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*— The high penetration of distributed energy resources in the distribution networks is facilitated by the structure of the microgrids (MGs). The MG operator (MGO) can schedule the MG resources to meet the local load and participate in wholesale markets. In this paper, a new model is developed for the MGO participation in the day-ahead (energy and reserve) and the real-time (RT) energy markets under uncertainty. For this purpose, the effect of uncertainties in the demand and generation from renewable energy sources on the MGO decisions is modeled through a two-stage stochastic model. The MGO bids in the DA and RT markets are modeled as the first and the second stage decisions, respectively. Moreover, the information gap decision theory (IGDT) method is used to model the behavior of the MGO to address the uncertainties of the RT energy market price and the probability of calling the reserve. The results show that as the RT price uncertainty radius increases, the energy sold to the RT market decreases/increases in the risk-averse/risk-taker strategy. Furthermore, to manage the uncertainty related to the probability of calling the reserve, the reserve capacity provided by the MGO in the risk-averse and the risk-taker strategies decreases and increases, respectively.**

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
l/*L*	Index/cardinality of loads
t/*T*	Index/cardinality of time
ω/W	Index/cardinality of scenarios

Parameters

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

Variables

$i_{i,j,t,\omega}^{MGN}$	The current of feeders [p.u.]
$p_{f,t}^{RES}$	The power generation of RESs in markets* [MW]
$p_{k,t}^{DG}$	The power generation of DGs in markets [MW]
$p_{k,t}^{DG\_Dep}$	The reserve deployment by DGs in RT [MW]
$p_{e,t}^{ES_c}$	The power charging of EES in markets [MW]
$p_{e,t}^{ES_d}$	The power discharging of EES in markets [MW]
$p_{k,t}^{ES\_Dep}$	The reserve deployment by EES in RT [MW]
$p_t^{MG\_E_{in}}$	The purchased power by MG from markets [MW]
$q_t^{MG\_E_{in}}$	The reactive power received from the grid [Mvar]
$p_t^{MG\_E_{out}}$	The sold power by MG to markets [MW]
$p_t^{MG\_Dep}$	The reserve deployment by MG in RT [MW]
$p_{k,t}^{DG\_Re}$	The reserve provided by DGs [MW]

$p_{e,t}^{\text{ES\_Re}}$ The reserve provided by EES [MW]
$p_{t}^{\text{MG\_Re}}$ The reserve provided by MG [MW]
$p_{i,j,t,\omega}^{\text{Flow}}$ The active power flow in feeders [MW]
$q_{i,j,t,\omega}^{\text{Flow}}$ The reactive power flow in feeders Mvar]
$p_{i,j,t,\omega}^{\text{Loss}}$ The active power loss of feeders [MW]
$q_{i,j,t,\omega}^{\text{Loss}}$ The reactive power loss of feeders [Mvar]
$U_{k,t}^{\text{ch}}$ Binary variable used for power charging in markets
$U_{k,t}^{\text{dch}}$ Binary variable used for power discharging in markets
$U_{t}^{\text{MG\_in}}$ Binary variable used for purchased power from markets
$U_{t}^{\text{MG\_out}}$ Binary variable used for sold power to markets
$v_{i,t,\omega}^{\text{MGN}}$ The voltage of buses [p.u.]
$\alpha^{\text{RT\_E}}/\alpha^{\text{Re}}$ The uncertainties radius

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 numerous benefits for the power systems, their presence challenges the system operators. The complexity of the distribution network operation problem increases with DERs. Furthermore, the management of DERs in the wholesale energy markets is a major challenge for the independent system operator (ISO). Microgrids (MGs) are appropriate solutions for the management of DERs in the power system [1]. On the one hand, DERs are integrated in the MG structure to meet the local load, where the MG operator (MGO) is responsible for the operation of the 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 ISO and distribution system operator (DSO) problems decreases as they are only collaborating with the MGO rather than several DERs.

The MGO supplies the local demand of the MG through participation in the wholesale energy markets and through the optimal scheduling of the MG resources. In addition, MGOs have the ability to provide reserve capacity for the market regarding the flexible energy resources of the MGs, i.e., dispatchable distributed generators (DGs) and electrical energy storage (EES). For this purpose, several models have been developed in the literature to investigate the MGO decisions in day-ahead (DA) only energy markets or in both DA energy and reserve markets. Participation in the RT energy market creates a new opportunity for the MGO to trade energy in this market for greater profits. Therefore, modeling MGO strategies to participate in both the DA (energy and reserve) and RT energy markets is a new challenge that is addressed in this paper. In this case, the uncertain trend in the RT energy market price and the probability of calling the reserve place the MGO at greater risk in its decision-making process in both the DA and RT markets. Therefore, an appropriate risk management tool is required to assist the MGO decisions in markets that encounter these uncertain parameters. Modeling the uncertain behavior of the RT market price through the probability distribution function (PDF) leads to a high forecast error. Moreover, it is difficult to construct a PDF to model the uncertainty of the probability of calling the reserve. To model the uncertainties of such parameters with unknown PDFs or parameters difficult to predict with low forecasting error, the information gap decision theory (IGDT) method can be used [2]. The MGO decision problem in the markets is then formulated in this paper as a risk-based model using the IGDT approach to manage the uncertainties of RT market price and probability of calling the reserve.

A. Literature review and contributions

Appropriate decision-making models have been proposed in the previous studies to model the MGO decisions in the wholesale DA energy market. The operation problem of a MG has been formulated as a two-level model considering the demand response programs (DRPs) under uncertainty in [3]. The uncertainties of the output power of renewable energy sources (RESs) and of the demand in a MG have been modeled through a two-stage robust optimization approach in [4]. The MGO participates in the wholesale energy market in [5] to meet the required energy of its system, including plug-in electric vehicles. For this purpose, a robust optimization model has been developed to model the MGO decisions under the uncertainty of the energy market price. The MGO decisions in the DA energy market have been modeled in [6] considering the uncertainties of demand and the outage probabilities of the RESs. The DA scheduling problem of a MG including RESs and EESs has been modeled as a scenario-based stochastic optimization problem in [7]. The authors of [8] have proposed a two-stage robust model for the optimal DA scheduling of a MG considering the uncertainty of real-time (RT) energy market price. The energy management problem of a hybrid AC/DC MG has been modeled using a robust optimization approach in [9] considering the DA energy market price. The DA scheduling problem of a MG has been modeled in [9], where the machine learning method has been used to model the uncertain behavior of demand and RESs.

The bidding strategies of the MGO in the DA energy and reserve markets have been modeled considering the uncertainties of the RESs in [10]. The DA energy and reserve scheduling of the MGs with electric vehicles has been modeled with a robust optimization approach in [11]. The MGO bids in the DA energy and reserve markets have been determined using a risk-based approach in [12]. The information gap decision theory (IGDT) approach has been used in [13] to model the uncertainties of MGO bid acceptance in the DA reserve market. In [10-13], the MGO decisions in the DA energy and reserve market have been investigated considering uncertainties.

However, the effect of the MGO participation in the RT market on its DA decisions was not addressed.

