Information Gap Decision Theory-Based Approach for Modeling Operation Problem of a Grid-Connected Micro-Grid With Uncertainties

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Abstract—Distributed energy resources (DERs) change the supply-demand balance of power systems. To better manage these resources, they are operated as micro-grids (MGs) in both grid-connected and standalone modes. In the presence of MGs, the decision making framework in power systems is changing from the centralized structure into the decentralized one. In such framework, modeling the operation problem of MGs with the participation in energy and reserve markets in the presence of uncertainties is considered as an important challenge. Most of the studies use probability distribution functions (PDFs) to model the uncertain parameters. In this paper, the operation problem of a grid-connected MG is modeled while the MG operator (MGO) faces with uncertainties of renewable energy sources (RESs) without considering their PDFs. For this purpose, an information gap decision theory (IGDT)-based approach is employed to model the uncertain behavior of RESs as well as to control the risk level of the MGO on the optimal scheduling of DERs. To investigate the effectiveness of the model, a modified 15-bus low voltage MG us used as a test system. The results show that optimal decisions of the risk-averse MGO are different from those of a risky one.

Index Terms—Information gap decision theory; micro-grid; renewable energy resources; uncertainties.

NOMENCLATURE

Acronyms

DER	Distributed energy resource
DG	Distributed generator
$Disco$	Distribution company
DN	Distribution network
DR	Demand response
DRP	Demand response program
DSO	Distribution system operator
$IGDT$	Information gap decision theory
IL	Interruptible load
MG	Micro grid
MGO	Micro-grid operator
PDF	Probability distribution functions
RES	Renewable energy source
TC	Total cost

Indices and Sets

nl, NL	Index and set of loads
l, NR	Index and set of renewable resource
i, $NB/\, j,J$	Indices and sets of MG bus
n, NDG	Index and set of DGs
t,T	Index and set of time period
k, NES	Index and set of energy storage

Parameters

C_n^{DG}	Operation cost of DGs (€/kWh)
C_t^{IL}	IL Cost (€/kWh)
C_t^{EM}	Energy market price (€/kWh)
C_t^{RM}	Reserve market price (€/kWh)
κ_t^{RM}	Probability of calling reserve (%)
$P_{nl,i,t}^{load}$	Load at bus i and time t (kW)
η^{Grid}	Grid's transformer efficiency
η^{ES}	Energy storage efficiency
$\overline{P}^{Grid-in} / \overline{P}^{grid-out}$	Maximum power trading limits between Disco with MG (kW)
$\overline{P}_{l,t}^{RES} / \underline{P}_{l,t}^{RES}$	Maximum/ minimum output power of RESs (kW)
$\underline{P}_n^{DG} / \overline{P}_n^{DG}$	Upper/Lower limit of DG (kW)
$\overline{P}_{nl,t}^{IL}$	Maximum amount of load interruption (kW)
$\underline{E}^{ES} / \overline{E}^{Es}$	Upper/Lower limit of battery energy
$\underline{P}_t^{ES-charge} / \overline{P}_t^{ES-charge}$	Upper/Lower limit of energy storage power
$\underline{P}_t^{ES-Discharge} / \overline{P}_t^{ES-Discharge}$	Upper/Lower limit of energy storage power
$R_{i,j}$	Resistance between bus i,j
$Z_{i,j}$	Impedance between bus i,j
$\underline{I}/\bar{I}$	Upper/Lower limit of current magnitude
$\underline{V}/\bar{V}$	Upper/Lower limit of voltage magnitude
β^{IGDT}	IGDT risk aversion parameter
ψ^{IGDT}	IGDT risk taker parameter

Variables

$P_{n,t}^{DG}$	Output power of DGs
$P_{nl,t}^{IL}$	The amount of interruptible load
$P_{i,t}^{D}$	The amount of demand at DN bus (kW)
$P_{i,t}^{Gen}$	Generated power by DERs (kW)
$P^{Grid-in}/P^{grid-out}$	Power trading limitations between Disco with MG (kW)
$P_{l,t}^{RES}$	Output power of RESs (kW)
$P_{k,t}^{ES}$	Output power of energy storage system (kW)
$P_{k,t}^{ES-Discharge} / P_{k,t}^{ES-charge}$	Discharge/charge power of energy storage system (kW)
$E_{k,t}^{ES}$	The amount of battery storage (kWh)
$P_{i,j,t}^{flow}$	The amount of power flow from bus i to j (kW)
$P_{i,j,t}^{loss}$	The amount of active power losses (kW)
$R_{n,t}^{DG}$	The amount of reserve provided by DGs (kW)
$R_{nl,t}^{IL}$	The amount of reserve provided by interrupted loads (kW)
$R_{k,t}^{ES}$	The amount of reserve provided by energy storage (kW)
R_t^{Dis}	Total reserve provided by resources to Disco (kW)

