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Plug-in Electric Vehicles Parking Lot Equilibria with Energy and Reserve Markets

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***Abstract*—This paper proposes a comprehensive model for the interactions of the plug-in electric vehicles (PEVs) involved parties. An aggregator with mixed resources is assumed to be the interface between the parking lot (PL) and the upstream energy and reserve markets. On the other hand, the interactions of the PEV owners and the PL are also modeled as they impose restrictions to the PL's behavior. Therefore, a bilevel problem is constructed where in the upper-level the objective of the aggregator is to maximize its profit through its interactions and in the lower-level the PL maximizes its own profit limited to the preferences of PEVs. The objectives of the upper and lower level are contradictory; hence, an equilibrium point should be found to solve the problem. In this regard, the duality theorem is employed to convert the bilevel model to a mathematical program with equilibrium constraints (MPEC). The model is implemented on the IEEE 37-bus network with added distributed generations (DGs). Various cases are thoroughly investigated and conclusions are duly drawn.**

***Index terms*—Aggregator, energy and reserve markets, mathematical programming with equilibrium constraints (MPEC), parking lot (PL), plug-in electric vehicle (PEV).**

NOMENCLATURE

Capital letters denote parameters and small ones denote variables.

Subscripts

j,k	Bus number
l	Power line
m	DG number
t	Time interval
ω	Scenario and scenario set

Superscripts

Agg	Aggregator
Aux	Auxiliary variable
ar	Arrived PEVs to the PL
cha	Charging mode
D	Demand
$dcha$	Discharging mode
del	Delegated energy (probability of reserve call)
dep	Departed PEVs from the PL
DG	Distributed Generation
DSO	Distribution system operator
ED	Energy delivery to demand
EDG	Energy purchase from DG
EM	Energy Market
$Extra$	Extra payment for V2G participation
EV	Electric vehicle
fix	Fixed SOC requirement
$flex$	Flexible SOC requirement
$G2V$	Grid to Vehicle
IL	Interruptible load
in	Power injected into the system or the PL
$Incentive$	Incentive payment to interruptible loads
$Line$	Distribution Lines
LL	Lower level problem
$Loss$	Power loss
out	Output energy from PL
PL	Parking Lot
Re	Reserve
RM	Reserve Market
Sc	Scenario
$Tariff$	Tariff from PEV owners entering PL
TM	Trade with Market
TPL	Trade with PL
$Total$	Total amount of demand
ToU	Time of Use
UL	Upper level problem
$V2G$	Vehicle to Grid

Operators

$\overline{\ },\underline{\ }$	Maximum and minimum amount of a variable
$\hat{\ }$	Expected value of a variable
$\acute{\ }$	Identification of variable on the selected node

Variables and Parameters

C	Capacity of a PL (kW)
Cd	Cost of equipment degradation
FOR	Forced outage rate (%)
i,I	Line current (A)
n,N	Number of parked PEVs
p,P	Active power (kW)
q,Q	Reactive Power (kVar)
r,R	Reserve (kW)
R,X	Resistance and reactance of a line (Ω)
Si	Binary variable indicating the site of resources
soc,SOC	State of Charge (kWh)
Z	Variable for linearizing the conditional term
α	Percentage of interruptible load from total demand
β	Coefficient determining the share of each PEV category from hourly vehicle departure

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θ	Coefficient determining the share of each PEV category from total PEVs in the PL in each hour
ϕ	Coefficient determining the minimum departure SOC requirement of each PEV category
γ, Γ	Charge/Discharge rate
ρ	Probability
η	Efficiency
π, Π	Price
λ	Dual variable for equality constraints
$\underline{\mu}, \bar{\mu}$	Dual variable for lower and upper limits in inequality constraints

I. Introduction

A. Motivation and Aim

Electrification of transportation is an emerging trend in power system studies, traffic planning and urban studies. Penetration of electric vehicles in everyday life has several aspects that should be dealt with. Deployment of plug-in electrical vehicles (PEVs) not only affects the operation of the power system, but also imposes some necessary interactions that have not existed in the system before. These interactions regard the technical impacts of PEVs as well as economics, traffic and allocation of PEVs and occur among all the parties that are involved with the PEVs. The parties could be the owners of the PEVs, the operator of the charging stations, the distribution system operator (DSO), the urban planner, etc.

Vast penetration of PEVs in the system requires foreseeing the necessary infrastructures. One of the recent solutions to provide the needed platform for better utilization of PEVs is the PEVs' parking lot (PL). PLs provide a medium for the PEVs to charge their batteries and an aggregated version of PEVs to act as storage. The grid to vehicle (G2V) and vehicle to grid (V2G) modes gives the PL the potential of being a resource in the system as well as the flexible load. Therefore, the PL will be a new party in the interactions of the PEV-involved parties and will bring more conflicts and challenges to the problem.

On the other hand, the traffic pattern of the area where the PL is installed and the behavior of the PEV owners that use the PL considerably affect the operation of the PL. The arrival and departure pattern of PEVs and their stay duration influences the PL's behavior. Besides, their charging requirements impose other restrictions to the PL operation. As a result, modeling the PEVs behavior and their obligations' effects on the PL's behavior is necessary for studying the transactions of the PL and the market. Confronting with the above-mentioned challenges, the aim of this paper is to investigate the interactions of the PL in the market place affected by the PEVs' preferences in a mixed resource environment.

B. Literature Review

The subject of PEVs has been the focus of many recent studies; however, the literature related to the subject of this paper can be categorized into three groups: The first group which covers the introduction of PEV aggregator as a new entity to the power system; the second group that considers the market participation of PEVs through an aggregator and the third one that investigates the interaction of PEVs in a PL.

As for the first category, the preliminary impressions of agents for PL were brought by Kempton [1] indicating that the presence of an agent is necessary for the operation of PEVs in the system; Lopes [2] encouraging the aggregation of the PEVs in order to have a considerable effect on the system is inevitable; Guille [3] that proposed the aggregator as a critical entity to enable the V2G operation of EVs. A comprehensive survey on EV aggregation can be found in [4]. The real-time regulation allocation on EV aggregators is presented in [5] with welfare-maximization objective. Jin et al. in [6] reported an optimized EV charging schedule through an aggregator while considering the aggregator's revenue and the EVs' charging demand. In [7], the scheduling of EVs by aggregators to take part in V2G regulation is studied where the forecast of schedules based on the uncertainties of EVs is performed by multi-level aggregators.

Regarding the second category, a considerable number of available studies have dedicated the focus of their study to the integration of EVs into marketplace through aggregators. Bessa et al. in [8] introduce an EV aggregation agent and propose an optimization approach for the agent to bid and participate in day-ahead and reserve markets. However, it considers individual EVs plugged to the grid from charging stations and the aggregator controls the EV charging for specific time duration based on the contract between each EV and the aggregator. The authors also investigated the model for hour-ahead market in [9] as well as the manual reserve, not considering the V2G mode though. In [10] a coordination approach between EV aggregator and system operator is presented in both electricity market and ancillary services. The authors in [11] developed a model for charging the EVs while the aggregator trades with energy and reserve markets. In [11], it is considered that the charging of EVs is optimized with the presence of electric storage. However, it does not consider the V2G mode of the EV operation. Similarly, in [12] a bidding strategy for the stochastic behavior of EV aggregator is acquired to participate in energy and regulation markets. Reference [12] also considers the EVs to be operated in G2V mode only and the aggregated EV potential is deployed as regulation up/down. Li et al. in [13] used an EV aggregator model in their locational marginal pricing method to alleviate the congestion caused by EVs' load. Although most of the studies have only considered the G2V mode of the EVs to participate in the electricity market, there are some studies that consider the V2G mode. Sortomme and El-Sharkawi in [14] and [15] developed a V2G algorithm for an EV aggregator to participate in both energy and ancillary service markets.

