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Day-Ahead Optimal Scheduling of Resources in a Distribution System in Joint Energy, Regulation and Ramp Markets

Amin Naseri[1], Sajjad Fattaheian-Dehkordi[1, 2], Ali Abbaspour[1], Matti Lehtonen[2]

Abstract – *The increasing trend of integrating Renewable Energy Sources (RESs) into power systems could cause operational challenges in the system from flexibility and reliability perspectives. Respectively, utilities would be relied on local flexible resources to address the flexibility requirements in power systems. In this respect, local resources in distribution systems could participate in ancillary markets along with the wholesale energy markets to address the flexibility capacity shortage in the system. Consequently, this paper aims to provide a framework to optimize the scheduling of resources in distribution networks while participating in energy, regulation, and ramp markets. Correspondingly, this approach would maximize the profits of the local resources in distribution systems whereas providing Flexible Ramp Product (FRP) and regulation reserve for the system operators. Respectively, an optimized bidding strategy is developed to maximize the profits of the local resources, while modeling the operational constraints of the distribution grids and power losses to improve the accuracy of the proposed scheme. Furthermore, the chance constrained concept is taken into account in the proposed scheme to model the uncertainty of RESs. Finally, the model is applied on the IEEE-37-bus-test-system and the sensitivity analysis is employed to investigate its effectiveness in the management of the system.*

***Keywords**: Flexibility, Flexibility Market, Energy Market, Regulation Market, Active Distribution System, Flexible Ramp Product, Chance Constraint, Renewable Energy, Flexible Distribution Resources*

Nomenclature

RES	Renewable Energy Source
EV	Electrical Vehicle
BESS	Battery Energy Storage System
FRP	Flexible Ramp Product
CAISO	California Independent System Operator
MISO	Mid-Continent Independent System Operator
RT	Real-Time
DA	Day-Ahead
CC	Chance Constrained
PV	Photovoltaic
RTED	Real-Time Economic Dispatch
RTUC	Real-Time Unit Commitment
DSO	Distribution System Operator
ADS	Active Distribution System
PCC	Point of the Common Coupling
ADSO	Active Distribution System Operator
M	Set of scenarios with index m
N	Set of scenarios which is used in chance-constrained modeling with index n
I, J	Set of network buses with index i and j
T	Set of time intervals with index t
EV	Set of electrical vehicles with index ev
ES	Set of battery energy storages with index es
Ω_{ev}	Buses that ev connects to
ω_m, ω_n	Probability of scenario m and n
$prob_{acc}^{re+}$, $prob_{dep}^{re+}$	Expected acceptance/deployment probability of upward regulation reserve in DA /RT
$prob_{acc}^{re-}$, $prob_{dep}^{re-}$	Expected acceptance/deployment probability of downward regulation reserve in DA /RT

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$prob_{acc}^{ra+}$, $prob_{dep}^{ra+}$	Expected acceptance/deployment probability of upward FRP in DA /RT
$prob_{acc}^{ra-}$, $prob_{dep}^{ra-}$	Expected acceptance/deployment probability of downward FRP in DA /RT
$prob_{sh}^{re+}$, $prob_{sh}^{re-}$	Expected probability of upward/downward regulation reserve shortage in RT
$prob_{sh}^{ra+}$, $prob_{sh}^{ra-}$	Expected probability of upward/downward FRP shortage in RT
$\lambda_{t,m}^{RE+}$, $\lambda_{t,m}^{RE-}$	Upward/downward regulation reserve's capacity price in interval *t* and scenario *m* [$/MWh]
$\lambda_{t,m}^{RA+}$, $\lambda_{t,m}^{RA-}$	Upward/downward FRP's capacity price in interval *t* and scenario *m* [$/MWh]
$\lambda_{t,m}^{RT}$, $\lambda_{t,m}^{DA}$	RT/DA energy price in interval *t* and scenario *m* [$/MWh]
K_{ev}, K_{es}	Per-unit degradation cost of *ev/es* battery [$/MWh]
$SCF_{i,t,m,n}$	Sensitivity Coefficient Factor of bus *i* in interval *t* in scenarios *m* and *n*
$AV_{ev,t}$	Binary parameter showing availability of *ev* in interval *t*
η_{ev}^{ch}, η_{ev}^{dch}	Charging/discharging efficient of *ev*
η_{es}^{ch}, η_{es}^{dch}	Charging/discharging efficient of *es*
$E_{ev,t,m}$	Energy demand (for daily trip) of *ev* in interval *t* in scenario *m*
Soc_{ev}^{dep}	Minimum energy state of charge for *ev* in departure interval
$\overline{Soc_{ev}}$, $\underline{Soc_{ev}}$	Maximum/Minimum allowable energy state of charge for *ev*
$\overline{P_{ev}}$, $\overline{P_{es}}$	Maximum allowable charging or discharging power for *ev/es*
Soc_{es}^{init}	Initial energy state of charge of *es*
$\overline{Soc_{es}}$, $\underline{Soc_{es}}$	Maximum/Minimum allowable energy state of charge for *es*
$\overline{P_{i,t,n}^{RES}}$	Forecasted available power of renewable generation in bus *i*, interval *t* and scenario *n*
$G_{i,j}$, $B_{i,j}$	Conductance/susceptance of line between buses *i* and *j*
$Pd_{i,t}$, $Qd_{i,t}$	Active/reactive load of bus *i* in interval *t*
$\overline{V}$, $\underline{V}$	Maximum/minimum allowable voltage magnitude of network buses
$S_{i,j}$	Maximum allowable flow of line between buses *i* and *j*
ξ	Constant used in linear load flow model
ε	Constant showing risk level
$B_{m,n}^{EN}$	Profit/cost of providing/purchasing energy
$B_{m,n}^{RE\_EV}$, $B_{m,n}^{RA\_EV}$	Expected profit of providing regulation-reserve/FRP by EVs in scenario *m* and *n*
$B_{m,n}^{RE\_ES}$, $B_{m,n}^{RA\_ES}$	Expected profit of providing regulation-reserve/FRP by BESSs in scenario *m* and *n*
$B_{m,n}^{RE\_RES}$, $B_{m,n}^{RA\_RES}$	Expected profit of providing regulation-reserve/FRP by renewable resources in scenario *m* and *n*
$C_{m,n}^{DEG\_EV}$, $C_{m,n}^{DEG\_ES}$	Degradation cost of EVs/BESSs in scenario *m* and *n*
$C_{m,n}^{RE\_EV}$, $C_{m,n}^{RA\_EV}$	Expected shortage cost of regulation-reserve/FRP by EVs in scenario *m* and *n*
$C_{m,n}^{RE\_ES}$, $C_{m,n}^{RA\_ES}$	Expected shortage cost of regulation-reserve/FRP by BESSs in scenario *m* and *n*
$C_{m,n}^{RE\_RES}$, $C_{m,n}^{RA\_RES}$	Expected shortage cost of regulation-reserve/FRP by renewable resources in scenario *m* and *n*
$P_{t,m,n}^{re+\_EV}$, $P_{t,m,n}^{re-\_EV}$	Upward/downward capacity of regulation-reserve offered by EVs in interval *t*, scenario *m* and *n*
$P_{t,m,n}^{ra+\_EV}$, $P_{t,m,n}^{ra-\_EV}$	Upward/downward capacity of FRP offered by EVs in interval *t*, scenario *m* and *n*
$P_{t,m,n}^{re+\_ES}$, $P_{t,m,n}^{re-\_ES}$	Upward/downward capacity of regulation reserve offered by BESSs in interval *t*, scenario *m* and *n*
$P_{t,m,n}^{ra+\_ES}$, $P_{t,m,n}^{ra-\_ES}$	Upward/downward capacity of FRP offered by BESSs in interval *t*, scenario *m* and *n*
$p_{ev,t,m,n}^{dch\_EV}$, $p_{ev,t,m,n}^{ch\_EV}$	Discharging/charging power of *ev* in interval *t*, scenario *m* and *n*
$e_{ev,t,m,n}^{re+\_EV}$, $e_{ev,t,m,n}^{re-\_EV}$	Expected amount of deployed energy for upward/downward regulation reserve of *ev* in interval *t*, scenario *m* and *n*
$e_{ev,t,m,n}^{ra+\_EV}$, $e_{ev,t,m,n}^{ra-\_EV}$	Expected amount of deployed energy for upward/downward FRP of *ev* in interval *t*, *m* and *n*