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$I_{i,j,t}$	Current magnitude between bus i,j
$V_{i,t}$	Voltage magnitude at bus i
$P_{i,j,t}^{Inj}$	Active power injection between bus i,j
$P_{i,j,t}^{Flow}$	Active power flow between bus i,j
$P_{i,j,t}^{Loss}$	Active power losses between bus i,j
α^{IGDT}	Uncertainty radius

I. INTRODUCTION

A. Motivation and Background

Distributed energy resources (DERs) have penetrated in distribution networks (DNs) during the recent years. DERs provide reliable, effective and economic energy and they are appropriate solution to solve the environmental and the technical problems of power systems. DERs consist of distributed generations (DGs), energy storages (ESs), and interruptible loads (ILs) are utilized to meet the demand locally in the DNs [1]. Micro-grids (MGs) are small-scale systems including DERs, consumers, possibly with controllable elastic loads, all deployed across a limited geographic area [2]. MG operator (MGO) can contract with distribution company (Disco) to trade energy and providing ancillary services. Since renewable energy sources (RESs) have uncertain behavior, the uncertainties of them should be modeled in the operation problem of MGs [3] which is the main aim of this paper.

B. Relevant Literature

To model the uncertain parameters of MGs, different approaches have presented including probabilistic and stochastic models and also several methods are used to control the risk of decision-making under the uncertainties including variance, Value-at-Risk (VaR), and Conditional Value-at-Risk (CVaR) [4]. In [5], a deterministic model of real-time energy management in MG optimization problem is proposed. In [6], day-ahead energy management of a MG in which the emission pollution is minimized without considering uncertainties is solved. In [7], stochastic approach for modelling a stand-alone MG is presented in absence a risk management method for controlling the impact of the intermittent natural of the uncertain parameters. In [8], a two-stage stochastic programming model for a grid-connected MG considering nonlinear demand response programs (DRPs) with the aim of risk-aversion strategy decision-making is provided. In [9], the RESs and demand uncertainties associated with a standalone MG are modeled using a two-stage stochastic programming approach with the purpose of making risk-based decision-making. In [10], the optimal scheduling of a central concentrating solar power (CSP) plant is investigated in the presence of different uncertainties such as energy market price and solar irradiation. For this purpose, a new hybrid information gap decision theory (IGDT)-stochastic method is introduced. In [11], an optimal grid-connected MG operation problem in the presence of DRPs wherein upstream grid price is considered as uncertain parameter has been modeled by information gap decision theory (IGDT) approach, but the participation of MG in reserve market has not been considered.

C. Contributions and Organization

Although the different approaches are used for modeling the uncertain parameters, they need the probability distribution functions (PDFs) of the parameters [12]. Since producing the PDFs for each parameter in each region cannot be done and may lead to inexact results, new approaches are needed to model the uncertain parameters in the operation problem of MGs. In this paper, an IGDT approach is employed as a new applicable method to provide a reliable risk-based decision-making approach to model the operation problem of MGs with uncertainties. For this purpose, the uncertainties of the forecast output power of wind turbines (WTs) and photovoltaic (PV) arrays that are considered as RESs are modeled using this approach. Therefore, the main contribution of this paper is proposing a new operation problem for the MGO to participate in both energy and reserve markets with uncertainties using an IGDT approach as a reliable risk-based decision making method. Problem description is provided in Section II. Section III provides the mathematical formulation. The results are analyzed in Section IV and Section V concludes the paper.

II. PROBLEM DESCRIPTION

In this paper, the operation problem of a grid-connected MG is modeled that it participates in energy and reserve markets, simultaneously. The MG consists of DGs, RESs, ESs, and interruptible loads (ILs) and can trade energy with the main grid which is operated by the distribution system operator (DSO). Moreover, the MGO can provide the required reserve of the Disco. For this purpose, according to Fig. 1, the Disco sends the prices of energy and reserve to the MGO regarding which the MGO decides on optimal scheduling of resources with respect to receive the DERs technical data and their operation cost with the aim of cost minimization. Finally, the MGO specifies the optimal energy and reserve scheduling.

To model the uncertainties of output power of RESs, the IGDT approach is proposed as Fig. 2. In steps 1 and 2, the deterministic operation problem regarding the forecast RESs output power and the other input data are solved and the decision variables are extracted by the MGO. Step 3 clarifies that the obtained optimal operation cost in step 2 is considered as the reference value for the proposed IGDT model. Making a risk-based decisions based on the comparison between the risk-based operation cost and the considered one by adjusting the risk-aversion and risk-taker parameter are carried out in steps 4 and 5. Eventually, the relation between the risk-averse and risk-taker decision-making and the amount of the scheduled power of RESs can be indicated.

