{MG\_DA\_E_{out}}} : \forall t \qquad (7)$$

- Reserve capacity constraint: The reserve capacity which can be provided by the MGO to the market is supplied from the DG and ES as shown in (8).

$$p_t^{\text{MG\_Re}} = \sum_{k=1}^{K} p_{k,t}^{\text{DG\_Re}} + \sum_{e=1}^{E} p_{e,t}^{\text{ES\_Re}} \quad :\forall t \tag{8}$$

- RESs constraints: The power generation of the RESs in the DA is lower than or equal to their forecast power as modeled in (9).

$$0 \le p_{f,t}^{\text{RES\_DA}} \le \hat{\text{P}}_{f,t}^{\text{RES}} \quad :\forall f,t \tag{9}$$

- DG constraints: The sum of the power generation of the DGs and its capacity to provide reserve is lower than or equal to their maximum power as described in (10). Moreover, the ramp-up and ramp-down limitations of DGs are modeled in (11) and (12), respectively.

$$p_{k,t}^{\text{DG\_DA}} + p_{k,t}^{\text{DG\_Re}} \le \overline{\text{P}}_k^{\text{DG}}, p_{k,t}^{\text{DG\_DA}}, p_{k,t}^{\text{DG\_Re}} \ge 0 : \forall k,t \tag{10}$$

$$\left(p_{k,t+1}^{\text{DG\_DA}} + p_{k,t+1}^{\text{DG\_Re}}\right) - \left(p_{k,t}^{\text{DG\_DA}}\right) \le \text{RU}_k \quad :\forall k,t \tag{11}$$

$$\left(p_{k,t}^{\text{DG\_DA}} + p_{k,t}^{\text{DG\_Re}}\right) - \left(p_{k,t+1}^{\text{DG\_DA}}\right) \le \text{RD}_k \quad :\forall k,t \tag{12}$$

- EES constraints: The power and energy constraints of the EESs to provide energy and reserve for the system are modeled in (13)-(19). The difference of the power discharging and charging plus the reserve provided by the EESs is less than or equal to the maximum power discharging of the EESs as modeled in (13). This equation shows that when the MGO decides to charge the EESs, its capacity to provide the reserve for the system increases. Equations (14)-(16) are used to limit the maximum power charging and discharging of the EESs and prevent from charging and discharging of the EESs, simultaneously. The time-based behavior of the energy stored in the EESs is shown in (17). The energy stored in the EESs is limited to its minimum and maximum values as described in (18). Moreover, the energy stored in the EESs in the last time step of the operation is equal to its initial value. The energy capacity of the EESs to provide reserve for the system is lower than or equal to the energy stored in the EESs minus its minimum value as (19).

$$(p_{e,t}^{\text{ES}_d\text{\_DA}} - p_{e,t}^{\text{ES}_c\text{\_DA}}) + p_{e,t}^{\text{ES\_Re}} \le \overline{\text{P}}_e^{\text{dch}} \quad :\forall e,t \tag{13}$$

$$0 \le p_{e,t}^{\text{ES}_c\text{\_DA}} \le \overline{\text{P}}_e^{\text{ch}} U_{e,t}^{\text{ch\_DA}} \quad :\forall e,t \tag{14}$$

$$0 \le p_{e,t}^{\text{ES}_d\text{\_DA}} \le \overline{\text{P}}_e^{\text{dch}} U_{e,t}^{\text{dch\_DA}} \quad :\forall e,t \tag{15}$$

$$U_{e,t}^{\text{ch\_DA}} + U_{e,t}^{\text{dch\_DA}} \le 1 \quad :\forall e,t \tag{16}$$

$$E_{e,t}^{\text{ES\_DA}} = E_{e,t-1}^{\text{ES\_DA}} + p_{e,t}^{\text{ES}_c\text{\_DA}} \eta^{\text{ch}} - \frac{p_{e,t}^{\text{ES}_d\text{\_DA}}}{\eta^{\text{dch}}} \quad :\forall e,t \tag{17}$$

$$\underline{\text{E}}_e^{\text{ES}} \le E_{e,t}^{\text{ES\_DA}} \le \overline{\text{E}}_e^{\text{ES}} \;:\forall e,t \;, E_{e,ini}^{\text{ES}} = E_{e,t=T}^{\text{ES\_DA}} \;:\forall e \tag{18}$$

$$E_{e,t}^{\text{ES\_Re}} \le E_{e,t}^{\text{ES\_DA}} - \underline{\text{E}}_e^{\text{ES}} \quad :\forall e,t \tag{19}$$

- Power trading constraints with the main grid: The reserve capacity of the MG which can provide for the market when the MGO purchases/sells energy from/to the DA market are modeled as (20) and (21), respectively. Equations (22)-(24) are used to limit the MGO' bids to the DA market to the maximum capacity of the MG's power trading with the main grid.

