



Robust Coordinated Operational Planning of Power Distribution Systems Considering Electric Vehicle Aggregators

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Robust Coordinated Operational Planning of Power Distribution Systems Considering Electric Vehicle Aggregators

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Abstract—This paper proposes a robust model that optimizes the joint cooperation between the distribution system operator (DSO) and the electric vehicle aggregators (EVAs) considering the forecasting uncertainties. The developed cooperation model considers electric vehicles (EVs) in a vehicle-to-grid operation, fuel-based distributed generators, and wind generators. The purpose of the proposed model is to optimize the operational planning that simultaneously minimizes the DSO’s energy cost and maximizes the revenue of each EVA. The proposed model is applied to a 14-bus distribution system to verify its effectiveness and robustness.

Keywords—distribution systems, electric vehicles, electric vehicle aggregators, mixed integer non-linear programming, robust optimization

NOMENCLATURE

A. Sets

Ω_N	Set of system buses, indexed by i
Ω_L	Set of distribution lines, indexed by ij
Ω_{DG}	Set of fuel-based distributed generators (DGs), indexed by k
Ω_{WG}	Set of wind generators (WGs), indexed by wg
Ω_{EVA}	Set of electric vehicle aggregators (EVAs), indexed by ag
Ω_{EV}	Set of electric vehicles (EVs), indexed by ev
$\Omega_{EV(ag)}$	Set of EVs controlled by EVA ag
T	Number of time-intervals, indexed by t

B. Parameters

a_k, b_k, c_k	Coefficients of production cost of DG k
B_{ij}	Susceptance of line ij
$C_{ev}^{B,inv}$	Cost of battery of EV ev
C_{wg}	Cost of production of WG wg
d_{ev}	Travel distance of EV ev since its last charging
d_{ev}^{max}	Maximum travel distance of EV ev
DR_k	Ramp-down limit of DG k
DT_k	Minimum down-time of DG k
$E_{ev}^{B,max}$	Maximum stored energy of battery of EV ev
$E_{ev}^{B,min}$	Minimum stored energy of battery of EV ev
E_{ev}^{con}	Required energy stored in battery of EV ev at departure time

$E_{ev}^{con,prev}$	Required energy stored in battery of EV ev at previous departure time
G_{ij}	Conductance of line ij
P_{ij}^{max}	Thermal limit of line ij
LT_{ev}	Life cycle of battery of EV ev
$P_{ev}^{Ch,max}$	Maximum charging power of EV ev
$P_{ev}^{Dch,max}$	Maximum discharging power of EV ev
$P_k^{DG,max}$	Maximum production of DG k
$P_k^{DG,min}$	Technical minimum of production of DG k
$P_{wg}(v)$	The power curve (S-curve) of WG wg
$P_{wg,t}^{fic}$	Forecasted active power output of WG wg at time-interval t
P_{wg}^{max}	Maximum active power output of WG wg
SDC_k	Shut-down cost of DG k
SUC_k	Start-up cost of DG k
T_{ev}^{arr}	Arrival time of EV ev
T_{ev}^{dep}	Departure time of EV ev
UR_k	Ramp-up limit of DG k
UT_k	Minimum up-time of DG k
v_{wg}^{in}	Cut-in wind speed of WG wg
v_{wg}^{out}	Cut-out wind speed of WG wg
v_t	Forecasted wind speed at time-interval t
$\mathcal{E}_{WS,t}^{max}$	Maximum deviation from the forecasted wholesale market price at time-interval t
$\mathcal{E}_{wg,t}^{max}$	Maximum deviation from the forecasted production of WG wg at time-interval t
Γ_0	Budget of uncertainty of forecasted value of wholesale market price
Γ_{wg}	Budget of uncertainty of forecasted active power output of WG wg
η_{ev}	Charging/discharging efficiency of EV ev
π_t^{WS}	Forecasted value of wholesale market price at time-interval t