The third group, however, regards another point of view in EVs' participation in power systems. The introduction of EV PLs to the system has changed the features of PEV penetration studies. Other than the problem of allocating PLs in the system [16], [17], the effects caused by the procedure of charging/discharging in the PL have been the matter of interest in the literature. The reason is that, as firstly proposed by [18], the utilization of EVs' V2G mode can be facilitated by deployment of PLs as an aggregated source of PEVs. Further studies such as [19] - [21] addressed the V2G mode of PL. However, the study on the simultaneous charging/discharging of the PL is still very limited. Some studies such as [22] and [23] have studied the management of the PL's interaction,

The significance of this work comparing to the abovementioned studies is that the market participation of the

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PL in both G2V andV2G mode has been considered while most of the studies only considered the G2V mode or the battery replacement procedure (especially first and second group). Moreover, the PL as the aggregation of the PEVs is different from a PEV aggregator because in the PL all the PEVs' location is fixed; hence, the vision of its market participation should be treated differently from an aggregator. On the other hand, as the PL has a limited capacity due to restricted number of PEV stations, it may not be able to participate individually in the market and should be examined in a mixed resource environment.

In addition, the complex interrelation of the PL with other PEV-involved parties such as PEV owners, aggregator, DSO, etc. is not addressed by the third group studies discussed in the literature review. Although these studies have somehow considered the preferences of PEV owners, the contradictory effects of the vehicle owners' behavior on PL's operation have not been addressed.

C. Contributions

Considering the issues discussed in the previous subsections, it is necessary to derive a comprehensive model that could address all the possibilities and limitations of the PL's operation. The intention of this paper is to present the model for the interactions of the PL with the market through an aggregator while considering the restrictions that the preferences of PEV owners impose to its behavior. The increased level of flexibility due to the PL in the system is investigated through its integrated operation with other resources such as distributed generation (DG) and demand response (DR). The impact of PEV owners' preferences on the PL's operation is addressed. In addition, a novel and practical framework to involve the PEVs' preferences in the PL's operation is proposed.

The paper's main contributions are:

1) To propose a model to impose the preferences of the PEVs who use the PL based on their choice of G2V/V2G mode, time of stay and their requirement of SOC on departure time;
2) To model the interaction of PL with a mixed resource aggregator based on a bilevel approach;
3) To investigate the effects of PEV preferences on equilibrium point of PL and aggregator interaction.

D. Paper Organization

The rest of the paper is organized as follows. Section II describes the various interactions of the components in a distribution system with the PL and aggregator. The mathematical formulation of the upper-level problem is described in sections III, while the lower-level problem is presented in section IV. The uncertainty of the PEVs behavior in the PL is modeled in section V. The numerical results are presented in section VI. A comprehensive discussion on the role of PEVs preferences on the PL behavior is presented in section VII. Finally, section VIII concludes the paper.

II. Problem Description

As comprehensively discussed in the literature review, numerous interconnections of PEVs should be managed through the new entity of PEV aggregator. Although a PL is an aggregated form of PEV, restrictions of its operation confine the PL to compete independently in the market. However, the potential of the PL as a resource in the system as well as its nature of being a flexible load cannot be disregarded. In fact, the special role of the PL as a prosumer in the system can be best employed along with other available resources in the system. Therefore, aggregating PL's opportunities with other resources such as DG and DR provides a suitable environment for the aggregator to achieve a higher level of flexibility.

On the above premises, this paper proposes a model in which an aggregator is the interface of local resources with the market. The basic visual of such environment is shown in Fig. 1. In this environment, the PL participates in the market through an aggregator which has to provide the required demand for the load retailer. Another resource (DG) is also present in the system to study the variations of price. The aggregator combines all the resources in the local network to maximize its profit when participating in the upstream energy and reserve markets. However, each of the components that are aggregated by the aggregator has its own objective and restrictions that may have conflict with the objective of the aggregator. Therefore, a bilevel problem is encountered in this situation. In the upper-level (UL) problem, the objective of the aggregator is to maximize its own profit through its interaction with the upstream market on one hand and the energy and reserve trade with the PL, energy purchase from the DG and providing the required demand on the other. On the lower-level (LL), the PL, the DG, and the load retailer are the components who also want to maximize their profit. As a result, an equilibrium point should be found for the operation of such system. The interactions between the two levels of the model are described in follows.

A. Aggregator-PL-PEV interactions

The PL provides the opportunity for the PEV owners to charge their batteries and take part in the V2G mode if they are willing to. The PL can act more efficiently in the market compared to charging stations because it enables the simultaneous G2V/V2G mode and it also benefits from the longer stay of the PEVs in the PL. Consequently, it can have the role of storage as well as flexible load in the system. However, when operating a PL, it is necessary to consider the preferences of the PEV owners. In some of the recent studies on this subject, such as [24]-[26] the behavior of PEVs has been considered pertaining their driven distance and state of charge. However, the owners of these vehicles may also have preferences other than the limitations of PEV.

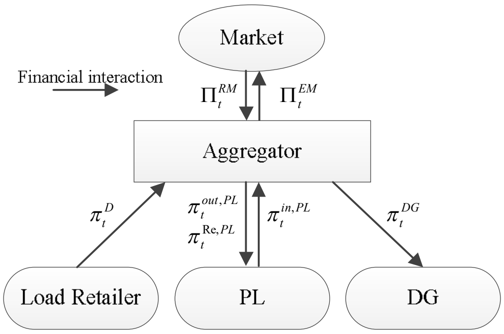

Fig. 1. Interactions of the components in the environment.