$$p_t^{\text{MG\_Re}} \le \overline{\text{P}}^{\text{MG}} + p_t^{\text{MG\_DA\_E}_{\text{in}}} \;, p_t^{\text{MG\_Re}} \ge 0 \;:\forall t \tag{20}$$

$$p_t^{\text{MG\_DA\_E}_{\text{out}}} + p_t^{\text{MG\_Re}} \le \overline{\text{P}}^{\text{MG}} \quad :\forall t \tag{21}$$

$$0 \le p_t^{\text{MG\_DA\_E}_{\text{in}}} \le \overline{\text{P}}^{\text{MG}} U_t^{\text{MG\_DA\_in}} \quad :\forall t \tag{22}$$

$$0 \le p_t^{\text{MG\_DA\_E}_{\text{out}}} \le \overline{\text{P}}^{\text{MG}} U_t^{\text{MG\_DA\_out}} \quad :\forall t \tag{23}$$

$$U_t^{\text{MG\_DA\_in}} + U_t^{\text{MG\_DA\_out}} \le 1 \quad :\forall t \tag{24}$$

B. MG's RT problem

The total cost of the MGO in the RT market is modeled as (25) consisting of four terms. The first one is the cost of trading power with the RT energy market as described in (26). The second term is the revenue of the MGO from deployment of the reserve in the real operation modeled in (27). The cost of MG's resources to provide energy and reserve for the system is considered as the third and fourth terms which are modeled in (28) and (29), respectively.

$$TC_\omega^{\text{RT}} = C_\omega^{\text{RT\_E}} - R_\omega^{\text{RT\_Re}} + C_\omega^{\text{RT\_DER\_E}} + C^{\text{DER\_Dep}} \tag{25}$$

$$C_\omega^{\text{RT\_E}} = \sum_{t=1}^{T} \lambda_t^{\text{RT\_E}} \left(p_{t,\omega}^{\text{MG\_RT\_E}_{\text{in}}} - p_{t,\omega}^{\text{MG\_RT\_E}_{\text{out}}}\right) \tag{26}$$

$$R_\omega^{\text{RT\_Re}} = \sum_{t=1}^{T} \lambda_t^{\text{RT\_E}} p_t^{\text{MG\_Re\_Dep}} \tag{27}$$

$$C_\omega^{\text{RT\_DER\_E}} = \sum_{t=1}^{T} \begin{bmatrix} \sum_{f=1}^{F} \text{C}_t^{\text{RES}} P_{f,t,\omega}^{\text{RES\_RT}} + \sum_{k=1}^{K} \text{C}_t^{\text{DG}} p_{k,t,\omega}^{\text{DG\_RT}} + \\ \sum_{e=1}^{E} \text{C}_t^{\text{ES}_d} p_{e,t,\omega}^{\text{ES}_d\text{\_RT}} - \sum_{e=1}^{E} \text{C}_t^{\text{ES}_c} p_{e,t,\omega}^{\text{ES}_c\text{\_RT}} \end{bmatrix} \tag{28}$$

$$C^{\text{DER\_Dep}} = \sum_{t=1}^{T} \left[\sum_{k=1}^{K} C_t^{\text{DG}} p_{k,t}^{\text{DG\_Dep}} + \sum_{e=1}^{E} C_t^{\text{ES\_dch}} p_{e,t}^{\text{ES\_Dep}} \right] \tag{29}$$

- RT power balance constraints: The power balance constraints of the MG in the reference bus, which connects the MG to the main grid, and in other buses are modeled in (30) and (31), respectively.

$$\begin{aligned} &\sum_f \left(P_{f,t}^{\text{RES\_DA}} + P_{f,t,\omega}^{\text{RES\_RT}}\right) + \sum_k \left(p_{k,t}^{\text{DG\_DA}} + p_{k,t,\omega}^{\text{DG\_RT}} + p_{k,t}^{\text{DG\_Dep}}\right) + \\ &\sum_e \left(p_{e,t}^{\text{ES}_d\text{\_DA}} + p_{e,t,\omega}^{\text{ES}_d\text{\_RT}} + p_{e,t}^{\text{ES\_Dep}}\right) + \left(p_t^{\text{MG\_DA\_E}_{\text{in}}} + p_{t,\omega}^{\text{MG\_RT\_E}_{\text{in}}}\right) \\ &-\left(p_t^{\text{MG\_DA\_E}_{\text{out}}} + p_{t,\omega}^{\text{MG\_RT\_E}_{\text{out}}} + p_t^{\text{MG\_Dep}}\right) - \left(p_{e,t}^{\text{ES}_c\text{\_DA}} + p_{e,t,\omega}^{\text{ES}_c\text{\_RT}}\right) \\ &-\sum_l \text{P}_{l,t,\omega}^{\text{MGL\_RT}} = \sum_j 0.5(p_{i,j,t,\omega}^{\text{Flow}} + p_{i,j,t,\omega}^{\text{Loss}}) \quad :\forall t,\omega, i = 1 \end{aligned}$$