C. Continuous Variables

C_{DSO}^{RCO}	Energy cost of distribution system operator (DSO) according to the robust coordinated optimization (RCO) model
C_{DSO}^{noEVA}	DSO’s energy cost solving the DSO’s sub-

	problem model without EVAs
$C_{DSO}^{RO,noEVA}$	DSO's energy cost solving the DSO's sub-problem model with robust optimization (RO) without EVAs
$C_{DSO}^{RO,EVA}$	DSO's energy cost solving the DSO's sub-problem model with RO with EVAs
$E_{ev,t}^B$	Energy of battery of EV ev at time-interval t
$P_{ag,t}$	Active power of EVA ag at time-interval t
$P_{ev,t}^{Ch}$	Charging active power of EV ev at time-interval t
$P_{ev,t}^{Dch}$	Discharging power of EV ev at time-interval t
$P_{k,t}^{DG}$	Active power output of DG k at time-interval t
$P_{ij,t}^{flow}$	Active power flow of line ij
$P_{i,t}^D$	Total active power demand at bus i at time-interval t
$P_{i,t}^G$	Total active power generation at bus i at time-interval t
P_t^{WS}	Power imported from the wholesale market at time-interval t
R_{ag}^{RCO}	Revenue of EVA ag solving the RCO model
R_{ag}^{\max}	Revenue of EVA solving the sub-problem model of EVA ag
$R_{ag}^{RO,\max}$	Revenue of EVA solving the sub-problem model of EVA ag with RO
w_0, z_{0t}	Auxiliary variables for RO concerning uncertainty of π_t^{WS}
$w_{1wg}, z_{1wg,t}$	Auxiliary variables for RO concerning uncertainty of $P_{wg,t}^{fre}$
$\delta_{i,t}$	Voltage angle of bus i at time-interval t
$\Delta V_{i,t}$	Voltage deviation of bus i at time-interval t
D. Binary Variables	
$u_{ev,t}^{Ch}$	Charging status of EV ev at time-interval t
$u_{ev,t}^{Dch}$	Discharging status of EV ev at time-interval t
$u_{k,t}$	Commitment status of DG k at time-interval t
$u_{k,t}^{OFF}$	Shut-down status of DG k at time-interval t
$u_{k,t}^{ON}$	Start-up status of DG k at time-interval t

I. INTRODUCTION

The electrification of transportation, which would otherwise be powered by fossil fuel, has the potential to produce significant public health, environmental, economic and grid management benefits [1]. EVs could outline a pathway to a more reliable, affordable and efficient low-carbon electrical system [2]. Charging EVs when renewable energy sources (RES) are more available helps the integration of such technologies. EVs also have the capability to inject power when needed, and in that manner they can serve as producers [3].

Over the past few years EVs have managed to penetrate the transportation market as part of the solution to the global pollution and fossil fuel consumption problem. As EVs are expected to gain more attention in the future, research has focused on the potential opportunities and challenges they may offer to the DSO [4]. Most research studies are focused

on the optimal charging/discharging schedule of EVs considering vehicle-to-grid (V2G) operation. For example, in [5], pricing mechanisms have been designed in order to guide the EV owners to charge their EVs during off-peak hours. In [6], a ramp rate limiting service has been developed to compensate wind power fluctuations in the grid based on the charging load of EVs. In [7], a multi-objective model is proposed for the optimal scheduling of EV charging/discharging.

However, it would be impractical for the DSO to separately control each EV from a large fleet of EVs. Additionally, the direct communication between the DSO and the EV owners may be another problem. To cope with these issues, the involvement of EVAs is proposed. An EVA is a mediator between the EVs and the DSO, responsible for controlling the aggregated charging/discharging process of EVs. In [8], a multi-objective optimization model is proposed for obtaining optimal coordinated operation of microgrids, including renewable generation and EVAs of plug-in EVs. The multi-objective model is solved using two different methods, i.e., the exponential weighted criterion method and a compromise programming method. In [9], EVAs collaborate to schedule the plug-in EV charging pattern. A bi-objective charging schedule problem is formulated to maximize the total EVAs' profit, while maximizing the number of EVs to be charged. In [10], a day-ahead operational planning is proposed to minimize the microgrid's daily operational cost based on load and source availability forecasting, in the presence of an EVA, while also considering the financial transactions between the EVA and the microgrid operator.

In [11], a robust optimization (RO) model is introduced to minimize the total cost of the distribution system, and a decentralized solution algorithm based on the alternating direction method of multipliers is introduced to preserve the independency of EVAs and to reduce the complexity of the proposed model. The authors of [12] investigate the optimal participation of a single EVA in the energy market with uncertain prices. The main goal of the proposed RO framework is to satisfy the economic goals of the EVA in an uncertain energy market. The authors of [13] present a RO technique to model the electricity price uncertainty, in order to obtain robust scheduling of a single EVA. In [14] an EVAs' bidding strategy model is proposed, which constitutes a generalized Nash equilibrium problem. RO is used to cope with uncertainties of energy prices.