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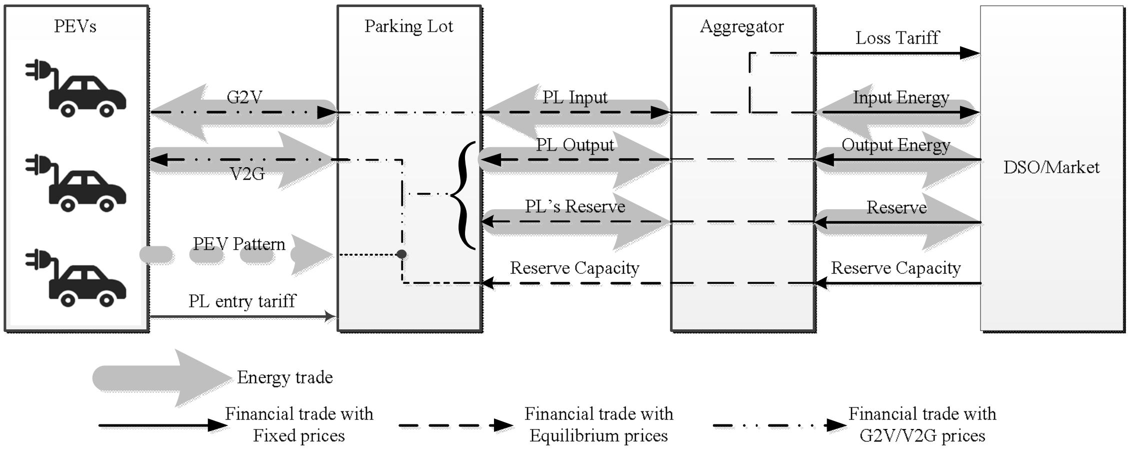

Fig. 2. The sequence of interactions from PEVs to Market

In this study, it is assumed that the PEVs who enter the PL restrict the PL's behavior in the marketplace with their choice on their participation as G2V or V2G. The reason is to consider the owners concern on their battery degradation in V2G mode or the probability of the sudden departure. In such cases, the owners may not want to participate in the V2G mode to be sure of adequate charge in their batteries for their next travel. Note that by V2G mode, we mean that PEVs are willing to take both G2V and V2G mode. For the sake of brevity, only the V2G term is used for this type of PEVs. Moreover, it is assumed that all PEVs specify a minimum amount of SOC of their batteries at the time of departure from the PL; however, some of the PEVs need a fixed amount of departure SOC while others agree to have a flexible departure SOC and the only limit for them is their minimum SOC. The reason for considering fixed departure SOC is to take into account the possible contracts of PEV owners with other PEV-aggregators which oblige them to keep a specific portion of their capacity empty. Therefore, four different categories of the PEVs enter the PL:

- G2V mode with fixed departure SOC;
- G2V mode with flexible departure SOC;
- Both G2V, V2G mode with fixed departure SOC;
- Both G2V, V2G mode with flexible departure SOC.

Each of these categories and their requirements restrict the PL in utilizing the total available capacity in the PL.

Figure 2 shows various interactions that occur from market to PEVs through the aggregator and PL. As shown, two main physical and financial interactions exist. The objectives of the PL and the aggregator due to its interactions with PL are based on financial transactions shown in Fig. 2. In each interface (aggregator or PL) different prices are applied to the transactions and are illustrated with different line types. As a result, an equilibrium point should be found between all the objectives

B. Mixed Resource Environment

As a main feature of the forthcoming power systems and for enabling the aggregator to have access to more resources, DGs are also considered in the system. It is assumed that the DGs offer their price and quantity to the aggregator, but they should reach an equilibrium point in their trade. Hence, the price that the aggregator buys the power from DG is the decision variable for the UL and the amount of power that DG should sell to the aggregator is the decision variable for the LL.

All the end-users in the system are served by a load-retailer which purchases the required amount from the aggregator. On the other hand, the load-retailer can play with its capability in providing the DR option. The DR option here is supposed to be the interruptible load (IL) which is a definite percent of the total demand. Therefore, the retailer has the opportunity to reduce its total demand by IL when the aggregator increases the demand price. On the other hand, it should consider paying an incentive to the interrupted loads.

C. Approach for solving the problem

The problem discussed in this paper is a bilevel problem with inter-related objectives. In this model, the UL problem is the aggregator's decision making and the LL problem is the decision making of local resources. As also employed in [27], the decision making conflict between two levels of players is modeled as a bilevel problem and converted to a mathematical program with equilibrium constraints (MPEC). This non-linear bilevel problem is converted to a single level mixed-integer linear programming (MILP) by implementing the duality theorem.

The procedure is as follows and is based on [28] and [29]:

- Formulate the LL problem as a linear and convex problem.
- Consider the decision vector of the UL problem as an input parameter for the LL problem.
- Implement the duality theorem and replace the LL problem with its Karush-Kuhn-Tucker (KKT) optimality conditions.
- Apply strong duality to the LL problem and linearize the non-linear terms of the UL objective function.

In this paper, the UL and LL are presented with their mathematical models in Sections III and IV, respectively. In order to implement the duality theorem, all the constraints of the LL problem are succeeded by the respective dual variables separated by a colon. They are classified into equality and inequality constraints with the respective dual variables represented by λ and μ, respectively. Finally, the Lagrangian equation for the LL problem is developed.

III. Upper Level Mathematical Model

In the UL, the aggregator manages its interactions with the upstream energy and reserve markets and is restricted by the objectives of its components as well as the loss tariff of the distribution network. It is assumed that the aggregator pays the loss tariff to the distribution system operator in response to the energy purchased from the distribution network. Therefore, the objective of the UL problem will be as (1):

$$Max\left\{profit^{Agg}\right\} = Max\left\{\begin{matrix} profit^{TM} + profit^{TPL} \\ +profit^{EDG} + profit^{ED} \end{matrix}\right\} \quad (1)$$

Each of the components of the objective function is explained below. The aggregator trades energy and reserve with the upstream market based on the market prices, which are treated in the problem as known parameters (2). The aggregator participates in the reserve market through offering the PL's SOC in the market. Therefore, it is reimbursed for being ready to deliver reserve (Π^{RM}) and if by the probability of reserve call (${\rho_t}^{del}$) it is summoned to provide the reserve, it will be paid by energy price (Π^{EM}). Otherwise, if the aggregator fails to deliver the amount of reserve due to FOR^{Agg}, it is subjected to a penalty based on the hourly energy price. The amount of FOR^{Agg} is dependent to the network and the LL resources' failure rate.

$$\begin{aligned} profit^{TM} = \sum_t \Big(& -p_t^{Agg}\Pi_t^{EM} + r_t^{Agg}\Pi_t^{RM} \\ & + r_t^{Agg}\rho_t^{del}\Pi_t^{EM} - r_t^{Agg}\rho_t^{del}FOR^{Agg}\Pi_t^{EM}\Big) \end{aligned} \quad (2)$$

The profit of the aggregator from its interaction with the PL is caused by the revenue from selling power to PL for charging its vehicles minus the costs of purchasing energy and reserve from the PL. The PL interacts with the aggregator with the equilibrium prices of energy and reserve ($\pi_t^{in,PL}$, $\pi_t^{out,PL}$, $\pi_t^{Re,PL}$). Note that in this study various uncertainty scenarios are considered for arrival, departure and duration of stay in the PL. As a result, the amount of PL's input/output power will be different for each scenario. However, as the PL's internal interactions does not affect the aggregator's decision making it trades with the aggregator with the expected values (i.e. $\hat{p}_t^{in,PL}$, $\hat{p}_t^{out,PL}$, $\hat{r}_t^{PL}$).

$$\begin{aligned} profit^{TPL} = \sum_t \Big(& \hat{p}_t^{in,PL}\pi_t^{in,PL} - \hat{p}_t^{out,PL}\pi_t^{out,PL} - \hat{r}_t^{PL}\pi_t^{Re,PL} \\ & -\hat{r}_t^{PL}\rho_t^{del}\pi_t^{out,PL} + \hat{r}_t^{PL}\rho_t^{del}FOR^{PL}\pi_t^{out,PL}\Big) \end{aligned} \quad (3)$$