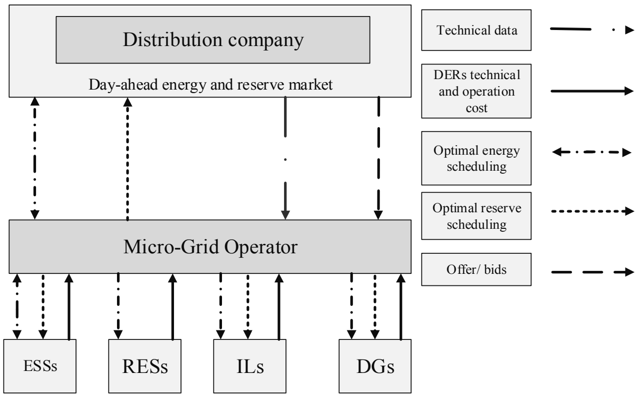

Fig. 1. The information flow of the MG operation problem

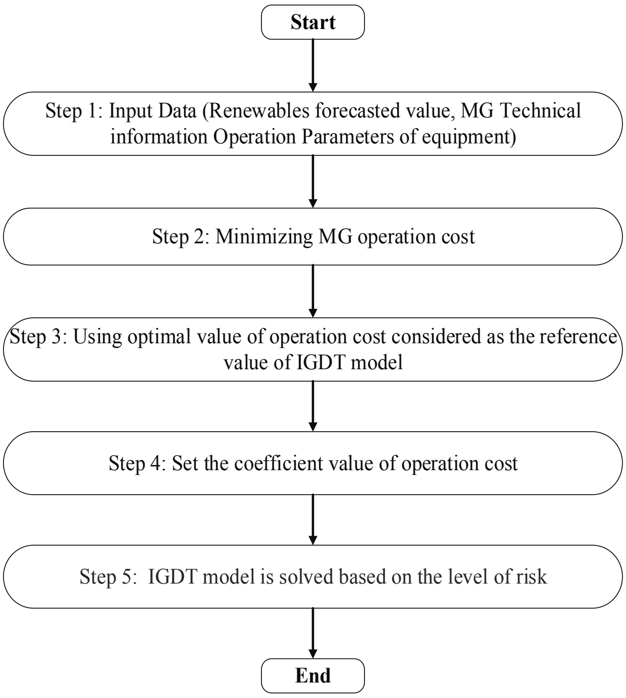

Fig. 2. Proposed IGDT-based of MGO decision making

III. MATHEMATICAL FORMULATION

A. Objective function and constraints

The MG operation cost is modeled as (1). The energy cost includes the DGs operation cost, the load interruption cost, the cost/revenue from trading energy with the Disco, and the revenue from selling energy to the MG loads. Moreover, the part related to the reserve clarifies the cost of DGs and load interruption for providing the amount of invoked reserve needed by the Disco as the first term. The fix revenue from providing the contracted amount of reserve among the MG and the Disco, and the revenue from selling the amount of invoked reserve to the Disco as the second and third terms, respectively.

$$TC=\sum_{t=1}^{T}\left[\begin{array}{l}\sum_{n=1}^{NDG}\left(C_n^{DG}P_{n,t}^{DG}\right)+\sum_{nl=1}^{NL}\left(C_t^{IL}P_{NL,t}^{IL}\right)+\\ C_t^{EM}\left(P_t^{Grid-in}-P_t^{Grid-out}\right)-\sum_{i=1}^{NB}C_t^{EM}P_{i,t}^{D}\\ +C_t^{IL}\kappa_t^{RM}R_{nl,t}^{IL}+C_n^{DG}\kappa_t^{RM}R_{n,t}^{DG}-C_t^{RM}R_t^{Dis}-C_t^{EM}\kappa_t^{RM}R_t^{Dis}\end{array}\right] \tag{1}$$

where the amount of demand on each bus is the difference between the initial load and interrupted load, calculated as(2):

$$P_{i,t}^{D}=\left(\sum_{nl=1}^{NL}\left(P_{nl,i,t}^{Load}-P_{nl,i,t}^{IL}\right)\right)\quad \forall\ \mathrm{i}\in \mathrm{NB},\ t\in T. \tag{2}$$

The MG energy is satisfied by DGs, RESs, energy storage, and trading with the Disco. However, power balance at reference bus and the other ones are expressed in (3) and (4), also the linearized power flow which is comprehensively described in [13] is used to solve the problem.