As discussed, EVAs have been optimally integrated in the distribution systems for different objectives, representing their importance in power systems. The existing literature usually takes into consideration the maximization of revenue of a single or multiple EVAs, as well as the uncertainties of energy market prices. However, the potential optimal cooperation between the DSO and the EVAs should be investigated in order all the included parties to obtain satisfactory financial benefits. Additionally, a more complex energy mix of the distribution system should be taken into account, as well as the uncertainties of RES.

This paper proposes a RO model for the joint cooperation between the DSO and the EVAs in a power distribution system that also includes fuel-based DGs and wind generators. Hereafter, the proposed model is called robust coordinated optimization (RCO) model. The RCO model consists of two sub-problems both formulated as mixed

integer non-linear programming (MINLP) problems. The first one minimizes the energy production cost for the DSO, whereas the second one maximizes the revenue of each EVA separately. Subsequently, these two models are modified for RO to take into account the maximum expected deviation from the hourly forecasted values of the wholesale market price and the produced active power of WG. The results of the RO sub-problems are used as input parameters for the proposed RCM, which, in turn, seeks a trade-off between the objectives of the included stakeholders, i.e., DSO and EVA, altogether. The proposed RCO model, which is also a MINLP problem, is applied to a 14-bus power distribution system to demonstrate its effectiveness and robustness.

The contributions of this paper are the following:

- 1) A new optimization model is introduced, called RCO model, which simultaneously co-optimizes the objective of the DSO and the objectives of each EVA participating in the distribution system.
- 2) The proposed model is a RO model, so the worst-case uncertainties of the forecasted parameters, wholesale market prices and WG production, are taken into account.
- 3) The problem is formulated considering a complex energy mix with multiple distributed energy resources, such as renewables, conventional fuel-based DGs, and electric vehicles.

The remainder of this paper is organized as follows. In Section II, the sub-problems of minimizing the DSO's energy cost and maximizing the revenue of each EVA are formulated. Section III formulates the RO models of Section II sub-problems. Section IV introduces the proposed RCO model. Section IV briefly outlines the case study and discusses the obtained results, while Section V concludes.

II. PROBLEM FORMULATION

In this section, the main problem of optimizing the operational planning of a distribution system is split in two sub-problems, each one related to the objectives of the entities participating in the system, i.e., the DSO's sub-problem, and the sub-problem of multiple EVAs. The sub-problems that are formulated are: a) minimization of the DSO's energy cost and b) maximization of the revenue of each EVA. In that setting, EVAs gather the data of the EVs (i.e., technical characteristics of the EVs, arrival/departure time) and send them to the DSO. The DSO optimizes the operational planning of the distribution system determining the charging/discharging schedule of the EVs. The proposed model adopts the formulation of [11] for the fuel-based DGs and EVAs, as well as the power flow equations of [15].

A. Minimization of DSO's energy cost

The objective of the DSO is to minimize the total operational cost of the distribution system:

$$\min C_{DSO} = F_1 + F_2 + F_3 + F_4 \quad (1)$$

$$F_1 = \sum_{t=1}^{T} \pi_t^{WS} P_t^{WS} \quad (2)$$

$$F_2 = \sum_{t=1}^T \sum_{k \in \Omega_{DG}} SUC_k u_{k,t}^{ON} + \sum_{t=1}^T \sum_{k \in \Omega_{DG}} SDC_k u_{k,t}^{OFF} + \sum_{t=1}^T \sum_{k \in \Omega_{DG}} c_k u_{k,t} + b_k P_{k,t}^{DG} + a_k (P_{k,t}^{DG})^2 \quad (3)$$

$$F_3 = \sum_{t=1}^T \sum_{wg \in \Omega_{wg}} C_{wg} P_{wg,t}^{frc} \quad (4)$$

$$F_4 = \sum_{t=1}^T \sum_{ag \in \Omega_{EV(ag)}} \sum_{ev \in \Omega_{EV(ev)}} \frac{C_{ev}^{B,inv}}{LT_{ev}} P_{ev,t}^{Dch} \quad (5)$$