(30)

$$\begin{aligned} &\sum_f \left(P_{f,t}^{\text{RES\_DA}} + P_{f,t,\omega}^{\text{RES\_RT}}\right) + \sum_k \left(p_{k,t}^{\text{DG\_DA}} + p_{k,t,\omega}^{\text{DG\_RT}} + p_{k,t}^{\text{DG\_Dep}}\right) \\ &+\sum_e \left(p_{e,t}^{\text{ES}_d\text{\_DA}} + p_{e,t,\omega}^{\text{ES}_d\text{\_RT}} + p_{e,t}^{\text{ES\_Dep}}\right) - \left(p_{e,t}^{\text{ES}_c\text{\_DA}} + p_{e,t,\omega}^{\text{ES}_c\text{\_RT}}\right) \\ &-\sum_l \text{P}_{l,t,\omega}^{\text{MGL\_RT}} = \sum_j 0.5(p_{i,j,t,\omega}^{\text{Flow}} + p_{i,j,t,\omega}^{\text{Loss}}) \quad :\forall t,\omega, i \ne 1 \end{aligned}$$

(31)

- RT reserve deployed: The reserve deployment of the MG and its resources in the real operation is determined through multiplying the reserve capacity with the probability of calling reserve as modeled in (32).

$$p_t^{\text{MG\_Dep}} = \varphi^{\text{Re}} p_t^{\text{MG\_Re}},\ p_{k,t}^{\text{DG\_Dep}} = \varphi^{\text{DG\_Re}} p_{k,t}^{\text{DG\_Re}},\ p_{e,t}^{\text{ES\_Dep}} = \varphi^{\text{ES\_Re}} p_{e,t}^{\text{ES\_Re}} \quad :\forall t \tag{32}$$

- RESs constraints: The sum of the power generation of RESs in the DA and RT is limited as (33).

$$0 \le p_{f,t}^{\text{RES\_DA}} + p_{f,t,\omega}^{\text{RES\_RT}} \le \text{P}_{f,t,\omega}^{\text{RES}} \quad :\forall f,t,\omega \tag{33}$$

- DGs constraints: The power generation of the DGs in the DA and RT considering the reserve deployment is limited to its maximum capacity of DGs in (34). Moreover, the ramp rate limitations of the DGs in real operation are described in (35) and (36).

$$p_{k,t}^{\text{DG\_DA}} + p_{k,t,\omega}^{\text{DG\_RT}} + p_{k,t}^{\text{DG\_Dep}} \le \overline{\text{P}}_k^{\text{DG}} \quad :\forall k,t,\omega \tag{34}$$

$$\left(p_{k,t+1}^{\text{DG\_DA}} + p_{k,t+1,\omega}^{\text{DG\_RT}} + p_{k,t+1}^{\text{DG\_Re\_Dep}}\right) - \left(p_{k,t}^{\text{DG\_DA}} + p_{k,t,\omega}^{\text{DG\_RT}}\right) \le \text{RU}_k \quad :\forall k,t,\omega \tag{35}$$

$$\left(p_{k,t}^{\text{DG\_DA}} + p_{k,t,\omega}^{\text{DG\_RT}} + p_{k,t}^{\text{DG\_Re\_Dep}}\right) - \left(p_{k,t+1}^{\text{DG\_DA}} + p_{k,t+1,\omega}^{\text{DG\_RT}}\right) \le \text{RD}_k \quad :\forall k,t,\omega \tag{36}$$

- EES constraints: The power constraints of the ESS in the real time operation are modeled as (37)-(40). Equation (41) is used to model the time-based behavior of the EES in the RT operation. The energy stored in the EES is limited to its minimum and maximum limitations in (42). The energy stored in the EESs in the last time step of the operation is equal to its initial value as modeled in (43).

$$p_{e,t}^{\text{ES}_d\text{\_DA}} + p_{e,t,\omega}^{\text{ES}_d\text{\_RT}} + p_{e,t}^{\text{ES\_Dep}} \le \overline{\text{P}}_e^{\text{dch}} \quad :\forall e,t,\omega \tag{37}$$

$$0 \le p_{e,t,\omega}^{\text{ES}_c\text{\_RT}} \le \overline{\text{P}}_e^{\text{ch}} U_{e,t,\omega}^{\text{ch\_RT}} \quad :\forall e,t,\omega \tag{38}$$

$$0 \le p_{e,t,\omega}^{\text{ES}_d\text{\_RT}} \le \overline{\text{P}}_e^{\text{dch}} U_{e,t,\omega}^{\text{dch\_RT}} \quad :\forall e,t,\omega \tag{39}$$

$$U_{e,t,\omega}^{\text{ch\_RT}} + U_{e,t,\omega}^{\text{dch\_RT}} \le 1 \quad :\forall e,t,\omega \tag{40}$$

