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Provision of the Flexible Ramping Product in a Microgrid Considering the Trading Strategies in the Energy Markets

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Abstract

The Flexible Ramping Product (FRP) market has been created as a new ancillary service market for the power systems to manage the severe ramp rates in the net load of the system. Microgrids (MGs) can provide the required ramp service for this market. The MG manager (MGM) sends its bids to the FRP market. The mutual effects of these bids on the MGM trading strategies in the day-ahead (DA) and real-time (RT) energy markets have not been considered in the previous studies. For this purpose, a new formulation is developed in this paper to model the MGM decisions in the FRP market while participating in the DA and RT energy markets. Moreover, the uncertainty on the probability of bid acceptance in the FRP market is modeled in the MGM decision-making problem using the information gap decision theory approach. The results show that changing the MGM strategies in participating in the markets, the objective function of the MGM improves when it participates in the DA energy, FRP and RT energy market, in comparison with the cases in which the MGM does not participate in the FRP market or the RT energy market. Also, the results show how the risk-averse MGM changes its strategies to provide the ramp service for the FRP market to make its decisions robust against the uncertain parameter.

Keywords: Day-ahead; energy markets; flexible ramping product; microgrid; real-time; renewable energy sources; risk; two-stage stochastic.

Nomenclature

Acronyms:

CAISO	California ISO
CVaR	Conditional value at risk
DA	Day-ahead
DER	Distributed energy resources
DG	Distributed generation
EES	Electrical energy storage
EMS	Energy management system
ETC	Expected total cost
FP	Flexibility provider
FRP	Flexible ramping product
IGDT	Information gap decision theory
IRENA	International Renewable Energy Agency
ISO	Independent System Operator
LFO	Local flexibility operator
MG	Microgrid
MGCC	Microgrid control center
MGL	Microgrid load
MGM	Micro-grid manager
MILP	Mixed-integer linear programming
PCC	Point of common coupling
RES	Renewable energy source
RT	Real-time

Indices/Sets:

e/E	Index/set of EESs
f/F	Index/set of RESs
i, I/ j, J	Index/set of MG bus
k/K	Index/set of DGs
l/L	Index/set of MGLs
D	Index used instead of RES, DG, ES_ch, and ES_dch
M_i^{RES}	Set of RESs
M_i^{ES}	Set of EESs
M_i^{DG}	Set of DGs
M_i^{L}	Set of MGLs
t/T	Index/cardinality of time
ω/W	Index/cardinality of the scenarios
$Conec(i,j)$	Set of buses directly connected to bus *i*

Parameters:

C^{D}	Energy bid of DERs ($/MWh)
$\mathrm{C}^{\mathrm{D\_RU}}/\mathrm{C}^{\mathrm{D\_RD}}$	Upward/Downward ramp bid of DERs ($/MWh)
$\underline{\mathrm{E}}^{\mathrm{ES}}/\overline{\mathrm{E}}^{\mathrm{ES}}$	Minimum/Maximum energy stored in EESs (MWh)
$\mathrm{E}_{ini}^{\mathrm{ES}}$	Initial energy stored in EESs (MWh)
$\overline{\mathrm{I}}_{i,j}^{\mathrm{MG}}$	Maximum current flows from bus *i* to *j* (p.u)
$\widehat{\mathrm{P}}^{\mathrm{MGL\_DA}}/\mathrm{P}^{\mathrm{MGL\_RT}}$	Forecast MGL in DA/RT (MW)
$\widehat{\mathrm{P}}^{\mathrm{RES\_DA}}/\mathrm{P}^{\mathrm{RES\_RT}}$	Forecast RESs power in DA/RT (MW)
$\overline{\mathrm{P}}^{\mathrm{ch}}/\overline{\mathrm{P}}^{\mathrm{dch}}$	Maximum charging/discharging power of EESs (MW)
$\overline{\mathrm{P}}^{\mathrm{DG}}$	Maximum DGs power (MW)
$\overline{\mathrm{P}}^{\mathrm{MG}}$	Maximum power exchange with grid (MW)
RU /RD	Ramp-up/down limitations of DG (MW/h)

$\overline{\mathrm{V}}_i^{\mathrm{MG}}/\underline{\mathrm{V}}_i^{\mathrm{MG}}$ Voltage amplitude limitations (p.u)

$\mathrm{Z}_{i,j}^{\mathrm{MG}}/\mathrm{R}_{i,j}^{\mathrm{MG}}$ Feeder impedance modulus/resistance (p.u)

η_{ch}/η_{dch} Charging/Discharging efficiency of ESs

$\lambda^{\mathrm{DA\_E}}/\lambda^{\mathrm{RT\_E}}$ DA/RT energy price ($/MWh)

$\lambda^{\mathrm{DA\_RU}}/\lambda^{\mathrm{DA\_RD}}$ Upward/Downward FRP prices ($/MWh)

$\varphi^{\mathrm{DA\_RU}}/\varphi^{\mathrm{DA\_RD}}$ Probability of upward/downward ramp bid acceptance of MG

$\psi^{\mathrm{RT\_RU}}/\psi^{\mathrm{RT\_RD}}$ Probability of upward/downward FRP deployment

τ_{ω} Occurrence probability of scenarios

γ Risk aversion parameter

Variables:

$C^{\mathrm{DA\_E}}/C^{\mathrm{RT\_E}}$ DA/RT cost of power trading with market ($)

$C^{\mathrm{DA\_DER\_E}}$ DA cost of trading power with DER owners ($)

$C^{\mathrm{RT\_DER}}$ RT cost paid to DER owners ($)

$C^{\mathrm{DA\_DER\_FRP}}$ DA cost of providing ramp by DER owners ($)

$C^{\mathrm{DER\_E}}$ RT cost of power trading with DER owners ($)

$R^{\mathrm{DA\_FRP\_Dep}}$ The cost paid to DER owners to deploy the FRP capacity ($)

$R^{\mathrm{RT\_FRP}}$ RT revenue of deployment ramp of MGM ($)

$E^{\mathrm{ES\_DA}}$ Energy stored in ESs in DA (MWh)

$E^{\mathrm{ES\_RU}}/E^{\mathrm{ES\_RD}}$ Upward/Downward energy used for FRP market (MWh)

$E^{\mathrm{ES\_RT}}$ Energy stored in ESs in RT (MWh)

ETC/ETC_b Expected total cost/Expected total cost base ($)

$i^{\mathrm{MG}}/v^{\mathrm{MG}}$ Feeder current/voltage bus (p.u)

$p^{\mathrm{D\_DA}}$ DA power scheduling of DERs (MW)

$p^{\mathrm{D\_RU}}/p^{\mathrm{D\_RD}}$ Upward/Downward ramp capacity provided by DERs (MW)

$p^{\mathrm{D\_RT}}$ RT power dispatching of DERs (MW)

$p^{\mathrm{D\_RU\_Dep}}/p^{\mathrm{D\_RD\_Dep}}$ Upward/Downward ramp capacity of DERs deployed in RT (MW)

$p^{\mathrm{Flow}}/p^{\mathrm{Loss}}$ Power flow/Power loss (MW)

$p^{\mathrm{MG\_DA\_Ein}}/p^{\mathrm{MG\_DA\_Eout}}$ Power purchased from/sold to DA market (MW)

$p^{\mathrm{MG\_RT\_Ein}}/p^{\mathrm{MG\_RT\_Eout}}$ Power purchased from/sold to RT market (MW)

$p^{\mathrm{MG\_DA\_RU}}/p^{\mathrm{MG\_DA\_RD}}$ Upward/Downward ramping capacity provided to FRP market (MW)

$p^{\mathrm{MG\_RU\_Dep}}/p^{\mathrm{MG\_RD\_Dep}}$ Deployed upward/downward ramping capacity in FRP market (MW)

$TC^{\mathrm{DA}}/TC_{\omega}^{\mathrm{RT}}$ DA total cost/RT total cost in each scenario ($)

$U^{\mathrm{ch}}/U^{\mathrm{dch}}$ Binary variables of ESs used in DA and RT operations

$U^{\mathrm{MG\_in}}/U^{\mathrm{MG\_out}}$ Binary variables related to power exchange with DA and RT market

$\alpha, \alpha_1 - \alpha_2$ Uncertainty radius

1. Introduction

1.1. The Flexible Ramping Product

The goal of decreasing the emissions of greenhouse gases and local pollutants in the electrical energy sector can be addressed by expanding the deployment of renewable energy sources (RESs) such as wind turbines (WTs) and photovoltaic (PV) systems [1]. To integrate more RESs in the power systems, some solutions have been proposed, as reported by the International Renewable Energy Agency (IRENA) [2]. These solutions are categorized in four main aspects: enabling technologies, business models, market design, and system operation. One of the main solutions from the viewpoint of market design is the creation of the new ancillary service named *flexible ramping product* (FRP), already activated by two Independent System Operators (ISOs): California ISO (CAISO) and Midcontinent ISO. The FRP service is aimed at managing the high ramp rates of the system net load[1] created by the variable behavior of the RESs, especially wind and PV systems. For this purpose, the ISOs may deploy two main strategies. First, considering the FRP in the real-time (RT) market to manage the required flexible capacity in the RT dispatch intervals, e.g., 5-minute intervals in the US markets. The procurement of flexible reserve capacity in RT intervals is modelled in [3] for integrating intra-hourly ramping requirements and constraints into a multi-timing day-ahead (DA) scheduling problem. The RT unit commitment problem is formulated as a two-stage stochastic model in [4] considering the adequacy of the flexible ramp capacity provided by wind power producers with which the overall system costs can be reduced. The relation between the minimum generation cost in the 5-minute RT market and the requirements for up- and down-flexible ramping is established in [5]. Possible issues leading to ramping capacity shortage in the conventional unit commitment formulation are indicated in [6], together with the proposal of a

[1] As reported by CAISO, the maximum ramp down and ramp up of the system net load on 6th July 2021 were 3881 MW and 4785 MW occurring in hours 07:00 and 18:00, respectively. Moreover, CAISO needed 10451 MW ramp up between 16:45 and 19:45 on that day.

method to guarantee proper definition of the flexible ramp capacity that can be procured. A robust optimization approach is proposed in [7] to model the unit commitment problem of a system in which the electrical and natural gas systems are coordinated considering the FRP. Provision of sufficient FRP from wind power systems is discussed in [8] with the identification of a specific wind power ramping product to be considered in multi-timescale power system operation. The characterization of wind power ramping by using conditional probability distributions is conducted in [9], followed by the allocation of FRP reserves based on an adjustable chance-constrained approach in which also the confidence level is a decision variable. The spatio-temporal correlations among demand and wind power uncertainties are incorporated in [10] in the FRP modelling and are addressed through a distributionally-robust chance constrained multi-interval optimal power flow. An extension of the DA market model that encompasses enhanced FRP design for increasing the dispatch flexibility in 15-min markets is proposed in [11], including market-based incentives for making available higher ramping capabilities. A joint energy and flexible ramping reserve market is addressed from the viewpoint of the ISO in [12] for integrated energy systems with heat and power generation and demand, using a hybrid stochastic–information gap-decision theory (IGDT) network-constrained unit commitment model. The unit commitment problem of the ISO is formulated in [13] with the aim of the optimal scheduling of resources to provide energy, reserve, and flexible ramp for the system considering 5-minute power balance in the RT operation.

The ISO forecasts the required ramp capacity of the system in the RT operation. The ISO attempts to procure some of this required capacity through the FRP market in the DA. In this case, different flexible providers (FPs) can provide the FRP for the system with participating in this FRP market.

Using electrical energy storage (EES), the bidding strategy with EES in both the DA energy and FRP markets is modeled as a mixed-integer linear programming (MILP) model in [14].

The decision-making framework of an ESS aggregator to participate in the DA energy, regulation, and the FRP markets is formulated as a risk-based model in [15]. Also electric vehicles can participate in the provision of the FRP, as shown in [16], by considering the uncertainty of the system net load in a model solved with the dynamic programming approach. The potential of using electric vehicles to provide FRP is further addressed in [17] by considering locational marginal pricing of energy and marginal pricing of FRPs. More generally, the bidding strategy of an energy hub in the DA energy and FRP market is modeled as a robust optimization approach in [18] where the uncertainty of the RT energy price is modeled using the interval approach.