subject to:

$$P_{i,t}^G - P_{i,t}^D = \sum_{ij \in \Omega_L} P_{ij,t}^{flow} \quad \forall i, j, t \quad (6)$$

$$P_{ij,t}^{flow} = f^P(\Delta V_{i,t}, \Delta V_{j,t}, \delta_{i,t}, \delta_{j,t}, G_{ij}, B_{ij}) \quad \forall i, j, t \quad (7)$$

$$\Delta V_{i,t} \leq 4\% \quad \forall i, t \quad (8)$$

$$-P_{ij}^{\max} \leq P_{ij,t}^{flow} \leq P_{ij}^{\max} \quad \forall i, j, t \quad (9)$$

$$P_k^{DG, \min} u_{k,t} \leq P_{k,t}^{DG} \leq P_k^{DG, \max} u_{k,t} \quad \forall k, t \quad (10)$$

$$P_{k,t}^{DG} - P_{k,t-1}^{DG} \leq UR_k (1 - u_{k,t}^{ON}) + P_k^{DG, \min} u_{k,t}^{ON} \quad \forall k, t \quad (11)$$

$$P_{k,t}^{DG} - P_{k,t-1}^{DG} \leq DR_k (1 - u_{k,t}^{OFF}) + P_k^{DG, \min} u_{k,t}^{OFF} \quad \forall k, t \quad (12)$$

$$\sum_{h=t}^{t+UT_k-1} u_{k,h} \geq UT_k \cdot u_{k,t}^{ON} \quad \forall k, t \quad (13)$$

$$\sum_{h=t}^{t+DT_k-1} (1 - u_{k,h}) \geq DT_k \cdot u_{k,t}^{OFF} \quad \forall k, t \quad (14)$$

$$u_{k,t+1}^{ON} = u_{k,t+1} (1 - u_{k,t}) \quad \forall k, t \quad (15)$$

$$u_{k,t+1}^{OFF} = u_{k,t} (1 - u_{k,t+1}) \quad \forall k, t \quad (16)$$

$$E_{ev}^{B, \min} \leq E_{ev,t}^B \leq E_{ev}^{B, \max} \quad \forall ev, t \quad (17)$$

$$E_{ev,t}^B = E_{ev}^{Con, prev} - (d_{ev} / d_{ev}^{\max}) E_{ev}^{B, \max} \quad t = T_{ev}^{arr}, \forall ev \quad (18)$$

$$E_{ev,t}^B = E_{ev}^{Con} \quad t = T_{ev}^{dep}, \forall ev \quad (19)$$

$$u_{ev,t}^{Ch} u_{ev,t}^{Dch} = 0 \quad \forall t \notin (T_{ev}^{arr}, T_{ev}^{dep}), \forall ev \quad (20)$$

$$u_{ev,t}^{Ch} + u_{ev,t}^{Dch} = 0 \quad \forall t \in (T_{ev}^{arr}, T_{ev}^{dep}), \forall ev \quad (21)$$

$$0 \leq P_{ev,t}^{Ch} \leq u_{ev,t}^{Ch} \cdot P_{ev}^{Ch, \max} \quad \forall ev, t \quad (22)$$

$$0 \leq P_{ev,t}^{Dch} \leq u_{ev,t}^{Dch} \cdot P_{ev}^{Dch, \max} \quad \forall ev, t \quad (23)$$

$$E_{ev,t+1}^B = E_{ev,t}^B + u_{ev,t}^{Ch} \cdot P_{ev,t}^{Ch} \cdot \eta_{ev} - u_{ev,t}^{Dch} \cdot P_{ev,t}^{Dch} / \eta_{ev} \quad \forall t \in (T_{ev}^{arr}, T_{ev}^{dep}), \forall ev \quad (24)$$

$$P_{ag,t} = \sum_{ev \in \Omega_{EV(ag)}} (P_{ev,t}^{Dch} - P_{ev,t}^{Ch}) \quad \forall ev, t, ag \quad (25)$$

The objective function (1) consists of four terms. The first term (2) is the cost of the power imported from the external grid. The second term (3) gives the cost of DG units that comprise the start-up, fuel and shut-down costs, respectively. The third term (4) gives the purchase cost of the active power produced by WG. The last term (5) denotes the compensation cost to be paid to the EVA. The cost of (5) is related to the remuneration paid to the EV owners for using the battery of their vehicles.