$$E_{e,t,\omega}^{\text{ES\_RT}} = E_{e,t-1,\omega}^{\text{ES\_RT}} + \left(\left(p_{e,t}^{\text{ES}_c\text{\_DA}} + p_{e,t,\omega}^{\text{ES}_c\text{\_RT}}\right)\eta^{\text{ch}}\right) - \left(\left(p_{e,t}^{\text{ES}_d\text{\_DA}} + p_{e,t,\omega}^{\text{ES}_d\text{\_RT}} + p_{e,t,\omega}^{\text{ES\_Dep}}\right)\Big/\eta^{\text{dch}}\right) :\forall e,t,\omega \tag{41}$$

$$\underline{\text{E}}_e^{\text{ES}} \le E_{e,t,\omega}^{\text{ES\_RT}} \le \overline{\text{E}}_e^{\text{ES}} \quad :\forall e,t,\omega \tag{42}$$

$$E_{e,ini}^{\text{ES}} = E_{e,t=T,\omega}^{\text{ES\_RT}} \ :\forall e,\omega \tag{43}$$

- Power trading constraints with the main grid: The relation among the amount of power trading of the MGO with the RT market with its offers in the DA market and the reserve deployment in the RT is shown in (44) and (45). Equations (46)-(48) are used to model the fact that the MG can trade energy with the main grid in only one direction.

$$p_t^{\text{MG\_DA\_E}_{\text{in}}} + p_{t,\omega}^{\text{MG\_RT\_E}_{\text{in}}} - p_t^{\text{MG\_Dep}} \le \overline{\text{P}}^{\text{MG}} \quad :\forall t,\omega \tag{44}$$

$$p_t^{\text{MG\_DA\_E}_{\text{out}}} + p_{t,\omega}^{\text{MG\_RT\_E}_{\text{out}}} + p_t^{\text{MG\_Dep}} \le \overline{\text{P}}^{\text{MG}} \quad :\forall t,\omega \tag{45}$$

$$0 \le p_{t,\omega}^{\text{MG\_RT\_E}_{\text{in}}} \le \overline{\text{P}}^{\text{MG}} U_{t,\omega}^{\text{MG\_RT\_in}} \quad :\forall t,\omega \tag{46}$$

$$0 \le p_{t,\omega}^{\text{MG\_RT\_E}_{\text{out}}} \le \overline{\text{P}}^{\text{MG}} U_{t,\omega}^{\text{MG\_RT\_out}} \quad :\forall t,\omega \tag{47}$$

$$U_{t,\omega}^{\text{MG\_RT\_in}} + U_{t,\omega}^{\text{MG\_RT\_out}} \le 1 \quad :\forall t,\omega \tag{48}$$

- Power flow equations: The feeders' current is calculated as (49). Also, the limitations of the feeder currents and bus voltages are modeled in (50) and (51), respectively. The power flow between feeders is modeled as (52) and the power loss of each feeder is calculated as (53).

$$i_{i,j,t,\omega}^{\text{MGN}} = \frac{v_{i,t,\omega}^{\text{MGN}} - v_{j,t,\omega}^{\text{MGN}}}{Z_{i,j}^{\text{MGN}}} \quad :\forall i,j,t,\omega \tag{49}$$

$$-\overline{\text{I}}_{i,j}^{\text{MGN}} \le i_{i,j,t,\omega}^{\text{MGN}} \le \overline{\text{I}}_{i,j}^{\text{MGN}} \quad :\forall i,j,t,\omega \tag{50}$$

$$\underline{\text{V}}_i^{\text{MGN}} \le v_{i,t,\omega}^{\text{MGN}} \le \overline{\text{V}}_i^{\text{MGN}} \quad :\forall i,t,\omega \tag{51}$$

$$p_{i,j,t,\omega}^{\text{Flow}} = \frac{\text{R}_{i,j}^{\text{MGN}}\text{S}^{\text{base}}}{\left(\text{Z}_{i,j}^{\text{MGN}}\right)^2}\left(\left(v_{i,t,\omega}^{\text{MGN}}\right)^2 - \left(v_{j,t,\omega}^{\text{MGN}}\right)^2\right) :\forall i,j,t,\omega \tag{52}$$

$$p_{i,j,t,\omega}^{\text{Loss}} = \text{R}_{i,j}^{\text{MGN}}\left(i_{i,j,t,\omega}^{\text{MGN}}\right)^2 \text{S}^{\text{base}} \quad :\forall i,j,t,\omega \tag{53}$$

C. IGDT-based optimization model

In this paper, a risk-based decision-making process is implemented by the MGO to model the uncertainties of the RT energy market price. This strategy is formulated as Eqs. (54)-(58). It is worth mentioning that ξ is defined as the risk aversion parameter. In other words, the MGO can control the risk-level in the decision-making process through changing this parameter from 0 to 1. Note that Eqs. (57) or (58) are separately implemented in the proposed model in the case of risk-averse and risk-taker MGO, respectively.

$$\max\{\alpha\} \tag{54}$$

subject to Eqs. (7)-(24) and (30)-(53).

$$ETC_b = \{ETC : \text{minimize } ETC\} \tag{55}$$

$$ETC \le ETC_b(1+\zeta) \quad , \quad 0 \le \zeta \le 1 \tag{56}$$

$$\lambda_t^{\text{RT\_E}} \le (1-\alpha)\overline{\lambda}_t^{\text{RT\_E}} \tag{57}$$

$$\lambda_t^{\text{RT\_E}} \le (1+\alpha)\overline{\lambda}_t^{\text{RT\_E}} \tag{58}$$

The resulting mixed integer linear programming (MILP) optimization model has been implemented in GAMS 24.1.2 and has been solved via CPLEX12 solver on a PC with 2.8-GHz Core i5 with 6GB RAM. The model statistics contains 1370473 single equations, 712201 single variables, and 3840 discrete variables.