1.2. Flexibility in distribution networks

The previous sub-section has indicated the role of the ISO to deploy FRP in transmission networks. The flexibility service can also be used by the DSO in distribution networks, to solve operational problems such as congestion management, power losses, and voltage violation. For this purpose, the DSO can apply two strategies. In the first strategy, the DSO sends its request directly to the FPs, e.g., MGMs and aggregators. In this case, the DSO requests the FPs to change their power taken from / injected into the grid to specific values. The FPs reschedule their resources under control to respond to this DSO request, regarding which their total cost/profit changes. Then, the price with which the DSO pays the FPs to provide this service is calculated regarding the opportunity cost, as described in details in [19]. A mathematical formulation is proposed in [20] from the viewpoint of the DSO to flatten the net load of the distribution network to avoid the occurrence of severe upward and downward ramps. For this purpose, an incentive-based approach is developed to encourage the FPs to reschedule their energy resources regarding the DSO request. A bi-level optimization approach is developed in [21] to model the interactions between the DSO, as the leader, and the MGMs, as the followers, to incentivize the rescheduling of MG flexible resources for reducing the ramp-up associated with the overall net load of the distribution network.

In the second strategy, the DSO sends its request to the local flexibility operator (LFO). Then, the LFO announces the FPs about the required flexibility of the DSO, regarding which the FPs send their bids to the local flexibility market. This strategy is considered in [22] in the day-ahead congestion management problem of a distribution network. It should be noted that providing the flexibility service for the DSO by the MGM is beyond the scope of this paper.

1.3. Energy Management in Microgrids

Microgrids (MGs) provide an appropriate framework to facilitate the integration of the RESs into the distribution network. The presence of flexible energy resources such as electrical energy storage (EES) and distributed generations (DG) in the MGs, gives the ability to the MG managers (MGMs) to provide ancillary services such as the FRP for the market.

The energy management problem in MGs considering the MGM participation in the energy and ancillary service markets has been considered in many studies.

The MGM participation in the DA energy market considering demand response (DR) programs is addressed in [23] with a risk-based stochastic approach, in [24] with a DR-based optimization model formulated for the operation problem of a MG to satisfy the load, and in [25] to determine the scheduling of the distributed energy resources (DERs) for the energy management problem of the MGs.

The authors of [26] propose a multi-objective optimization problem considering economic and pollutant emission indices for the energy and reserve scheduling of a MG. In [27], participation of a MGM in the DA energy and reserve markets is specified with the objective of not only minimizing the MG operation cost, but also providing an applicable reliability services. Electric vehicles are considered in [28] as flexible resources to provide FRP in microgrids. The bidding strategy of a MGM in both DA energy and reserve markets is modeled in [29] where the uncertainty of the acceptance amount of reserve in the market is modeled using the IGDT approach. The bidding strategy of a MG in the energy and ancillary services markets is modeled as a stochastic model in [30] where the MGM risk level is managed through the conditional value at risk (CVaR) method. A robust multi-objective model is developed in [31] to model the MG energy and reserve scheduling under uncertainty.

1.4. Research Gaps and Proposed Contributions

Although providing the ramp service for the FRP market is a new opportunity for the market participants especially the MGMs, there are few mathematical models which address this issue. The review paper [32] issued in 2017 considers the management of ramp capacity on the distribution grid as an interesting topic for the future. In the first attempt to model the participation of the MGM in the FRP market [33] the optimal bidding strategy of a MGM is modeled in the DA energy, reserve, and FRP markets with the purpose of maximizing its revenues. The day-ahead self-scheduling of MGs, considering that the MGM is able to provide reserve and FRP services to the ISO and reschedules its resources to provide services to the distribution system operator, is presented in [19].

Therefore, this problem still requires appropriate formulations to address the research gaps of the previous studies. The proposed models in the previous studies are reviewed in Tables 1 and 2[1]. The main issues, which are not addressed in the previous studies, are as follows:

- The market participation problem of the MGM is addressed in [23]-[31] without considering the MGM's decisions to provide the flexibility service for the market. In the previous studies which address the decision makers' problem (i.e., for MGM, energy hub, and aggregator) to provide the ramp service, the problem is modeled only

[1] As mentioned previously, there are two main approaches to employ the flexibility service by the ISO. In the first approach, the energy market clearing problem of the ISO is extended to consider providing the FRP service for the system as proposed in [3]-[13]. In the second approach, the required ramp of the ISO is supplied through the FRP market, and the FPs such as MGMs and aggregators participate in this market to supply the required flexibility of the system. Since the focus of this paper is on the second approach, the studies which addressed this strategy are reviewed in Table 1 and Table 2.

considering the DA market [14]-[19], [23]-[31], and [33]. For example, the participation problem of the EES aggregator in the DA energy, FRP, and regulation markets is addressed in [15]. The model proposed in [33] addresses the participation problem of a MGM in the DA energy, reserve, and FRP markets. This is while, the bids of the MGMs to participate in the DA energy and FRP markets and the RT decisions of the MGMs considering the conditions of the RT operation due to the different uncertainties have mutual effects on each other. Therefore, when the strategy of the MGM to schedule the MG resources to trade energy with (or provide ramp capacity for) the DA market is determined, the MGM decisions in the RT operation should be considered. Although it seems that participating in the RT energy market may change the behavior of the MGM to participate in the DA markets, such modeling is not addressed in the previous studies as shown in Table 1 and Table 2.

- The maximum power trading limitation of the MG with the main grid is the main constraint which impacts on the MGM decisions in both the DA and the RT markets. Therefore, appropriate modeling is required in which the relation among the MGM decision variables in the DA energy, DA FRP, and the RT energy markets with the maximum limitation of the MG power trading with the market is modeled. As shown in Table 2, the power trading limitation with the grid in the RT operation is not modeled in all reviewed studies. Also, in the previous studies which model the decision makers' bids in the DA energy and FRP markets [14]-[17] and [33], this constraint in the DA problem is not also considered. In [33], it is assumed that there is no limitation for trading energy with the main grid when the MGM participates in the DA markets. In the model proposed in [18], the constraints of modeling the power limitation with the main grid are presented without considering the decision maker's decisions to provide the ramp capacity for the market.

- Regarding the procedure of clearing the DA FRP market[1], all the ramp capacity proposed by the market participants, especially the price-taker players such as MGMs, may not be accepted. Therefore, the MGMs face major risk in accepting their bids in the FRP market which should be considered. In fact, changing the probability of the MGM bid acceptance in the FRP market, the MGM strategies to participate in the FRP market may be changed. This uncertainty is not modeled in all the previous studies reported in Table 1.

Table 1: Comparison of the model proposed in this paper with the previous studies from the viewpoint of decision variables, uncertain parameters, and decision makers.

Ref.	DM	DA problem: Decision variables			RT operation: Decision variables			Uncertain parameters			
		Energy bids	FRP bids	RS*	Energy bids	RD*	PFV*	Probability of bid acceptance in the FRP market	Demand	RESs	Market price
[14]	Aggregator	✓	✓	✓							
[15]	Aggregator	✓	✓	✓							
[16]	Aggregator	✓	✓	✓					✓		
[17]	Aggregator	✓	✓	✓					✓	✓	
[18][2]	Energy hub	✓	✓	✓							✓
[23]	MGM	✓		✓					✓	✓	✓
[24]	MGM	✓		✓					✓	✓	
[25]	MGM	✓		✓							
[26]	MGM	✓		✓					✓	✓	
[27]	MGM	✓		✓							✓
[28]	MGM	✓		✓					✓	✓	
[29]	MGM	✓		✓					✓	✓	✓
[30]	MGM	✓		✓						✓	
[31]	MGM	✓		✓					✓	✓	✓
[33]	MGM	✓	✓	✓						✓	✓
[19]	MGM	✓	✓	✓					✓	✓	✓
This Paper	MGM	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

* DM: Decision maker; RS: Resource scheduling; RD: Resource dispatching; PFV: Power flow variables

[1] The procedure is described in Section 2.3.

[2] In this study, the power imbalance in the RT operation is considered, where the DERs may be rescheduled in the RT operation. In fact, participation in the RT energy market considering the proposed decision variables and constraints listed in Table 1 and Table 2 is not considered in [18]. Details on the difference between modeling the RT power imbalance and participating in the RT energy market are presented in [34].

Table 2: Comparison of the model proposed in this paper with the previous studies from the viewpoint of the technical constraints.

Ref.	DA problem: Constraints			RT operation: Constraints		
	Power balance	Resource constraints	Power trading limitation with grid	Power balance	Resource constraints	Power trading limitation with grid
[14]	✓	✓				
[15]	✓	✓				
[16]	✓	✓				
[17]	✓	✓				
[18]	✓	✓	✓			
[23]	✓	✓	✓			
[24]	✓	✓	✓			
[25]	✓	✓				
[26]	✓	✓				
[27]	✓	✓				
[28]	✓	✓	✓			
[29]	✓	✓	✓			
[30]	✓	✓	✓			
[31]	✓	✓	✓			
[33]	✓	✓				
[19]	✓	✓	✓			
This Paper	✓	✓	✓	✓	✓	✓

In this paper, a new mathematical formulation is developed to address these research gaps following the idea applied in [19]. This formulation models the problem of the MGM participation in the DA energy and FRP markets and the RT energy market simultaneously. For this purpose, a two-stage stochastic optimization model is employed. Since, the two-stage stochastic model is a well-known mathematical formulation used in previous studies, using this model is not presented in this paper as a contribution. Instead, the aim of this paper is to use this approach to model the stochastic decisions of the MGM in the RT operation in the decision-making problem of the MGMs in the DA energy and FRP markets. Also, the uncertainty of the probability of the bid acceptance in the FRP market is modeled in the decision-making problem of the MGM using the IGDT approach. Since the IGDT also is a well-known method to model the uncertainties, it is not presented in this paper as a contribution. Instead, the IGDT approach is applied in this paper to model the risk-averse behavior of the MGM in the markets to address the uncertainty related to the probability of the MGM's bid acceptance in the FRP market. On these bases, the main contributions of this paper are as follows:

- Modeling the MGM decisions to provide the ramp service for the FRP market considering the energy trading strategies in the DA and the RT energy markets.
- Modeling the risk-based strategies of the MGM to provide the ramp service for the FRP market and to trade energy in the energy markets considering the uncertainty of the probability of bid acceptance in the FRP market.

1.5. Paper Organization

The rest of the paper is organized as follows. The problem description is presented in Section 2. The problem is formulated in Section 3. Section 4 presents the numerical results. The conclusions are reported in Section 5.

2. Problem description

2.1. The Decision-making Framework

In this paper, the bids of the MGM in the DA energy and FRP markets are optimized considering the stochastic behavior of the MGM in the RT operation. The MGM can deploy the capacity of the DERs[1] in the MG to meet the demand and to participate in the wholesale markets. The MG can trade energy with the main grid through the point of common coupling (PCC). The decision-making framework of the MGM is described in Fig. 1. As shown in this figure, the bids of the MGM in the DA energy and FRP markets are determined in four steps as follows:

1) The output power of the WTs and PV systems, the MG demand, and the wholesale market prices, are considered as uncertain parameters. A service provider forecasts the uncertain parameters and sends the forecast values of these parameters to the MG control center (MGCC). Also, the DER owners send their bids together with the technical constraints of their resources to the MGCC.

[1] DERs consist of PV, WT, DGs, and EESs in this paper.

2) The MGCC sends the data to the energy management system (EMS) where the mathematical formulation for the MGM participation in the wholesale market is developed. At first, the MGM's problem is formulated as a two-stage stochastic model to address the uncertainties of the output power of the RESs, demand, and the RT energy market price. Then, this model is reformulated as a risk-based model to manage the uncertainty related to the probability of the bid acceptance in the FRP market.
3) The mathematical model in the EMS is solved using an appropriate solver, calculating the decision variables of the MGM to participate in the markets and schedule the MG resources, as shown in Fig. 1. Then, the results are sent to the MGCC.
4) The MGCC sends the optimal bids of the MGM to the DA market and sends the DA scheduling of the DERs to their owners.