$p^{dch\_ES}_{es,t,m,n}$, $p^{ch\_ES}_{es,t,m,n}$	Discharging/charging power of *es* in interval *t*, scenario *m* and *n*
$e^{re+\_ES}_{es,t,m,n}$, $e^{re-\_ES}_{es,t,m,n}$	Expected amount of deployed energy for upward/downward regulation reserve of *es* in interval *t*, scenario *m* and *n*
$e^{ra+\_ES}_{es,t,m,n}$, $e^{ra-\_ES}_{es,t,m,n}$	Expected amount of deployed energy for upward/downward FRP of *es* in interval *t*, scenario *m* and *n*
$Soc^{EV}_{ev,t,m,n}$, $Soc^{ES}_{es,t,m,n}$	Energy state of charge of *ev/es* in interval *t*, scenario *m* and *n*
$x_{ev,t,m,n}$	Binary variable indicating the direction of charging or discharging in *ev* in interval *t*, scenario *m* and *n*
$P^{re+\_RES}_{t,m,n}$, $P^{re-\_RES}_{t,m,n}$	Upward/downward capacity of regulation reserve offered by renewable resources in interval *t*, scenario *m* and *n*
$P^{ra+\_RES}_{t,m,n}$, $P^{ra-\_RES}_{t,m,n}$	Upward/downward capacity of FRP offered by renewable resources in interval *t*, scenario *m* and *n*
$p^{RES}_{i,t,m,n}$	Output-power by renewable generation of bus *i* in interval *t*, scenario *m* and *n*
$re^{+RES}_{i,t,m,n}$, $re^{-RES}_{i,t,m,n}$	Expected amount of deployed energy for upward/downward regulation reserve from renewable resource of bus *i* in interval *t*, scenario *m* and *n*
$ra^{+RES}_{i,t,m,n}$, $ra^{-RES}_{i,t,m,n}$	Expected amount of deployed energy for upward/downward FRP from renewable generation of bus *i* in interval *t*, scenario *m* and *n*
$Psell_{t,m,n}$	Total bidding power for selling energy to upstream network in interval *t*, scenario *m* and *n*
$Pline_{i,j,t,m,n}$, $Qline_{i,j,t,m,n}$	Active / reactive power flow of line between buses *i* and *j* network in interval *t*, scenario *m* and *n*
$V_{i,t,m,n}$, $\theta_{i,t,m,n}$	Voltage-magnitude and phase of bus *i* in interval *t*, scenario *m* and *n*
$Pinj_{i,t,m,n}$, $Qinj_{i,t,m,n}$	Injected active/reactive power of bus *i* in interval *t*, scenario *m* and *n*
$z_{i,t,m,n}$	Auxiliary binary variable used in Big-M method for bus *i* in interval *t*, scenario *m* and *n*

I. Introduction

The significant integration of Renewable Energy Sources (RESs) in power systems has resulted in the increase of variability and intermittency of the systems' net-load. In this regard, due to the decreasing level of flexibility of the power systems, system operators and planners should employ efficient procedures in order to improve flexibility of the system. This procedure by ensuring the demand-supply balance in all the operating horizons in the system would finally result in preventing the power imbalance and frequency fluctuations [1], [2]; which would improve the reliability and flexibility of power systems. Respectively, while the scarcity of the ramping capability in power systems would increase the operational costs; the increase in the ramping capability would facilitate the integration of RESs without deteriorating the reliability criteria. Traditionally, power system operators rely on bulk generation units connected to transmission networks to provide the required flexibility service; while the decreasing operational costs of RESs, as well as high investment costs and construction time of conventional resources, would decrease the ramping capacity provided by bulk power units [1], [3], [4]. That is why system operators should focus on activating the flexibility service from active distribution systems. Consequently, distribution systems could play a key role in improving the reliability, flexibility, and security of power systems. In this respect, aggregation of resources in active distribution systems could participate in wholesale energy and ancillary service markets. In this context, the fast responsive resources such as Electrical Vehicles (EVs) and Battery Energy Storage Systems (BESSs) could significantly improve the ramping capability of the system [5].

In recent years, Flexible-Ramping-Product (FRP) is defined by California Independent System Operator (CAISO) and Mid-continent Independent System Operator (MISO) to improve the flexibility of power systems in Real-Time (RT) market [6]. Nevertheless, this product as an ancillary service could also be purchased by the system operators in the Day-Ahead (DA) market like common ancillary services, e.g, regulation reserve, to be deployed in the RT operation of the system [5]. The primary benefit of FRP is the cost reduction in the operation of the system, which motivates the system operators to consider this product in the DA and RT markets. In this regard, the differences between FRP and other ancillary services as well as their pricing methods are investigated in [5], which shows the advantages of considering the FRP in optimizing the participation of local flexible resources in power system markets. In the optimal bidding problem of distribution system's resources in energy and reserve markets, the risk of uncertain decision parameters like DA energy and reserve capacity prices should be noticed and employed in the optimization problem in order to improve the accuracy and efficacy of the developed scheme. In this regard, stochastic and robust optimization methods are the common methodologies for considering uncertainty in optimization problems [7]. Furthermore, the uncertainties could also be taken into account in the deterministic optimization models by using Chance Constraint (CC) and conditional value at risk techniques.

Authors in [8] have developed a risk-averse stochastic model for finding optimal biddings of a fleet of BESSs and EVs in the DA market while merely considering regulation reserve service. Moreover, optimal bidding of EV aggregators and BESSs in the DA energy and reserve markets are respectively modeled in [9], and [5].

Furthermore, authors in [10] have developed the bidding strategy of an EV aggregator in the energy and reserve market while considering reserve deployment shortages in the RT operation. It is essential to mention that the optimization model in [9] and [10] does not consider the FRP product. [11] presents an optimal bidding model for microgrids in joint energy and ancillary service markets with RESs and BESSs.

Uncertainties of wind units are modeled using robust optimization technique. However, the proposed model does not account for technical constraints of the energy network. In the deregulated structure of power systems, distribution systems could provide flexibility requirements of the system considering the role of shiftable loads and flexible demands. In this regard, the authors in [12] have proposed a model based on the swarm optimization algorithm to provide flexibility in a distribution system by managing household demands.

Furthermore, RESs such as photovoltaic (PV) and wind power units could provide ancillary services in power systems. In this context, in [13], the application of wind power products in providing FRP is investigated in the RT market considering a two-stage problem. Thus, the Real-Time Unit Commitment (RTUC) and the Real-Time Economic Dispatch (RTED) are considered in the two-stage model and finally, the efficiency of these resources in the provision of ramp product has concluded in [13]. Furthermore, [14] utilizes a bi-level optimization to represent the involvement of wind power units in the DA energy and regulation reserve markets, in which the uncertainties of wind power units are taken into account in the upper-level stage. The authors of [15] have created a stochastic model for an EV aggregator's participation in the DA energy and reserve markets. This model accounts for the risks associated with the considered scenarios.

Note that, in this study, only the uncertainties of energy and reserve prices are considered. The attributes of EVs are modeled in detail in [16] to optimize the profit of the commitment of the EV fleets in the regulation reserve market. In [17], scheduling of a virtual power plant is optimized while participating in the DA energy market considering the regulation reserve service provided by the PV and BESS units. In this study, the uncertainties of the PV units and demands are also considered utilizing the robust optimization technique. In [18] the authors propose a new framework for utilizing the flexibility of EVs and other heating loads to provide demand response services to the grid. [19] proposes new control and management principles for distributed energy resources to increase their participation in providing frequency control locally, but the ramp service is not considered in this paper. Similarly, in [20] the economic viability of using BESS for multiple purposes, such as outage mitigation and frequency regulation is explored without considering their ability to provide flexible ramp product.[21] presents a modeling framework for predicting the behavior of EV charging loads and their impact on the power balance of the grid. The study shows that EVs can provide significant flexibility to the grid. Authors in [22] have proposed a multi-stage optimization model, in which the industrial and residential flexible demands are managed to provide the up/down regulation reserve services. EVs can have a significant effect in reducing the cost of operation in distribution systems and microgrids. Therefore, [22] studies the effects of EVs in the operational cost reduction of the system while optimizing the optimal bidding model of a microgrid in the DA energy and reserve markets. Note that, the stochastic optimization method is used in this paper to model demand and wind power uncertainties. Moreover, authors in [10] utilized this method to model the uncertainty of reserve service deployment in the RT, while, in [23], a robust optimization technique is employed for considering the uncertainty associated with the reserve service. Based on the above discussions, Table I presents a simplified comparison between the methods developed in previous studies to optimize the participation of local resources in providing regulation reserve service and ramping service.

To the best of our knowledge, previous studies in the context of optimizing the FRP and regulation reserve services have not considered the operational constraints of the network, which could lead to non-optimal optimization results [24].