V. Numerical Results

The effectiveness of the proposed model is confirmed by applying it on the 15-bus MG test system as depicted in Fig. 2 [14]. The MG load (MGL) and the forecast output power of WTs and PVs are shown in Figs. 3 and 4, respectively. The bids of the DERs and their technical constraints are given in Table I [15, 16]. The bids of the RESs to the MGO are 2 \$/MWh. The maximum power exchange of the MG with the distribution grid at the supply point is 5 MVA, and the minimum and maximum limitations to the MG bus voltages are 0.9 p.u. and 1.1 p.u., respectively. The DA and RT energy market price and the reserve market price are shown in Figs. 5 and 6, respectively [17]. The reserve capacity deployment is set to 0.1. For the calculations in per units, the base power is S^{base} = 1 MVA, and the base voltages are equal to the nominal voltages for the distribution system and the MG.

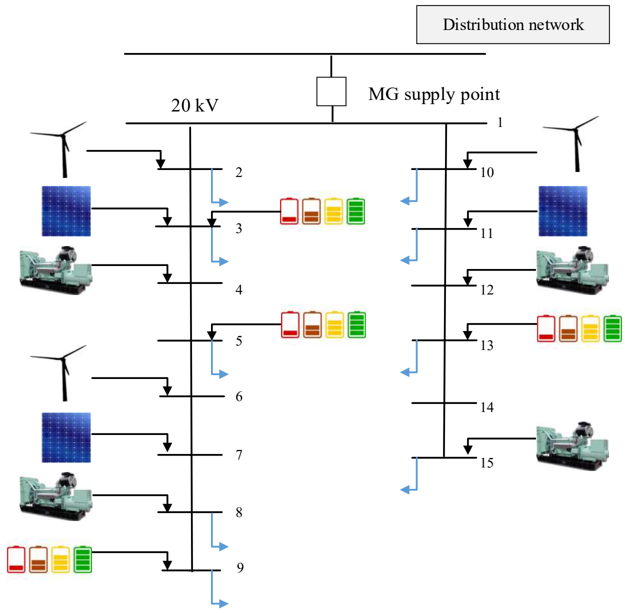

Fig. 2. The 15-bus MG structure used as the test system.

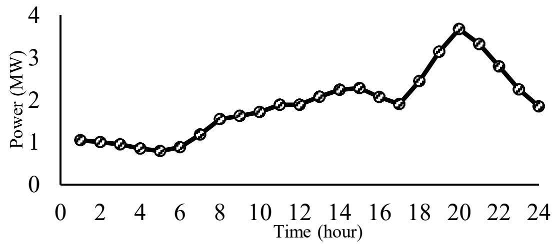

Fig. 3. The forecast MGL in the operation time period.

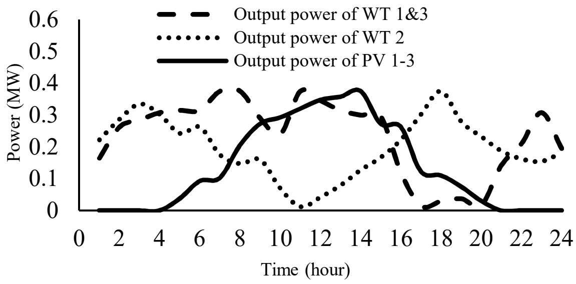

Fig. 4. The forecast output power of the RESs.

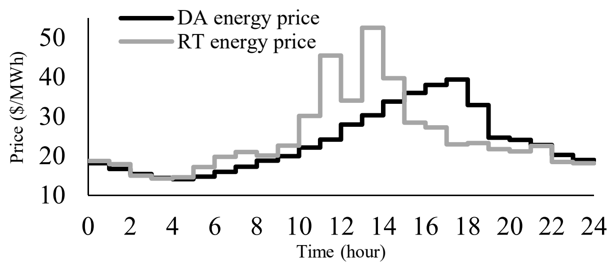

Fig. 5. The DA and RT energy markets prices.