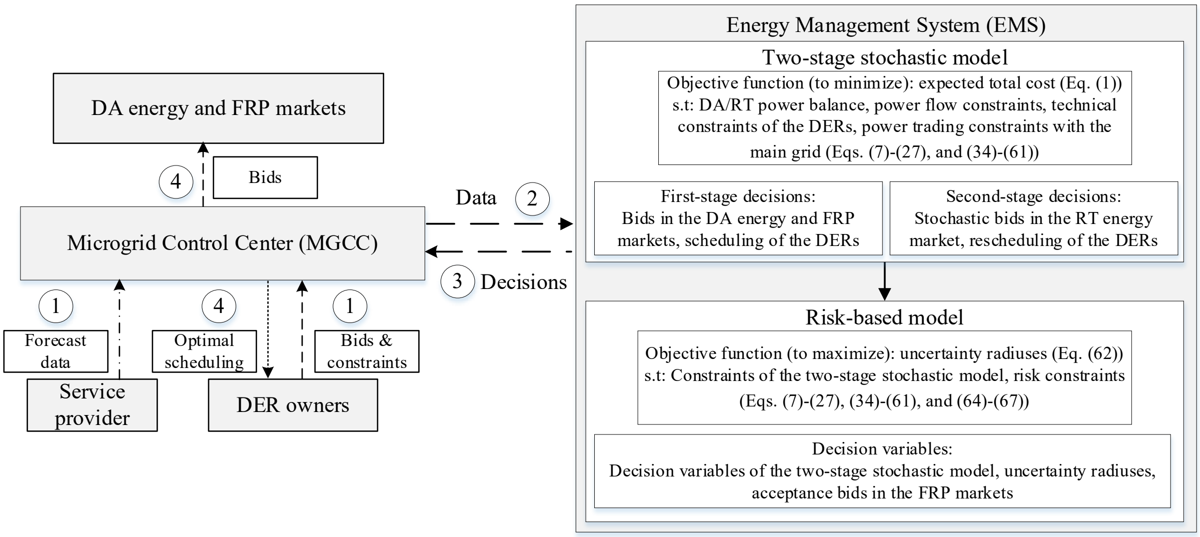


Fig. 1. The decision-making framework of the MGM.

2.2. Bidding Timeline in the Wholesale Markets

The deadline of submitting bids in the DA and RT markets in the CAISO markets are 10:00 am of the previous day of real operation and 75 minutes before the implementation of the RT market in the operation day, respectively. Therefore, the optimized bids of the MGMs obtained in this paper are sent to the DA energy and FRP markets before its deadline. To participate in the RT energy market, at first, the MGM should estimate the generated scenario closest to the

RT conditions. The results obtained from solving the proposed two-stage model in that scenario are considered as the MGM bids in the RT market.

2.3. Bid Acceptance Probability in the FRP Market

The required upward and downward ramp capacities of the system are determined by calculating the error of the net load forecasting using the historical data. In addition, the price of the FRP market is calculated by multiplying the penalty price of the RT power balance shortage with the probability of occurrence of this shortage without the FRP service. Then, the ISO clears the FRP market considering the opportunity cost[1] of the market participants, the FRP market price, and the required amount of the ramp service. For this purpose, the quantity bids of those participants can be accepted if their opportunity costs are lower than or equal to the FRP market prices. Among them, the market participants with lower opportunity cost are selected by the ISO to supply the ramp of the system. Moreover, for the price taker players, e.g., MGMs, with zero price bid in the DA market, their opportunity costs are equal to the DA energy price, which may higher than the FRP price. For these players, it can be assumed that they can provide the ramp for the FRP market at the FRP price [15]. However, considering the required ramp capacity of the system, the bids of all market participants to the FRP market could not be accepted. Therefore, the probability of bid acceptance of the MGMs in the FRP market is a main challenge for these players, whose uncertainty should be modeled. In this paper, the uncertainty aspects are addressed in the risk-based framework presented below.

2.4. Risk-based Two-stage Stochastic Approach

To optimize the MGM bids in the DA energy and FRP markets, the MGM decisions to trade energy with the RT market should be considered through modeling the RT conditions with some scenarios. For this purpose, the uncertain behaviors of wind speed and solar

[1] The opportunity cost is the difference between the market participant bids in the DA energy market and the DA energy market price.

irradiance are modeled through the Weibull probability density functions (PDFs). Moreover, the uncertainties of demand and RT energy price are modeled through the normal PDF. Each PDF is divided into several intervals with specified probabilities, regarding which a large number of uncertain parameters are produced. Then, the scenario tree approach is used [35] to generate several scenarios, which are then reduced to 15 scenarios by using the approach proposed in [35]. Considering the generated scenarios, the MGM problem is modeled as a two-stage stochastic problem, where the first-stage decisions are the MGM bids in the DA energy and FRP markets and the optimal scheduling of the DGs and EESs. The decisions of the MGM in the RT market and its decisions to reschedule the DGs and the EESs are considered as the second-stage variables as shown in Fig. 1.

The IGDT approach is used to model the uncertainty of the bid acceptance in the FRP market, without the need of knowing the PDF of the uncertain parameter, in the decision-making problem of the MGM. Therefore, the MGM decision-making problem is reformulated as a risk-based two-stage stochastic model, where the MGM bids in the DA markets may be changed depending on the risk aversion parameter.

3. Mathematical Modeling

The proposed decision-making problem for the MGM is formulated in this section.

3.1. Two-stage Stochastic Model

The two-stage stochastic model is presented in this sub-section. The expected total cost (*ETC*) of the MGM is modeled in (1) where the total cost *TC* in the DA and RT problems (i.e., first and second stages, respectively) are modeled as the first and second terms, respectively. The RT problem is formulated by considering the $\omega = 1, \ldots, W$ scenarios, with the associated probabilities of occurrence τ_{ω}.

$$\text{Minimize } ETC = TC^{\text{DA}} + \sum_{\omega=1}^{W} \tau_{\omega} TC_{\omega}^{\text{RT}} \tag{1}$$

3.1.1 The DA problem

The DA total cost is defined as Eq. (2), consisting of the cost of power exchange with the DA market (Eq. (3)), the cost of providing energy (Eq. (4)) and ramp capacities (Eq. (5)) for the MGM by the DER owners, and the revenue from providing the ramp capacity for the FRP market (Eq. (6)), respectively. The first, second, and third terms of (4) model the cost of providing energy by the RESs, DGs, and the EESs which is paid by the MGM to the owners, respectively. Since the MGM sells energy to the EES owner regarding its charging bids ($C_t^{\text{ES\_ch}}$), the last term of Eq. (4) is modeled as a revenue term. The cost of providing ramp capacities for the MGM is modeled as (5) considering the DER bids to provide the upward (RU) and downward (RD) ramp capacities and the probabilities $\varphi^{\text{DA\_RU}}$ and $\varphi^{\text{DA\_RD}}$ of upward/downward ramp bid acceptance in the FRP market. The revenue of the MGM from providing the upward and downward ramp capacities for the market is modeled as the first and the second terms of (6) regarding the upward/downward FRP market prices ($\lambda_t^{\text{DA\_RU}}$ and $\lambda_t^{\text{DA\_RD}}$) and the probability of the MGM's bid acceptance in these markets ($\varphi^{\text{DA\_RU}}$ and $\varphi^{\text{DA\_RD}}$).

$$TC^{\text{DA}} = C^{\text{DA\_E}} + C^{\text{DA\_DER\_E}} + C^{\text{DA\_DER\_FRP}} - R^{\text{DA\_FRP}} \tag{2}$$

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

$$C^{\text{DA\_DER\_E}} = \sum_{t=1}^{T} \left[\begin{array}{l} \sum_{f=1}^{F} C_t^{\text{RES}} p_{f,t}^{\text{RES\_DA}} + \sum_{k=1}^{K} C_t^{\text{DG}} p_{k,t}^{\text{DG\_DA}} + \\ \sum_{e=1}^{E} C_t^{\text{ES\_dch}} p_{e,t}^{\text{ESdch\_DA}} - \sum_{e=1}^{E} C_t^{\text{ES\_ch}} p_{e,t}^{\text{ESch\_DA}} \end{array} \right] \tag{4}$$

$$C^{\text{DA\_DER\_FRP}} = \sum_{t=1}^{T} \left[\begin{array}{l} \varphi^{\text{DA\_RU}} \left(\sum_{f=1}^{F} C_t^{\text{RES\_RU}} p_{f,t}^{\text{RES\_RU}} + \sum_{k=1}^{K} C_t^{\text{DG\_RU}} p_{k,t}^{\text{DG\_RU}} + \sum_{e=1}^{E} C_t^{\text{ES\_dch\_RU}} p_{e,t}^{\text{ES\_RU}} \right) \\ + \varphi^{\text{DA\_RD}} \left(\sum_{f=1}^{F} C_t^{\text{RES\_RD}} p_{f,t}^{\text{RES\_RD}} + \sum_{k=1}^{K} C_t^{\text{DG\_RD}} p_{k,t}^{\text{DG\_RD}} + \sum_{e=1}^{E} C_t^{\text{ES\_ch\_RD}} p_{e,t}^{\text{ES\_RD}} \right) \end{array} \right] \tag{5}$$

$$R^{\text{DA\_FRP}} = \sum_{t=1}^{T} \lambda_t^{\text{DA\_RU}} \left(\varphi^{\text{DA\_RU}} p_t^{\text{MG\_DA\_RU}} \right) + \sum_{t=1}^{T} \lambda_t^{\text{DA\_RD}} \left(\varphi^{\text{DA\_RD}} p_t^{\text{MG\_DA\_RD}} \right) \tag{6}$$

The technical constraints related to the DERs and the power exchange with the main grid in the DA problem are described as follows:

- *Power balance:* The sum of the scheduled power generation of RESs and DGs, the discharging power of the EESs, and the purchased power from the market is equal to the sum of the forecast of the MG load (MGL), the charging power of EESs, and the sold power to the market as modeled in (7), for each time step.

$$\sum_{f=1}^{F} p_{f,t}^{\mathrm{RES\_DA}} + \sum_{k=1}^{K} p_{k,t}^{\mathrm{DG\_DA}} + \sum_{e=1}^{E} p_{e,t}^{\mathrm{ESdch\_DA}} + p_{t}^{\mathrm{MG\_DA\_E_{in}}} = \sum_{l=1}^{L} \hat{\mathrm{P}}_{l,t}^{\mathrm{MGL\_DA}} + \sum_{e=1}^{E} p_{e,t}^{\mathrm{ESch\_DA}} + p_{t}^{\mathrm{MG\_DA\_E_{out}}} \; : \forall t \tag{7}$$

- *Ramp capacity balance:* At each time step, the upward and downward ramp capacity provided by the MGM for the FRP market is equal to the sum of these ramp capacities provided by the DERs as shown in (8) and (9), respectively.

$$p_{t}^{\mathrm{MG\_DA\_RU}} = \sum_{f=1}^{F} p_{f,t}^{\mathrm{RES\_RU}} + \sum_{k=1}^{K} p_{k,t}^{\mathrm{DG\_RU}} + \sum_{e=1}^{E} p_{e,t}^{\mathrm{ES\_RU}} \qquad : \forall t \tag{8}$$

$$p_{t}^{\mathrm{MG\_DA\_RD}} = \sum_{f=1}^{F} p_{f,t}^{\mathrm{RES\_RD}} + \sum_{k=1}^{K} p_{k,t}^{\mathrm{DG\_RD}} + \sum_{e=1}^{E} p_{e,t}^{\mathrm{ES\_RD}} \qquad : \forall t \tag{9}$$

- *RES constraints:* The DA scheduling of RESs considers the RES forecast output power as modeled in (10).