Equation (6) represents the active power balance at each bus of the distribution system. Equation (7) represents the active power flow of each line of the distribution system. Equation (8) limits the voltage deviation of each bus from the nominal value. Equation (9) determines the thermal limits of each distribution line, given in MW. Equation (10) determines the upper and lower limits of the power produced by the fuel-based DGs. Equations (11) and (12) give the ramp-up and ramp-down limits of the DG production, respectively. Equation (13) determines the minimum time a DG can operate, whereas (14) gives the minimum time a DG can be out of operation. Equations (15) and (16) determine the turn-on and turn-off status of a DG, respectively. The

state of charge (stored energy) of each EV is limited by (17). The state of charge at the arrival time and the departure time of each EV are given by (18) and (19), respectively, while (20) denotes that an EV cannot be charged or discharged before its arrival and after its departure to/from the charging station. Equation (21) ensures charging and discharging cannot occur at the same time. The upper limits of charging and discharging power of each EV are given by (22) and (23), accordingly, while ensuring non negative values for the charging and discharging power variables of each EV. Equation (24) presents the energy balance of each EV battery. Equation (25) calculates the aggregated active power each EVA absorbs or injects at each time-interval.

It should be noted that for environmental reasons the production of the wind generators is not curtailed by the DSO. It is also assumed that the WG production solely depends on the wind speed, as calculated by (26):

$$P_{wg,t}^{frc} = \left\{ \begin{array}{ll} 0 & v_t \leq v_{wg}^{in}, v_t \geq v_{wg}^{out} \\ P_{wg}(v_t) & v_{wg}^{in} < v_t < v_{wg}^{out} \end{array} \right\} \quad \forall wg, t \quad (26)$$

It should be also noted that the absence of EVAs (in which case the EVs act only as loads) is possible to be realized by only considering zero power injection to the distribution network, i.e., $P_{ev,t}^{Dch} = 0, \forall ev, t$.

B. Maximization of EVAs' revenue

The objective of each EVA, given in (28), is to maximize its revenue by selling the EV energy that is discharged to the grid from the V2G operation.

$$\max R_{ag} = \sum_{t=1}^T \sum_{ev \in \Omega_{EV}(ag)} P_{ev,t}^{Dch} \frac{C_{ev}^{B,inv}}{LT_{ev}} \quad \forall ag \quad (27)$$

subject to:

$$F_1 + F_2 + F_3 + F_4 \leq C_{DSO}^{noEVA} \quad (28)$$

and (2)–(26).

Equation (28) ensures that the DSO's energy cost will not exceed an upper bound. This upper bound is the cost occurred, when EVs cannot be discharged (without EVAs).

III. ROBUST OPTIMIZATION

The optimization models of Section II ignore the forecasting errors that are always present. To deal with this issue, the models of RO [16] for the sub-problems of Section II are formulated here. In general, a RO model derives the optimal solution that is partly or fully immunized against uncertainties [17]. This paper considers the wholesale market price and the WG production as uncertain parameters.

A. Minimization of DSO's energy cost (RO model)

The robust counterpart of the model that minimizes the cost for the DSO can be reformulated as follows:

$$\min C_{DSO}^{RO} = F_1' + F_2 + F_3' + F_4 \quad (29)$$

$$F_1' = \sum_{t=1}^T \pi_t^{WS} P_t^{WS} + \Gamma_0 w_0 + \sum_{t=1}^T z_{0,t} \quad (30)$$

$$F_3' = \sum_{t=1}^T \sum_{wg \in \Omega_{WG}} C_{wg}(P_{wg,t}^{frc} + \Gamma_{wg} w_{1wg} + z_{1wg,t}) \quad (31)$$

subject to:

$$\sum_{ij \in \Omega_L} P_{ij,t}^{flow} = P_{i,t}^G - P_{i,t}^D + \sum_{wg \in \Omega_{WG}} (\Gamma_{wg} w_{1wg} + z_{1wg,t}) \quad \forall k, m, t \quad (32)$$

$$w_0 + z_{0,t} \geq \varepsilon_{WS,t}^{\max} P_t^{WS} \quad \forall t \quad (33)$$