TABLE I
COMPARISON OF RESEARCH WORKS IN THE CONTEXT OF OPERATIONAL OPTIMIZATION OF LOCAL RESOURCES IN A DISTRIBUTION SYSTEM CONSIDERING THE RAMP/REGULATION SERVICES

Ref. Num.	FRP Service	Regulation Reserve Service	Uncertainty Modeling	Chance Constrained Technique	Network Modeling	Modeling Different Kinds of Flexible Resources
[4]	✓	✓	✓			
[7]		✓	✓		✓	
[8]		✓	✓			
[9]		✓	✓			
[10]	✓	✓	✓			✓
[12]	✓	✓	✓			
[13]		✓	✓			
[17]		✓	✓			✓
[18]		✓	✓			
This paper	✓	✓	✓	✓	✓	✓

In this regard, in this paper, in addition to the operational constraints of flexible resources, the operational constraints of the grid, as well as the power losses due to deployment of ancillary services and energy exchanges in the RT market, are taken into account in the proposed model.

To this end, the sensitivity coefficients are employed in the proposed model to optimize the FRP and the regulation reserve that could be sold by the Distribution System Operator (DSO) to the upper system. In this respect, DSO would act as the responsible entity for optimizing the bidding strategy of the RESs and flexible resources in the distribution system while participating in the joint energy, ramp, and regulation reserve markets.

Moreover, the uncertainty associated with the forecasted prices is represented using probability functions. The chance-constrained method is used to model the uncertainties associated with the wind and PV units. Respectively, the big-M method is deployed to convert the chance-constrained model of the PV and wind units to a deterministic one. Finally, while previously developed methods merely focus on modeling the regulation or ramp market as well as studying the role of one type of flexible resources in their optimization schemes; this paper strives to develop a comprehensive model and analyse the role of different kinds of flexible resources in the operational management of distribution systems. The contribution of the paper can be summarized as follow:

- An optimal bidding strategy is developed in an active distribution system with aggregation of EVs, BESSs, PVs, and wind units in energy as well as regulation, and ramp markets. In this regard, while the proposed approaches in [3], [6], [25]-[29] have merely investigated optimizing the high-ramping in distribution systems, the developed bidding approach optimizes the bidding of local resources participating in wholesale markets. In this regard, the proposed approach would result in improving the flexibility of the overall power system;
- The uncertainties of EVs, PVs, and wind units as well as the forecasted DA prices are taken into account in the proposed model to improve its efficacy and accuracy;
- Operational constraints of the distribution grid and power losses in the grid are considered in the proposed scheme considering the energy exchanges and the deployment of ancillary services;
- The sensitivity analysis is employed to analyze the effects of key parameters, e.g. deployment and acceptance probabilities of ancillary services, in the developed optimization model.

The rest of the paper is organized as follows. The methodology of the work including the proposed framework is defined in Section III. In Section IV mathematical formulation of the optimization problem and the model of the resources are described. Moreover, the case study and results are discussed in Section V.

Finally, the paper is concluded in Section VI.

II. Methodology

II.1. System Modeling

This paper aims to develop a framework for optimizing the profits of the resources in the distribution system while participating in the joint energy, regulation, and ramp markets, as previously mentioned. It is assumed that the wind and PV units as well as EVs and BESSs are local resources connecting to the active distribution system. DSO is conceived as the aggregator of these local resources, which would participate in the wholesale energy and ancillary markets. Figure 1 shows the overview of the system structure, which is considered in the proposed scheme. The system aggregator is responsible for participating in the DA market to provide sufficient energy for the loads, such as residential loads and EV demands, located in the distribution system. In addition, the system aggregator would participate in the regulation and FRP markets to maximize their respective profits.

II.2. The Proposed Framework

Based on the system modeling, it is assumed that the aggregator participates in the DA energy regulation reserve, and ramp markets to maximize the total monetary profits of local resources while improving the flexibility of the power system by providing the required ancillary services. According to the market structure of the MISO [5], entities could receive profits by participating in the ancillary service markets from two perspectives. Firstly, the aggregator will get profit from the capacity bidding which is accepted by the upstream system operator. Secondly, the aggregator will be paid in the case that the accepted ancillary offers in DA scheduling are deployed in the RT operation of the system. In this context, the aggregator should model the uncertainty associated with the ancillary service acceptance and deployment in the optimization model to improve accuracy of the obtained results.

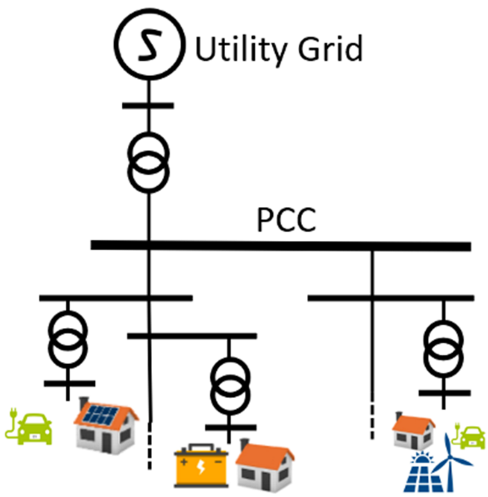

Fig. 1. A simple view of the distribution system model and resources connected to the feeders

In this regard, the probability of acceptance and deployment of ancillary services as well as the expected profits and the costs in the economic model could be taken into account to model the uncertainty associated with the ancillary services. In this paper, similar to the concept presented in [5], aside from the expected profits of regulation and ramp services, the costs associated with their shortages are modeled as a risk-averse decision by taking into account the risk of over-offering for regulation and ramp services. Furthermore, in this study, the chance-constrained technique is taken into account to model the uncertainties of wind and PV units.

Respectively, the big-M method is employed to convert the chanced constraints to linear constraint forms. As mentioned, unlike previous studies, the operational modeling of distribution grids is considered in this paper to improve the accuracy of the obtained results. In this regard, the power losses in the distribution network should be taken into account in the proposed scheme. Fig. 2 depicts the algorithm used to consider the power losses in the proposed model. As a result, the Sensitivity Coefficient Factors (SCFs) are employed to model the effects of the changes in the power injection of each node of the system to the power exchanges between the distribution and transmission systems. As presented in Fig. 2, SCFs are updated in an iterative manner until the step in which, this algorithm converges to the final optimal solution. In multi-agent ADSs, ADSO would act as the responsible entity for operating the grid in a reliable manner; while, each agent schedules their sources independently. As mentioned, conventional regulating voltage procedures may not adapt to the new operating condition in active ADSs with the high-level integration of RESs.

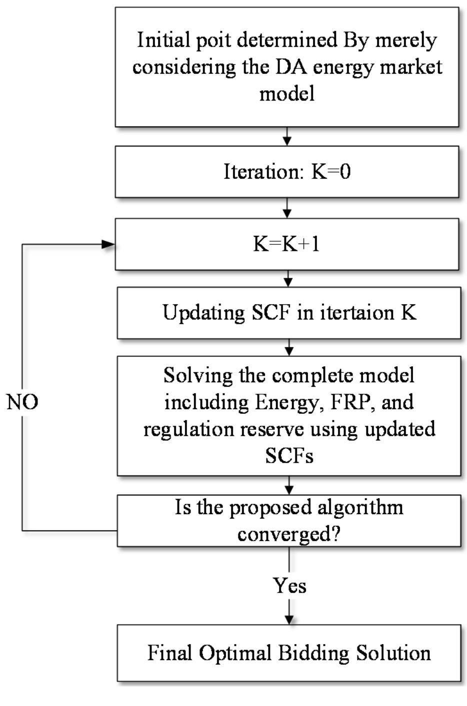

Fig. 2. The proposed step-wise algorithm for determining the optimal bidding solution of local resources

III. Mathematical Formulation

The optimization problem of the resources in the distribution system is a benefit-cost problem, which is formulated in this section. The developed optimization model contains the objective function and related constraints associated with the operation of local resources, which are detailed in the following sections.

Firstly, the objective function of this problem is formulated in (1):

$$\max \left(\sum_{M} \sum_{N} \omega_m \omega_n \begin{pmatrix} B_{m,n}^{EN} + B_{m,n}^{RE\_EV} + B_{m,n}^{RE\_ES} + \\ + B_{m,n}^{RE\_RES} + B_{m,n}^{RA\_EV} + \\ + B_{m,n}^{RA\_ES} + B_{m,n}^{RA\_RES} + \\ - C_{m,n}^{DEG\_EV} - C_{m,n}^{DEG\_ES} + \\ - C_{m,n}^{RE\_EV} - C_{m,n}^{RE\_ES} + \\ - C_{m,n}^{RE\_RES} - C_{m,n}^{RA\_EV} + \\ - C_{m,n}^{RA\_ES} - C_{m,n}^{RA\_RES} \end{pmatrix} \right) \quad (1)$$

The objective function in (1) presents the profit of the system considering the DA energy, regulation, and ramp service offers as well as the costs related to the operation of EVs and BESSs. Moreover, the risk cost of the over-offering in regulation and ramp services is considered in the objective function in (1). These benefits and the cost terms are considered in each scenario in two sets. The first set which is shown by M models the scenarios associated with the market prices and the energy requirements of EVs. The other scenario set represented by N is utilized to model the uncertainties of wind and PV units. In the following sections, the terms of the objective function as well as the detailed operational constraints of the resources are presented.