$$p_{f,t}^{\mathrm{RES\_DA}} + p_{f,t}^{\mathrm{RES\_RU}} \le \hat{\mathrm{P}}_{f,t}^{\mathrm{RES}} \;\; , \;\; p_{f,t}^{\mathrm{RES\_DA}} - p_{f,t}^{\mathrm{RES\_RD}} \ge 0 \qquad : \forall f, t \tag{10}$$

- *DG constraints:* The DA scheduling decisions of the DGs to provide energy and ramp capacity for the MGM are determined considering the maximum capacity of DGs (Eq. (11)) and the DG ramp-up and ramp-down limitations (Eqs. (12) and (13), respectively). For t=1, the variables with subscript t-1 in Eqs. (12) and (13) are replaced with their initial values.

$$p_{k,t}^{\mathrm{DG\_DA}} + p_{k,t}^{\mathrm{DG\_RU}} \le \overline{\mathrm{P}}_{k}^{\mathrm{DG}} \;\; , \;\; p_{k,t}^{\mathrm{DG\_DA}} - p_{k,t}^{\mathrm{DG\_RD}} \ge 0 \qquad : \forall k, t \tag{11}$$

$$\left(p_{k,t}^{\mathrm{DG\_DA}} + p_{k,t}^{\mathrm{DG\_RU}}\right) - \left(p_{k,t-1}^{\mathrm{DG\_DA}} - p_{k,t-1}^{\mathrm{DG\_RD}}\right) \le \mathrm{RU}_{k} \qquad : \forall k, t \tag{12}$$

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

- *EES constraints:* The DA power scheduling of EESs to charge/discharge and to provide the upward and downward ramp capacities for the MGM are determined considering the maximum charging and discharging capacity of the EESs as modeled in (14) and (15), respectively. Eqs. (16)-(18) are used to avoid simultaneous charging and discharging of the EES in a time step. The stored energy in the EESs in each time step is obtained regarding the amount of their power charging and discharging as modeled in (19) and the minimum and maximum limitations of the stored energy in EESs are modeled as (20). The energy constraints of the EESs to provide the ramp capacity are modeled in (21). The required energy capacity of the EES to provide the upward ($E_{e.t}^{\text{ES\_RU}}$) and the downward ($E_{e.t}^{\text{ES\_RD}}$) ramp capacities depend on the stored energy in the ESS and its minimum and maximum capacities. These variables are defined as $E_{e.t}^{\text{ES\_RU}}=p_{e.t}^{\text{ES\_RU}}/\eta^{\text{dch}}$ and $E_{e.t}^{\text{ES\_RD}}=p_{e.t}^{\text{ES\_RD}}\eta^{\text{ch}}$. Eq. (22) is used to model this issue that the stored energy in the EES in the final time step is equal to its initial value.

$$p_{e,t}^{\text{ESch\_DA}}+p_{e,t}^{\text{ES\_RD}}-p_{e,t}^{\text{ESdch\_DA}}\leq \overline{\text{P}}_e^{\text{ch}} \quad :\forall e,t \tag{14}$$

$$-p_{e,t}^{\text{ESch\_DA}}+p_{e,t}^{\text{ESdch\_DA}}+p_{e,t}^{\text{ES\_RU}}\leq \overline{\text{P}}_e^{\text{dch}} \quad :\forall e,t \tag{15}$$

$$0\leq p_{e,t}^{\text{ESch\_DA}}\leq \overline{\text{P}}_e^{\text{ch}}U_{e,t}^{\text{ch\_DA}} \quad :\forall e,t \tag{16}$$

$$0\leq p_{e,t}^{\text{ESdch\_DA}}\leq \overline{\text{P}}_e^{\text{dch}}U_{e,t}^{\text{dch\_DA}} \quad :\forall e,t \tag{17}$$

$$U_{e,t}^{\text{ch\_DA}}+U_{e,t}^{\text{dch\_DA}}\leq 1 \quad :\forall e,t \tag{18}$$

$$E_{e,t}^{\text{ES\_DA}}=E_{e,t-1}^{\text{ES\_DA}}+\left(p_{e,t}^{\text{ESch\_DA}}\eta^{\text{ch}}\right)-\left(p_{e,t}^{\text{ESdch\_DA}}/\eta^{\text{dch}}\right) \quad :\forall e,t \tag{19}$$

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

$$E_{e,t}^{\text{ES\_RU}}\leq E_{e,t}^{\text{ES\_DA}}-\underline{\text{E}}_e^{\text{ES}} \quad , \quad E_{e,t}^{\text{ES\_RD}}\leq \overline{\text{E}}_e^{\text{ES}}-E_{e,t}^{\text{ES\_DA}} \quad :\forall e,t \tag{21}$$

$$E_{e,ini}^{\text{ES}}=E_{e,t=T}^{\text{ES\_DA}} \quad :\forall e \tag{22}$$

- *Constraints of power exchange with the grid:* The constraints of MG power trading with the grid when the MGM purchases energy from the DA market and sells energy to this market are modeled in (23) and (24), respectively. The details of modeling these constraints are described in the Appendix. The upward and downward ramp capacity provided to the FRP market are positive variables as modeled in Eq. (25). According to (26) and (27), the MG cannot simultaneously purchase/sell power from/to the DA market at each time step, simultaneously.

$$p_t^{\mathrm{MG\_DA\_E_{in}}} + p_t^{\mathrm{MG\_DA\_RD}} \le \overline{\mathrm{P}}^{\mathrm{MG}} \quad , \quad p_t^{\mathrm{MG\_DA\_RU}} \le \overline{\mathrm{P}}^{\mathrm{MG}} + p_t^{\mathrm{MG\_DA\_E_{in}}} \quad : \forall t \tag{23}$$

$$p_t^{\mathrm{MG\_DA\_E_{out}}} + p_t^{\mathrm{MG\_DA\_RU}} \le \overline{\mathrm{P}}^{\mathrm{MG}} \quad , \quad p_t^{\mathrm{MG\_DA\_RD}} \le \overline{\mathrm{P}}^{\mathrm{MG}} + p_t^{\mathrm{MG\_DA\_E_{out}}} \quad : \forall t \tag{24}$$

$$p_t^{\mathrm{MG\_DA\_RU}} \ge 0 \quad : \forall t \ , \ p_t^{\mathrm{MG\_DA\_RD}} \ge 0 \quad : \forall t \tag{25}$$

$$0 \le p_t^{\mathrm{MG\_DA\_E_{in}}} \le \overline{\mathrm{P}}^{\mathrm{MG}} U_t^{\mathrm{MG\_DA\_in}} \quad , \quad 0 \le p_t^{\mathrm{MG\_DA\_E_{out}}} \le \overline{\mathrm{P}}^{\mathrm{MG}} U_t^{\mathrm{MG\_DA\_out}} \quad : \forall t \tag{26}$$

$$U_t^{\mathrm{MG\_DA\_in}} + U_t^{\mathrm{MG\_DA\_out}} \le 1 \quad : \forall t \tag{27}$$

3.2.2 The RT problem

The RT total cost of the MGM is formulated as Eq. (28), consisting of three terms as (29)-(33). The first one is the cost of power exchange with the RT market (Eq. (29)). The revenue due to the downward/upward ramp capacity deployed in the RT operation is modeled as the second term (Eqs. (30)). Since deploying the downward ramp capacity in the RT operation leads to decreasing the injected power of the MGM to the main grid, this term is modeled as a cost term in (30). The last term is the cost of power exchange between the MGM and the DERs' owners (Eqs. (31)-(33)). The cost of RT rescheduling of the DERs in each scenario is modeled as (32). The cost of providing energy by the DERs when their ramp capacities are deployed in the RT operation is modeled as (33). Since deploying the downward FRP by the DERs is considered as the revenue terms from the viewpoint of the MGM, these terms are modeled with the minus sign in (33).

$$TC_{\omega}^{\mathrm{RT}} = C_{\omega}^{\mathrm{RT\_E}} + C_{\omega}^{\mathrm{RT\_DER}} - R_{\omega}^{\mathrm{RT\_FRP}} \tag{28}$$

$$C_{\omega}^{\mathrm{RT\_E}} = \sum_{t=1}^{T} \lambda_{t,\omega}^{\mathrm{RT\_E}} \left(p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}} - p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}} \right) \tag{29}$$

$$R_{\omega}^{\mathrm{RT\_FRP}} = \sum_{t=1}^{T} \lambda_{t,\omega}^{\mathrm{RT\_E}} \left(p_{t}^{\mathrm{MG\_RU\_Dep}} - p_{t}^{\mathrm{MG\_RD\_Dep}} \right) \tag{30}$$

$$C_{\omega}^{\mathrm{RT\_DER}} = C_{\omega}^{\mathrm{DER\_E}} + C^{\mathrm{DER\_FRP\_Dep}} \tag{31}$$

$$C_{\omega}^{\mathrm{DER\_E}} = \sum_{t=1}^{T} \left[\begin{array}{l} \sum_{f=1}^{F} C_{t}^{\mathrm{RES}} P_{f,t,\omega}^{\mathrm{RES\_RT}} + \sum_{k=1}^{K} C_{t}^{\mathrm{DG}} p_{k,t,\omega}^{\mathrm{DG\_RT}} + \\ \sum_{e=1}^{E} C_{t}^{\mathrm{ES\_dch}} p_{e,t,\omega}^{\mathrm{ESdch\_RT}} - \sum_{e=1}^{E} C_{t}^{\mathrm{ES\_ch}} p_{e,t,\omega}^{\mathrm{ESch\_RT}} \end{array} \right] \tag{32}$$

$$C^{\mathrm{DER\_FRP\_Dep}} = \sum_{t=1}^{T} \left[\begin{array}{l} \sum_{k=1}^{K} C_{t}^{\mathrm{RES}} \left(p_{k,t}^{\mathrm{RES\_RU\_Dep}} - p_{k,t}^{\mathrm{RES\_RD\_Dep}} \right) + \sum_{k=1}^{K} C_{t}^{\mathrm{DG}} \left(p_{k,t}^{\mathrm{DG\_RU\_Dep}} - p_{k,t}^{\mathrm{DG\_RD\_Dep}} \right) + \\ \sum_{e=1}^{E} \left(C_{t}^{\mathrm{ES\_dch}} p_{e,t}^{\mathrm{ES\_RU\_Dep}} - C_{t}^{\mathrm{ES\_ch}} p_{e,t}^{\mathrm{ES\_RD\_Dep}} \right) \end{array} \right] \tag{33}$$

The technical constraints of the RT problem are described as follows:

- *RT power balance constraint:* The power balance of the MGM in the RT is modeled as (34) and (35) for the first and the other buses, respectively. In these equations, all decision variables of the MGM in the markets, optimal scheduling of the DERs in the DA and the RT operation, and the amount of the upward/downward FRP capacities of the MGM and the DERs deployed in the RT operation are considered. Regarding these variables and the RT stochastic demand of the MG, the power losses of the network and the power flows among the network buses are determined.