$$w_{1wg} + z_{1wg,t} \geq \varepsilon_{wg,t}^{\max} P_{wg,t}^{frc} \quad \forall P_{wg,t}^{frc} \leq P_{wg}^{\max} / (1 + \varepsilon_{wg,t}^{\max}) \quad (34)$$

$$w_{1wg} + z_{1wg,t} = P_{wg}^{\max} - P_{wg,t}^{frc} \quad \forall P_{wg,t}^{frc} \geq P_{wg}^{\max} / (1 + \varepsilon_{wg,t}^{\max}) \quad (35)$$

$$w_0, w_{1wg}, z_{0,t}, z_{1wg,t} \geq 0 \quad (36)$$

and (3), (5), (7)–(26).

B. Maximization of EVAs' revenue (RO model)

The robust counterpart of the model that maximizes the revenue of each EVA is reformulated as follows:

$$\max R_{ag}^{RO} = \sum_{t=1}^T \sum_{ev \in \Omega_{EV}(ag)} \frac{C_{ev}^{B,inv}}{LT_{ev}} P_{ev,t}^{Dch} \quad \forall ag \quad (37)$$

subject to:

$$F_1' + F_2 + F_3' + F_4 \leq C_{DSO}^{RO,noEVA} \quad (38)$$

and (3), (5), (7)–(26), (31)–(36).

Equation (37) ensures that the DSO's energy cost will be lower than or equal to the cost that occurs without EVAs considering RO.

If either model is partly immunized against the uncertainties of the wholesale market prices, Γ_0 should be set in the interval $[0, T]$. As Γ_0 grows, the scenario worsens and the model gets more immunized against these uncertainties. If the model is partly immunized against the uncertainties of the WG production, Γ_{wg} should be set in the interval $[0, 1]$. As Γ_{wg} grows, the scenario worsens and the model gets more immunized against these uncertainties.

IV. PROPOSED ROBUST COORDINATED OPTIMIZATION MODEL

The proposed RCO model for the joint cooperation between the DSO and the EVAs takes into consideration the minimum energy cost of the DSO including the presence of EVAs, the minimum energy cost of the DSO without considering the EVAs' activation, and the maximum revenue of each EVA. The proposed robust cooperation model is formulated as follows:

$$\min F^{RCO} = (C_{DSO}^{RCO} - C_{DSO}^{RO,EVA}) + \sum_{ag \in \Omega_{EVA}} (R_{ag}^{RO,max} - R_{ag}^{RCO}) \quad (39)$$

subject to:

$$C_{DSO}^{RCO} = F_1' + F_2 + F_3' + F_4 \quad (40)$$

$$C_{DSO}^{RO,EVA} \leq C_{DSO}^{RCO} \leq C_{DSO}^{RO,noEVA} \quad (41)$$

$$R_{ag}^{RCO} = \sum_{t=1}^T \sum_{ev \in \Omega_{EV}(ag)} \frac{C_{ev}^{B,inv}}{LT_{ev}} P_{ev,t}^{Dch} \quad (42)$$

and (3), (5), (7)–(26), (31)–(36).

The objective of (39) aims to find a consensus between the objectives of the DSO and the EVAs, thus to minimize the deviation from the DSO's target cost and from the EVAs' target revenue, altogether. The DSO's energy cost that occurs from the RCO model is given by (40), and is limited by (41). The revenue of each EVA is given by (42).

V. CASE STUDY & RESULTS

The proposed RCO model is applied to a modified 14-bus distribution system (depicted in Fig. 1), the detailed data of which (bus loads and line data) can be found in [18]. The 14-bus distribution system consists of two diesel DGs (3.0 MW each), two wind farms consisting of four commercial WGs of 0.45 MW each (data available in [19]), and two EVAs. EVA1 is located on bus 5 and controls 400 EVs. All the EVs of EVA1 are assumed to remain plugged in the charging station from 07:00 to 16:00. EVA2 is located on bus 7 and controls 400 EVs as well. 200 EVs of the EVA2 fleet remain in the charging station from 07:00 to 16:00 and the rest 200 EVs from 16:00 to 00:00. The detailed EV data can be found in [11]. The forecasted wind speed values are sourced from [20] and are used to calculate the forecasted active power output of the WG using (26). The forecasted wholesale market prices are taken from [21]. The maximum deviation from the forecasted value of the wholesale market price is considered equal to 10%, whereas that of WG production is considered equal to 20%.