Moreover, the reserve is provided by DGs, energy storage, and interruption loads formulated as (5). Eqs. (6) and (7) clarify the limitations of the power generation of DGs for providing the energy and reserve.

$$\begin{array}{l}P_t^{Grid-in}\eta^{Grid}-P_t^{Grid-out}/\eta^{Grid}+\sum_{n=1}^{NDG}P_{n,t}^{DG}+\sum_{l=1}^{NR}P_{l,t}^{RES}+\\ \sum_{k=1}^{NES}P_{k,t}^{ES}-P_{i,t}^{D}=\sum_{j}P_{i,j,t}^{Inj}\quad \forall\ i\in NB,\ i=1,\ t\in T\end{array} \tag{3}$$

$$\begin{array}{l}\sum_{n=1}^{NDG}P_{n,t}^{DG}+\sum_{l=1}^{NR}P_{l,t}^{RES}+\sum_{k=1}^{NES}P_{k,t}^{ES}-\\ P_{i,t}^{D}=\sum_{j}P_{i,j,t}^{Inj}\quad \forall\ i\in NB,\ i\neq 1,\ t\in T\end{array} \tag{4}$$

$$R_t^{Dis}=\sum_{n=1}^{NDG}R_{n,t}^{DG}+\sum_{nl=1}^{NL}R_{nl,t}^{IL}+\sum_{k=1}^{NES}R_{k,t}^{ES}\quad \forall\ t\in T \tag{5}$$

$$\underline{P}_n^{DG}\leq P_{n,t}^{DG}+R_{n,t}^{DG}\leq \overline{P}_n^{DG}\qquad \forall\ n\in NDG,\ t\in T \tag{6}$$

$$P_{n,t}^{DG}\geq 0\quad ,\quad R_{n,t}^{DG}\geq 0\qquad \forall\ n\in NDG,\ t\in T \tag{7}$$

$$P_{nl,t}^{IL}+R_{nl,t}^{IL}\leq \overline{P}_{nl,t}^{IL}\qquad \forall\ nl\in NL,\ t\in T \tag{8}$$

$$P_{nl,t}^{IL}\geq 0\ ,\quad R_{nl,t}^{IL}\geq 0\qquad \forall\ nl\in NL,\ t\in T \tag{9}$$

$$\underline{P}_{l,t}^{RES}\leq P_{l,t}^{RES}\leq \overline{P}_{l,t}^{RES}\qquad \forall\ l\in NR,\ t\in T \tag{10}$$

$$P_{k,t}^{ES}=P_{k,t}^{ES-Discharge}\eta^{ES}-\frac{P_{k,t}^{ES-Charge}}{\eta^{ES}}\quad \forall\ k\in NES,\ t\in T \tag{11}$$

$$\underline{P}_t^{ES-Discharge}\leq P_{k,t}^{ES-Discharge}\leq \overline{P}_t^{ES-Discharge}\ \forall\ k\in NES,\ t\in T \tag{12}$$

$$\underline{P}_t^{ES-Charge}\leq P_{k,t}^{ES-Charge}\leq \overline{P}_t^{ES-Charge}\ \forall\ k\in NES,\ t\in T \tag{13}$$

$$\underline{E}_t^{ES}\leq E_{k,t}^{ES}\leq \overline{E}_t^{ES}\qquad \forall\ k\in NES,\ t\in T \tag{14}$$

$$\left(R_{k,t}^{ES}+P_{k,t}^{ES-Discharge}\right)/\eta^{ES}\leq E_{k,t}^{ES}\quad \forall\ k\in NES,\ t\in T \tag{15}$$

$$R_{k,t}^{ES}-P_{k,t}^{ES-Charge}+P_{k,t}^{ES-Discharge}\leq \overline{P}_k^{ES}\ \forall\ k\in NES,\ t\in T \tag{16}$$

$$R_{k,t}^{ES}\leq \overline{P}_k^{ES}\qquad \forall\ k\in NES,\ t\in T \tag{17}$$

$$E_{k,t}^{ES}=E_{k,t-1}^{ES}+P_{k,t}^{ES-Charge}-P_{k,t}^{ES-Discharge}\ \forall k\in NES,t\in T \tag{18}$$

$$0\leq P_t^{Grid-out}+R_t^{Dis}\leq \overline{P}^{Grid-out}\qquad \forall\ t\in T \tag{19}$$

$$0\leq P_t^{Grid-in}\leq \overline{P}^{Grid-in}\qquad \forall\ t\in T \tag{20}$$

$$P_{i,j,t}^{Inj}=P_{i,j,t}^{Flow}+P_{i,j,t}^{Loss}\quad \forall\ i,j\in NB,\ t\in T \tag{21}$$

$$P_{i,j,t}^{Flow}=\frac{R_{i,j}}{Z_{i,j}^{2}}\left(V_{i,t}^{2}-V_{j,t}^{2}\right)\quad \forall\ i,j\in NB,\ t\in T \tag{22}$$

$$P_{i,j,t}^{Loss}=R_{i,j}I_{i,j,t}^{2}\quad \forall\ i,j\in NB,\ t\in T \tag{23}$$

$$I_{i,j,t}=\frac{V_{i,t}-V_{j,t}}{Z_{i,j}}\quad \forall\ i,j\in NB,\ t\in T \tag{24}$$

$$\underline{I}\leq I_{i,j,t}\leq \overline{I}\quad \forall\ i,j\in NB,\ t\in T \tag{25}$$

$$\underline{V}_{i,t}\leq V_{i,t}\leq \overline{V}_{i,t}\quad \forall\ i\in NB,\ t\in T \tag{26}$$

The limitations of the interruptible loads to meet the part of the energy and reserve are illustrated in Eqs. (8) and (9). Eq. (10) demonstrates the upper and lower limitations of the RESs.