It is assumed that there can be multiple numbers of DGs in the network and sell their power to the aggregator with equilibrium price of DG (π_t^{DG}) as in (4).

$$profit^{EDG} = \sum_t \left(-\sum_m p_{m,t}^{DG}\pi_t^{DG} \right) \quad (4)$$

The demand is delivered to the end-users with the hourly equilibrium demand price (π_t^D). It is also assumed that the aggregator has to pay for the network loss (5).

$$profit^{ED} = \sum_t \left(p_t^D\pi_t^D - \sum_k\sum_j R_{j,k}\left(i_{j,k,t}\right)^2\Pi_t^{Loss} \right) \quad (5)$$

The assumptions and constraints of the above objective are as follows. It is assumed that the only reserve provider in the system is the PL. Hence, the total reserve that the aggregator can present in the market is equal to the expected amount of reserve that the PL can provide (6).

$$r_t^{Agg} = \hat{r}_t^{PL} \quad (6)$$

The expected value for the PL's reserve, input and output power is the summation of their amount in each scenario multiplied by the probability of each scenario. These are shown in (7)-(9) for the reserve, input and output power, respectively.

$$\hat{r}_t^{PL} = \sum_\omega \rho_\omega r_{\omega,t}^{PL} \quad (7)$$

$$\hat{p}_t^{in,PL} = \sum_\omega \rho_\omega p_{\omega,t}^{in,PL} \quad (8)$$

$$\hat{p}_t^{out,PL} = \sum_\omega \rho_\omega p_{\omega,t}^{out,PL} \quad (9)$$

The total power of the aggregator is equal to the amount of demand in each node, the input power of the PL to the node on which it is installed minus the output power of the PL on that node and the output power of the DG (10). In order to identify the node on which the PL or DG is installed the binary variable (*Si*) is defined as in (11) to (13).

$$p_t^{Agg} = \sum_j \left(p_{j,t}^D + p_{j,t}'^{in,PL} - p_{j,t}'^{out,PL} - p_{j,t}'^{DG} \right) \quad (10)$$

$$p_{j,t}'^{in,PL} = Si_j^{PL}\hat{p}_t^{in,PL} \quad (11)$$

$$p_{j,t}'^{out,PL} = Si_j^{PL}\hat{p}_t^{out,PL} \quad (12)$$

The load flow equations are presented in (13) – (17). It is assumed the power injected from the upstream network ($p_{j,t}^{DSO,in}$) or delivered to it is affected by the efficiency of the connector transformer. In order to calculate the share of IL on each node, the assumption of spread share of IL on all loads is used. As a result, the share of the demand after IL (p_t^D) from total demand ($p_t^{D,total}$) is multiplied by the load of each node ($p_{j,t}^D$). Besides, the power factor of IL is considered equal to the power factor of the whole system; hence, the same approach can be used for the reactive power. The approach to perform the load flow of the system is based on [30], [31] and is linearized in the problem as explained in [17].

$$\begin{aligned} & p_{j,t}^{DSO,in}\eta_j^{Trans} - \frac{p_{j,t}^{DSO,out}}{\eta_j^{Trans}} + \sum_l p_{k,j,t}^{Line} - \sum_l\left[p_{j,k,t}^{Line} + R_{j,k}\left(i_{j,k,t}\right)^2\right] = \\ & \qquad \frac{p_t^D}{P_t^{D,Total}}P_{j,t}^D + p_{j,t}'^{in,PL} - p_{j,t}'^{out,PL} - p_{j,t}'^{DG} \end{aligned} \quad (13)$$

$$q_{j,t}^{DSO,in} - q_{j,t}^{DSO,out} + \sum_l q_{k,j,t}^{Line} - \sum_l\left[q_{j,k,t}^{Line} + X_{j,k}\left(i_{j,k,t}\right)^2\right] = \frac{p_t^D}{P_t^{D,Total}}Q_{j,t}^D \quad (14)$$

$$\begin{aligned} & v_{j,t}^2 - 2\left[R_{j,k}\left(p_{j,k,t}^{Line} - p_{k,j,t}^{Line}\right) + X_{j,k}\left(q_{j,k,t}^{Line} - q_{k,j,t}^{Line}\right)\right] \\ & \quad - Z_{j,k}^2 i_{j,k,t}^2 - v_{k,t}^2 = 0 \end{aligned} \quad (15)$$

$$v_{j,t}^2 i_{j,k,t}^2 = \left(p_{j,k,t}^{Line}\right)^2 + \left(q_{j,k,t}^{Line}\right)^2 \quad (16)$$

$$\underline{V}_j \le v_{j,t} \le \overline{V}_j \ , \ -\overline{I}_{j,k} \le i_{j,k,t} \le \overline{I}_{j,k} \quad (17)$$

Considering the objective and constraints of the UL problem, the decision vector of the UL for the bilevel model will be as (18).

$$\mathbf{DV^{UL}} = \left[p_t^{Agg}, r_t^{Agg}, \pi_t^{in,PL}, \pi_t^{out,PL}, \pi_t^{Re,PL}, \pi_t^{DG}, \pi_t^D\right] \quad (18)$$

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IV. LOWER LEVEL MATHEMATICAL MODEL

The objective on the LL problem consists of the objectives of the players on the LL based on their contribution in the equilibrium price. These objectives are for the trades of PL with the aggregator, the interactions of the PL with PEV owners, the trade of DG with the aggregator and the opportunity of IL on behalf of the retailer. In this regard, the objective of the LL will be as (19).

$$Max\left\{profit^{LL}\right\} = Max\left\{profit^{PL-Agg} + profit^{PL-PEV} + profit^{DG-Agg} + profit^{D-Agg}\right\} \quad (19)$$

A. PL-Aggregator interaction

The profit gained by the PL owner through its interaction with the aggregator is shown in (20). In this level, the vehicles that participate in both G2V and V2G mode are separated from those who are only operated in G2V mode. It is obvious that the output power of the PL is only due to the opportunity of V2G. On the other hand, the reserve presented to the market is from the opportunity of V2G, hence is treated with the same price of output power whenever it is called. If the PL fails to deliver the required reserve amount (FOR^{PL}), it will be charged with the output energy rate. It can be observed that in (20), there are common terms with the UL objective (3) that make the equilibrium point with UL.

$$profit^{PL-Agg} = \sum_t \left(\sum_\omega \left(\left(p_{\omega,t}^{out,V2G} \right) \pi_t^{out,PL} - \left(p_{\omega,t}^{in,V2G} + p_{\omega,t}^{in,G2V} \right) \pi_t^{in,PL} + r_{\omega,t}^{PL} \pi_t^{Re,PL} + r_{\omega,t}^{PL} \rho_t^{del} \pi_t^{out,PL} - r_{\omega,t}^{PL} \rho_t^{del} FOR^{PL} \pi_t^{out,PL} \right) \right) \quad (20)$$

The interaction of the PL with the PEV owners that use the PL is modeled with details in (21).