The participation problem of a MGO in the DA energy and reserve market considering the RT energy market has been formulated as a two-stage stochastic model in [14]. The decision problem of a hydrogen-based MG in the DA energy and reserve markets as well as the RT energy market has been addressed in [15]. In this study, the uncertainties of the market price and the hydrogen demand have been modeled through the stochastic approach. A robust optimization approach has been developed in [16] to model the optimal scheduling of a MG to satisfy both the electrical and thermal loads considering the MGO participation in the wholesale markets. In this model, the bidding strategies of the MGO in the DA energy and ancillary service market are optimized for obtaining the least cost to meet the MG power balance in the RT operation. In these studies [14-16], the aim of the MGO is to minimize the power imbalance (i.e., the deviation of the RT power trading with the main grid from the DA scheduled power) to avoid receiving the imbalance penalty in the RT operation. Therefore, although it is mentioned that the MGO decisions in the DA markets are determined with respect to the RT energy market in [14-16], the MGO does not participate in the RT energy market and only tries to manage its own power imbalance in RT operation. Therefore, the main gap of the previous studies is still the modeling of the MGO participation in the RT energy market, besides its participation in the DA energy and reserve market.

The main differences between the model proposed in this paper and those proposed in [14-16] are the following:

- In the models proposed in [14-16], the MGOs are settled with regard to imbalance prices. In this case, the power delivered in the day of operation is metered, then the power imbalance and consequently the imbalance prices are calculated. The imbalance prices are published in the next day of the real operation day. This is while, in the model proposed in this paper, the MGO is settled in the RT energy market and the MGO bids are sent to the market in a short time before the day of operation. Details of the timeline of the MGO participation in the DA and RT markets are described in sub-section III-C.
- In this paper, the aim of the MGO is to obtain greater profits from employing different strategies to participate in both the DA energy and reserve markets and in the RT energy market, or either of these with regard to the market prices. This is while the aim of the MGO in [14-16] is to manage its power imbalance.

The differences mentioned lead to develop a different mathematical model in this paper, compared to the models proposed in [14-16]. In these studies, the power imbalance is considered in the DA power balance constraint, in relation to which only the DA decision variables are considered for the MG resources, e.g., DGs and EESs. This is while, in the model proposed in this paper, both the DA and the RT energy balance constraints are modeled, with respect to which the DA and RT decision variables are considered for the DGs and the EESs.

Therefore, to fill the mentioned gap in the previous studies, a mathematical formulation is developed in this paper to model the mutual effect of the MGO decisions in the DA and RT markets under uncertainties. The uncertainties of the demand and RES output power are modeled using appropriate probability distribution functions (PDFs). For this purpose, some scenarios are generated, on which the MGO problem is formulated as a two-stage stochastic model. Since the timeline of participation in the DA and RT markets is different, the MGO decisions in the DA markets are considered as first-stage decisions. Furthermore, the stochastic decisions of the MGO in the RT energy market are modeled as second-stage decisions. Then, to model the risk-based behavior of the MGO to manage the uncertainties of RT energy market price and probability of calling the reserve, the IGDT approach is used. Therefore, the main contributions of this paper are the following:

- Modeling the MGO bids in the DA energy and reserve markets considering stochastic decisions in the RT markets.
- Proposing a risk-based model that uses the IGDT approach to manage the effect of uncertainties relating to the RT energy price and the probability of calling the reserve on the MGO bids in the DA (energy and reserve) and RT energy markets.

B. *Paper organization*

The rest of the paper is organized as follows. The problem description is presented in Section III. This problem is mathematically formulated in Section IV. The 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 energy and reserve markets is described in Fig. 1. The DER owners send their bids and technical constraints of resources to the MGO. Moreover, the forecast data related to RES output power, MG demand, and energy and reserve market prices, are sent to the MGO through a service provider. Regarding this data, the MGO solves its optimization problem (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 energy and reserve markets. The MGO sends its bids with technical constraints of trading energy and reserve capacity with the main grid to the ISO, which is responsible of clearing the wholesale energy and reserve markets. The discussion of the clearing process of the wholesale markets is beyond the scope of this paper. After clearing the wholesale markets, the market results are announced to the MG. The control signals are sent from the MG central control (MGCC) to the local controllers (LCs) of the MG resources. As far as these signals are concerned, the DERs trade energy with the distribution network.

A. *Modeling uncertainties of demand and RESs*

The normal, Weibull, and irradiance PDFs are used to model the uncertain behavior of demand, wind speed, and solar irradiance, respectively. To model these uncertainties in the decision problem of the MGO, these PDFs are discretized into certain intervals. Details of determining the value of uncertain parameters in each interval and their probabilities are described in [17]. As for the probability of each interval of uncertain parameters, the high number of samples are generated. Then, the scenarios are obtained through the scenario tree construction method. In this method, the stages of the scenario tree are the time steps of the problem, and the generated samples are considered as the nodes. This method generates 1000 scenarios, which are then reduced to 15 using the fast-forward scenario reduction technique.

B. Two-stage stochastic formulation

As for the scenarios obtained in the previous sub-section, the decision 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 scenarios occur. The MGO bids in the RT market are considered as second-stage decisions determined after the scenarios occur. The MGO decisions on the optimal scheduling of the DERs are considered in both stages.

C. Timeline

The MGOs participate in the wholesale markets as price-taker (self-scheduling) players as regards the low capacity of the MGs compared to other energy market players. In this case, the bids of the MGOs in the markets are quantity-only, with no price. In fact, the MGOs accept the market price to trade energy with the market and to provide reserve for the market.

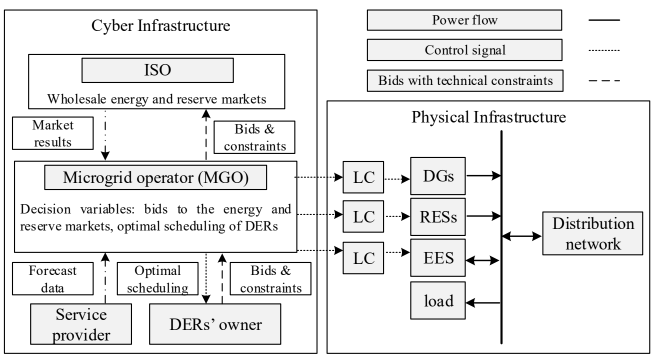


Fig.1. The cyber-physical infrastructure of the problem.

The deadline of submitting bids for the DA energy and reserve markets is usually before noon on the day before the actual operation (e.g., 10 a.m. at California ISO (CAISO)). The deadline for submitting the bids to the RT energy market starts after the publication of the DA market results until shortly before the real operation (i.e., 75 min before the real operation at CAISO). Therefore, the model proposed in this paper is used by the MGO before the deadline for submitting bids in the DA markets. For the RT market, the MGO waits to see the forecast data, with respect to which it submits the bids to that 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 results obtained from 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)-(59). The aim of the MGO is to minimize its expected total cost (ETC) over the operation time period as modeled in (1). The first term of (1) models the total cost of the MGO in the DA operation and the second term is used to model the expected cost of the MGO in the RT operation. These terms are described in the next two sub-sections. The time step is one hour and is not explicitly indicated in the equations.

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

A. The DA problem for the MGO

The total cost of the MGO in the DA market is modeled as (2) made up of four terms. The first term is the cost of trading energy with the DA energy market as described in (3). The second term is the revenue of the MGO from providing the reserve capacity to the market, modeled in (4). The third and fourth terms express the costs of MG resources to provide energy and reserve for the system, modeled in (5) and (6), respectively.