Eqs. (11)-(18) describe the operational modelling of energy storage to provide energy and reserve. Eq. (11) defines the power of energy storage used in power balance constraints.

Eqs. (12)-(14) indicate the limitations of discharging and charging power, and energy stored of battery, respectively.

Eqs. (15)-(17) show the limitation of battery to provide energy and reserve and also the state of charge of the battery is illustrate in Eq. (18). The summation of energy and reserve exchange with the Disco is lower than the maximum power exchange with the Disco as described in (19)-(20).

Eqs. (21)-(23) indicates the injected power constraints in the MG containing the active power flow and the power losses between bus i and j. Eqs. (24) and (25) determine the MG current magnitude and the limitation of it, respectively. Upper and lower limits of the voltage magnitude at MG buses are shown in Eq. (26).

B. *IGDT risk-based decision-making model*

IGDT model descriptions are available in [11]. In the proposed model for operation problem of the MG, the uncertain parameter is the output power of RESs appeared in Eqs. (3)-(4) and (10). In addition, the MG operation problem in the basic model (without considering the uncertainties) is described as (27).

$$TC_b = Minimize\ TC \tag{27}$$

Subject to:

$$(3)-(26)$$

Eq. (27) describes the total operation cost in the basic mode in which the uncertain parameter is exactly equal to its forecast value. Due to the risk-averse/risk-taker MGO's decisions, the RESs output power decreases/increases which leads to increasing/decreasing the output power of DGs and ES, the purchased energy from the Disco and also, the operation cost of the MG. In other words, the risk-averse/risk-taker MGO prefers to maximize/minimize the uncertainty radius defined the objective function of the proposed IGDT model according to the decreasing/increasing of the RESs output power due to their intermittent behavior (see Eqs. (28) and (29)). It should be noted that, the level of risk-aversion/risk-taking of the MGO's decisions is specified by changing the amount of β. Finally, the proposed IGDT-based decision making model associated with the risk-averse and also the risk-taker MGO are as follows:

- Risk-averse MGO:

$$\max\ \alpha^{IGDT} \tag{28}$$

(3)-(26)

$$TC \le \left(1+\beta^{IGDT}\right)TC_b \tag{29}$$

$$P_t^R \le \left(1-\alpha^{IGDT}\right)\overline{P}_t^R \tag{30}$$

- Risk-taker MGO:

$$\min\ \alpha^{IGDT} \tag{31}$$

(3)-(26)

$$TC \le \left(1-\psi^{IGDT}\right)TC_b \tag{32}$$

$$P_t^R \le \left(1+\alpha^{IGDT}\right)\overline{P}_t^R \tag{33}$$

IV. NUMERICAL RESULTS

A. *Input Data*

To investigate the effectiveness of the proposed model, it is applied on a 15-bus MG test system as shown in Fig. 3. The characteristics of MG's loads, DGs, and ES are described in [8, 14].

Also, the forecasted output power of the RESs is illustrated in Fig. 4.

The reserve cost of micro-turbines (MTs) and fuel cells (FCs) considered as two types of the DGs are 0.0287 €/kWh and 0.021 €/kWh, respectively. The maximum amount of power exchange between the MG and the Disco is 200 kW.

The price of power exchange with the Disco and the reserve price are extracted from the sample day of Red Electrica De Espana S.A. market [15] as shown in Fig. 5.

Also the invoked reserve probability is given in [12]. The lower and upper limitations for the voltage magnitude are 390 and 400V and also, for the current are -0.462 and 0.462 KA, respectively.

Moreover, the proposed model is implemented in GAMS software environment [16] using CPLEX12 as the solver.