The financial transaction of PL with each group of vehicles should be different and proportional to the opportunity they bring because they lead to different levels of profit for the PL. The naming and clustering of these categories are shown in Table I. Moreover, in each hour and in each scenario, the share of each category should be determined. On the other hand, it should be specified that the amount of departed SOC belong to which category.

The share of each category in the departure SOC is needed for precisely calculating the hourly revenue and costs of PL. For this purpose, two coefficients are defined to impose the preferences of the PEV owners to the objective of the PL. The coefficient β is defined to determine the share of each category from departing vehicles. Another coefficient ϕ is defined to determine the preference of each category for the minimum required SOC at their departure. Besides, the coefficient θ determines the amount of PEVs in G2V or V2G mode in each hour.

In this study, the PEVs that agree to take part in the V2G mode are paid an incentive amount for being ready (as reserve or energy). This amount is calculated through the multiplication of their available capacity by the incentive price (Π^{Extra}). However, when actual energy is purchased from V2G PEVs, they are paid by V2G price (Π^{V2G}) as well as the degradation cost. Moreover, all the PEVs that enter the PL have to pay the usage tariff based on the total hours that they have stayed in the PL multiplied by the PL tariff (Π^{Tariff}). Also in Table I it is shown that different G2V price are considered for different categories. The reason is that the PL owner encourages the PEVs to participate in flexible modes by selling the energy with lower prices to them (Π^{G2V3}<Π^{G2V2}<Π^{G2V1}).

As shown in (23) and (24) the PL's SOC in each hour is separated for G2V and V2G modes. It is assumed that the PL starts with an initial amount of SOC at *t=1* and the arrival and departure SOC as well as the power traded with grid form the hourly SOC of the PL. The facilities in the PL restrict the charging/discharging of PL due to their efficiencies ($\eta^{cha,PL}$, $\eta^{dcha,PL}$).

TABLE I
PEV OWNERS CLUSTERING

Mode	Fixed departure SOC requirement			Flexible departure SOC requirement		
	Naming	Price of G2V	Price of V2G	Naming	Price of G2V	Price of V2G
G2V	*fix1*	Π^{G2V1}	-	*flex1*	Π^{G2V2}	-
V2G	*fix2*	Π^{G2V3}	Π^{Extra}	*flex2*	Π^{G2V3}	Π^{Extra}, Π^{V2G}

$$soc_{\omega,t}^{PL,G2V} = soc_{\omega,t-1}^{PL,G2V}\Big|_{t>1} + SOC_{\omega,t_0}^{PL,G2V}\Big|_{t=1} + soc_{\omega,t}^{ar,G2V} - soc_{\omega,t}^{dep,G2V} + p_{\omega,t}^{in,G2V}\eta^{cha,PL} \quad : \quad \lambda_{\omega,t}^{PL,G2V} \quad (21)$$

$$soc_{\omega,t}^{PL,V2G} = soc_{\omega,t-1}^{PL,V2G}\Big|_{t>1} + SOC_{\omega,t_0}^{PL,V2G}\Big|_{t=1} + soc_{\omega,t}^{ar,V2G} - soc_{\omega,t}^{dep,V2G} + p_{\omega,t}^{in,V2G}\eta^{cha,PL} - p_{\omega,t}^{out,V2G} / \eta^{dcha,PL} \quad : \quad \lambda_{\omega,t}^{PL,V2G} \quad (22)$$

The hourly departure SOC of the PL is equal to the minimum requirement of PEVs with fixed departure SOC and those who accept to have flexible departure SOC. This is applicable to both G2V and V2G modes as (24) and (25), respectively.

$$soc_{\omega,t}^{dep,G2V} = \phi_{\omega,t}^{fix1}\beta_{\omega,t}^{fix1}C_{\omega,t}^{dep,PL} + soc_{\omega,t}^{dep,flex1} \quad : \quad \lambda_{\omega,t}^{dep,G2V} \quad (23)$$

$$soc_{\omega,t}^{dep,V2G} = \phi_{\omega,t}^{fix2}\beta_{\omega,t}^{fix2}C_{\omega,t}^{dep,PL} + soc_{\omega,t}^{dep,flex2} \quad : \quad \lambda_{\omega,t}^{dep,V2G} \quad (24)$$

Although some PEVs agree to have a flexible amount of departure SOC, the departure SOC is still limited to their minimum preference and the maximum possible SOC due to the limitation of their capacity as in (26) and (27).

$$\begin{aligned} profit^{PL-PEV} = \sum_t \Bigg(\sum_\omega \Big(& \left(\phi_{\omega,t}^{fix1}\beta_{\omega,t}^{fix1}C_{\omega,t}^{dep,PL} - SOC_{\omega,t}^{dep,fix1,Sc}\right)\left(\Pi_t^{G2V1}\right) + \left(soc_{\omega,t}^{dep,flex1} - SOC_{\omega,t}^{dep,flex1,Sc}\right)\left(\Pi_t^{G2V2}\right) \\ & + \left(\phi_{\omega,t}^{fix2}\beta_{\omega,t}^{fix2}C_{\omega,t}^{dep,PL} - SOC_{\omega,t}^{dep,fix2,Sc}\right)\left(\Pi_t^{G2V3} + Cd^{PL}\right) - \left(\beta_{\omega,t}^{fix2}C_{\omega,t}^{dep,PL} - \phi_{\omega,t}^{fix2}\beta_{\omega,t}^{fix2}C_{\omega,t}^{dep,PL}\right)\Pi_t^{Extra} \\ & + \left(soc_{\omega,t}^{dep,flex2} - SOC_{\omega,t}^{dep,flex2,Sc}\right)\left(\Pi_t^{G2V3} + Cd^{PL}\right)\Big|_{\left(soc_{\omega,t}^{dep,flex2} \geq SOC_{\omega,t}^{dep,flex2,Sc}\right)} - \left(SOC_{\omega,t}^{dep,flex2,Sc} - soc_{\omega,t}^{dep,flex2}\right)\Pi_t^{V2G}\Big|_{\left(soc_{\omega,t}^{dep,flex2} < SOC_{\omega,t}^{dep,flex2,Sc}\right)} \\ & - \left(\beta_{\omega,t}^{flex2}C_{\omega,t}^{dep,PL} - \phi_{\omega,t}^{flex2}\beta_{\omega,t}^{flex2}C_{\omega,t}^{dep,PL}\right)\Pi_t^{Extra} - \left(p_{\omega,t}^{out,V2G} + p_{\omega,t}^{in,V2G} + r_{\omega,t}^{PL}\rho_t^{del}\right)Cd^{PL} + N_{\omega,t}^{PL}\Pi^{Tariff} - r_{\omega,t}^{PL}\rho_t^{del}\Pi_t^{V2G} \Big) \Bigg) \end{aligned} \quad (25)$$