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

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

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

$$C^{\text{DA\_DER}} = \sum_{t=1}^{T} \left[\begin{array}{l} \sum_{f=1}^{F} C_t^{\text{RES}} p_{f,t}^{\text{RES\_DA}} + \sum_{k=1}^{K} C_t^{\text{DG}} p_{k,t}^{\text{DG\_DA}} + \\ \sum_{e=1}^{E} C_t^{\text{ES}_d} p_{e,t}^{\text{ES}_d\text{\_DA}} - \sum_{e=1}^{E} C_t^{\text{ES}_c} p_{e,t}^{\text{ES}_c\text{\_DA}} \end{array} \right] \qquad (5)$$

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

The technical constraints of the DA problem are as follows:

- Equations (7) and (8) show the active and the reactive power balance constraints of the system in the DA operation.

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

$$q_t^{\text{MG\_DA\_E}_{\text{in}}} = \sum_{l=1}^{L} \hat{\text{Q}}_{l,t}^{\text{MGL\_DA}} : \forall t \qquad (8)$$

- The reserve capacity that can be provided by the MGO to the market is supplied from the DG and ES as shown in (9).

$$p_t^{\text{MG\_Re}} = \sum_{k=1}^{K} p_{k,t}^{\text{DG\_Re}} + \sum_{e=1}^{E} p_{e,t}^{\text{ES\_Re}} \quad : \forall t \qquad (9)$$

- The power generation of the RESs in the DA is lower than or equal to their forecast power as modeled in (10).

$$0 \le p_{f,t}^{\text{RES\_DA}} \le \hat{\text{P}}_{f,t}^{\text{RES}} \quad : \forall f, t \qquad (10)$$

The sum of the power generation of the DGs and the DG capacity to provide reserve are lower than or equal to their maximum power as described in (11). Moreover, the ramp-up and ramp-down limitations of DGs are modeled in (12) and (13), respectively.

$$p_{k,t}^{\text{DG\_DA}} + p_{k,t}^{\text{DG\_Re}} \le \overline{\text{P}}_k^{\text{DG}}, p_{k,t}^{\text{DG\_DA}}, p_{k,t}^{\text{DG\_Re}} \ge 0 : \forall k, t \qquad (11)$$

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

$$\left(p_{k,t}^{\text{DG\_DA}}+p_{k,t}^{\text{DG\_Re}}\right)-\left(p_{k,t+1}^{\text{DG\_DA}}\right)\le \text{RD}_k \quad :\forall k,t \tag{13}$$

- The power and energy constraints of the EESs to provide energy and reserve for the system are modeled in (14)-(20). The difference of the discharge and charge power plus the reserve provided by the EESs is less than or equal to the maximum discharge power of the EESs as modeled in (14). This equation shows that when the MGO decides to charge the EESs, its capacity to provide the reserve for the system increases. Equations (15)-(17) are used to limit the maximum charge and discharge power of the EESs and prevent simultaneous charging and discharging of the EESs. The time-based behavior of the energy stored in the EESs is shown in (18). The limits of the energy stored in the EESs are described in (19). 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 in (20).

$$(p_{e,t}^{\text{ES}_d\text{\_DA}}-p_{e,t}^{\text{ES}_c\text{\_DA}})+p_{e,t}^{\text{ES\_Re}}\le \overline{\text{P}}_e^{\text{dch}} \quad :\forall e,t \tag{14}$$

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

$$0\le p_{e,t}^{\text{ES}_d\text{\_DA}}\le \overline{\text{P}}_e^{\text{dch}}U_{e,t}^{\text{dch\_DA}} \quad :\forall e,t \tag{16}$$

$$U_{e,t}^{\text{ch\_DA}}+U_{e,t}^{\text{dch\_DA}}\le 1 \quad :\forall e,t \tag{17}$$

$$E_{e,t}^{\text{ES\_DA}}=E_{e,t-1}^{\text{ES\_DA}}+p_{e,t}^{\text{ES}_c\text{\_DA}}\eta^{\text{ch}}-\frac{p_{e,t}^{\text{ES}_d\text{\_DA}}}{\eta^{\text{dch}}} \quad :\forall e,t \tag{18}$$

$$\underline{\text{E}}_e^{\text{ES}}\le E_{e,t}^{\text{ES\_DA}}\le \overline{\text{E}}_e^{\text{ES}} \ :\forall e,t \ ,E_{e,ini}^{\text{ES}}=E_{e,t=T}^{\text{ES\_DA}} \ :\forall e \tag{19}$$

$$E_{e,t}^{\text{ES\_Re}}\le E_{e,t}^{\text{ES\_DA}}-\underline{\text{E}}_e^{\text{ES}} \quad :\forall e,t \tag{20}$$

- The reserve capacity the MG can provide for the market when the MGO purchases/sells energy from/to the DA market is modeled as (21) and (22), respectively. Equations (23)-(25) are used to limit the MGO bids to the DA market to the maximum capacity of the MG power trading with the main grid.

$$p_t^{\text{MG\_Re}}\le \overline{\text{P}}^{\text{MG}}+p_t^{\text{MG\_DA\_E}_{\text{in}}} \ ,p_t^{\text{MG\_Re}}\ge 0 \ :\forall t \tag{21}$$

$$p_t^{\text{MG\_DA\_E}_{\text{out}}}+p_t^{\text{MG\_Re}}\le \overline{\text{P}}^{\text{MG}} \quad :\forall t \tag{22}$$

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

$$0\le p_t^{\text{MG\_DA\_E}_{\text{out}}}\le \overline{\text{P}}^{\text{MG}}U_t^{\text{MG\_DA\_out}} \quad :\forall t \tag{24}$$

$$U_t^{\text{MG\_DA\_in}}+U_t^{\text{MG\_DA\_out}}\le 1 \quad :\forall t \tag{25}$$

B. *The RT problem for the MG*

The total cost of the MGO in the RT market is modeled as (26) made up of four terms. The first term is the cost of trading energy with the RT energy market as described in (27). The second term is the revenue of the MGO from the deployment of the reserve in the actual operation, modeled in (28). The cost of MG resources to provide energy and reserve for the system is considered to be the third and fourth term modeled in (29) and (30), respectively.

$$TC_\omega^{\text{RT}}=C_\omega^{\text{RT\_E}}-R_\omega^{\text{RT\_Re}}+C_\omega^{\text{RT\_DER\_E}}+C^{\text{DER\_Dep}} \tag{26}$$

$$C_\omega^{\text{RT\_E}}=\sum_{t=1}^{T}\lambda_t^{\text{RT\_E}}\left(p_{t,\omega}^{\text{MG\_RT\_E}_{\text{in}}}-p_{t,\omega}^{\text{MG\_RT\_E}_{\text{out}}}\right) \tag{27}$$

$$R_\omega^{\text{RT\_Re}}=\sum_{t=1}^{T}\lambda_t^{\text{RT\_E}}p_t^{\text{MG\_Re\_Dep}} \tag{28}$$

$$C_\omega^{\text{RT\_DER\_E}}=\sum_{t=1}^{T}\begin{bmatrix}\sum_{f=1}^{F}\text{C}_t^{\text{RES}}P_{f,t,\omega}^{\text{RES\_RT}}+\sum_{k=1}^{K}\text{C}_t^{\text{DG}}p_{k,t,\omega}^{\text{DG\_RT}}+\\ \sum_{e=1}^{E}\text{C}_t^{\text{ES}_d}p_{e,t,\omega}^{\text{ES}_d\text{\_RT}}-\sum_{e=1}^{E}\text{C}_t^{\text{ES}_c}p_{e,t,\omega}^{\text{ES}_c\text{\_RT}}\end{bmatrix} \tag{29}$$

$$C^{\text{DER\_Dep}}=\sum_{t=1}^{T}\left[\sum_{k=1}^{K}C_t^{\text{DG}}p_{k,t}^{\text{DG\_Dep}}+\sum_{e=1}^{E}C_t^{\text{ES\_dch}}p_{e,t}^{\text{ES\_Dep}}\right] \tag{30}$$