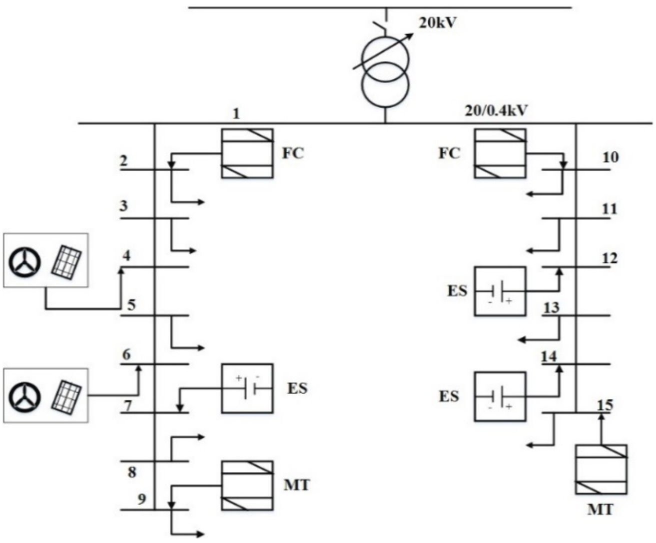

Fig. 3. 15-bus MG system test

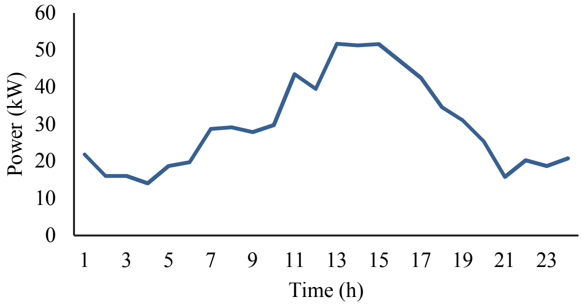

Fig. 4. The forecasted output power of the RESs

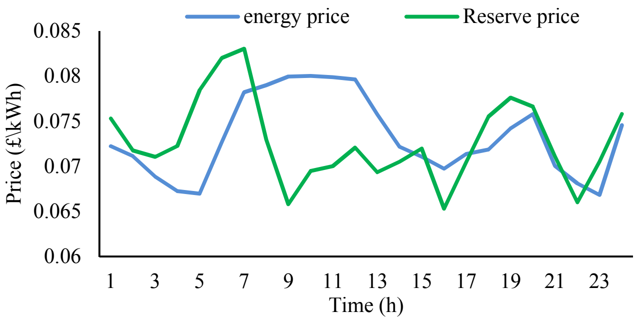

Fig. 5. Forecast energy and reserve prices

B. *Risk-neutral results without IGDT*

The MG energy and reserve balance for risk-neutral based decision-making $(\beta = 0)$ are illustrated in Figs. 6 and 7. In this case, since the operation cost of RESs is low, the MGO prefers to use all capacity of them and also use the sources with lower operation costs. The value of total operation cost of the MG by solving the proposed deterministic model is -488.684 €. At hour 1, the demand is supplied by purchasing power from the Disco and the surplus generated power from the DG (FC) and the RESs is utilized to charge the ES with the purpose of preparing the indicated amount of energy to participate in the reserve market at hours 2-24. It is clear that, the amount of purchased power from the Disco due to its high price compared to the operation costs of the DG (FC) and increasing of the power losses as well decreases at hours 5-7.

C. *Results of risk-aversion strategy function*

The risk-aversion strategy optimization framework with respect to control the RESs uncertainty has been solved and then, the optimum risk-aversion strategy function value is optimized by the MGO. The results which are shown in Fig. 8 illustrate that the uncertainty radius increases as the amount of the risk-aversion parameter changes from 0 to 0.2. As a result, when the risk-aversion parameter regarding the risk-level of the MGO's decisions increases, the total cost of the MG operation comes up. In other words, stronger strategy by the MGO for gradually eliminating the impact of the RESs' unexpected behavior lead to the higher cost.