$$\begin{array}{l} \left(p_{t}^{\mathrm{MG\_DA\_E_{in}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}} \right) - \left(p_{t}^{\mathrm{MG\_DA\_E_{out}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}} \right) + \left(p_{t}^{\mathrm{MG\_RD\_Dep}} - p_{t}^{\mathrm{MG\_RU\_Dep}} \right) \\ + \sum_{f \in M_{i}^{RES}} \left(P_{f,t}^{\mathrm{RES\_DA}} + P_{f,t,\omega}^{\mathrm{RES\_RT}} + \left(P_{f,t}^{\mathrm{RES\_RU\_Dep}} - P_{f,t}^{\mathrm{RES\_RD\_Dep}} \right) \right) + \\ \sum_{k \in M_{i}^{DG}} \left(p_{k,t}^{\mathrm{DG\_DA}} + p_{k,t,\omega}^{\mathrm{DG\_RT}} + \left(p_{k,t}^{\mathrm{DG\_RU\_Dep}} - p_{k,t}^{\mathrm{DG\_RD\_Dep}} \right) \right) + \sum_{e \in M_{i}^{ES}} \left(p_{e,t}^{\mathrm{ESdch\_DA}} + p_{e,t,\omega}^{\mathrm{ESdch\_RT}} + p_{e,t,\omega}^{\mathrm{ES\_RU\_Dep}} \right) \\ - \sum_{e \in M_{i}^{ES}} \left(p_{e,t}^{\mathrm{ESch\_DA}} + p_{e,t,\omega}^{\mathrm{ESch\_RT}} + p_{e,t,\omega}^{\mathrm{ES\_RD\_Dep}} \right) \\ - \sum_{l \in M_{i}^{L}} \mathrm{P}_{l,t,\omega}^{\mathrm{MGL\_RT}} = \sum_{j \in Conec(i,j)} 0.5 \left(p_{i,j,t,\omega}^{\mathrm{Flow}} + p_{i,j,t,\omega}^{\mathrm{Loss}} \right) \quad : \forall t, \omega, i = 1 \end{array} \tag{34}$$

$$\sum_{f\in M_i^{RES}}\left(P_{f,t}^{\text{RES\_DA}}+P_{f,t,\omega}^{\text{RES\_RT}}+\left(P_{f,t}^{\text{RES\_RU\_Dep}}-P_{f,t}^{\text{RES\_RD\_Dep}}\right)\right)+$$
$$\sum_{k\in M_i^{DG}}\left(p_{k,t}^{\text{DG\_DA}}+p_{k,t,\omega}^{\text{DG\_RT}}+\left(p_{k,t}^{\text{DG\_RU\_Dep}}-p_{k,t}^{\text{DG\_RD\_Dep}}\right)\right)+$$
$$\sum_{e\in M_i^{ES}}\left(p_{e,t}^{\text{ESdch\_DA}}+p_{e,t,\omega}^{\text{ESdch\_RT}}+p_{e,t,\omega}^{\text{ES\_RU\_Dep}}\right)-\sum_{e\in M_i^{ES}}\left(p_{e,t}^{\text{ESch\_DA}}+p_{e,t,\omega}^{\text{ESch\_RT}}+p_{e,t,\omega}^{\text{ES\_RD\_Dep}}\right)- \tag{35}$$
$$\sum_{l\in M_i^{L}}\mathrm{P}_{l,t,\omega}^{\text{MGL\_RT}}=\sum_{j\in Conec(i,j)}0.5(p_{i,j,t,\omega}^{\text{Flow}}+p_{i,j,t,\omega}^{\text{Loss}})\ :\forall t,\omega,i\neq 1$$

- *RT energy deployed:* The amount of deployed upward/downward ramp capacity provided by the DERs and the MG is modeled as (36). Since this equation is same for MG, DGs, RESs, and EESs, the letter "y" is used as a general index to represent any of them.

$$p_t^{\text{y\_RU\_Dep}}=\varphi^{\text{DA\_RU}}\psi^{\text{RT\_RU}}p_t^{\text{y\_RU}}\quad,\quad p_t^{\text{y\_RD\_Dep}}=\varphi^{\text{DA\_RD}}\psi^{\text{RT\_RD}}p_t^{\text{y\_RD}} \tag{36}$$

- *RESs constraints:* The RT dispatching constraints of RESs considering their stochastic output power in each scenario and the amount of ramp capacity deployed are modeled in (37) and (38).

$$p_{f,t}^{\text{RES\_DA}}+p_{f,t,\omega}^{\text{RES\_RT}}+p_{f,t}^{\text{RES\_RU\_Dep}}\leq\mathrm{P}_{f,t,\omega}^{\text{RES}}\quad:\forall f,t,\omega \tag{37}$$
$$p_{f,t}^{\text{RES\_DA}}+p_{f,t,\omega}^{\text{RES\_RT}}-p_{f,t}^{\text{RES\_RD\_Dep}}\geq 0\quad:\forall f,t,\omega \tag{38}$$

- *DGs constraints:* The RT dispatching decisions of the DGs to provide energy and upward and downward ramp deployed for the MGM are determined considering the constraints (39) and (40), respectively. The effect of ramp-up and ramp-down limitations of DGs on their RT dispatching is modeled in (41) and (42), respectively. For t=1, the variables with subscript t-1 in Eqs. (41) and (42) are replaced with their initial values.

$$p_{k,t}^{\text{DG\_DA}}+p_{k,t,\omega}^{\text{DG\_RT}}+p_{k,t}^{\text{DG\_RU\_Dep}}\leq\overline{\mathrm{P}}_k^{\text{DG}}\quad:\forall k,t,\omega \tag{39}$$
$$p_{k,t}^{\text{DG\_DA}}+p_{k,t,\omega}^{\text{DG\_RT}}-p_{k,t}^{\text{DG\_RD\_Dep}}\geq 0\quad:\forall k,t,\omega \tag{40}$$
$$\left(p_{k,t}^{\text{DG\_DA}}+p_{k,t,\omega}^{\text{DG\_RT}}+p_{k,t}^{\text{DG\_RU\_Dep}}\right)-\left(p_{k,t-1}^{\text{DG\_DA}}+p_{k,t-1,\omega}^{\text{DG\_RT}}-p_{k,t-1}^{\text{DG\_RD\_Dep}}\right)\leq\mathrm{RU}_k\quad:\forall k,t,\omega \tag{41}$$
$$\left(p_{k,t-1}^{\text{DG\_DA}}+p_{k,t-1,\omega}^{\text{DG\_RT}}+p_{k,t-1}^{\text{DG\_RU\_Dep}}\right)-\left(p_{k,t}^{\text{DG\_DA}}+p_{k,t,\omega}^{\text{DG\_RT}}-p_{k,t}^{\text{DG\_RD\_Dep}}\right)\leq\mathrm{RD}_k\quad:\forall k,t,\omega \tag{42}$$

- *EESs constraints:* The RT power charge/discharge of EESs and their power related to deployment of the upward and the downward ramp capacities for the MGM are determined considering the maximum charging and discharging capacity of the EESs as modeled in (43) and (44), respectively. In these equations, the RT decisions about charging/discharging power of the EESs are limited to the DA power charging/discharging and the deployment of the upward/downward FRP capacities in the RT operation. To avoid simultaneous charging and discharging of the EES in the RT, Eqs. (45)-(47) are used. As modeled in (47) in each time step, only one binary variable can be equal to unity. When $U_{e,t,\omega}^{\text{ch\_RT}} = 1$, the EES can only be charged, while when $U_{e,t,\omega}^{\text{dch\_RT}} = 1$ the EES can only be discharged. The DA and RT power charging/discharging and the amount of deployed ramp are affected on the stored energy in the EESs in each time step as modeled in (48). Since deploying the downward and upward capacities in the RT operation increases and decreases the stored energy of the EES, in (48) these variables are added to the charging and discharging power, respectively. The minimum and maximum limitations of stored energy in the EESs are considered as (49). The reason of using Eq. (50) is the same described for (22).

$$p_{e,t}^{\text{ESch\_DA}} + p_{e,t,\omega}^{\text{ESch\_RT}} + p_{e,t}^{\text{ESch\_RD\_Dep}} - p_{e,t}^{\text{ESdch\_RU\_Dep}} \le \overline{\mathrm{P}}_e^{\text{ch}} \quad :\forall e,t,\omega \tag{43}$$

$$p_{e,t}^{\text{ESdch\_DA}} + p_{e,t,\omega}^{\text{ESdch\_RT}} + p_{e,t}^{\text{ESdch\_RU\_Dep}} - p_{e,t}^{\text{ESch\_RD\_Dep}} \le \overline{\mathrm{P}}_e^{\text{dch}} \quad :\forall e,t,\omega \tag{44}$$

$$0 \le p_{e,t,\omega}^{\text{ESch\_RT}} \le \overline{\mathrm{P}}_e^{\text{ch}} U_{e,t,\omega}^{\text{ch\_RT}} \quad :\forall e,t,\omega \tag{45}$$

$$0 \le p_{e,t,\omega}^{\text{ESdch\_RT}} \le \overline{\mathrm{P}}_e^{\text{dch}} U_{e,t,\omega}^{\text{dch\_RT}} \quad :\forall e,t,\omega \tag{46}$$

$$U_{e,t,\omega}^{\text{ch\_RT}} + U_{e,t,\omega}^{\text{dch\_RT}} \le 1 \quad :\forall e,t,\omega \tag{47}$$

$$\begin{aligned} E_{e,t,\omega}^{\text{ES\_RT}} = E_{e,t-1,\omega}^{\text{ES\_RT}} + \left(\left(p_{e,t}^{\text{ESch\_DA}} + p_{e,t,\omega}^{\text{ESch\_RT}} + p_{e,t,\omega}^{\text{ES\_RD\_Dep}}\right)\eta^{\text{ch}}\right) - \\ \left(\left(p_{e,t}^{\text{ESdch\_DA}} + p_{e,t,\omega}^{\text{ESdch\_RT}} + p_{e,t,\omega}^{\text{ES\_RU\_Dep}}\right)\Big/\eta^{\text{dch}}\right) :\forall e,t,\omega \end{aligned} \tag{48}$$

$$\underline{\mathrm{E}}_e^{\text{ES}} \le E_{e,t,\omega}^{\text{ES\_RT}} \le \overline{\mathrm{E}}_e^{\text{ES}} \quad :\forall e,t,\omega \tag{49}$$

$$E_{e,ini}^{\text{ES}} = E_{e,t=T,\omega}^{\text{ES\_RT}} \; :\forall e,\omega \tag{50}$$

7) Constraints of power exchange with the grid: Eqs. (51) and (52) are used to model the limitations of the MGM purchased power from the RT market when the downward and upward ramp capacities are deployed, respectively. The limitations of the MGM sold power to the RT market when the downward and upward FRPs are deployed are modeled as (53) and (54), respectively. The details on how to obtain these equations are described in the Appendix. Eqs. (55) and (56) are used to avoid purchase/sell power from/to the RT market in a time step, simultaneously.

$$p_t^{\mathrm{MG\_DA\_E_{in}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}} + p_t^{\mathrm{MG\_RD\_Dep}} \le \overline{\mathrm{P}}^{MG} \quad :\forall t,\omega \tag{51}$$

$$p_t^{\mathrm{MG\_DA\_E_{in}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}} - p_t^{\mathrm{MG\_RU\_Dep}} \le \overline{\mathrm{P}}^{\mathrm{MG}} \quad :\forall t,\omega \tag{52}$$

$$p_t^{\mathrm{MG\_DA\_E_{out}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}} - p_t^{\mathrm{MG\_RD\_Dep}} \le \overline{\mathrm{P}}^{\mathrm{MG}} \quad :\forall t,\omega \tag{53}$$

$$p_t^{\mathrm{MG\_DA\_E_{out}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}} + p_t^{\mathrm{MG\_RU\_Dep}} \le \overline{\mathrm{P}}^{\mathrm{MG}} \quad :\forall t,\omega \tag{54}$$

$$0 \le p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}} \le \overline{\mathrm{P}}^{\mathrm{MG}} U_{t,\omega}^{\mathrm{MG\_RT\_in}} \;:\forall t \;\;,\;\; 0 \le p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}} \le \overline{\mathrm{P}}^{\mathrm{MG}} U_{t,\omega}^{\mathrm{MG\_RT\_out}} \;:\forall t,\omega \tag{55}$$

$$U_{t,\omega}^{\mathrm{MG\_RT\_in}} + U_{t,\omega}^{\mathrm{MG\_RT\_out}} \le 1 \quad :\forall t,\omega \tag{56}$$

8) Power flow constraints: Eqs. (57)-(61) are presented to model the power flow problem in the RT operation. The amount of current which flows through MG feeders and also, the limitations related to the capacity of the lines are indicated by Eqs. (57) and (58), respectively. In addition, Eq. (59) limits the voltage amplitude at each MG network bus. Eqs. (60) and (61) describe the amount of active power flows through MG feeders as well as the amount of active power losses. Note that, such variables are associated with the square of voltage and current amplitude, respectively. To avoid the addition of mentioned non-linear terms to the proposed model, the linearization method, referring to [36] is adopted.