- The active and reactive 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 (31)-(34).

$$\begin{aligned}&\sum_f\left(P_{f,t}^{\text{RES\_DA}}+P_{f,t,\omega}^{\text{RES\_RT}}\right)+\sum_k\left(p_{k,t}^{\text{DG\_DA}}+p_{k,t,\omega}^{\text{DG\_RT}}+p_{k,t}^{\text{DG\_Dep}}\right)+\\&\sum_e\left(p_{e,t}^{\text{ES}_d\text{\_DA}}+p_{e,t,\omega}^{\text{ES}_d\text{\_RT}}+p_{e,t}^{\text{ES\_Dep}}\right)+\left(p_t^{\text{MG\_DA\_E}_{\text{in}}}+p_{t,\omega}^{\text{MG\_RT\_E}_{\text{in}}}\right)\\&-\left(p_t^{\text{MG\_DA\_E}_{\text{out}}}+p_{t,\omega}^{\text{MG\_RT\_E}_{\text{out}}}+p_t^{\text{MG\_Dep}}\right)-\left(p_{e,t}^{\text{ES}_c\text{\_DA}}+p_{e,t,\omega}^{\text{ES}_c\text{\_RT}}\right)\\&-\sum_l \text{P}_{l,t,\omega}^{\text{MGL\_RT}}=\sum_j 0.5(p_{i,j,t,\omega}^{\text{Flow}}+p_{i,j,t,\omega}^{\text{Loss}}) \quad :\forall t,\omega,i=1\end{aligned} \tag{31}$$

$$\begin{aligned}&\sum_f\left(P_{f,t}^{\text{RES\_DA}}+P_{f,t,\omega}^{\text{RES\_RT}}\right)+\sum_k\left(p_{k,t}^{\text{DG\_DA}}+p_{k,t,\omega}^{\text{DG\_RT}}+p_{k,t}^{\text{DG\_Dep}}\right)\\&+\sum_e\left(p_{e,t}^{\text{ES}_d\text{\_DA}}+p_{e,t,\omega}^{\text{ES}_d\text{\_RT}}+p_{e,t}^{\text{ES\_Dep}}\right)-\left(p_{e,t}^{\text{ES}_c\text{\_DA}}+p_{e,t,\omega}^{\text{ES}_c\text{\_RT}}\right)\\&-\sum_l \text{P}_{l,t,\omega}^{\text{MGL\_RT}}=\sum_j 0.5(p_{i,j,t,\omega}^{\text{Flow}}+p_{i,j,t,\omega}^{\text{Loss}}) \quad :\forall t,\omega,i\neq 1\end{aligned} \tag{32}$$

$$\begin{aligned}&\left(q_t^{\text{MG\_DA\_E}_{\text{in}}}+q_{t,\omega}^{\text{MG\_RT\_E}_{\text{in}}}\right)-\sum_l Q_{l,t,\omega}^{\text{MGL\_RT}}=\\&\qquad\sum_j(q_{i,j,t,\omega}^{\text{Flow}}+q_{i,j,t,\omega}^{\text{Loss}}) \quad :\forall t,\omega,i=1\end{aligned} \tag{33}$$

$$\sum_l Q_{l,t,\omega}^{\text{MGL\_RT}}+\sum_j(q_{i,j,t,\omega}^{\text{Flow}}+q_{i,j,t,\omega}^{\text{Loss}})=0 \quad :\forall t,\omega,i\neq 1 \tag{34}$$

- The reserve deployment of the MG and its resources in the RT operation is determined through multiplying the reserve capacity with the probability of calling the reserve, as modeled in (35).

$$\begin{aligned}&p_t^{\text{MG\_Dep}}=\varphi^{\text{Re}}p_t^{\text{MG\_Re}} \ ,\ p_{k,t}^{\text{DG\_Dep}}=\varphi^{\text{DG\_Re}}p_{k,t}^{\text{DG\_Re}},\\&\qquad p_{e,t}^{\text{ES\_Dep}}=\varphi^{\text{ES\_Re}}p_{e,t}^{\text{ES\_Re}} \quad :\forall t\end{aligned} \tag{35}$$

- The sum of the power generation of RESs in the DA and RT is limited as (36).

$$0\le p_{f,t}^{\text{RES\_DA}}+p_{f,t,\omega}^{\text{RES\_RT}}\le \text{P}_{f,t,\omega}^{\text{RES}} \quad :\forall f,t,\omega \tag{36}$$

- The technical constraints of DGs in the RT operation considering the reserve deployment are described in (37)-(39).

$$p_{k,t}^{\text{DG\_DA}}+p_{k,t,\omega}^{\text{DG\_RT}}+p_{k,t}^{\text{DG\_Dep}}\le \overline{\text{P}}_k^{\text{DG}} \quad :\forall k,t,\omega \tag{37}$$

$$\left(p_{k,t+1}^{\mathrm{DG\_DA}}+p_{k,t+1,\omega}^{\mathrm{DG\_RT}}+p_{k,t+1}^{\mathrm{DG\_Re\_Dep}}\right) -\left(p_{k,t}^{\mathrm{DG\_DA}}+p_{k,t,\omega}^{\mathrm{DG\_RT}}\right)\leq \mathrm{RU}_k \quad :\forall k,t,\omega \tag{38}$$

$$\left(p_{k,t}^{\mathrm{DG\_DA}}+p_{k,t,\omega}^{\mathrm{DG\_RT}}+p_{k,t}^{\mathrm{DG\_Re\_Dep}}\right) -\left(p_{k,t+1}^{\mathrm{DG\_DA}}+p_{k,t+1,\omega}^{\mathrm{DG\_RT}}\right)\leq \mathrm{RD}_k \quad :\forall k,t,\omega \tag{39}$$

- The power and energy constraints of the ESS in the RT operation are modeled as (40)-(46).