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$$\phi_{\omega,t}^{flex1}\beta_{\omega,t}^{flex1}C_{\omega,t}^{dep,PL} \le soc_{\omega,t}^{dep,flex1} \le \overline{soc}^{EV}\beta_{\omega,t}^{flex1}C_{\omega,t}^{dep,PL} : \quad \underline{\mu}_{\omega,t}^{dep,flex1}, \overline{\mu}_{\omega,t}^{dep,flex1} \tag{26}$$

$$\phi_{\omega,t}^{flex2}\beta_{\omega,t}^{flex2}C_{\omega,t}^{dep,PL} \le soc_{\omega,t}^{dep,flex2} \le \overline{soc}^{EV}\beta_{\omega,t}^{flex2}C_{\omega,t}^{dep,PL} : \quad \underline{\mu}_{\omega,t}^{dep,flex2}, \overline{\mu}_{\omega,t}^{dep,flex2} \tag{27}$$

The SOC of PL in G2V mode should not pass the maximum available capacity of G2V vehicles in the PL multiplied by the maximum possible SOC of each EV (28). For the V2G vehicles, as the PL has the control to discharge the PEVs' batteries a minimum limit also should be bounded by the SOC of PL in each hour (29). Due to variable levels of PL's capacity resulting from PEVs arrival/departure, the hourly SOC of the PL is considered in kWh instead of the ratio of the total capacity.

$$soc_{\omega,t}^{PL,G2V} \le \theta_{\omega,t}^{PL}C_{\omega,t}^{PL}\overline{soc}^{EV} : \quad \overline{\mu}_{\omega,t}^{PL,G2V} \tag{28}$$

$$\left(1-\theta_{\omega,t}^{PL}\right)C_{\omega,t}^{PL}\underline{soc}^{EV} \le soc_{\omega,t}^{PL,V2G} \le \left(1-\theta_{\omega,t}^{PL}\right)C_{\omega,t}^{PL}\overline{soc}^{EV} : \quad \underline{\mu}_{\omega,t}^{PL,V2G}, \overline{\mu}_{\omega,t}^{PL,V2G} \tag{29}$$

The facilities in the PL's stations have a charging/discharging rate (γ^{PL}) that limits the maximum amount of input/output power of the PL (30)-(32).

$$0 \le p_{\omega,t}^{in,G2V} \le \gamma^{PL}\theta_{\omega,t}^{PL}N_{\omega,t}^{PL} : \quad \underline{\mu}_{\omega,t}^{in,G2V}, \overline{\mu}_{\omega,t}^{in,G2V} \tag{30}$$

$$0 \le p_{\omega,t}^{in,V2G} \le \gamma^{PL}\left(1-\theta_{\omega,t}^{PL}\right)N_{\omega,t}^{PL} : \quad \underline{\mu}_{\omega,t}^{in,V2G}, \overline{\mu}_{\omega,t}^{in,V2G} \tag{31}$$

$$0 \le p_{\omega,t}^{out,V2G} + r_{\omega,t}^{PL} \le \gamma^{PL}\left(1-\theta_{\omega,t}^{PL}\right)N_{\omega,t}^{PL} : \quad \underline{\mu}_{\omega,t}^{in,V2G1}, \overline{\mu}_{\omega,t}^{in,V2G1} \tag{32}$$

The maximum amount that PL can offer in the market (including energy and reserve) should not pass the limit of available SOC from V2G vehicles and the minimum SOC that can remain in the PEVs' batteries (33).

$$0 \le \left(p_{\omega,t}^{out,V2G} + r_{\omega,t}^{PL}\right)/\eta^{dcha,PL} \le soc_{\omega,t}^{PL,V2G} - \underline{soc}^{EV}\left(1-\theta_{\omega,t}^{PL}\right)C_{\omega,t}^{PL} : \quad \underline{\mu}_{\omega,t}^{in,V2G2}, \overline{\mu}_{\omega,t}^{in,V2G2} \tag{33}$$

The reserve and energy output of the PL are defined as positive variables (34), (35).

$$0 \le r_{\omega,t}^{PL} : \quad \underline{\mu}_{\omega,t}^{\mathrm{Re},PL} \tag{34}$$

$$0 \le p_{\omega,t}^{out,V2G} : \quad \underline{\mu}_{\omega,t}^{out,PL} \tag{35}$$

For the purpose of linearization in (22), a variable ($Z_{\omega,t}^{PL}$) is defined to compare the departed SOC in each hour with the scenario pattern (36)-(39).

$$\begin{aligned}&\left(soc_{\omega,t}^{dep,flex2} - SOC_{\omega,t}^{dep,flex2,Sc}\right)\left(\Pi_t^{G2V3} + Cd^{PL}\right)\Big|_{\left(soc_{\omega,t}^{dep,flex2} \ge SOC_{\omega,t}^{dep,flex2,Sc}\right)} \\ &-\left(SOC_{\omega,t}^{dep,flex2,Sc} - soc_{\omega,t}^{dep,flex2}\right)\Pi_t^{V2G}\Big|_{\left(soc_{\omega,t}^{dep,flex2} < SOC_{\omega,t}^{dep,flex2,Sc}\right)} = \\ &\left(soc_{\omega,t}^{dep,flex2} - SOC_{\omega,t}^{dep,flex2,Sc}\right)\left(\left(\left(\Pi_t^{G2V3} + Cd^{PL}\right) + \Pi_t^{V2G}\right)/2\right) \\ &-Z_{\omega,t}^{PL}\left|\Pi_t^{V2G} - \left(\left(\Pi_t^{G2V3} + Cd^{PL}\right) + \Pi_t^{V2G}\right)/2\right|\end{aligned} \tag{36}$$

$$Min\left\{Z_{\omega,t}^{PL}\right\} \tag{37}$$

$$\left(soc_{\omega,t}^{dep,flex2} - SOC_{\omega,t}^{dep,flex2,Sc}\right) \le Z_{\omega,t}^{PL} : \quad \underline{\mu}_{\omega,t}^{Aux,PL1} \tag{38}$$

$$\left(SOC_{\omega,t}^{dep,flex2,Sc} - soc_{\omega,t}^{dep,flex2}\right) \le Z_{\omega,t}^{PL} : \quad \underline{\mu}_{\omega,t}^{Aux,PL2} \tag{39}$$

B. DG-Aggregator interaction

In (40) the profit gained by the DG owner from selling energy to the aggregator is shown

$$profit^{DG-Agg} = \sum_t\left(\sum_m\left(p_{m,t}^{DG}\pi_t^{DG} - A_m^{DG}p_{m,t}^{DG}\right)\right) \tag{40}$$

where A_m^{DG} is the marginal cost for m^{th} DG. All the DGs should be limited to their maximum generating power (41).

$$0 \le p_{m,t}^{DG} \le \overline{P}_m^{DG} : \quad \underline{\mu}_{m,t}^{DG}, \overline{\mu}_{m,t}^{DG} \tag{41}$$

C. Demand-Aggregator interaction

The loads in the system are supplied by a load retailer who purchases the required amount of energy from the aggregator with equilibrium price (π_t^D) and sell it to the load with the time of use tariff (Π_t^{ToU}). The users who participate as IL are also paid an incentive ($\Pi_t^{Incentive}$).

$$profit^{D-Agg} = \sum_t\left(p_t^D\left(\Pi_t^{ToU} - \pi_t^D\right) - p_t^{IL}\Pi_t^{Incentive}\right) \tag{42}$$