III.1. Scheduling of EVs

EVs can participate in the reserve and ramp markets as flexible resources. The profits of EVs while participating in the reserve and regulation markets are represented by (2) and (3), respectively. The risk costs related to the over-offering of regulation and ramp services are shown by (4) and (5). The cost that models the degradation of the batteries is presented by (6) since EV batteries depreciate with charging and discharging processes.

$$\begin{aligned} B_{m,n}^{RE\_EV} &= \sum_{T} \Delta t \begin{pmatrix} prob_{acc}^{re+} \times \lambda_{t,m}^{RE+} \times P_{t,m,n}^{re+\_EV} \\ + prob_{acc}^{re-} \times \lambda_{t,m}^{RE-} \times P_{t,m,n}^{re-\_EV} \end{pmatrix} \\ &+ \sum_{T} \Delta t \left(prob_{acc}^{re+} \times prob_{dep}^{re+} \times \lambda_{t,m}^{RT} \times \left(\eta_{ev}^{dch} P_{t,m,n}^{re+\_EV} \right) \right) \end{aligned} \quad (2)$$

$$\begin{aligned} B_{m,n}^{RA\_EV} &= \sum_{T} \Delta t \begin{pmatrix} prob_{acc}^{ra+} \times \lambda_{t,m}^{RA+} \times P_{t,m,n}^{ra+\_EV} \\ + prob_{acc}^{ra-} \times \lambda_{t,m}^{RA-} \times P_{t,m,n}^{ra-\_EV} \end{pmatrix} \\ &+ \sum_{T} \Delta t \left(prob_{acc}^{ra+} \times prob_{dep}^{ra+} \times \lambda_{t,m}^{RT} \times \left(\eta_{ev}^{dch} P_{t,m,n}^{ra+\_EV} \right) \right) \end{aligned} \quad (3)$$

$$C_{m,n}^{RE\_EV} = = prob_{sh}^{re+}\sum_{T}\Delta t\left(\lambda_{t,m}^{RT}\left(\begin{array}{l}P_{t,m,n}^{re+\_EV}-prob_{acc}^{re+}\times\\ \times prob_{dep}^{re+}\times P_{t,m,n}^{re+\_EV}\end{array}\right)\right)+ +prob_{sh}^{re-}\sum_{T}\Delta t\left(\lambda_{t,m}^{RT}\left(\begin{array}{l}P_{t,m,n}^{re-\_EV}-prob_{acc}^{re-}\times\\ \times prob_{dep}^{re-}\times P_{t,m,n}^{re-\_EV}\end{array}\right)\right) \quad (4)$$

$$C_{m,n}^{RA\_EV} = = prob_{sh}^{ra+}\sum_{T}\Delta t\left(\lambda_{t,m}^{RT}\left(\begin{array}{l}P_{t,m,n}^{ra+\_EV}-prob_{acc}^{ra+}\times\\ \times prob_{dep}^{ra+}\times P_{t,m,n}^{ra+\_EV}\end{array}\right)\right)+ +prob_{sh}^{ra-}\sum_{T}\Delta t\left(\lambda_{t,m}^{RT}\left(\begin{array}{l}P_{t,m,n}^{ra-\_EV}-prob_{acc}^{ra-}\times\\ \times prob_{dep}^{ra-}\times P_{t,m,n}^{ra-\_EV}\end{array}\right)\right) \quad (5)$$

$$C_{m,n}^{DEG\_EV} = =\sum_{EV}\left(\begin{array}{l}K_{ev}\left(\Delta t\times p_{ev,t,m,n}^{dch\_EV}+\Delta t\times p_{ev,t,m,n}^{ch\_EV}+\right.\\ \left.+e_{ev,t,m,n}^{re+\_EV}+e_{ev,t,m,n}^{re-\_EV}+e_{ev,t,m,n}^{ra+\_EV}+e_{ev,t,m,n}^{ra-\_EV}\right)\end{array}\right) \quad (6)$$

Note that the EVs' profits in regulation and ramp services presented in (2) and (3) have two parts. The first part is the capacity revenue which is paid proportional to the accepted bidding power in both upward and downward directions. In (2), $prob_{acc}^{re+}$ and $prob_{acc}^{re-}$ represent the acceptance probability of the upward and downward regulation service biddings, respectively.

The second part is the expected deployment profit which is proportional to the expected deployed power amounts. Furthermore, due to the uncertainty associated with the expected deployed regulation and reserve services in RT and their respective potential shortages, two costs proportional to the maximum possible shortages in regulation and ramp services are formulated in (4) and (5), respectively. Based upon the model proposed in [30], $prob_{acc}^{re+}$ in (4) denotes the probability of shortage for upward regulation which is equal to $prob_{acc}^{re+}\times prob_{dep}^{re+}\times\left(1-prob_{dep}^{re+}\right)$. In addition, (6) represents the degradation cost of all EVs. Charging and discharging of EV batteries for providing each service would result in the reduction of the battery life, which should be taken into account to motivate the participation of EVs in the multi-product markets. Note that $e_{ev,t,m,n}^{re+\_EV}$, $e_{ev,t,m,n}^{re-\_EV}$, $e_{ev,t,m,n}^{ra+\_EV}$ and $e_{ev,t,m,n}^{ra-\_EV}$ in (6), respectively, indicate the expected deployment of upward regulation, downward regulation, upward ramp, and downward ramp values. Finally, the relations of $e_{ev,t,m,n}^{re+\_EV}$, $e_{ev,t,m,n}^{re-\_EV}$, $e_{ev,t,m,n}^{ra+\_EV}$, and $e_{ev,t,m,n}^{ra-\_EV}$ with the total biddings in the energy and ancillary service markets considering the network effects are shown in (7)-(10):

$$\sum_{EV}\left(SCF_{i,t,m,n}\times e_{ev,t,m,n}^{re+\_EV}\right)= =\Delta t\times prob_{acc}^{re+}\times prob_{dep}^{re+}\times P_{t,m,n}^{re+\_EV} \quad (7)$$

$$\sum_{EV}\left(SCF_{i,t,m,n}\times e_{ev,t,m,n}^{re-\_EV}\right)= =\Delta t\times prob_{acc}^{re-}\times prob_{dep}^{re-}\times P_{t,m,n}^{re-\_EV} \quad (8)$$

$$\sum_{EV}\left(SCF_{i,t,m,n}\times e_{ev,t,m,n}^{ra+\_EV}\right)= =\Delta t\times prob_{acc}^{ra+}\times prob_{dep}^{ra+}\times P_{t,m,n}^{ra+\_EV} \quad (9)$$

$$\sum_{EV}\left(SCF_{i,t,m,n}\times e_{ev,t,m,n}^{ra-\_EV}\right)= =\Delta t\times prob_{acc}^{ra-}\times prob_{dep}^{ra-}\times P_{t,m,n}^{ra-\_EV} \quad (10)$$

As discussed previously, the power bidding strategy of the distribution system in the power markets is based on the power exchanges between the distribution and the transmission systems at the Point of the Common Coupling (PCC).

As a result, sensitivity coefficient factors SCF are employed in the formulation to relate the power injection at each node of the system to the power exchanges at PCC. In other words, unlike previous works in the same context, utilization of sensitivity factors would facilitate modeling the power losses of the distribution grid in the proposed optimization model.

Thus, the summation of the expected energy deployment of regulation and ramp services in (7)-(10) are weighted by their related sensitivity coefficient factors to consider the power losses in the grid. Finally, the operational constraints of EVs are formulated in (11)-(17):

$$Soc_{ev,t,m,n}^{EV}=Soc_{ev,t-1,m,n}^{EV}+\Delta t\times\eta_{ev}^{ch}\times p_{ev,t,m,n}^{ch\_EV}+ -\Delta t\times p_{ev,t,m,n}^{dch\_EV}/\eta_{ev}^{dch}-\left(1-AV_{ev,t}\right)E_{ev,t,m} \quad (11)$$

$$Soc_{ev,td,m,n}^{EV}\geq Soc_{ev}^{dep} \quad (12)$$

$$\underline{Soc_{ev}}\leq Soc_{ev,t,m,n}^{EV}\leq\overline{Soc_{ev}} \quad (13)$$

$$e_{ev,t,m,n}^{re+\_EV}+e_{ev,t,m,n}^{ra+\_EV}\leq Soc_{ev,t,m,n}^{EV}-\underline{Soc_{ev}} \quad (14)$$

$$e_{ev,t,m,n}^{re-\_EV}+e_{ev,t,m,n}^{ra-\_EV}\leq\overline{Soc_{ev}}-Soc_{ev,t,m,n}^{EV} \quad (15)$$

$$\Delta t\times p_{ev,t,m,n}^{dch\_EV}+e_{ev,t,m,n}^{re+\_EV}+e_{ev,t,m,n}^{ra+\_EV}\leq \leq\Delta t\times\overline{P_{ev}}\times x_{ev,t,m,n}\times AV_{ev,t} \quad (16)$$

$$\Delta t\times p_{ev,t,m,n}^{ch\_EV}+e_{ev,t,m,n}^{re-\_EV}+e_{ev,t,m,n}^{ra-\_EV}\leq \leq\Delta t\times\overline{P_{ev}}\times\left(1-x_{ev,t,m,n}\right)\times AV_{ev,t} \quad (17)$$

(11) shows the formulation of the state of the charge of batteries of EVs in each time interval. Note that $E_{ev,t,m}$ depicts the energy requirements of the EVs at the time t, when it is in the daily trip. Moreover, $AV_{ev,t}$ is a binary parameter that shows the availability and connection of the EVs to the network. Respectively, $AV_{ev,t}$ equals to one, when the EV is connected to the network. In addition, (12) enforces that the state of the charge of EVs at the departure time should be at least Soc_{ev}^{dep} which is the energy requirement of the EV daily trip. Constraint (13) enforces the limitations over $Soc_{ev,t,m,n}^{EV}$.