$$i_{i,j,t,\omega}^{\mathrm{MG}} = \frac{v_{i,t,\omega}^{\mathrm{MG}} - v_{j,t,\omega}^{\mathrm{MG}}}{Z_{i,j}^{\mathrm{MG}}} \quad :\forall i,j,t,\omega \tag{57}$$

$$-\overline{\mathrm{I}}_{i,j}^{\mathrm{MG}} \le i_{i,j,t,\omega}^{\mathrm{MG}} \le \overline{\mathrm{I}}_{i,j}^{\mathrm{MG}} \quad :\forall i,j,t,\omega \tag{58}$$

$$\underline{\mathrm{V}}_{i}^{\mathrm{MG}} \le v_{i,t,\omega}^{\mathrm{MG}} \le \overline{\mathrm{V}}_{i}^{\mathrm{MG}} \quad :\forall i,t,\omega$$
(59)

$$p_{i,j,t,\omega}^{\mathrm{Flow}} = (\frac{R_{i,j}^{\mathrm{MG}}}{\left(Z_{i,j}^{\mathrm{MG}}\right)^2})\left(\left(v_{i,t,\omega}^{\mathrm{MG}}\right)^2 - \left(v_{j,t,\omega}^{\mathrm{MG}}\right)^2\right) \quad :\forall i,j,t,\omega \tag{60}$$

$$p_{i,j,t,\omega}^{\mathrm{Loss}} = \mathrm{R}_{i,j}^{\mathrm{MG}} \left(i_{i,j,t,\omega}^{\mathrm{MG}}\right)^2 \quad :\forall i,j,t,\omega \tag{61}$$

3.2. Risk-based Model

In this paper, the uncertainty related to the probability of bid acceptance in the FRP market is modeled using the IGDT approach. The rationale and formulation of the IGDT approach are as follows:

- Without considering risks, the ETC is equal to its *base value* identified as ETC_b, calculated by solving the equations (1)-(61).
- The *level of risk* is represented by introducing the risk aversion parameter γ, variable from 0 to 1, where the value 0 identifies the risk-neutral behavior of the MGM, and the value 1 models the high-level of risk of the MGM.
- The *uncertain parameters* are the probabilities of bid acceptance in the ramp-up FRP $\varphi^{\mathrm{DA_RU}}$and ramp-down FRP $\varphi^{\mathrm{DA\_RD}}$, with the corresponding base values $\bar{\varphi}^{\mathrm{DA\_RU}}$ and $\bar{\varphi}^{\mathrm{DA\_RD}}$, respectively.
- Each uncertain parameter is associated with an *uncertainty radius* denoted as α, variable from 0 to 1. A risk-averse MGM maximizes the uncertainty radius to make its decisions robust against the uncertain parameter. A risk-taker MGM would minimize the uncertainty radius, accepting to deal with higher uncertainty.

For the risk-averse MGM, the optimization problem (62) maximizes the sum of the uncertainty radiuses, subject to the constraints (63)-(67). The ETC modeled in (64) is lower than or equal to the base ETC (identified as ETC_b, without modeling risk) when the risk aversion parameter is $\gamma = 0$. When the risk aversion is $\gamma = 1$, the ETC of the risk-averse MGM in the worst case is obtained where the minimum values for the uncertain parameters, i.e.,

$\varphi^{\mathrm{DA\_RU}} = \varphi^{\mathrm{DA\_RD}} = 0$ is obtained. For this purpose, the maximum values for their related uncertainty radius, i.e., α_1=$\alpha_2 = 1$, is obtained. Therefore, in the worst case when the risk aversion parameter is 1, the objective function is equal to 2.

The uncertain parameters are modeled as the variables with the limitations modeled in (64)-(66).

$$\max \quad \alpha = \alpha_1 + \alpha_2 \tag{62}$$

s.t.:

Eqs. (7)-(27) and (34)-(61). (63)

$$ETC \le ETC_b \left(1+\gamma\right) \quad , \quad 0 \le \gamma \le 1 \tag{64}$$

$$0 \le \varphi^{\mathrm{DA\_RU}} \le \left(1-\alpha_1\right) \overline{\varphi}^{\mathrm{DA\_RU}} \quad , \quad 0 \le \varphi^{\mathrm{DA\_RD}} \le \left(1-\alpha_2\right) \overline{\varphi}^{\mathrm{DA\_RD}} \tag{65}$$

$$0 \le \alpha_1 \le 1 \tag{66}$$

$$0 \le \alpha_2 \le 1 \tag{67}$$

The resulting mixed integer linear programming (MILP) optimization model is implemented in GAMS 24.1.2 and is solved via CPLEX12 solver on a PC with 2.8-GHz Core i5 with 6GB RAM.

4. Numerical Results and Discussions

To validate the effectiveness of the proposed model, the 15-bus MG test system [34] is used. The MGL profile and the forecast power of the RESs are the same considered in [19]. Moreover, the technical characteristics and the bids of the DER owners are assumed as in [19]. The initial power of DGs in both DA and RT operation is null. Also, the initial stored energy of the EESs is 1 MWh. The bids of the DERs' owner to provide the ramp capacity are equal 40% of their energy bids. The maximum power exchange of the MG with the grid at the PCC is 5 MVA. The minimum and maximum limitations of the MG bus voltages are 0.9 p.u. and 1.1 p.u., respectively. The location of the DERs in the test system and the proportion of each bus from the MGL are given in Table 3. The probability of the bid acceptance and the amount of the deployment are equal 0.5 and 0.3, respectively [15]. The DA and RT energy prices, and the price of the FRP markets are given in Table 4 [19, 34].

Table 3. Data of the test 15-bus MG

DERs	Location of DERs (Bus number)	Load number	Location of loads (Bus number)	Percentage of the MG load	Load number	Location of loads (Bus number)	Percentage of the MG load
PV	3, 7, and 11	L1	2	15	L6	10	7.5
WT	2, 6, and 10	L2	3	15	L7	11	10
DG	4, 8, 12, and 15	L3	5	12.5	L8	13	10
EES	3, 5, 9, and 13	L4	8	12.5	L9	15	10
		L5	9	7.5			

Table 4. The DA and the RT market prices ($/MWh)

Time (hour)	DA energy market	RT energy market	Upward FRP market	Downward FRP market
1	18.15	18.75	1.60	3.80
2	16.71	17.93	2.00	2.90
3	15.36	14.96	5.30	2.00
4	14.44	14.23	5.50	2.00
5	14.09	14.60	5.75	2.00
6	14.74	17.14	2.00	3.00
7	15.94	19.80	5.50	2.00
8	17.23	21.02	2.40	4.20
9	18.83	20.13	6.80	2.00
10	19.93	22.61	7.20	2.00
11	22.15	30.15	2.80	0.85
12	24.13	45.49	6.00	1.00
13	27.94	34.08	2.20	1.80
14	30.31	52.54	5.60	2.00
15	33.78	39.75	5.60	2.00
16	36.03	28.46	5.85	1.60
17	38.05	27.20	2.90	0.85
18	39.38	22.97	6.00	1.20
19	32.92	23.22	6.50	0.30
20	24.62	21.68	3.00	0.70
21	24.08	21.18	6.40	0.50
22	22.81	22.52	7.00	0.30
23	20.23	18.48	3.00	0.70
24	18.96	18.15	6.00	1.90

4.1. The MGM Decisions in the Markets

The DA decisions of the MGM to schedule the DERs and to participate in the DA energy and FRP markets are shown in Fig. 2 and Fig. 3. Also, the RT MGM decisions are described in Fig. 4. The results show the following strategies of the MGM to minimize its expected total cost.

The MGM decisions at hours 1-10 are completely dependent on the upward FRP prices. When the upward FRP price increases at hour 2 in comparison with hour 1, the upward ramp capacity increases and this trend continues at hours 3-5. With decreasing and increasing the upward FRP price at hours 6-10, the upward ramp capacity provided by the MGM to the FRP market has the same trend as shown in Fig. 3. The main reason of increasing the upward ramp capacity at hour 8 in comparison with hour 6 is the high amount of RT price at hour 8. As shown in Fig. 3, the main resource of providing the ramp capacities for the FRP market is the EES[1]. As shown in Fig. 2 and Fig. 3, by increasing the charging power of the ESSs at hours 2, 5, and 7, the downward ramp capacity of the EESs decreases in these hours. Also, with discharging the EESs at hours 6, 9, and 10, the upward and downward ramp capacities decrease and increase, respectively[2].

As shown in Fig. 2, the MGM decides to supply most of the MGL through purchasing energy from the DA market at hours 11, 12, 14, and 15, for two main reasons: (i) to procure the DER capacities with the aim of providing the upward ramp capacity for the FRP market and generating energy in the RT operation to sell energy to the RT market in case of high RT energy market price, and (ii) to increase the capacity of the MG to provide the upward ramp capacity in the FRP market[3].

Since the upward FRP market price at hour 13 is lower than in other hours, the MGM decreases the upward ramp capacity and increases the downward ramp capacity provided to the market, by discharging the ESSs. The other reason for discharging the EESs in this hour is to release the EESs' capacities to charge at next hours, i.e., 14 and 15. As shown in Fig. 4, the MGM strategy about the EESs changes in the RT operation in comparison with the DA. In the RT operation, the EESs are discharged at hours 11, 12, 14, and 15 to sell energy to the RT market[4]. The main reason of charging the EESs at hour 13 is to increase the EES stored energy

[1] The downward ramp capacity provided by the MGM is only obtained from the EESs as shown in Fig. 3.
[2] This behavior of the EESs is modeled in Eqs. (13) and (14) where with increasing the charging power of the EESs, the MGM capability to provide the downward ramp decreases (Eq. (13). Also, with increasing the discharging power of the EESs, the MGM capability to provide the downward (Eq. (13) and the upward (Eq. (14) ramp capacity increases and decreases, respectively.
[3] This issue is modeled in (22) where with increasing the power purchased from the DA energy market, the upward ramp capacity can increase.
[4] For this purpose, the EESs are charged in the DA operation to increase the EESs' stored energy with the aim of discharging them in these hours. This behavior of the EESs is modeled in (47).

to discharge at hours 14 and 15, to sell energy to the RT market since the RT market price at hours 14 and 15 are higher than at hour 13.

At hour 16, the MGM decides to meet its load from the DGs and decreases the purchased power from the DA market since the DA energy market price is high in this hour. Also, the MGM uses the capacity of the EESs to provide the upward ramp capacity for the market since its price is high at this hour.

The MGM sells energy to the DA energy market through deploying the DGs and EESs at hour 17 and hour 18, considering the high DA market price in these hours. Since the MGM sells energy to the DA market in these hours, its capability to provide the upward ramp capacity decreases[1].

The main reason to purchase energy from the RT market at hours 17-19 is to charge the EESs with the aim of discharging them at hours 20-22 where the MGL has higher values. In fact, since the EESs are scheduled to discharge at hours 17-19 in the DA energy market, the MGM decides to charge them at these hours in the RT operation, to reach the appropriate capacity to discharge them at hours 20-22 as shown in Fig. 4.

At hours 20-22, the MGM purchases energy from the DA market and uses the DGs to meet its demand (with high values at these hours) and to charge the EESs. Also, the MGM provides the upward ramp capacity for the FRP market at these hours. As shown in Fig. 3, since the upward ramp price at hour 22 is higher than at hours 20 and 21, the upward ramp capacity of the MGM is higher at this hour. Also, these MGM decisions in the DA increase the MGM capability to sell more energy in the RT market, since the RT energy price at hours 20-22 are higher than at the next hours, i.e., hour 23 and hour 24. Since the downward ramp price is high at hour 24, the MGM decides to increase the downward ramp capacity at this hour.

[1] This behavior proves the proposed model in Eq. (23).