$$p_{e,t}^{\mathrm{ES}_d\mathrm{\_DA}}+p_{e,t,\omega}^{\mathrm{ES}_d\mathrm{\_RT}}+p_{e,t}^{\mathrm{ES\_Dep}}\leq \overline{\mathrm{P}}_e^{\mathrm{dch}} \quad :\forall e,t,\omega \tag{40}$$

$$0\leq p_{e,t,\omega}^{\mathrm{ES_c\_RT}}\leq \overline{\mathrm{P}}_e^{\mathrm{ch}}U_{e,t,\omega}^{\mathrm{ch\_RT}} \quad :\forall e,t,\omega \tag{41}$$

$$0\leq p_{e,t,\omega}^{\mathrm{ES_d\_RT}}\leq \overline{\mathrm{P}}_e^{\mathrm{dch}}U_{e,t,\omega}^{\mathrm{dch\_RT}} \quad :\forall e,t,\omega \tag{42}$$

$$U_{e,t,\omega}^{\mathrm{ch\_RT}}+U_{e,t,\omega}^{\mathrm{dch\_RT}}\leq 1 \quad :\forall e,t,\omega \tag{43}$$

$$E_{e,t,\omega}^{\mathrm{ES\_RT}}=E_{e,t-1,\omega}^{\mathrm{ES\_RT}}+\left(\left(p_{e,t}^{\mathrm{ES_c\_DA}}+p_{e,t,\omega}^{\mathrm{ES_c\_RT}}\right)\eta^{\mathrm{ch}}\right)- \left(\left(p_{e,t}^{\mathrm{ES_d\_DA}}+p_{e,t,\omega}^{\mathrm{ES_d\_RT}}+p_{e,t,\omega}^{\mathrm{ES\_Dep}}\right)/\eta^{\mathrm{dch}}\right) :\forall e,t,\omega \tag{44}$$

$$\underline{\mathrm{E}}_e^{\mathrm{ES}}\leq E_{e,t,\omega}^{\mathrm{ES\_RT}}\leq \overline{\mathrm{E}}_e^{\mathrm{ES}} \quad :\forall e,t,\omega \tag{45}$$

$$E_{e,ini}^{\mathrm{ES}}=E_{e,t=T,\omega}^{\mathrm{ES\_RT}} \quad :\forall e,\omega \tag{46}$$

- 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 (47) and (48). Equations (49)-(51) are used to model the fact that the MG can trade energy with the main grid in one direction only.

$$p_t^{\mathrm{MG\_DA\_E_{in}}}+p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}}-p_t^{\mathrm{MG\_Dep}}\leq \overline{\mathrm{P}}^{\mathrm{MG}} \quad :\forall t,\omega \tag{47}$$

$$p_t^{\mathrm{MG\_DA\_E_{out}}}+p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}}+p_t^{\mathrm{MG\_Dep}}\leq \overline{\mathrm{P}}^{\mathrm{MG}} \quad :\forall t,\omega \tag{48}$$

$$0\leq p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}}\leq \overline{\mathrm{P}}^{\mathrm{MG}}U_{t,\omega}^{\mathrm{MG\_RT\_in}} \quad :\forall t,\omega \tag{49}$$

$$0\leq p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}}\leq \overline{\mathrm{P}}^{\mathrm{MG}}U_{t,\omega}^{\mathrm{MG\_RT\_out}} \quad :\forall t,\omega \tag{50}$$

$$U_{t,\omega}^{\mathrm{MG\_RT\_in}}+U_{t,\omega}^{\mathrm{MG\_RT\_out}}\leq 1 \quad :\forall t,\omega \tag{51}$$

- Eqs. (52)-(59) are used to model the power flow constraints. The limitations of the feeder currents and bus voltages are modeled in (52) and (53), respectively. Also, the squares of the feeder currents and bus voltages are constrained by (54) and (55). In (56), the magnitude of the voltage at the final bus is calculated in terms of the magnitude of voltage at the initial bus, the active and reactive power flows, the magnitude of the feeder current, and the electrical parameters of the lines. The relation among the apparent, the active, and the reactive power is defined as (57). The active and reactive power losses of each feeder are calculated as (58) and (59), respectively. To maintain the linear form of the model, the square magnitudes of the voltage, current, active power, and reactive power are replaced with linear terms as in [18].

$$-\overline{\mathrm{I}}_{i,j}^{\mathrm{MGN}}\leq i_{i,j,t,\omega}^{\mathrm{MGN}}\leq \overline{\mathrm{I}}_{i,j}^{\mathrm{MGN}} \quad :\forall i,j,t,\omega \tag{52}$$

$$\underline{\mathrm{V}}_i^{\mathrm{MGN}}\leq v_{i,t,\omega}^{\mathrm{MGN}}\leq \overline{\mathrm{V}}_i^{\mathrm{MGN}} \quad :\forall i,t,\omega \tag{53}$$

$$(\underline{\mathrm{V}}_i^{\mathrm{MGN}})^2\leq v_{i,t,\omega}^{\mathrm{MGN\_sqr}}\leq (\overline{\mathrm{V}}_i^{\mathrm{MGN}})^2 \quad :\forall i,t,\omega \tag{54}$$

$$0\leq i_{i,j,t,\omega}^{\mathrm{MGN\_sqr}}\leq (\overline{\mathrm{I}}_{i,j}^{\mathrm{MGN}})^2 \quad :\forall i,j,t,\omega \tag{55}$$

$$v_{i,t,\omega}^{\mathrm{MGN\_sqr}}-2(\mathrm{R}_{i,j}^{\mathrm{MGN}}p_{i,j,t,\omega}^{Flow}+\mathrm{X}_{i,j}^{\mathrm{MGN}}q_{i,j,t,\omega}^{Flow})- \left(Z_{i,j}^{\mathrm{MGN}}\right)^2 i_{i,j,t,\omega}^{\mathrm{MGN\_sqr}}-v_{j,t,\omega}^{\mathrm{MGN\_sqr}}=0 \quad :\forall i,j,t,\omega \tag{56}$$

$$v_{i,t,\omega}^{\mathrm{MGN\_sqr}}i_{i,j,t,\omega}^{\mathrm{MGN\_sqr}}=p_{i,j,t,\omega}^{Flow\_sqr}+q_{i,j,t,\omega}^{Flow\_sqr} \tag{57}$$

$$p_{i,j,t,\omega}^{\mathrm{Loss}}=(\mathrm{R}_{i,j}^{\mathrm{MGN}}i_{i,j,t,\omega}^{\mathrm{MGN\_sqr}})\mathrm{S}^{\mathrm{base}} \quad :\forall i,j,t,\omega \tag{58}$$

$$q_{i,j,t,\omega}^{\mathrm{Loss}}=(\mathrm{X}_{i,j}^{\mathrm{MGN}}i_{i,j,t,\omega}^{\mathrm{MGN\_sqr}})\mathrm{S}^{\mathrm{base}} \quad :\forall i,j,t,\omega \tag{59}$$

C. IGDT-based optimization model

The IGDT approach is used to model the uncertainties of the RT energy market price and the probability of calling the reserve. For this purpose, Eqs. (60)-(63) are used to model the uncertainty related to the RT energy market price in the decision problem of the MGO in the markets. When the uncertain parameter is set to its forecast values, the base value of the ETC of the MGO, named ETC_b, is calculated. Regarding the effect of the uncertain parameter on the objective function, two strategies can be considered for the MGO, namely, risk-averse and risk-taker. In the risk-averse strategy, the aim of the MGO is to obtain an objective function which is robust against the uncertain parameter in the worst case. Since the MGO profit from participating in the markets decreases when the RT energy market price is lower than the forecast prices in the model proposed in this paper, the worst case is defined as the case in which the lowest RT energy market price is considered. For this purpose, the relation among the considered RT energy market price, the forecast one, and the uncertainty radius ($\alpha^{\mathrm{RT\_E}}$) is defined as (62). Therefore, when the uncertainty radius is maximized as (60), the worst case is obtained for the risk-averse MGO. In the risk-taker strategy, the best objective function is obtained for the MGO. For this purpose, maximizing the uncertainty radius results in a RT energy market price higher than the forecast one, as modeled in (63).