Furthermore, (14) and (15) show the relation between the deployed energy amounts and the state of the charge of each EV. Finally, (16) and (17) define the direction of power and ancillary services at each interval to ensure that only the ancillary services with the same physical direction can be provided by the EV (upward or downward). This limitation is enforced by employing the binary variable $x_{ev,t,m,n}$. Note that regardless of charging/discharging and the direction of the services, the sum of the power exchanges in each direction should not exceed the maximum power of the EV battery shown by $\overline{P_{ev}}$ in (16) and (17).

III.2. Scheduling of BESSs

The profits and cost terms related to BESSs in the objective function (1) are presented in (18) – (22) in which, (18) and (19) shows the BESSs expected profits in regulation and ramp services, respectively. The expected shortage costs for BESSs in regulation and ramp services are also shown in (20) and (21). Finally, (22) shows the degradation cost of all BESSs:

$$B_{m,n}^{RE\_ES} = \sum_T \Delta t \begin{pmatrix} prob_{acc}^{re+} \times \lambda_{t,m}^{RE+} \times P_{t,m,n}^{re+\_ES} + \\ + prob_{acc}^{re-} \times \lambda_{t,m}^{RE-} \times P_{t,m,n}^{re-\_ES} \end{pmatrix} + \sum_T \Delta t \begin{pmatrix} prob_{acc}^{re+} \times prob_{dep}^{re+} \times \\ \times \lambda_{t,m}^{RT} \times \left(\eta_{ev}^{dch} \times P_{t,m,n}^{re+\_ES}\right) \end{pmatrix} \quad (18)$$

$$B_{m,n}^{RA\_ES} = \sum_T \Delta t \begin{pmatrix} prob_{acc}^{ra+} \times \lambda_{t,m}^{RA+} \times P_{t,m,n}^{ra+\_ES} + \\ + prob_{acc}^{ra-} \times \lambda_{t,m}^{RA-} \times P_{t,m,n}^{ra-\_ES} \end{pmatrix} + \sum_T \Delta t \begin{pmatrix} prob_{acc}^{ra+} \times prob_{dep}^{ra+} \times \\ \times \lambda_{t,m}^{RT} \times \left(\eta_{ev}^{dch} \times P_{t,m,n}^{ra+\_ES}\right) \end{pmatrix} \quad (19)$$

$$C_{m,n}^{RE\_ES} = = prob_{sh}^{re+} \sum_T \Delta t \left(\lambda_{t,m}^{RT} \begin{pmatrix} P_{t,m,n}^{re+\_ES} - prob_{acc}^{re+} \times \\ \times prob_{dep}^{re+} \times P_{t,m,n}^{re+\_ES} \end{pmatrix} \right) + \quad (20)$$
$$+ prob_{sh}^{re-} \sum_T \Delta t \left(\lambda_{t,m}^{RT} \begin{pmatrix} P_{t,m,n}^{re-\_ES} - prob_{acc}^{re-} \times \\ \times prob_{dep}^{re-} \times P_{t,m,n}^{re-\_ES} \end{pmatrix} \right)$$

$$C_{m,n}^{RA\_ES} = = prob_{sh}^{ra+} \sum_T \Delta t \left(\lambda_{t,m}^{RT} \begin{pmatrix} P_{t,m,n}^{ra+\_ES} - prob_{acc}^{ra+} \times \\ \times prob_{dep}^{ra+} \times P_{t,m,n}^{ra+\_ES} \end{pmatrix} \right) + \quad (21)$$
$$+ prob_{sh}^{ra-} \sum_T \Delta t \left(\lambda_{t,m}^{RT} \begin{pmatrix} P_{t,m,n}^{ra-\_ES} - prob_{acc}^{ra-} \times \\ \times prob_{dep}^{ra-} \times P_{t,m,n}^{ra-\_ES} \end{pmatrix} \right)$$

$$C_{m,n}^{DEG\_ES} = = \sum_{ES} \left(K_{es} \begin{pmatrix} \Delta t \times p_{es,t,m,n}^{dch\_ES} + \Delta t \times p_{es,t,m,n}^{ch\_ES} + \\ + e_{es,t,m,n}^{re+\_ES} + e_{es,t,m,n}^{re-\_ES} + \\ + e_{es,t,m,n}^{ra+\_ES} + e_{es,t,m,n}^{ra-\_ES} \end{pmatrix} \right) \quad (22)$$

Finally, operational constraints of BESSs are formulated in (23)-(29):

$$Soc_{es,t,m,n}^{ES} = Soc_{es,t-1,m,n}^{ES} + \Delta t \times \eta_{es}^{ch} \times \times p_{es,t,m,n}^{ch\_ES} - \Delta t \times p_{es,t,m,n}^{dch\_ES} / \eta_{es}^{dch} \quad (23)$$

$$Soc_{es,'T',m,n}^{ES} = Soc_{es}^{init} \quad (24)$$

$$\underline{Soc_{es}} \le Soc_{es,t,m,n}^{ES} \le \overline{Soc_{es}} \quad (25)$$

$$e_{es,t,m,n}^{re+\_ES} + e_{es,t,m,n}^{ra+\_ES} \le Soc_{es,t,m,n}^{ES} - \underline{Soc_{es}} \quad (26)$$

$$e_{es,t,m,n}^{re-\_ES} + e_{es,t,m,n}^{ra-\_ES} \le \overline{Soc_{es}} - Soc_{es,t,m,n}^{ES} \quad (27)$$

$$\Delta t \times p_{es,t,m,n}^{dch\_ES} + e_{es,t,m,n}^{re+\_ES} + e_{es,t,m,n}^{ra+\_ES} \le \le \Delta t \times \overline{P_{es}} \times x_{es,t,m,n} \times AV_{es,t} \quad (28)$$

$$\Delta t \times p_{es,t,m,n}^{cch\_ES} + e_{es,t,m,n}^{re-\_ES} + e_{es,t,m,n}^{ra-\_ES} \le \le \Delta t \times \overline{P_{es}} \times \left(1 - x_{es,t,m,n}\right) \times AV_{es,t} \quad (29)$$

In the above formulation, the charging state of batteries of BESSs in each time interval is related to the previous interval in (23). Moreover, (24) shows the energy state of the charge BESSs at the initial state. In addition, (25) enforces the limitations over. The relation between the deployed energy amounts and $Soc_{es,t,m,n}^{ES}$ are formulated in (26) and (27). Finally, (28) and (29) define the direction of power and ancillary services at each interval to ensure that only the ancillary services with the same physical direction can be provided by the BESSs (upward or downward).