At hours 2, 11, 12, and 14-16, the downward ramp provided by the EESs reaches zero for two main reasons: (i) the high amount of charging power of the EESs at hours 2, 11, 12, 14, and 15 reduces the downward ramp capacity of the EESs (see Eq. (13)), and (ii) the MGM revenue from the ramp capacity is obtained through providing the ramp capacity in the DA FRP market and providing energy in the RT when the ramp capacity is deployed. The main point is that when both the upward and downward ramp capacities are deployed in the RT operation, the revenue decreases as modeled in Eq. (29). Therefore, when the RT energy market price is high at hours 11, 12, and 14-16, the MGM decides to decrease the downward ramp capacity to obtain the more profit from the deployment of the upward ramp capacity in the RT operation. The main reason for providing zero downward ramp capacity for the market at hours 19-23 is the lower amount of the downward FRP price in these hours.

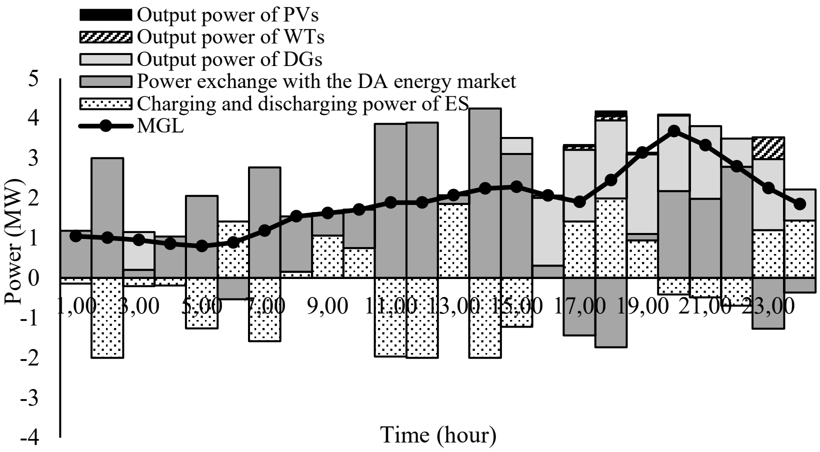


Fig. 2. Power balance in the DA energy market

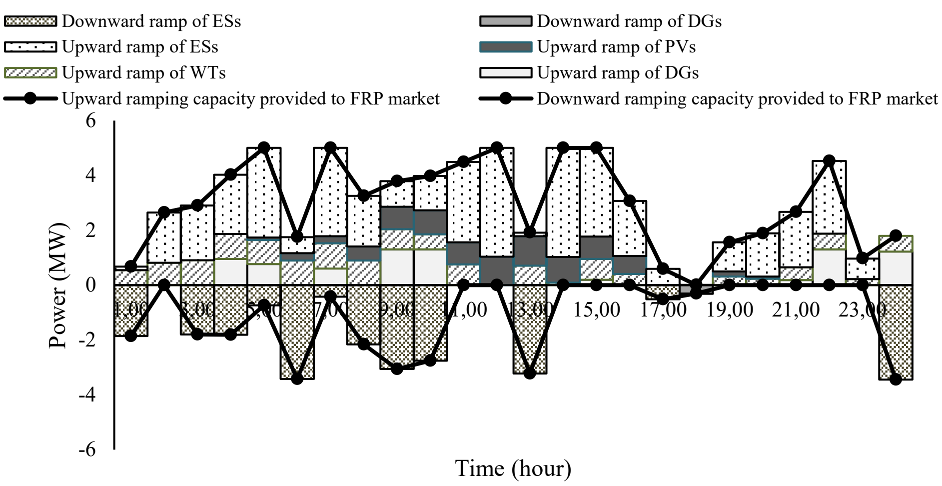


Fig. 3. The share of FRP providers in upward and downward ramping capacity

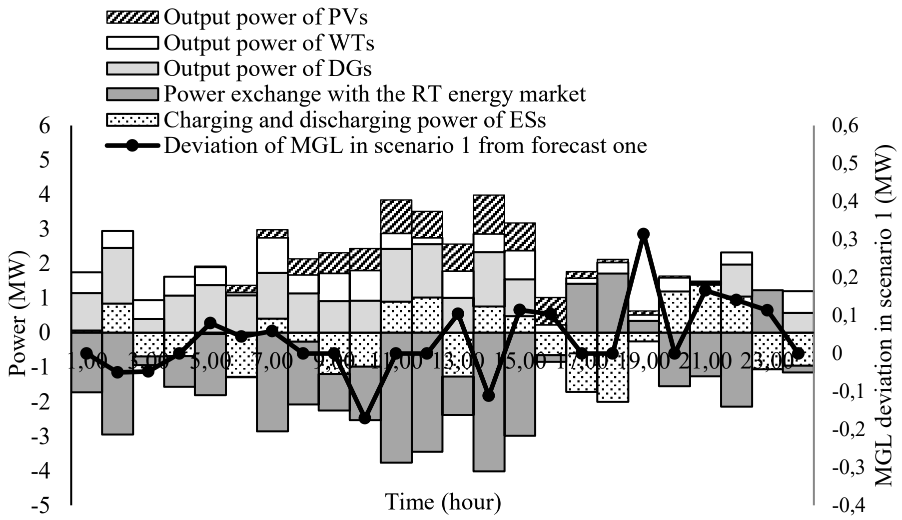


Fig. 4. The output power of MG resources and power exchange with the RT market in Case II.

The main conclusions from these results are presented as follows:

- The MGM has different strategies from participating in the DA energy and RT markets. It usually participates in the DA energy market as a consumer to purchase the required energy to meet the MGL and to charge the EESs. The MGM usually acts as a producer in the RT energy market, so that it sells energy to the market at hours 1-5, 7-16, 20-22, and 24.
- Traditionally, the EESs are scheduled considering the arbitrage behavior in the market to charge in the hours with low energy market price, then the EESs are discharged to sell energy to the market in the hours with high energy market price. In this paper, the results show the new strategy to schedule the EESs. In this case, charging/discharging of the EES is done with the aim of releasing its capacity to provide upward/downward ramp capacities for the market.

4.2. *Comparisons among the MGM Decisions to Participate in Different Markets*

Let us consider as *Base case* the MGM participation in both the DA and RT energy markets considering the FRP market. The aim of this sub-section is to show the effectiveness of the MGM participation by comparing the *Base case* with the following cases:

- Case I: The MGM participates in the DA and RT energy market without participating in the FRP market.
- Case II: The MGM participates in the DA energy and FRP markets without participating in the RT market.

The results of the cost/revenue of the MGM in these cases are given in Table 5. In this table, the objective function of the *Base case* and Case I is defined as the ETC, and the objective function of Case II is defined as TC[1]. The profit of the MGM from deploying the FRP capacities in this case is 174.7$. As shown in Table 5, the MGM obtains the best objective function in the *Base case* in comparison with other cases, for the following reasons:

- The MGM decides to use the DER capacities to provide the ramp service for the FRP market in the *Base case*. The MGM also increases the share of the DERs in supplying the required energy of the MG in the DA operation in the *Base case* in comparison with Case I. These decisions of the MGM change the MGM cost/revenue in the DA and the RT operation period as follows:
  1) Decreasing the purchased energy from the DA energy market in the *Base case* in comparison with Case I, which leads to decreasing its cost in the DA energy market from 941.00$ to 688.62$.
  2) Obtaining revenue from providing the ramp service for the FRP market, i.e., 213.69$ and providing energy in the RT when its capacities are deployed, i.e., 204.61$.
  3) Decreasing the revenue of the MGM from participation in the RT market in the *Base case* in comparison with Case I, since the lower capacity of the DERs is

[1] Since different scenarios which show the RT conditions are not modeled in this case, its objective function is defined as TC instead of the ETC.

employed to sell energy to the RT market. These decisions of the MGM increase its minus ETC from -17.23$ in Case I to -183.31$ in the *Base case*.

- Since the MGM does not participate in the RT energy market in Case II, the whole capacity of the DERs is used in the DA operation to sell energy to the market and to increase the share of the DERs in supplying the demand in Case II in comparison with the *Base case*. Although the MGM earns profit from trading energy with the DA energy market, these decisions increase the cost of providing energy by the DERs and decreases the MGM revenue from participating in the FRP market. Therefore, the objective function obtained in Case II is lower than one obtained in the *Base case*.

To show how participating in the RT energy market can change the strategies of the MGM to participate in the markets and to schedule its DERs, the optimal decisions of the MGM in the *Base case* and Case II are compared in Table 6. When the MGM only participates in the DA energy market, it usually acts as a producer in the market where it sells 9.02 MW to the market and only purchases 0.57 MW from the DA market. Conversely, in the *Base case* where the MGM participates in both the DA and RT energy markets, the MGM prefers to participate usually in the DA market as a consumer and then decides to participate in the RT energy market as a producer.

Table 5. Detail of the operation cost/revenue of MGM in scenario 1 in different cases

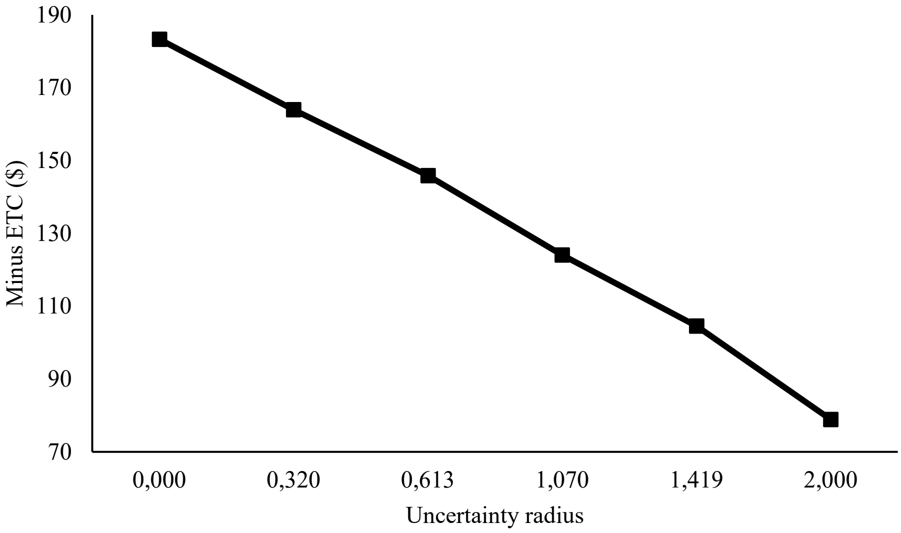
Cost/Revenue of MG in DA operation ($)				Cost/Revenue of MG in RT operation ($)				
	Base case	Case I	Case II			Base case	Case I	Case II
TC^{DA}	688.62	941.00	153.17	$TC_{\omega}^{\mathrm{RT}}$		-862.10	-960.83	-
$Cost^{\mathrm{DA\_E}}$	652.95	813.68	-181.95	$Cost_{\omega}^{\mathrm{RT\_E}}$		-944.43	-1322.85	-
$Revenue^{\mathrm{DA\_FRP}}$	213.69	0	141.74	$Revenue_{\omega}^{\mathrm{RT\_FRP}}$		204.61	0	-
$Cost^{\mathrm{DA\_DER}}$	249.36	127.31	476.86	$Cost_{\omega}^{\mathrm{RT\_DER}}$	$Cost_{\omega}^{\mathrm{DER\_E}}$	255.92	362.02	-
Objective function	-183.31	-17.23	-21.53		$Cost_{\omega}^{\mathrm{DER\_FRP\_Dep}}$	31.10	0	-

Table 6. Comparison of the results of base case and Case II (MW)