The DSO's energy cost with and without RO, with and without the activation of EVAs is shown in Table I. One can notice that the costs that derive from the RO models are about 10% higher than the models that do not consider uncertainties, i.e., without RO. This is mainly due to the expected deviation from the wholesale market price forecasting, which is assumed equal to 10%. It is also noted that the models that consider the activation of EVAs have lower cost than those with the EVAs deactivated. This goes to show that the optimal V2G operational planning is considered to be an effective practice for the DSO. The robust model that minimizes the DSO's energy cost, without EVAs, results to the charging/discharging schedule shown in Fig. 2. The EVs are being discharged when the industrial and residential loads are at their peak, while the EVs are charged when the wholesale market price is at its lowest values. Positive values indicate EV power consumption, whereas negative values indicate EV power injection.

As expected, the robust models that optimize the objectives of each EVA result to lower revenue for EVAs than their counterparts without RO. This mainly happens due to the considered maximum deviation from the forecasted WG production. According to the robust maximization model of EVA1, 91.38% of the total DSO's expenses paid to the EVAs is distributed to EVA1, while the remaining 8.62% is distributed to EVA2. Accordingly, considering the robust

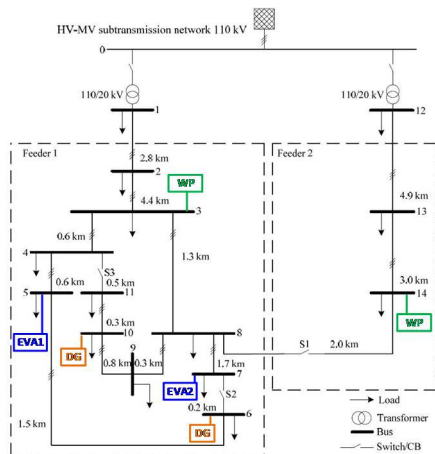


Fig. 1. The topology of the modified 14-bus distribution system.

TABLE I. ENERGY COST OF DSO

	With RO	Without RO	Difference
Without EVAs	81,478.97 €	74,151.92 €	9.88%
With EVAs	81,275.47 €	73,938.13 €	9.92%

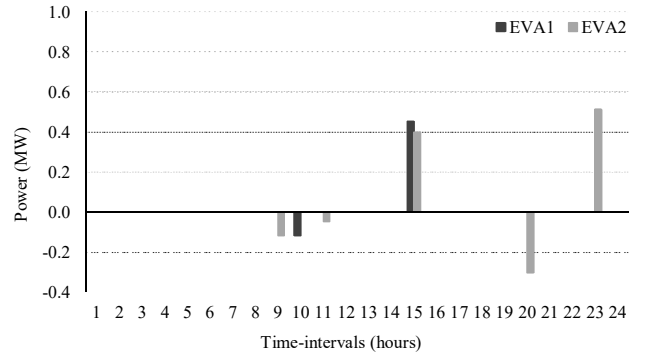


Fig. 2. Charging/discharging schedule that minimizes the DSO's energy cost.

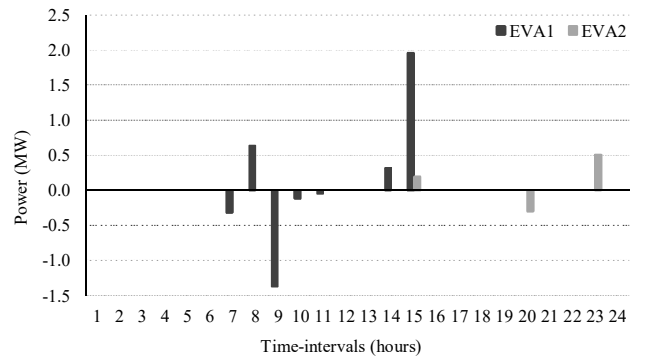


Fig. 3. Charging/discharging schedule that maximizes the revenue of EVA1.