It is assumed that the amount of demand that is purchased from the aggregator (p_t^D) is after the implementation of IL (43). Moreover, the demand after the IL implementation should be limited to the maximum total demand ($p_t^{D,total}$) and the minimum of not interruptible load (44).

$$p_t^{IL} = p_t^{D,total} - p_t^D : \quad \lambda_t^{IL} \tag{43}$$

$$\left(1-\alpha_t^D\right)P_t^{D,total} \le p_t^D \le P_t^{D,total} : \quad \underline{\mu}_t^{D,total}, \overline{\mu}_t^{D,total} \tag{44}$$

Considering all the equations presented for the LL problem the decision vector for lower level will be as (45).

$$\mathbf{DV^{LL}} = \left[p_{\omega,t}^{in,PL}, p_{\omega,t}^{out,PL}, r_{\omega,t}^{PL}, soc_{\omega,t}^{dep,PL}, p_{m,t}^{DG}, p_t^D\right] \tag{45}$$

As previously mentioned, the problem is formulated to convert the bilevel problem into an MPEC. For this purpose, firstly the Lagrangian of the LL problem is developed. The variables in this equation are the decision variable vectors in LL problem. The components of the Lagrangian are the LL objective (19), equality constraints (22-25, 43) and inequality constraints (26-39, 41, 44).

For linearization of the non-linear terms in the UL, the strong duality theorem is employed which states when a problem is convex, the primal and dual objective functions are equal at the optimum.

V. PEV Scenario Generation

Considering the real data from the surveys and the stay duration classification, the scenarios for the arrival of PEVs in the PL is generated using the approach in [17] where a lognormal distribution function is considered. Then the departure scenarios are derived from the arrival scenario and stay duration. However, due to the fixed number of stations in the PL, the scenarios generated for arrival/departure may result in PEVs' number in the PL more than the PL's capacity. To prevent this, a procedure is implemented on the scenario generation as shown in Fig. 3. The scenario of PEV numbers in the PL is generated from the summation of the remainder PEVs in the PL from the previous hour and the arrived PEVs in each hour minus the departed PEV. Whenever the PEV numbers exceed the PL's stations, the number of excess PEVs is reduced from the arrival scenario on that hour.

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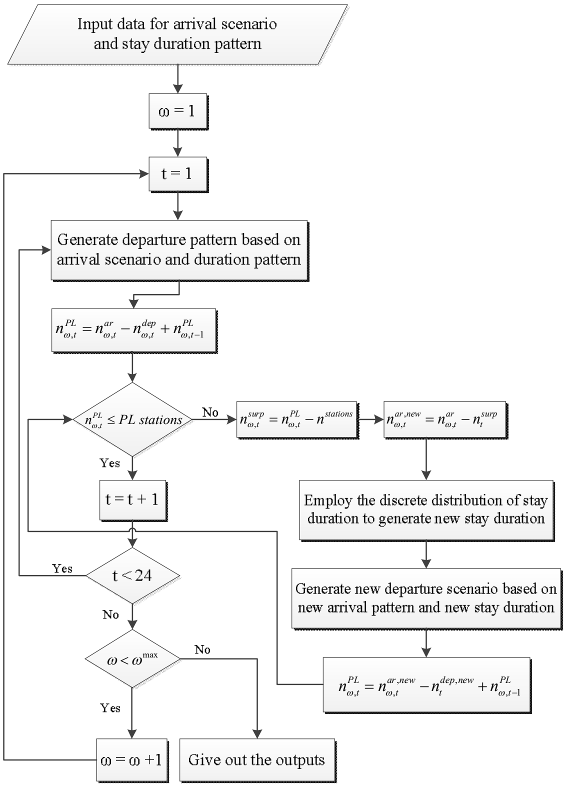

Fig. 3. Flowchart of generating scenario for PEVs' number in PL.

Now, the arrival scenarios need to be changed which consequently cause the change in the stay duration. Considering the discrete distribution of stay duration pattern, the new arrival scenario and stay duration scenario is formed. Based on the new arrival and stay duration scenario, the new departure scenario is generated. Once again the number of PEVs in PL is calculated. The procedure is performed until the PL's number scenario does not exceed the total PL's station number (Fig. 3).

VI. Numerical Results

The proposed model is implemented on a standard distribution network with PL, DG, and DR program. The IEEE 37-bus network [32] as shown in Fig. 4 is selected for the study. The location of the resources and their capacities are based on previous studies of DG integration in IEEE 37-bus network as in [33] and [34].

In this study, a PL with 250 stations in a commercial area is considered. Figures 5 and 6 depict the arrival and departure scenarios employed in this study. The total SOC of PEVs in the PL is shown in Fig. 7. The mean values for the scenarios are derived from reports and surveys on European driving pattern presented in [35] and [36] and the household travel survey in [37]. The data presented in [38] are employed to acquire the expected stay duration of PEVs as shown in Fig. 8. As at the PL is assumed to be in a commercial center, the PEVs that enter the PL may stay from 1 to 12 hours in the PL.

The values for coefficient φ which determines the minimum departure SOC requirement of each PEV category is shown in Table II. The values to determine the share of each category from the total departed PEVs are presented by coefficient β in Table III.

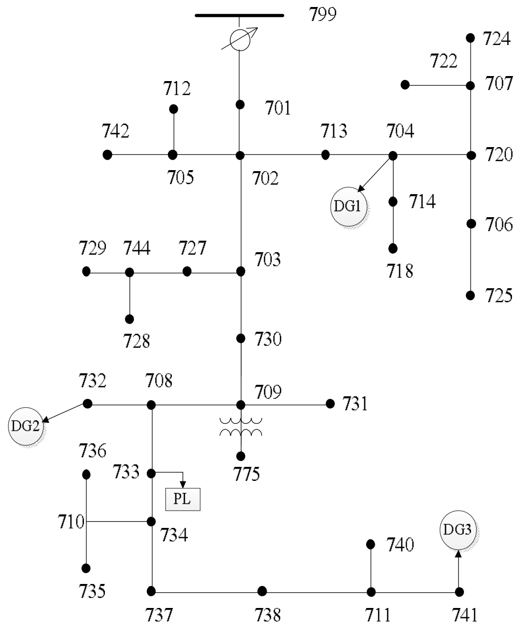

Fig. 4. IEEE 37-bus network under study with added resources.

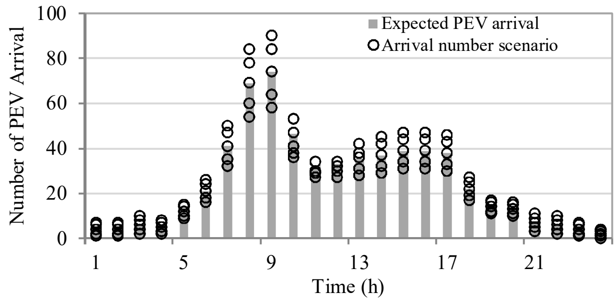

Fig. 5. Expected value of PEV arrival to PL and its scenarios.