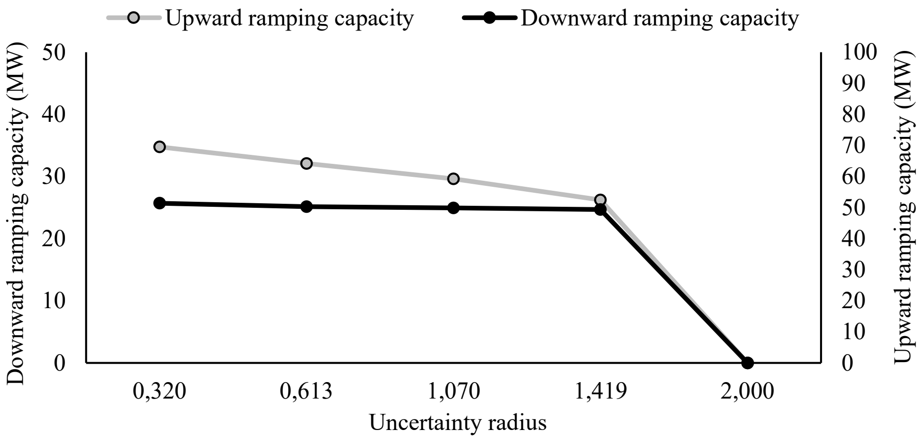
Decision variables		Base case		Case II
		DA decisions	RT decisions	
Purchased energy from the market		35.89	4.71	0.57
Sold power to the market		5.34	35.55	9.02
Charging power of the EESs		14.15	13.41	6.49
Discharging power of the EES		12.23	8.47	5.55
Power generation of DGs		15.75	19.18	30.17
Scheduled power of the RESs		1.03	18.94	25.83
Capacity provided for the upward FRP market by each resource	EESs	42.07	-	43.96
	DGs	7.83	-	14.2
	RESs	21.61	-	0
Capacity provided for the downward FRP market by each resource	EESs	25.2	-	0
	DGs	0.3	-	0
	RESs	0	-	0

4.3. *Results of the IGDT Approach*

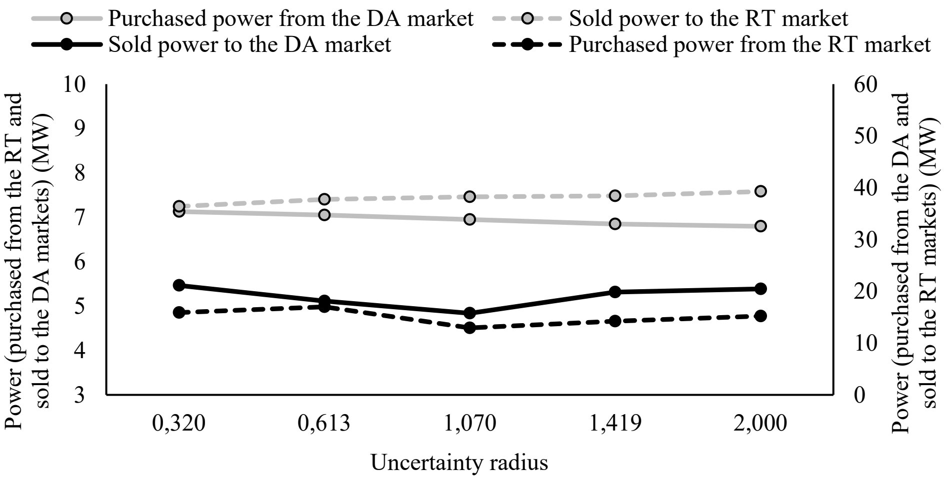
The MGM decisions to manage the uncertainty related to the probability of bid acceptance are investigated in this sub-section. From Fig. 5, the minus ETC experiences a significant reduction from 183.31$ to 78.90$ as the uncertainty radius increases. In fact, when the uncertainty radius increases, the probability of bid acceptance in the FRP market decreases, so that the risk-averse MGM decides to participate more in the energy markets than in the FRP market. In this case, the upward and the downward ramp capacities provided for the FRP market decrease from 71.53 MW and 25.51 MW to 0 MW, respectively. Therefore, the DER capacities are released to provide more energy for the MG, so that the power purchased from the DA market decreases from 35.88 MW to 32.54 MW and the power sold to the RT market increases from 35.55 MW to 39.26 MW.



(a)



(b)



(c)

Fig. 5. The sensitivity of MGM decisions to uncertainty radius in Case B.

4.4. Discussion on Confirming the Effectiveness of the Contributions

The aim of this sub-section is to show how the obtained results confirm that the contributions presented in this paper are effective.

The first contribution refers to model the MGM decision-making problem to provide the ramp service for the FRP market considering its trading energy with both the DA and RT energy markets (the situation indicated as *Base case* in the results). As the results show, the profit of the MGM increases in the *Base case* in comparison with Case II where the MGM does not participate in the RT energy market. This is done with changing the decision strategies of the MGM in the markets. In the *Base case* the MGM prefers to purchase more energy from the DA energy market and then decides to sell more energy to the RT market, while in Case II the MGM usually acts as a producer in the DA energy market.

The second contribution is the modeling the uncertainty of the MGM bid acceptance in the FRP market in the decision-making problem of the MGM. As the results show, this parameter has an important effect on the MGM decisions in the market, so that the risk-averse MGM decides to decrease its ramp capacity provided for the FRP market to zero when its risk aversion parameter increases. The results also prove the impact of exactly modeling the MG power constraints with the main grid on the MGM decisions in the markets. This issue was not considered in the previous studies.

5. Conclusions and future work

In this paper, a mathematical formulation has been developed to model the MGM bids in the FRP market, besides the MGM strategies to trade energy with both the DA and RT energy markets. To address the uncertainty of the probability of the bid acceptance in the FRP market, the MGM decision-making problem in the market has been reformulated as a risk-based optimization problem. To show the performance of the proposed model, three cases have considered in the numerical results. The main conclusions from the results are as follows.

- The minus ETC of the MGM in Case I, without participating in the FRP market, and in the *Base case*, with participating in the FRP market, are 17.23$ and 183.31$, respectively. The profit of the MGM in the *Base case* has been increased through changing the MGM strategies to participate in the DA and RT energy markets considering the FRP market. Without considering the FRP market, the MGM uses the DER capacities to sell more energy to the RT market. Conversely, considering the FRP market, the MGM uses the DERs to provide the ramp capacities for the FRP market to earn more profit.
- The MGM earns more profit in the *Base case* in comparison with Case II where the MGM does not participate in the RT energy market. This is also obtained changing the strategies of the MGM to participate in the energy markets. In Case II, the MGM acts mostly as a producer in the DA energy market, while in the *Base case* the MGM role in the DA energy market changes to consumer so that in most hours the MGM purchases energy from this market. Then, the MGM appears in the RT energy market as a producer where it usually sells energy to this market.
- The risk-averse MGM decreases its ramp capacities provided for the FRP market when the uncertainty radius increases (the probability of bids acceptance in the FRP market decreases). Regarding this decision, the MGM purchases less energy from the DA market and sells more energy to the RT market.

The proposed risk-based two-stage stochastic model in this paper can be extended in the future works with the aim of providing the flexibility service by the MGM for the DSO. For this purpose, if the DSO directly sends its request to the MGM, this request is considered in the power trading with the grid constraints regarding which the DA and the RT decisions variables of the MGM are determined. Also, if the flexibility request is sent for the MGM by the LFO, the MGM model has to be reformulated considering the local flexibility market variables. In this case, the MGM decision variables are the energy bids in the DA and the RT markets, the DA bids in the FRP market, the DA bids in the local flexibility market, and the DA and the RT scheduling of the resources.

6. References

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Appendix: Modeling the constraints of the MG power trading with the grid

The DA and RT decisions of the MG in the markets are determined regarding the technical constraints of MG power trading with the main grid as described in Fig. 6 and Table 7. In the left side of Fig. 6, it is assumed that the MGM decides to purchase power from the DA market, regarding which its technical constraints to trade power with the main grid are modeled. For this purpose, the point X is considered to model the first-stage decision of the MG to purchase energy from the DA market and to provide the ramp capacity for the FRP market. The constraints of this point are described in Table 7. When the upward and the downward ramp capacity of the MG are deployed in the RT operation, the decision points of the MGM change to points Y and Z, respectively. In these points, the MGM decisions in the RT market are limited regarding the constraints shown in Table 7. The same approach is used for the MG when the MGM decides to sell energy to the main grid where its constraints are modeled in the points A, B, and C.

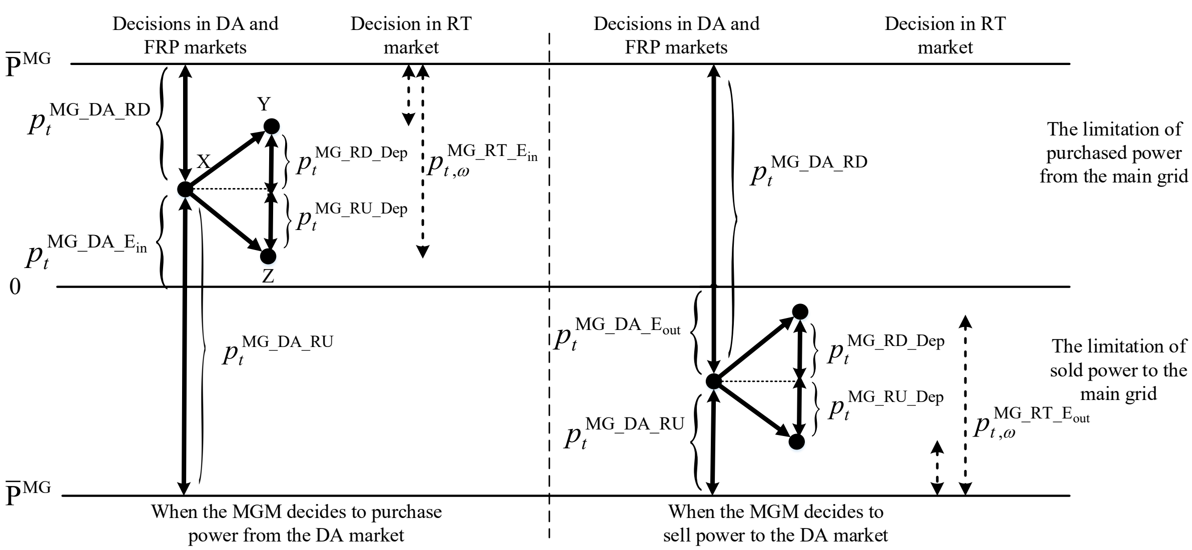

Fig. 6. Description of the MG power trading constraints with the main grid

Table 7. Description of the decision points in Fig. 6.

Decision in the DA market	Decision points	Decision Variables	Constraints
Purchased power	X	Decisions in DA energy and FRP markets	$p_t^{\mathrm{MG\_DA\_E_{in}}} + p_t^{\mathrm{MG\_DA\_RD}} \leq \overline{\mathrm{P}}^{\mathrm{MG}}$ $p_t^{\mathrm{MG\_DA\_RU}} \leq \overline{\mathrm{P}}^{\mathrm{MG}} + p_t^{\mathrm{MG\_DA\_E_{in}}}$
	Y	Decisions in RT market when downward ramp is deployed	$p_t^{\mathrm{MG\_DA\_E_{in}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}} + p_t^{\mathrm{MG\_RD\_Dep}} \leq \overline{\mathrm{P}}^{\mathrm{MG}}$
	Z	Decisions in RT market when upward ramp is deployed	$p_t^{\mathrm{MG\_DA\_E_{in}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{in}}} - p_t^{\mathrm{MG\_RU\_Dep}} \leq \overline{\mathrm{P}}^{\mathrm{MG}}$
Sold power	A	Decisions in DA and FRP markets	$p_t^{\mathrm{MG\_DA\_E_{out}}} + p_t^{\mathrm{MG\_DA\_RU}} \leq \overline{\mathrm{P}}^{\mathrm{MG}}$ $p_t^{\mathrm{MG\_DA\_RD}} \leq \overline{\mathrm{P}}^{\mathrm{MG}} + p_t^{\mathrm{MG\_DA\_E_{out}}}$
	B	Decisions in RT market when downward ramp is deployed	$p_t^{\mathrm{MG\_DA\_E_{out}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}} - p_t^{\mathrm{MG\_RD\_Dep}} \leq \overline{\mathrm{P}}^{\mathrm{MG}}$
	C	Decisions in RT market when upward ramp is deployed	$p_t^{\mathrm{MG\_DA\_E_{out}}} + p_{t,\omega}^{\mathrm{MG\_RT\_E_{out}}} + p_t^{\mathrm{MG\_RU\_Dep}} \leq \overline{\mathrm{P}}^{\mathrm{MG}}$