Eqs. (64)-(67) are used to model the uncertainty of the probability of calling the reserve. Since as the probability of calling the reserve decreases, the profit of the MGO decreases, the worst case is defined as the case in which the lowest probability is obtained. Therefore, the uncertainty radius (α^{Re}) is maximized to obtain the robust objective function in this case, with respect to which the least probability of calling the reserve is obtained, as described in (66). Furthermore, Eq. (67) is used to model the risk-taker MGO facing with the uncertainty of probability of calling the reserve, since by increasing this probability the ETC of the MGO decreases.

It should be noted that $\xi^{\mathrm{RT\_E}}$ and ξ^{Re} are defined as the risk aversion parameters related to the RT energy market price and the probability of calling the reserve, respectively. The MGO can control its own risk-level in the decision-making process by changing this parameter from 0 to 1. Moreover, both optimization problems described in (60)-(63) and (64)-(67) are solved considering Eqs. (7)-(25) and (31)-(59).

$$\max \ \alpha^{RT\_E} \tag{60}$$

$$ETC \le ETC_b\left(1+\zeta^{RT\_E}\right) \quad , \quad 0 \le \zeta^{RT\_E} \le 1 \tag{61}$$

$$\lambda_t^{RT\_E} \le \left(1-\alpha^{RT\_E}\right)\overline{\lambda}_t^{RT\_E} \tag{62}$$

$$\lambda_t^{RT\_E} \le \left(1+\alpha^{RT\_E}\right)\overline{\lambda}_t^{RT\_E} \tag{63}$$

$$\max \ \alpha^{Re} \tag{64}$$

$$ETC \le ETC_b\left(1+\zeta^{Re}\right) \quad , \quad 0 \le \zeta^{Re} \le 1 \tag{65}$$

$$\varphi^{Re} \le \left(1-\alpha^{Re}\right)\overline{\varphi}^{Re} \tag{66}$$

$$\varphi^{Re} \le \left(1+\alpha^{Re}\right)\overline{\varphi}^{Re} \tag{67}$$

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 1910003 single equations, 846531 single variables, and 21600 discrete variables.

V. Numerical Results

The effectiveness of the proposed model is confirmed by applying it on the 15-bus MG test system depicted in Fig. 2 [19]. The MG load (MGL) and the forecast output power of WTs and PVs are shown in Fig. 3 and Fig. 4, respectively. The bids of the DERs and their technical constraints are given in Table I [20, 21]. The bids of the RESs to the MGO are 2 \$/MWh. The capacity of the distribution transformer is 5 MVA and the power factor of the related load consumption is assumed to be 0.95. Therefore, the maximum active power exchange of the MG with the main grid is 4.75 MW. The maximum current of feeders is 5 kA and the minimum and maximum limitations to the MG bus voltages are 0.36 kV and 0.44 kV, respectively. The DA and RT energy market price and the reserve market price are shown in Figs. 5 and 6, respectively [22]. 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 20 kV and 0.4 kV for the distribution system and the MG, respectively.

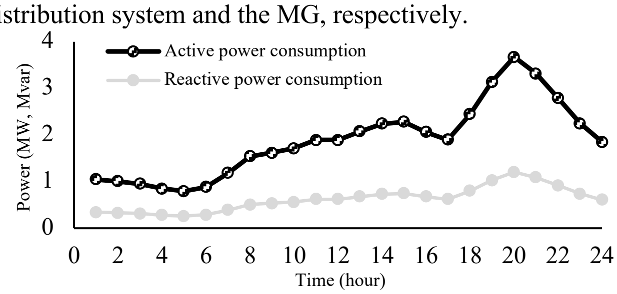


Fig. 3. The forecast MGL in the operation time period.

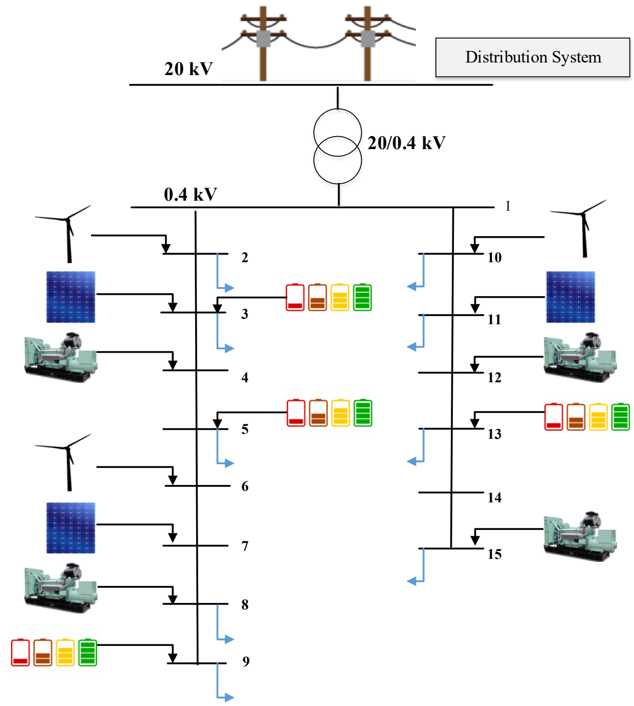


Fig. 2. The 15-bus MG structure used as the test system.

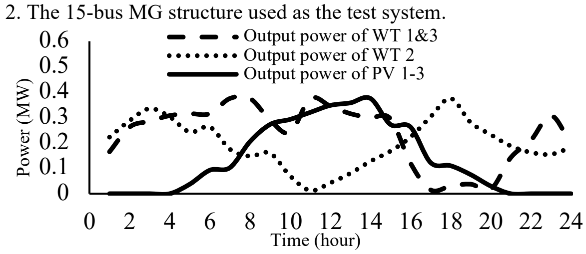


Fig. 4. The forecast output power of the RESs.

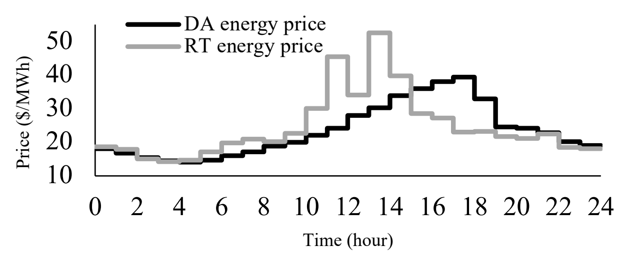


Fig. 5. The DA and RT energy markets prices.

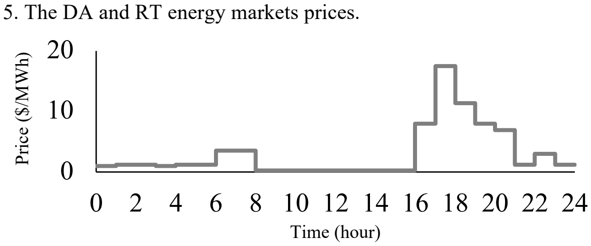


Fig. 6. The reserve market price.

Table I. Bids and Technical Constraints of the DERs

# DG	$\overline{P}_k^{DG}$	$\underline{P}_k^{DG}$	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	$\overline{P}_e^{ch}$ / $\overline{P}_e^{dch}$	$\underline{E}_e$	$\overline{E}_e$	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. The results of the two-stage model

The results including the MG operation cost, the optimal scheduling of the DERs, and the MGO bids in the energy and reserve markets are shown in Figs. 7-13 and Table II. The operating 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 energy from the market. Also, the MGO prefers to provide the reserve capacity for the reserve market using the EESs due to their lower operating 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 operating cost of the MGO when it participates in both energy and reserve markets (75.74 $) is lower than in the case where it participates in the energy market only (133.76 $). The main 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.