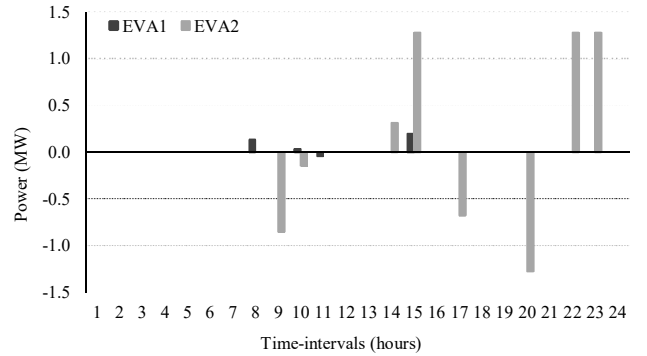


Fig. 4. Charging/discharging schedule that maximizes the revenue of EVA2.

maximization model of EVA2, 98.72% of the total compensation cost that the DSO pays all the EVAs is distributed to EVA2, while the remaining 1.28% is distributed to EVA1.

The optimal charging/discharging schedule that maximizes the revenue of EVA1 is shown in Fig. 3 and focuses on the discharge of the EVs controlled by EVA1 during the peak of the industrial loads in the morning and the discharge of the EVs of EVA2 during the peak of the residential loads in the evening. This is reasonable, because EVA1 cannot control EVs after 16:00. The optimal charging/discharging schedule that maximizes the revenue of EVA2 is shown in Fig. 4 and proposes discharge of the EVs under their control during both industrial and residential peak, because EVA2 is able to control EVs in the morning as well as in the evening.

TABLE II. RESULTS FOR EACH SUB-PROBLEM AND THE RCO MODEL

	min DSO's energy cost (€)	max EVA1 revenue (€)	max EVA2 revenue (€)
DSO's sub-problem (without EVAs)	81,478.97	0.00	0.00
DSO's sub-problem (with EVAs)	81,275.47	11.25	47.35
EVA1's sub-problem	–	192.41	–
EVA2's sub-problem	–	–	219.38
RCO model	81,410.85	69.65	105.79

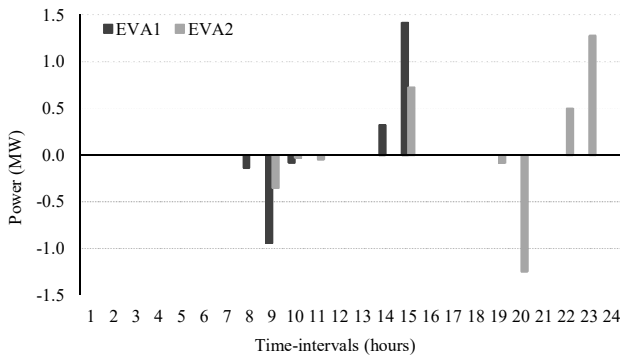


Fig. 5. Charging/discharging schedule of the proposed RCO model.

Using the results of DSO's energy cost and the results of EVAs' revenue as input parameters for the RCO model, the optimal charging/discharging schedule is shown in Fig. 5. The EVs of both EVAs are proposed to be discharged during load peaks and charged when the wholesale market price is low. The DSO's energy cost with the proposed RCO model is 81,410.85€, which is 0.84% lower than the DSO's energy cost of the DSO's sub-problem without EVAs and 1.67% higher than that of DSO's sub-problem with EVAs. The presence of EVAs reduces the energy cost for the DSO. The difference is not significant, because the cost of EV flexibility is slightly lower than the cost of the diesel DGs. Though, EVs are considered as a more eco-friendly technology than fuel-based DGs.

The values of the objective functions for each one of the sub-problems and the RCO model are summarized in Table II. The RCO model finds a consensus among the objectives of all parties, while also enhances a more intensive V2G operation. The financial results are very satisfactory as they verify that all parties, i.e., DSO and EVAs, cooperate evenly.

VI. CONCLUSION

This paper proposes a RO model for the cooperation of the DSO with EVAs. The model takes into consideration the forecasting uncertainties of the wholesale market price and those of wind generation. Moreover, the objectives of all parties are included in a RCO model. The RCO model seeks the operational schedule that simultaneously fulfills the objectives of the DSO as well as the objective of EVAs. Results from a 14-bus distribution system case study show that the RCO model is an effective approach to find a trade-off between the objectives of the DSO and those of EVAs. With the proposed RCO model, the participation of EVAs in local distribution markets is enhanced and the V2G operation is utilized as a more sustainable solution compared to fueled DGs.

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