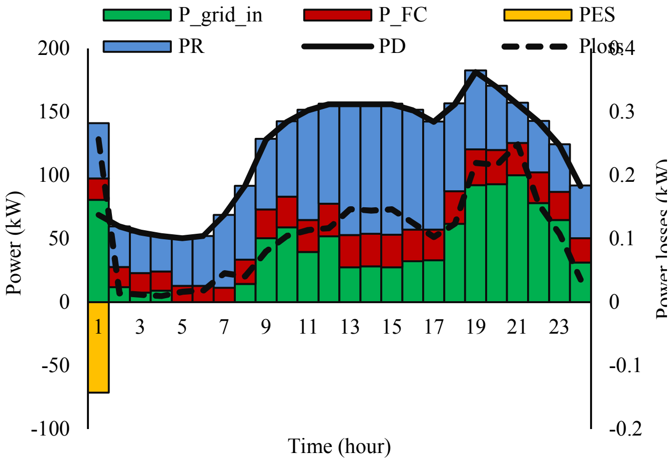

Fig. 6. Share of sources to supply MG load

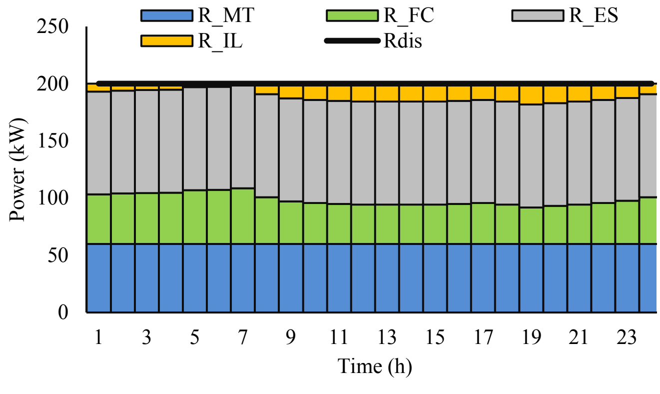

Fig. 7. Reserve provided by MG's resources for the Disco

Therefore, a higher total cost of the MG operation shows a state of being more risk-averse besides the lower amount of the RESs from a strategy taken by MGO. As it is shown in Fig. 8, for $\beta=0.2$, the total cost associated with the risk-aversion strategy is -390.947 and the maximum RESs uncertainty radius is $\alpha=0.916861$.

Increasing the risk-aversion parameter increases the uncertainty radius and lead to decreasing the RESs output power. Therefore, this reduction must be compensated. Hence, the MGO has to utilize other sources to compensate and supply the load.

In addition, as described in the previous sub-section, the MGO prefers to use its sources to participate in the reserve market for achieving the profit as much as possible. Thus, purchasing power from the Disco to compensate the imperfect power generation caused by decreasing the RESs output power increases the amount of MG power losses. For proving the mentioned claim, a sensitivity analysis is carried out as depicted in Fig. 9.

It is clear that, the amount of the power losses changes from 2.5 kW to 7 kW with respect to changes the risk-level of the MGO's decisions from $\beta = 0$ to $\beta = 0.2$. It is to be noted that, the MGO controls the risk-level of the decisions through considering a tradeoff among the RESs uncertainty radius, total operation cost, and the amount of power losses.

A. *Results of risk-taking strategy function*

As shown in Fig. 10, the uncertainty radius increases as the amount of the risk-taker parameter changes from 0 to 0.15. As a result, when the risk-taker parameter increases regarding the risk-level of the MGO's decisions, the total operation cost of the MG decreases.

It is clear that, a lower amount of the target cost requires a higher favorable RESs output power deviation from the forecasted value.

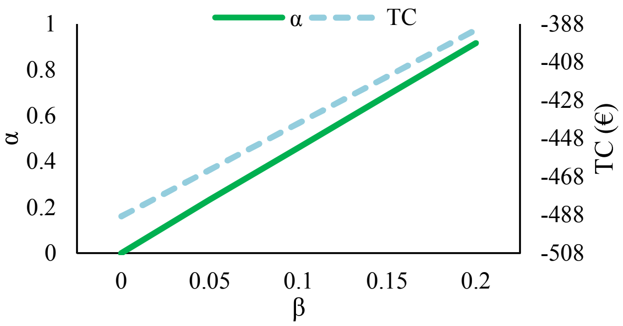

Fig. 8. Sensitivity of uncertainty radius and MG total cost to risk aversion parameter

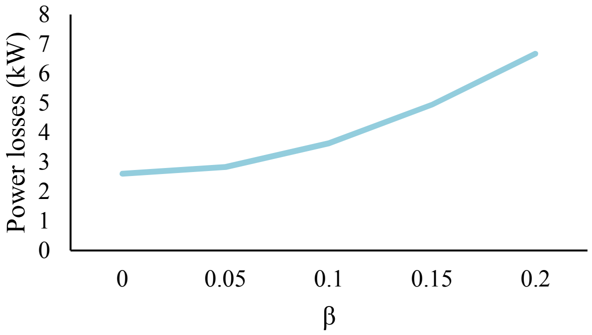

Fig. 9. Sensitivity of total power losses to risk aversion parameter

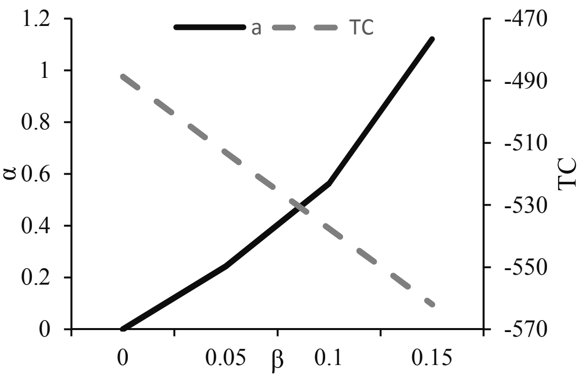

Fig. 10. Sensitivity of uncertainty radius and MG total cost to risk taker parameter

For instance, for the purpose of achieving a reduction of 10% in the total operation cost in the basic state, a deviation of 56.3% of the RESs output power will be needed.