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

Cost/revenue of the MG in the DA operation ($)				
TC^{DA}	C^{DA_E}	R^{DA_Re}	C^{DA_DER}	
1014.29	1063.45	98.78	49.63	
Cost/revenue of the MG in the RT operation ($)				
TC_{ω}^{RT}	$C_{\omega}^{RT\_E}$	$R_{\omega}^{RT\_Re}$	$C_{\omega}^{RT\_DER}$	
			$C_{\omega}^{DER\_E}$	$C_{\omega}^{DER\_Re\_Dep}$
-905.65	-1338.01	28.09	456.99	3.46

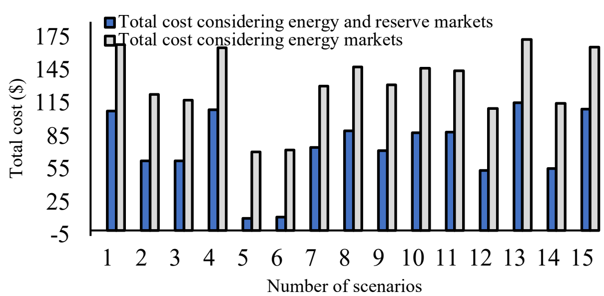


Fig. 7. Total cost of MG operation in each scenario (TC_{ω}).

The first-stage decisions of the MGO on the scheduling the MG 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. 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 energy 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 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 for decreasing the energy purchased from the DA energy market in high-price hours (e.g., 16 and 17). The second aim is associated with the reserve capacity provided for the 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.

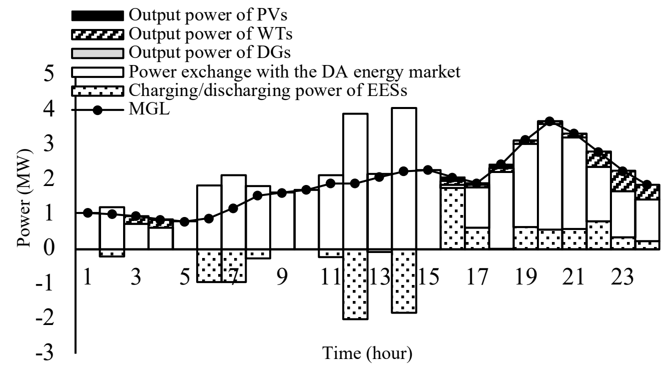


Fig. 9. Power balance in the DA energy market.

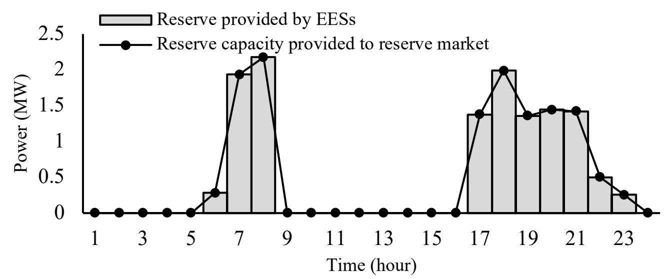


Fig. 10. The energy stored in the EESs to provide reserve capacity.

The MGO 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 energy to the RT market as much as possible. According to Fig. 11, it is clear that the MGO is able to deploy the DGs as well as RESs to sell energy as a producer in the RT market at all hours. It is worth noting that the MGO deploys all resources to sell much more energy 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 energy to the RT market affordably.

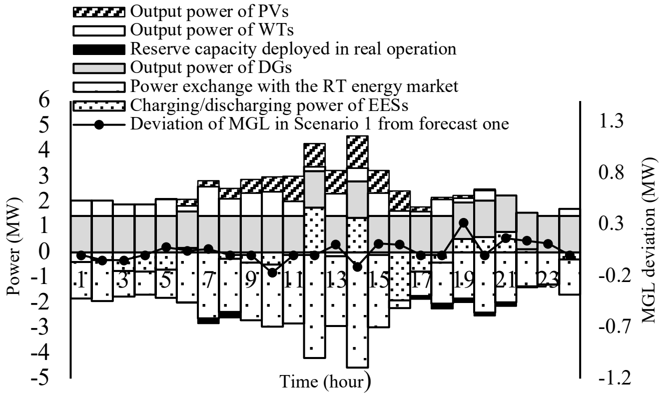


Fig. 11. The MGO decisions in the RT operation.

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

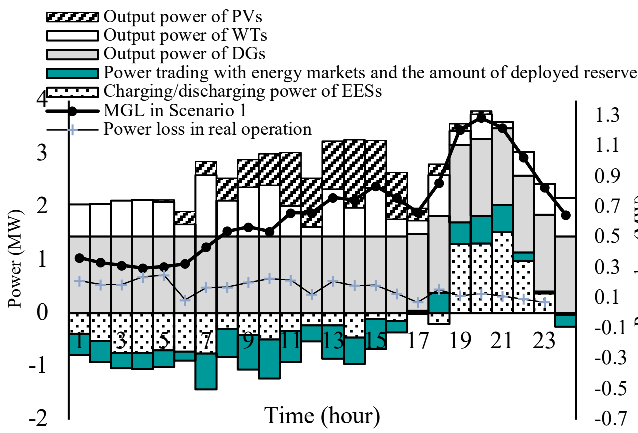


Fig. 12. The demand-supply balance in the real operation.

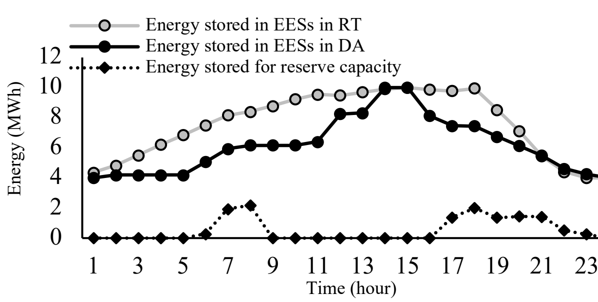


Fig. 13. The energy stored in the EESs in DA and RT operations.

B. The results for the IGDT approach

This sub-section investigates the decisions of the MGO to manage the uncertainties of the RT market price and the probability of calling the reserve using the IGDT approach. To this end, the RT market prices are supposed to change from 70% to 130% of the forecast prices. 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). For the MGO with risk-averse strategy (Case III), the probability of calling the reserve is changed from 0.1 to zero when the uncertainty radius increases from 0 to 1. Furthermore, for the risk-taker MGO (Case IV) as the uncertainty radius increases from 0 to 0.5, the probability of calling the reserve increases from 0.1 to 0.15.

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 assumes that the RT market price might be lower from the forecast prices. Therefore, the main findings are that the uncertainty radius increases from 0 to 0.3, after which the ETC increases from 75.74$ to 279.47$ due to the reduction of the MGO revenues from selling energy to the RT market. In addition, the MGO prefers to decrease the energy sold to the RT market with the aim of selling more energy to the DA market (from 0 to 8.49 MWh) and increasing the reserve capacity provided to the reserve market from 12.737 MW to 13.815 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 prices. As a result, when the uncertainty radius increases from 0 to 0.3, the ETC decreases. The main reason is that the energy sold to the RT market increases from 47.673 MWh to 51.169 MWh. On the other hand, the risky MGO tends to decrease the reserve capacity from 12.737 MW to 11.087 MW.