III.3. Scheduling of RESs

RESs in distribution systems can help the system to partly supply the load demand. In this context, RESs could be participated in energy and reserve markets to maximize their profits. Nevertheless, the uncertainty of RESs could have significant effects on their associated profits and costs; therefore, the aggregator should model the uncertainties of RESs in the optimization model:

$$B^{RE\_RES}_{m,n} = = \sum_{T} \Delta t \begin{pmatrix} prob^{re+}_{acc} \times \lambda^{RE+}_{t,m} \times P^{re+\_RES}_{t,m,n} + \\ +prob^{re+}_{acc} \times prob^{re+}_{dep} \times \\ \times \lambda^{RT}_{t,m} \times P^{re+\_RES}_{t,m,n} \end{pmatrix} + \sum_{T} \Delta t \begin{pmatrix} prob^{re-}_{acc} \times \lambda^{RE-}_{t,m} \times P^{re-\_RES}_{t,m,n} + \\ +prob^{re-}_{acc} \times prob^{re-}_{dep} \times \\ \times \lambda^{RT}_{t,m} \times P^{re-\_RES}_{t,m,n} \end{pmatrix} \quad (30)$$

$$B^{RA\_RES}_{m,n} = = \sum_{T} \Delta t \begin{pmatrix} prob^{ra+}_{acc} \times \lambda^{RA+}_{t,m} \times P^{ra+\_RES}_{t,m,n} + \\ +prob^{ra+}_{acc} \times prob^{ra+}_{dep} \times \\ \times \lambda^{RT}_{t,m} \times P^{ra+\_RES}_{t,m,n} \end{pmatrix} + \sum_{T} \Delta t \begin{pmatrix} prob^{ra-}_{acc} \times \lambda^{RA-}_{t,m} \times P^{ra-\_RES}_{t,m,n} + \\ +prob^{ra-}_{acc} \times prob^{ra-}_{dep} \times \\ \times \lambda^{RT}_{t,m} \times P^{ra-\_RES}_{t,m,n} \end{pmatrix} \quad (31)$$

$$C^{RE\_RES}_{m,n} = = prob^{re+}_{sh} \sum_{T} \Delta t \left(\lambda^{RT}_{t,m} \begin{pmatrix} P^{re+\_RES}_{t,m,n} - prob^{re+}_{acc} \times \\ \times prob^{re+}_{dep} \times P^{re+\_RES}_{t,m,n} \end{pmatrix} \right) + prob^{re-}_{sh} \sum_{T} \Delta t \left(\lambda^{RT}_{t,m} \begin{pmatrix} P^{re-\_RES}_{t,m,n} - prob^{re-}_{acc} \times \\ \times prob^{re-}_{dep} \times P^{re-\_RES}_{t,m,n} \end{pmatrix} \right) \quad (32)$$

$$C^{RA\_RES}_{m,n} = = prob^{ra+}_{sh} \sum_{T} \Delta t \left(\lambda^{RT}_{t,m} \begin{pmatrix} P^{ra+\_RES}_{t,m,n} - prob^{ra+}_{acc} \times \\ \times prob^{ra+}_{dep} \times P^{re+\_RES}_{t,m,n} \end{pmatrix} \right) + prob^{ra-}_{sh} \sum_{T} \Delta t \left(\lambda^{RT}_{t,m} \begin{pmatrix} P^{ra-\_RES}_{t,m,n} - prob^{ra-}_{acc} \times \\ \times prob^{ra-}_{dep} \times P^{ra-\_RES}_{t,m,n} \end{pmatrix} \right) \quad (33)$$

$$p^{RES}_{i,t,m,n} + re^{RES}_{i,t,m,n} + ra^{RES}_{i,t,m,n} \le \overline{P^{RES}_{i,t,n}} \quad (34)$$

$$p^{RES}_{i,t,m,n} - re^{-RES}_{i,t,m,n} - ra^{-RES}_{i,t,m,n} \ge 0 \quad (35)$$

$$\sum_{I} \left(re^{+RES}_{i,t,m,n} \times SFC_{i,t,m,n} \right) = = prob^{re+}_{acc} \times prob^{re+}_{dep} \times P^{re+\_RES}_{t,m,n} \quad (36)$$

$$\sum_{I} \left(re^{-RES}_{i,t,m,n} \times SFC_{i,t,m,n} \right) = = prob^{re-}_{acc} \times prob^{re-}_{dep} \times P^{re-\_RES}_{t,m,n} \quad (37)$$

$$\sum_{I} \left(ra^{+RES}_{i,t,m,n} \times SFC_{i,t,m,n} \right) = = prob^{ra+}_{acc} \times prob^{ra+}_{dep} \times P^{ra+\_RES}_{t,m,n} \quad (38)$$

$$\sum_{I} \left(ra^{-RES}_{i,t,m,n} \times SFC_{i,t,m,n} \right) = = prob^{ra-}_{acc} \times prob^{ra-}_{dep} \times P^{ra-\_RES}_{t,m,n} \quad (39)$$

In the above formulation, (30) and (31) shows the expected profits in regulation and ramp services for RESs. Furthermore, expected shortage costs for these resources in regulation and ramp services are formulated in (32) and (33), respectively. Operational limitations of RESs are represented in (34) and (35), where the $\overline{P^{RES}_{i,t,m}}$ shows the available power generation of RESs. (36) and (37) are employed to model the total biddings in the up and down regulation services considering the network effects for RESs, respectively. Similarly, (38) and (39) models the total biddings in the up and down ramp services considering the network effects.

III.4. Energy Service and Network Constraints

The formulations of energy service profits as well as the network constraints are presented as below:

$$B^{EN}_{m,n} = \Delta t \sum_{T} \lambda^{DA}_{t,m} Psell_{t,m,n} \quad (40)$$

$$Pline_{i,j,t,m,n} = = G_{i,j}\left(V_{i,t,m,n} - V_{j,t,m,n}\right) - B_{i,j}\left(\theta_{i,t,m,n} - \theta_{j,t,m,n}\right) \quad (41)$$

$$Qline_{i,j,t,m,n} = = B_{i,j}\left(V_{i,t,m,n} - V_{j,t,m,n}\right) + G_{i,j}\left(\theta_{i,t,m,n} - \theta_{j,t,m,n}\right) \quad (42)$$

$$Pinj_{i,t,m,n} = \sum_{J} Pline_{i,j,t,m,n} \quad (43)$$

$$Qinj_{i,t,m,n} = \sum_{J} Qline_{i,j,t,m,n} \quad (44)$$

$$Pinj_{i,t,m,n} = -Pd_{i,t} + + \sum_{EV} \left(\eta^{dch}_{ev} p^{dch\_EV}_{ev,t,m,n} - p^{ch\_EV}_{ev,t,m,n} \right) + + \sum_{ES} \left(\eta^{dch}_{es} p^{dch\_ES}_{es,t,m,n} - p^{ch\_ES}_{es,t,m,n} \right) + p^{RES}_{i,t,m,n} \quad (45)$$

$$Qinj_{i,t,m,n} = -Qd_{i,t} \quad (46)$$

$$Pinj_{"i0",t,m,n} = -Psell_{t,m,n} \quad (47)$$

$$Qinj_{"i0",t,m,n} = -Qsell_{t,m,n} \quad (48)$$

$$\underline{V} \leq V_{i,t,m,n} \leq \overline{V} \quad (49)$$

$$-S_{i,j} \leq Pline_{i,j,t,m,n} + \xi Qline_{i,j,t,m,n} \leq S_{i,j} \quad (50)$$

The profit of energy service presented by $B^{EN}_{m,n}$ in the objective function (1) is formulated in (40). The aggregator purchases energy if the variable $Psell_{t,m,n}$ (i.e., selling power) takes negative values and makes a profit proportional to positive values. Based on the model in [23], the line flow equation for active power is linearly modeled in (41) and (42) shows its formulation for reactive power. Additionally, (43) and (44) relate the active and reactive flows to the injected amounts of active and reactive power. Moreover, (46) and (47) relate the injected power amounts to bus demands and supplied power of resources located in each bus, while the relation of the selling active and reactive power amounts (i.e., DA bidding amounts) with the power injections in the PCC of the distribution and transmission systems is shown in (47) and (48). Constraint (49) determines the boundary of the voltage magnitude. $\overline{V}$ and $\underline{V}$ show the maximum and minimum acceptable voltage of buses. Finally, (50) shows the constraint on the line flows, where $S_{i,j}$ is the maximum permissible flow of the connected line between nodes *i* and *j*.

III.5. Chance Constraint Reformulation

As discussed earlier, the uncertainty associated with the forecasted power generation of RESs (i.e., $\overline{P^{RES}_{i,t,n}}$) in (34) is a random variable. Regarding this issue, the constraint (34) has rewritten in (51) which shows that the constraint (31) should be satisfied by probability of at least 1-ε where, ε shows the probability by which the constraint has a chance to be violated. For converting this probabilistic constraint to a linear form, the big-M method has been employed in this section. Constraint (52) shows the reformulation of (51) utilizing the big-M technique. It is assumed that there are *n* scenarios in which a binary variable shows whether the constraint has been violated or not. Respectively, $z_{i,t,m,n}$ shows the binary variable which takes the value of 1 if the constraint in the corresponding scenario is violated.

Finally, (53) restricts the number of scenarios in which the violation occurs, where ω_n shows the realization probability of each scenario in the related scenario set (*N*):

$$\Pr\left(p^{RES}_{i,t,m,n} + re^{+RES}_{i,t,m,n} + ra^{+RES}_{i,t,m,n} \leq \overline{P^{RES}_{i,t,n}} \right) \geq 1 - \varepsilon \quad (51)$$

$$p^{RES}_{i,t,m,n} + re^{+RES}_{i,t,m,n} + ra^{+RES}_{i,t,m,n} - \overline{P^{RES}_{i,t,n}} \leq BMz_{i,t,m,n} \quad (52)$$

$$\sum_{N} \omega_n z_{i,t,m,n} \leq \varepsilon \quad (53)$$

IV. Case Study

In this paper, the IEEE-37 bus test system has been considered to study the developed algorithm for the bidding strategy of local systems in energy, reserve, and ramp markets. The operational data of local resources as well as the test system are adapted from [31], [32], and presented in [33]. The probabilities associated with the acceptance and deployment of ramp and reserve services are respectively depicted in Figs. 3 and 4. Note that the energy and reserve prices are taken from [3]. Moreover, $\underline{V}$, $\overline{V}$, and ξ are set to 0.95, 1.05 and 0.3, respectively.