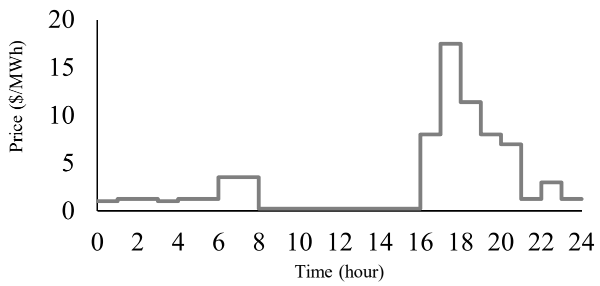

Fig. 6. The reserve market price.

TABLE I. BIDS AND TECHNICAL CONSTRAINTS OF THE DERS

# DG	$\bar{P}_k^{DG}$	$\underline{P}_k^{DG}$	RU_k	RD_k	P_{DG}^{ini}	C_k^{DG}	$C_k^{DG\_Re}$
1, 2	0.5	0	0.35	0.35	0	13	3.9
3, 4	0.5	0	0.30	0.30	0	10	3
# ES	$\bar{P}_e^{ch}/\bar{P}_e^{dch}$	$\underline{E}_e$	$\bar{E}_e$	η_{ch}, η_{dch}	E_e^{ini}	C_e^{ESch}/C_e^{ESdch}	$C_e^{ES\_Re}$
1, 2	0.5	1	2.5	0.95	1	2.5	0.75
3, 4	0.5	1	2.5	0.90	1	3.0	1.00

A. Results

The results including the MG operation cost, the optimal scheduling of the DERs, and the MGO's bids in the energy and reserve markets are shown in Figs. 7-13 and Table II. The operation cost of the MGO in the DA operation and in the RT energy market for the first scenario is given in Table II. As shown in this table, the MGO participates in the DA energy market as a consumer, where it purchases power from the market. Also, the MGO prefers to provide the reserve capacity for the reserve market using the EESs regarding their lower operation cost in comparison with the DGs. On the other hand, the MGO acts as a producer in the RT energy market, where it sells energy to this market.

The operation cost of the MGO in two cases, i.e., with and without participating in the reserve market, in all scenarios is compared in Fig. 7. The results show that the operation cost of the MGO when it participates in both energy and reserve markets (67.57$) is lower than the case where it participates in only energy market (124.83$). The major reason is that the MGO has an opportunity to gain the revenue not only from providing the reserve capacity in the reserve market (during the first-stage decisions), but also from selling the deployment of that capacity based on the RT market price in the RT operation.

The first-stage decisions of the MGO on the scheduling the MG's resources as well as the bidding strategies in both DA energy and reserve markets are shown in Figs. 9 and 10. According to Fig. 9, the MGL is considerably supplied by the EESs as well as the purchased energy from the DA energy market.

TABLE II. THE OPERATION COST/REVENUE OF THE MG IN SCENARIO 1.

Cost/revenue of the MG in the DA operation ($)				
TC^{DA}	C^{DA_E}	R^{DA_Re}	C^{DA_DER}	
1015.54	1064.41	98.39	49.52	
Cost/revenue of the MG in the RT operation ($)				
TC_ω^{RT}	$C_\omega^{RT\_E}$	$R_\omega^{RT\_Re}$	$C_\omega^{RT\_DER}$	
			$C_\omega^{DER\_E}$	$C_\omega^{DER\_Re\_Dep}$
-915.36	-1342.47	27.81	451.50	3.42

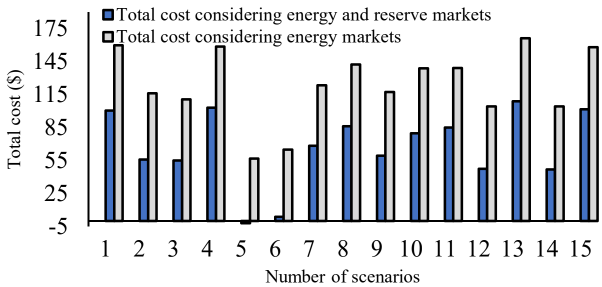

Fig. 7. Total cost of MG operation in each scenario (TC_ω).

Note that, due to the low bid of the EESs and the RESs, the MGO utilizes them to either meet the MGL during the peak-load hours (e.g., hours 18-23) or decrease the amount of purchased power from the DA energy market, especially in high-priced hours (e.g., 16, 17, and 19). It is worth mentioning that the MGO deals with a challenging decision related to the scheduling of the EESs for providing energy and reserve. Therefore, using the proposed co-optimization model, the EESs are charged/discharged in an optimal way to provide both energy and reserve services simultaneously. As concluded from Figs. 9 and 10, for instance, the MGO remarkably charges the EESs in hours 6, 7, 12, and 14 to achieve two main aims. The first aim is to engage the energy stored in the EESs to meet the MGL with the aim of decreasing the power purchased from the DA energy market in high-price hours (e.g., 16 and 17). The second one is associated with the reserve capacity provided for reserve market with high prices (e.g., hours 17 and 21) on the one hand, and the reserve capacity being deployed in the RT operation on the other hand.