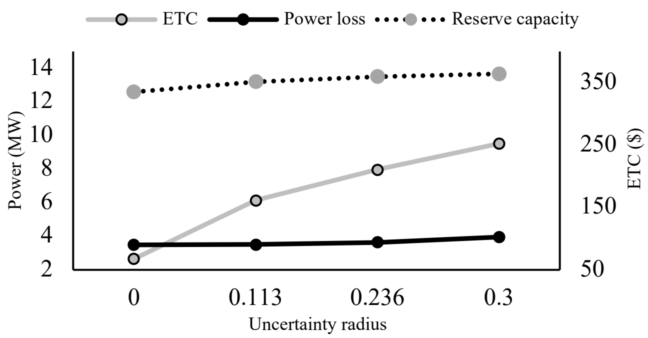
In Case III, as reported in Fig. 14(c), risk-based decisions are made on the lower probability of calling the reserve in comparison with the forecast one. In this case, the ETC of the MGO experiences an increase of 26.14$ in the worst case when the uncertainty radius changes from 0 to 1. This occurs as the MGO sells the lower amount of reserve deployed in the RT market. Therefore, as the uncertainty radius increases, the risk-averse MGO decides to provide less reserve capacity for the DA energy market, so that the amount of the reserve capacity decreases from 12.737 MW to 8.75 MW. The behavior of the risk-taker MGO to face with the uncertainty in the probability of calling the reserve is described in Fig. 14(d). For this purpose, the uncertainty radius increases from 0 to 0.5. In this case, as the uncertainty radius increases, the risk-taker MGO increases the reserve capacity provided for the market from 12.737 MW to 13.563 MW. This decision decreases the ETC of the MGO from 75.74$ to 67.41$.

C. Discussion on the results

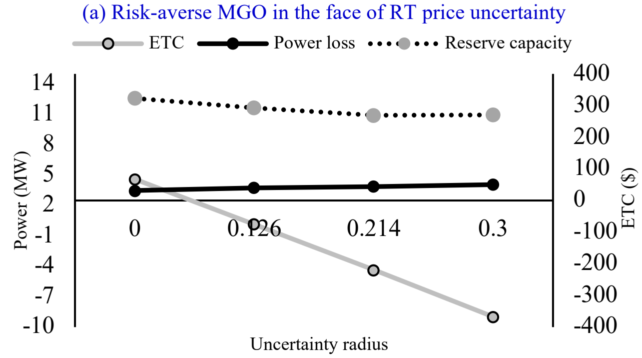
The model proposed in this paper addressed two main goals for the risk-based MGO decisions in markets considering uncertainties. The following conclusions from the results demonstrate the effectiveness of the proposed model to achieve these goals.

The first goal was to propose a new model for MGO to employ different strategies to schedule the MG resources to participate in the DA (energy and reserve) and RT energy markets. For this purpose, the MGO decides to use most of the capacity of its DGs, PVs, and WTs to sell energy to the RT energy market due to the high price in this market. In addition, EESs are used in both the DA and the RT energy markets to minimize the operating costs of the MG. It should be noted that all the reserve provided by the MGO to the market is supplied by the EESs. Therefore, the results show that the MGO schedules the MG resources optimally to participate in the DA energy and reserve markets and the RT energy market to minimize the ETC.

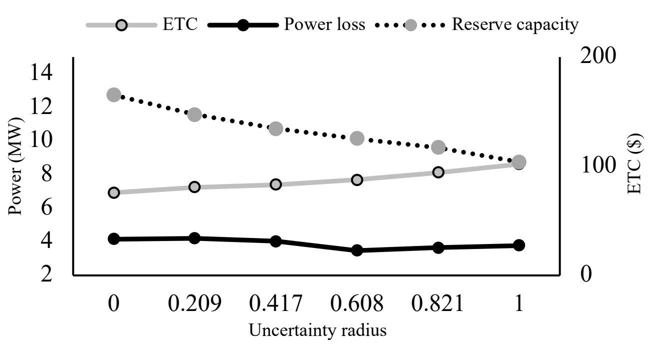
The second goal was to model the risk-based behavior of the MGO to manage uncertainties (i.e., RT market price and the probability of calling the reserve) by changing its strategies in the markets. The results show that the major concentration of the MGO to manage the uncertainty of the RT market price is on changing its sold energy to the RT energy market. In addition, the MGO prefers to change its reserve capacity provided for the DA reserve market when it encounters uncertainty about the probability of calling the reserve. In both cases, the aim of the IGDT-based model is to protect the MGO decisions against uncertainties in the worst case.



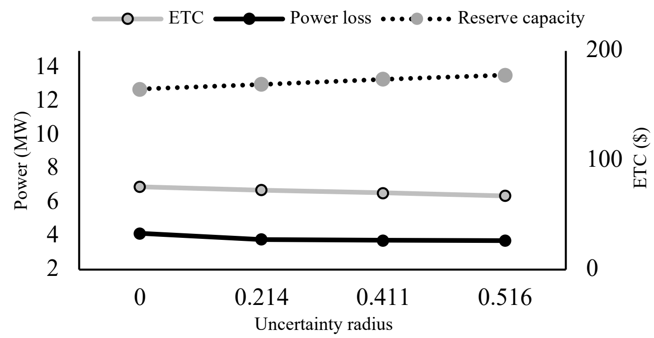
(a) Risk-averse MGO in the face of RT price uncertainty



(b) Risk-taker MGO in the face of RT price uncertainty



(c) Risk-averse MGO in the face of the uncertainty in the probability of calling the reserve



(c) Risk-taker MGO in the face of the uncertainty in the probability of calling the reserve

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

VI. Conclusion

In this paper, a two-stage stochastic optimization problem has been formulated to co-optimize the MGO bids in the DA energy and reserve markets considering the stochastic behavior in the RT market. Moreover, the risk-based decisions of the MGO to manage the uncertainties of the RT market price and the probability of calling the reserve have been modeled using the IGDT approach. The main conclusions deriving from the application of this model to the MG test system are the following:

- Using the co-optimization of the MGO participation in the energy and reserve markets, the ETC of the MG operation undergoes a more significant reduction than for the MGO participation in energy markets only. The ETC decreases from 133.76$ to 75.74$.
- The proposed two-stage stochastic programming approach ensures that the MGO makes convenient two-stage decisions on DERs as well as the bids in both DA and RT markets, taking into account the uncertainties. In other words, the MGO is able to control the deviations of RESs and MGL, satisfying the MGL as well as obtaining more revenue through its participation as a consumer/producer in the DA/RT markets.
- The risk-based decisions of the MGO showed that with considering RT price higher than the forecast one (risk-averse strategy), the energy sold of the MGO to the RT market decreases. To compensate for the revenue reduction in the RT market, the energy sold to the DA energy market and the reserve capacity provided for the reserve market increase. In the risk-taker strategy, the MGO sells more energy to the RT energy market and sells less reserve and energy to the DA markets.
- The risk-based behavior of the risk-averse MGO in the face of the uncertainty in the probability of calling the reserve showed that, as the uncertainty radius increases, the MGO decreases the reserve capacity provided for the market. In fact, since the MGO revenues from calling the reserve in the RT market decrease as the uncertainty radius increases, the MGO prefers to provide less reserve capacity for the market. This is while the risk-taker MGO increases its reserve capacity for the market as the uncertainty radius increases.

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