It is to be noted that, the operation cost of the MG in the cases of risk-neutral, risk-averse, and risk-taker MGO is -488.684, -439.816, and -537.552$, respectively.

B. Model statistics

To validate the effectiveness as well as the solvability of the proposed model to apply in the real application, the model statistics are shown in Table I.

TABLE I. MODEL STATISTIC OF THE PROPOSED MODEL

	Solution Time (s)	# Single Equation	# Single Variables
Deterministic model	1.37	91299	48915
Risk-averse Strategy	1.25	91326	48918
Risk-taker Strategy	1.62	91326	48918

V. CONCLUSION

In this paper, a risk-constrained method for modelling the short term scheduling of a grid-connected MG, which participates in energy and reserve markets, was proposed. The uncertainty associated with the RESs output power has been modeled using the IGDT approach without considering their associated PDFs. Numerical results indicated that changing the amount of the risk-aversion parameter with the aim of restricting the effects of the RESs on the MGO's decisions increased the dependency of purchasing power from the Disco and the total operation cost as well. Also, modeling the power losses (structure of the MG) and participation in the reserve market changed the strategy of the MGO for controlling its risk-level in decision-making.

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REFERENCES

[1] W. Alharbi and K. J. E. P. S. R. Raahemifar, "Probabilistic coordination of microgrid energy resources operation considering uncertainties," vol. 128, pp. 1-10, 2015.

[2] R. H. J. P. o. t. I. Lasseter, "Smart distribution: Coupled microgrids," vol. 99, no. 6, pp. 1074-1082, 2011.

[3] J. Soares, M. A. F. Ghazvini, N. Borges, and Z. J. E. P. S. R. Vale, "A stochastic model for energy resources management considering demand response in smart grids," vol. 143, pp. 599-610, 2017.

[4] A. J. Conejo, M. Carrión, and J. M. Morales, *Decision making under uncertainty in electricity markets*. Springer, 2010.

[5] M. Elsied, A. Oukaour, H. Gualous, and O. A. L. Brutto, "Optimal economic and environment operation of micro-grid power systems," *Energy conversion and management,* vol. 122, pp. 182-194, 2016.

[6] H. Kanchev, F. Colas, V. Lazarov, and B. Francois, "Emission reduction and economical optimization of an urban microgrid operation including dispatched PV-based active generators," *IEEE Transactions on sustainable energy,* vol. 5, no. 4, pp. 1397-1405, 2014.

[7] L. Guo, W. Liu, B. Jiao, B. Hong, and C. Wang, "Multi-objective stochastic optimal planning method for stand-alone microgrid system," *IET Generation, Transmission & Distribution,* vol. 8, no. 7, pp. 1263-1273, 2014.

[8] P. Sheikhahmadi, R. Mafakheri, S. Bahramara, M. Damavandi, and J. Catalão, "Risk-Based Two-Stage Stochastic Optimization Problem of Micro-Grid Operation with Renewables and Incentive-Based Demand Response Programs," *Energies,* vol. 11, no. 3, p. 610, 2018.

[9] S. Bahramara, P. Sheikhahmadi, and H. Golpîra, "Co-optimization of Energy and Reserve in Standalone Micro-Grid Considering Uncertainties," *Energy,* 2019.

[10] S. Nojavan, H. Pashaei-Didani, K. Saberi, and K. Zare, "Risk assessment in a central concentrating solar power plant," *Solar Energy,* vol. 180, pp. 293-300, 2019.

[11] A. Mehdizadeh, N. Taghizadegan, and J. Salehi, "Risk-based energy management of renewable-based microgrid using information gap decision theory in the presence of peak load management," *Applied energy,* vol. 211, pp. 617-630, 2018.

[12] S. Bahramara, M. Yazdani-Damavandi, J. Contreras, M. Shafie-Khah, and J. P. Catalão, "Modeling the strategic behavior of a distribution company in wholesale energy and reserve markets," *IEEE Transactions on Smart Grid,* vol. 9, no. 4, pp. 3857-3870, 2018.

[13] M. J. Rider, J. M. López-Lezama, J. Contreras, and A. Padilha-Feltrin, "Bilevel approach for optimal location and contract pricing of distributed generation in radial distribution systems using mixed-integer linear programming," *IET Generation, Transmission & Distribution,* vol. 7, no. 7, pp. 724-734, 2013.

[14] P. Sheikhahmadi, S. Bahramara, J. Moshtagh, and M. Yazdani Damavandi, "A risk-based approach for modeling the strategic behavior of a distribution company in wholesale energy market," *Applied energy,* vol. 214, no. C, pp. 24-38, 2018.

[15] https://www.esios.ree.es/en.

[16] A. U. G. GAMS, New York, NY, USA, 2008.