Different profits and costs of aggregators considering the ramp price of 8 \$/MWh for both directions are depicted in Fig. 5.

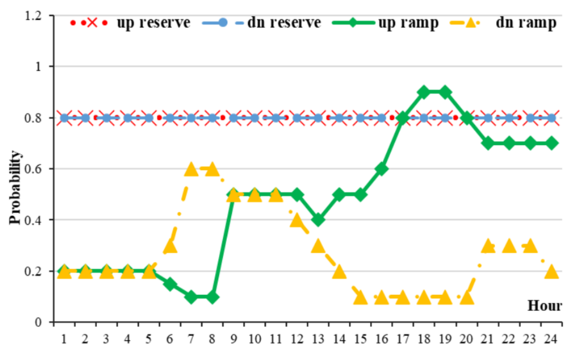

Fig. 3. Acceptance probability of ramp and reserve services

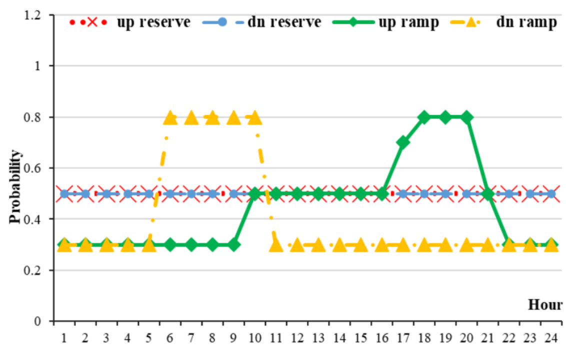

Fig. 4. Deployment probability of ramp and reserve services

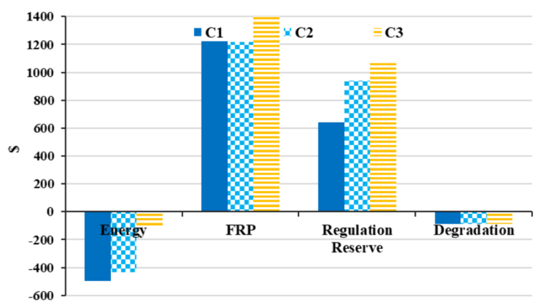

Fig. 5. Profits or cost for energy and ancillary services and degradation cost of EV and BESS's batteries

Based upon the obtained results, the profits are shown with positive values and the costs are shown with negative values. The results are compared for three different cases: C1, C2, and C3, which are depicted as follows:

- *C1:* In this case, the model includes the proposed algorithm presented in Fig 2 and the network constraints;
- *C2:* In this case, only the proposed algorithm in Fig. 2 is considered without considering network constraints;
- *C3:* In this case, the model doesn't use any of these restrictions.

According to the obtained results in C1 (i.e., considering the proposed algorithm and the network constraints), profits associated with the ramp and regulation reserve services have decreased compared to C3. Moreover, this is inversely has affected the cost of energy service due to the power losses in the network.

These results in Fig. 5 also highlight the importance of the FRP and the higher profitability of this service compared to regulation reserve and energy products. The presented degradation costs of BESSs and EVs batteries shows that this cost can be ignored in comparison with the profits of the ramp and reserve services. The total FRP and reserve offers for both upward and downward directions are depicted by Figs. 6-9. According to the obtained results, the bidding for FRP is much more beneficial than the regulation reserve in most time intervals. Additionally, these amounts are different in three cases which shows the importance of considering power losses and the network constraints in the optimization model.

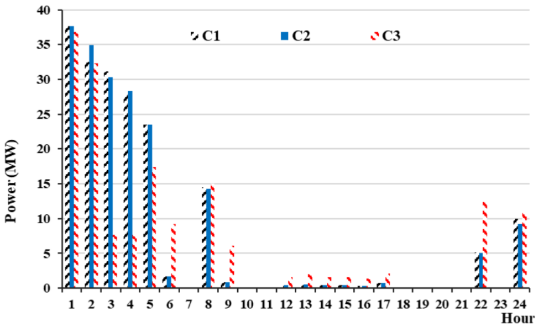

Fig. 6. Bidding powers for upward FRP

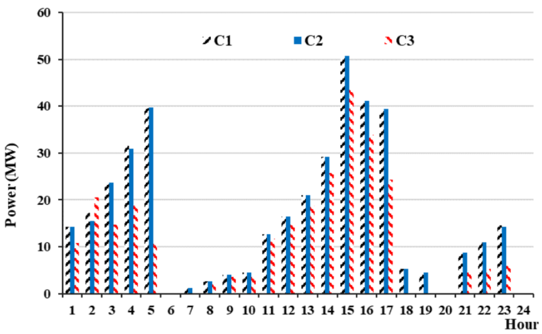

Fig. 7. Bidding powers for downward FRP

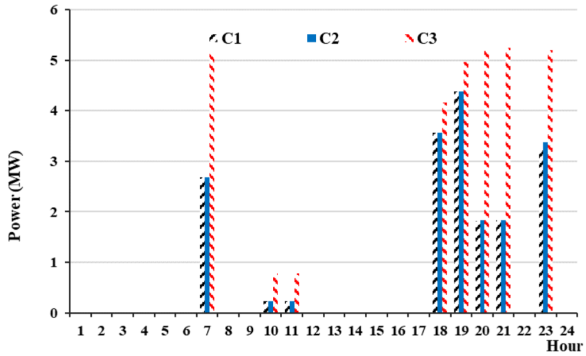

Fig. 8. Bidding powers for upward regulation reserve

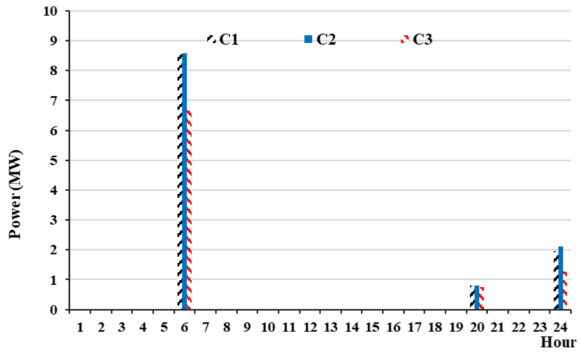

Fig. 9. Bidding powers for downward regulation reserve

Total profits for regulation reserve and FRP are dependent on FRP prices as well as the acceptance and deployment probabilities of this service. These parameters also affect the total energy cost of the network.

In this regard, a sensitivity analysis has been performed on these parameters, which are shown in Figs. 10-12 considering the price, acceptance probability, and deployment probability of FRP service. As shown in Fig. 10, the profit of the FRP service increases with the increase of its price but the regulation reserve's profit decreases by increasing the price. This is based on the point that it is more beneficial to offer FRP rather than regulation reserve when the FRP price is higher. To show the sensitivity of profit and costs to acceptance or deployment probabilities, these profits and costs are shown for three multipliers of probability quantities in Figs. 11, 12.

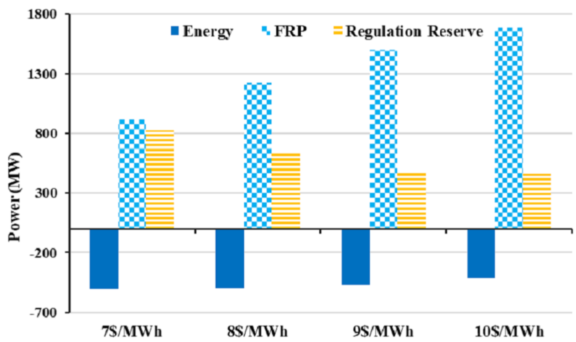

Fig. 10. Total Profits and Costs for different FRP's prices

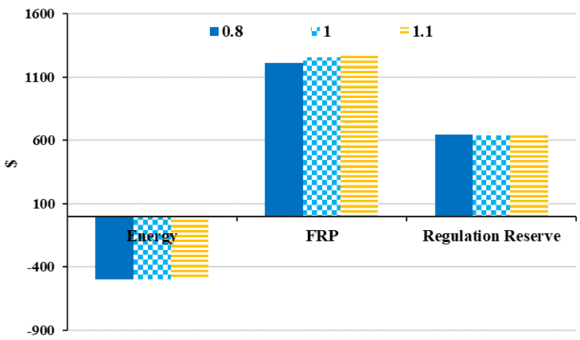

Fig. 11. Total profits and costs for different acceptance probabilities of FRP service