The MGO's decisions in the RT operation in Scenario 1 are shown in Fig. 11. There are two main objectives for the MGO to participate in the RT energy market. At first, the MGO includes its power balance constraint in the RT operation in the presence of the uncertainties of RESs and demand. The second one is to achieve much more revenue by selling power to the RT market as much as possible. According to Fig. 11, it is clear that the MGO is capable of deploying the DGs as well as RESs to sell power as a producer in the RT market at all hours. It is worth noting that the MGO deploys all resources to sell much more power to the RT energy market in hours 12 and 14 with the highest market prices (i.e., 45.49$ and 52.54$, respectively). Moreover, the EESs have the key role in the control of the deviation of the RESs as well as the demand to sell power to the RT market affordably.

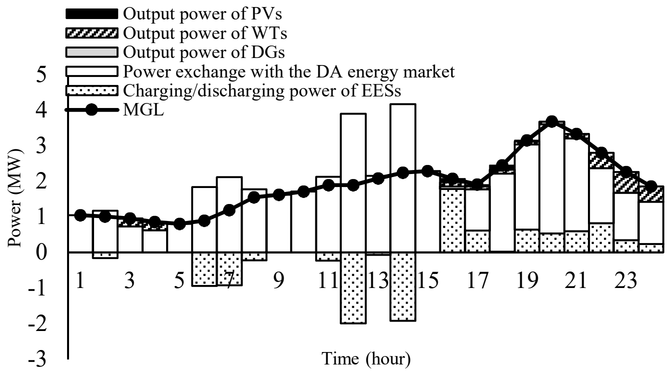

Fig. 9. Power balance in the DA energy market.

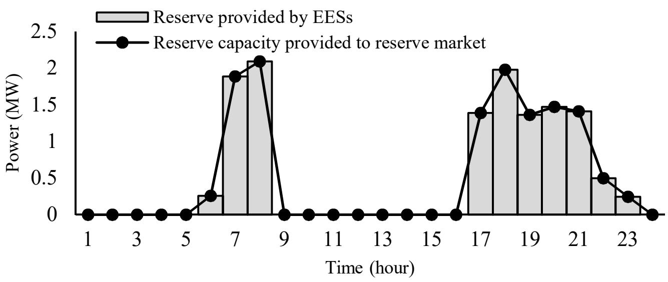

Fig. 10. The energy stored in the EESs to provide reserve capacity.

Fig. 12 specifies the demand-supply balance in the RT operation of the MG in Scenario 1. In other words, the MGO's decisions to supply the MGL considering the power loss of the system are shown in this figure. Fig. 13 indicates the energy stored in the EESs related to two-stage decision-making process during the operation time of the MG. In the first-stage decisions, the MGO charges/discharges the EESs to meet the MGL on one hand and to provide the reserve capacity for the market on the other hand. The second-stage decisions are made to reschedule the EESs to participate in the RT market.

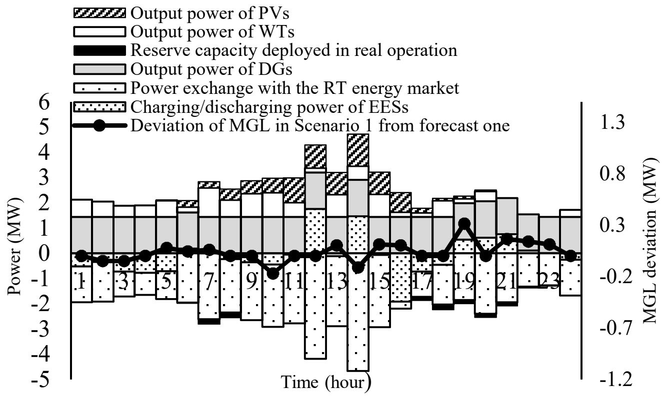

Fig. 11. The MGO's decisions in the RT operation.

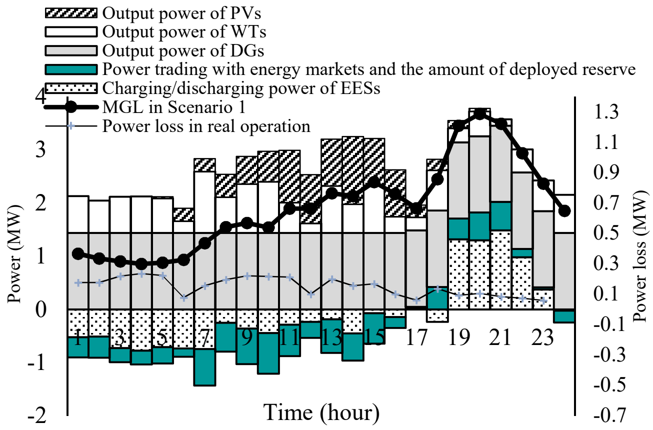

Fig. 12. The demand-supply balance in the real operation.