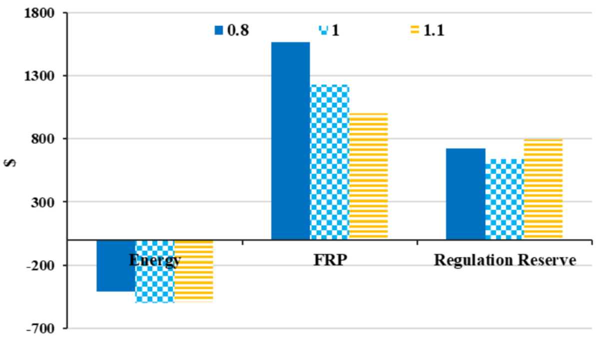

Fig. 12. Total profits and costs for different deployment probabilities of FRP service

In this regard, Fig. 11 shows the profits and costs for three cases of acceptance probability multipliers and Fig. 12 shows them for three cases of deployment probability multipliers. According to these results, the obtained profits (specifically the FRP profits) are more sensitive to the deployment probability rather than the acceptance probability. By increasing the deployment probability, the profits of the FRP service decrease. This is based on the point that the shortage probability and the expected shortage cost increase which would cause the total reduction in net profit of the service. In this paper, a sensitivity analysis is also performed for different values of ε, and the results are shown in Fig. 13 for three values of ε (i.e., 0.2, 0.3, and 0.5). Comparison of FRP and regulation reserve's profits for different values of ε shows that by increasing ε, the amount of profits also increases and the FRP profit increases more than regulation reserve service profits.

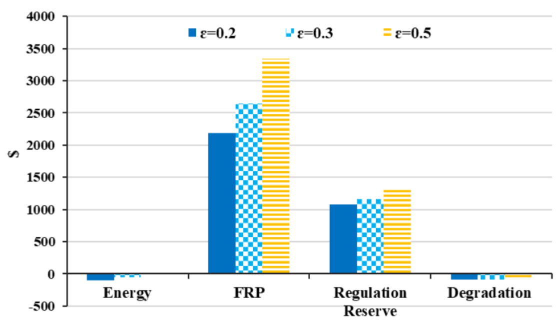

Fig. 13. Total profits and costs for different values of ε

The reason for this is that the amount of FRP during the 24 hours is more than the regulation reserve. In addition, the share of RESs in FRP is more than the regulation reserve. Bidding powers for upward FRP, downward FRP, upward regulation reserve and downward regulation reserve for three values of ε are depicted in Figs. 14-17, respectively. According to Fig. 14, the total bidding powers for upward FRP in three cases are similar. The reason is zero shares of RESs capacity in three cases in the upward FRP service.

However, as shown in Fig. 16, for upward regulation reserve the share of RESs is only zero in hours 10, 11, 20, 21, and 23. In other hours like 7, RESs capacity is available and due to this, the bidding powers are different for each value of ε. In these times, as excepted, the bidding powers increase with increasing of ε which shows the acceptable risk index decided by the aggregator. Consequently, by bidding more, the expected profit of aggregator in the considered service and also its total expected profit increases.

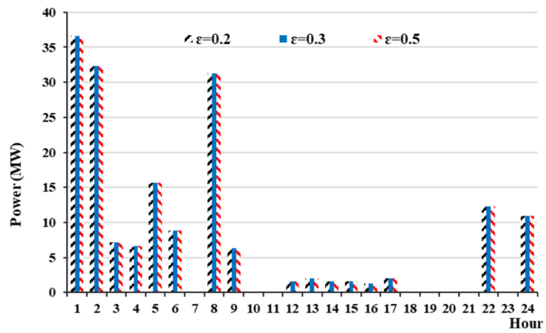

Fig. 14. Bidding powers for upward FRP for different values of ε

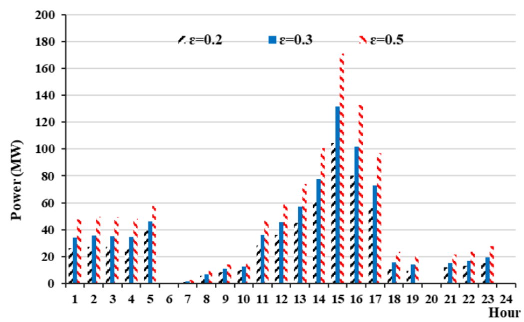

Fig. 15. Bidding powers for downward FRP for different values of ε

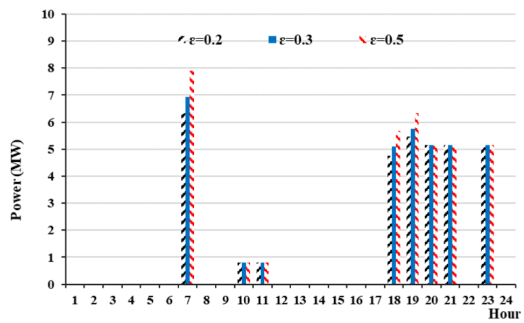

Fig. 16. Bidding powers for upward regulation reserve for different values of ε

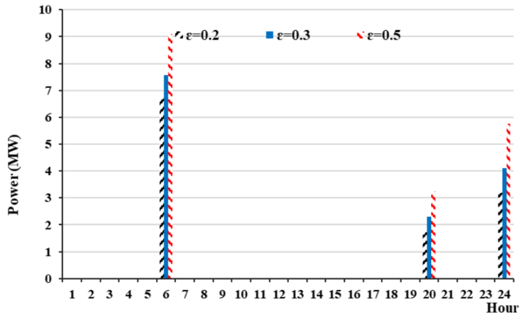

Fig. 17. Bidding powers for downward regulation reserve for different values of ε

V. Conclusion

In this paper, a model of an active distribution system in the presence of renewable generation and BESSs and EVs is considered to study the optimized bidding strategy of the DSO as an aggregator in DA energy and regulation reserve, and ramp markets. The developed model considers FRP, network constraints, and power loss as well as expected deployment of FRP and regulation reserve services to optimize the bidding strategy. Moreover, the proposed model is applied to a 37-bus test system to analyse the developed bidding approach from different perspectives. Based on the obtained results, considering FRP in the model, brings a lot of benefits for the system. Finally, the study explored the dependence of the aggregator's profits on crucial parameters in the model. Additionally, an investigation was conducted on the effect of the risk parameter in the considered chance-constrained model on the profitability and bidding capabilities of both the regulation reserve service and FRP services. The developed strategy and the study results show the importance of the proposed approach in optimizing the scheduling of local resources in a distribution system while participating in energy, regulation reserve, and ramp markets.

For future work, we plan to model the interaction of aggregators in decentralized methods to consider privacy issues of aggregators' data. Additionally, we intend to explore the implementation of machine learning methods to improve price and renewable generation forecast accuracy, ultimately leading to more efficient bidding strategies in energy and ancillary services markets. Our study demonstrates the importance of optimizing scheduled local resources in distribution systems while participating in these markets to achieve optimal outcomes.

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Authors' information

[1]Department of Electrical Engineering, Sharif University of Technology, Iran.

[2]Department of Electrical Engineering and Automation, Aalto University, Finland.

Amin Naseri received his MS.c. degree in electrical engineering, power systems, from Sharif University of Technology, Tehran, Iran in 2021. Currently, he is completing his PhD in electrical engineering, power systems, at Sharif University of Technology. His research interests include power systems planning, operations, optimization and smart grids.

Sajjad Fattaheian-Dehkordi received his MS.c. degree in electrical engineering, power systems, from Sharif University of Technology, Tehran, Iran in 2014. Currently, he is completing his PhD in electrical engineering, power systems, at Sharif University of Technology and Aalto University, Espoo, Finland. His research interests include power systems planning, operations, and economics with focus on issues relating with the integration of renewable energy resources into the system.

Ali Abbaspour received the B.Sc. degree in electrical engineering from the Amirkabir University of Technology, Tehran, Iran, in 1973, the M.Sc. degree in electrical engineering from Tehran University, Tehran, in 1976, and the Ph.D. degree in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, in 1983. Currently, he is a Professor with the Department of Electrical Engineering, Sharif University of Technology, Tehran.

Matti Lehtonen was with VTT Energy, Espoo, Finland, from 1987 to 2003, and since 1999 has been a professor at the Helsinki University of Technology, nowadays Aalto University, where he is head of Power Systems and High Voltage Engineering. Matti Lehtonen received both his Master's and Licentiate degrees in Electrical Engineering from Helsinki University of Technology, in 1984 and 1989, respectively, and the Doctor of Technology degree from the Tampere University of Technology in 1992. The main activities of Dr. Lehtonen include power system planning and asset management, power system protection including earth fault problems, harmonic related issues and applications of information technology in distribution systems.