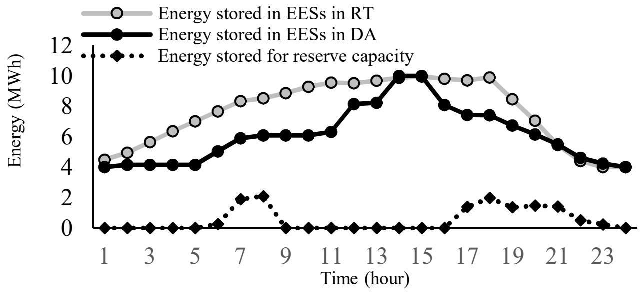

Fig. 13. The energy stored in the EESs in DA and RT operations.

B. *The results for IGDT approach*

In this sub-section, the decisions of the MGO to manage the uncertainties of the RT market price using the IGDT approach are investigated. To this end, the RT market prices are supposed to change from 70% to 130% of the forecast ones. Note that, for the range 70% to 100% of the forecast price, the MGO is a risk-averse decision-maker (Case I). Conversely, for the range 100% to 130% of the forecast price, the risk-taker MGO makes the opportunistic decisions (Case II).

In Case I, as can be seen in Fig. 14(a), the risk-aversion parameter (ξ) increases from 0 to 1. In other words, the risk-averse MGO supposes that the RT market price might be lower from the forecast ones. Thus, the major results are that the uncertainty radius increases from 0 to 0.3, following which the ETC increases from 67.57$ to 252.32$ due to the reduction of the MGO's revenue from selling power to the RT market. In addition, the MGO prefers to decrease the power sold to the RT market with the aim of selling more power to the DA market (from 0 MW to 8.28 MW) and increasing the reserve capacity provided to the reserve market from 12.589 MW to 13.668 MW, as well. In Case II, as shown in Fig. 14(b), the risk-taker MGO makes decisions on the case of RT market prices higher than the forecast ones. As a result, when the uncertainty radius increases from 0 to 0.3, the ETC decreases. The main reason is that the power sold to the RT market increases from 47.672 MW to 51.172 MW. On the other hand, the risky MGO tends to decrease the reserve capacity from 12.589 MW to 10.958 MW.

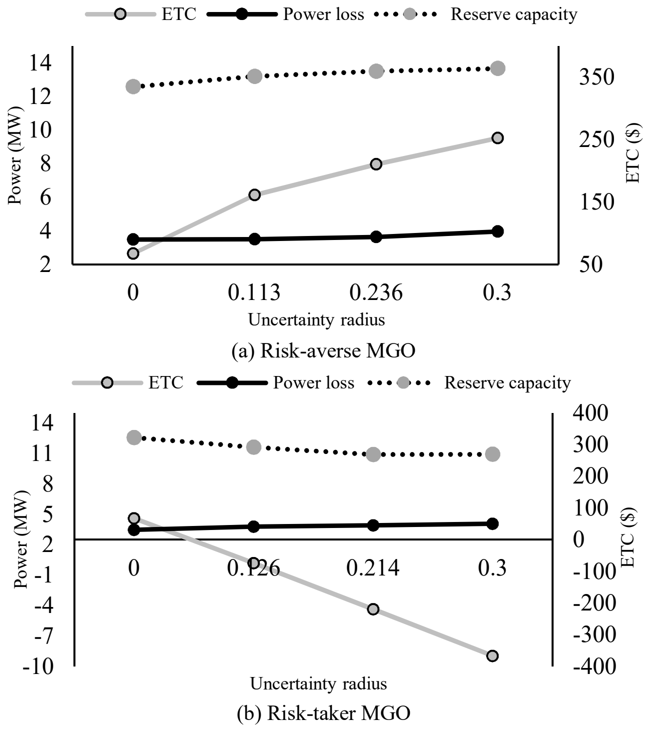

Fig. 14. The sensitivity of MGO's decisions to uncertainty radius.

VI. Conclusion

In this paper, a two-stage stochastic optimization problem is developed to co-optimize the MGO's bids in the DA energy and reserve markets considering stochastic behavior in the RT market. Moreover, the risk-based decisions of the MGO to manage the uncertainty of the RT market price are modeled using the IGDT approach. The main conclusions from applying this model on the MG test system are as follows:

- Using the co-optimization of the MGO's participation in the energy and reserve markets, the ETC of the MG operation has experienced a more significant reduction than the MGO's participation in only energy markets. The ETC decreases from 124.83$ to 67.57$.
- The proposed two-stage stochastic programming causes the MGO to make affordable two-stage decisions on the DERs as well as the bids in both DA and RT markets considering the uncertainties. In other words, the MGO is capable of controlling the deviations of RESs and MGL, satisfying the MGL besides obtaining more revenue through its participation as a consumer/producer in the DA/RT markets.
- Modeling the uncertainties of the RT market price in the MGO's problem has shown that by increasing the risk level of the MGO, the summation of the ETC, the reserve capacity, and the power sold to the DA market increases. In particular, the risk-taker MGO prefers to increase the power sold to the RT market and decreases the reserve capacity to achieve lower ETC.

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