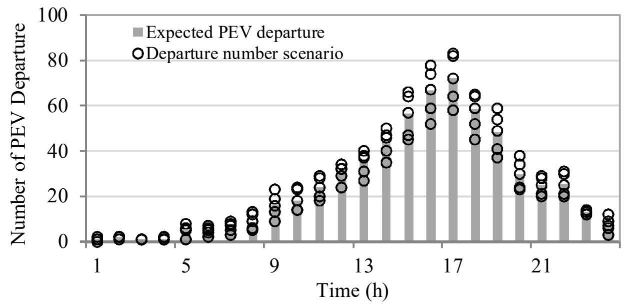

Fig. 6. Expected value of PEV departure from the PL and its scenarios.

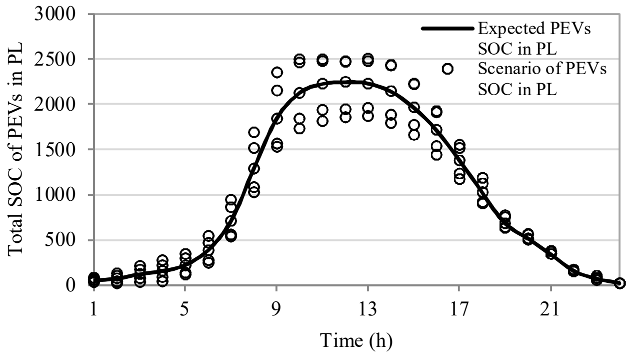

Fig. 7. Expected value of PEV SOC in the PL and its scenarios.

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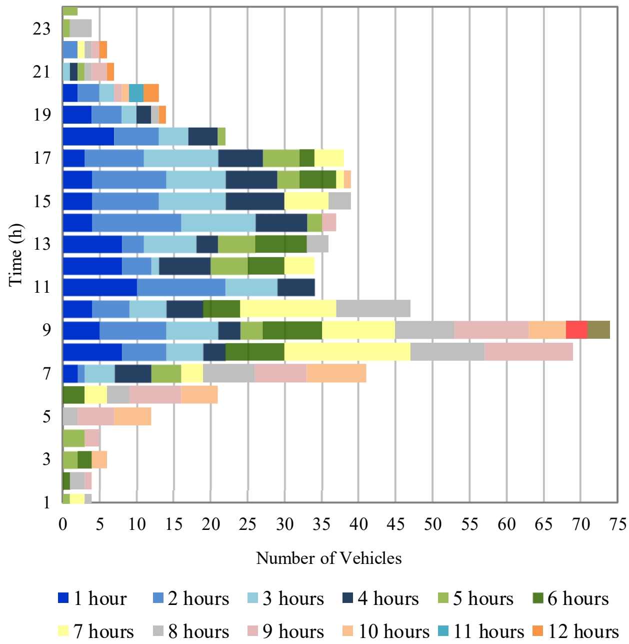

Fig. 8. Total number of PEVs in the PL in each hour based on their expected stay duration.

TABLE II
VALUES OF ϕ FOR DIFFERENT PEV CATEGORIES

Mode	Departure SOC Requirement	Duration of stay (hours)		
		1-3	4-8	9-12
G2V	Fix	0.6	0.8	0.9
	Flex	0.4	0.6	0.6
G2V+V2G	Fix	0.4	0.5	0.6
	Flex	0.3	0.4	0.5

TABLE III
VALUES OF β FOR DIFFERENT PEV CATEGORIES

Mode	Departure SOC Requirement	Duration of stay (hours)		
		1-3	4-8	9-12
G2V	Fix	0.56	0.32	0.08
	Flex	0.14	0.08	0.02
G2V+V2G	Fix	0.06	0.12	0.18
	Flex	0.24	0.48	0.72

The prices for energy and reserve market are from the Spanish electricity market [39] and are adapted to the distribution level based on [40]. In [40] it is mentioned that a surplus should be added to the upstream energy prices when it is implemented to lower voltage levels. This surplus is divided between the aggregator and the LL components of the problem. In this study the surplus is considered as 5 cents. Therefore, 3 cents are added to the upstream market energy price and then implemented to the energy trades of the aggregator with the upstream network. The remaining 2 cents is added to the LL resources transaction price. Note that the trades between the aggregator and LL resources take place based on the equilibrium prices

In this study, all the stations in the PL are the same and are quick charging stations with a charging rate of 11 kW per hour as in [17]. Other specifications of the PEVs and tariffs are based on [41].

In this paper, two case studies are investigated to evaluate the proposed model. On the first approach, the Pay as Bid pricing model is investigated to examine the individual interaction of LL resource with the aggregator. In the second approach, the cross effect of the resources in their market participation is investigated through uniform pricing. The problem is modeled as an MILP problem and implemented in GAMS using CPLEX12 solver.

A. Case I: Pay as Bid

In this case, as each resource receives payment based on its bidding, the aggregator interacts with each component individually. Therefore, the aggregation approach causes a leader/follower framework. In order to bind the profit of the leader, a price cap is put on the maximum trade price between the aggregator and each of the LL components. The cap is 10 cents per kWh. This case is studied as a base case to show the different behavior of the aggregator and the resources when one equilibrium point is found comparing to individual interaction.

In Fig. 9 the prices of the upstream EM (i.e., the amount paid by the aggregator to the upstream market), the PL price (i.e., the price paid by the PL to the aggregator for energy purchase), and the DG price are shown.

The PL price reaches the price cap for the whole 24 hours. The variations of prices in this case comply with the energy interaction balance of the system in Fig. 10. It can be seen that the behavior of the aggregator is relatively justifiable to the EM price variations. For example, during hours 2-7 A.M. when the upstream energy price has the lowest amount, none of the resources in the LL is activated. For the remaining hours, only DG1 is committed to supply energy. Therefore, the PL's power exchange is only for input power as in Fig. 11. Moreover, with this price cap, it is not profitable for the load retailer to activate the IL and thus it provides the total demand from the EM.

The reserve market price and the aggregator-PL reserve price are shown in Fig. 12. It shows that during the high commuting hours the reserve price reaches its peak amount. The PL can make a profit through its participation in the upstream reserve market. Being the only reserve source of the aggregator, all the possible SOC of PL is presented in the reserve market. Accordingly, the price of the reserve paid to the PL can be a motivating factor to change the PL's behavior. It indicates that considerable higher payment to the PL in order to maintain its SOC for participating in reserve market is profitable in this case. The SOC of the PL for various PEV categories in the PL is shown in Fig. 13.

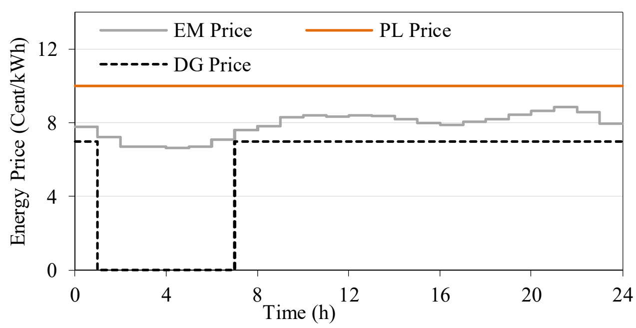

Fig. 9. Energy prices for aggregator, PL, and DG in Case I.

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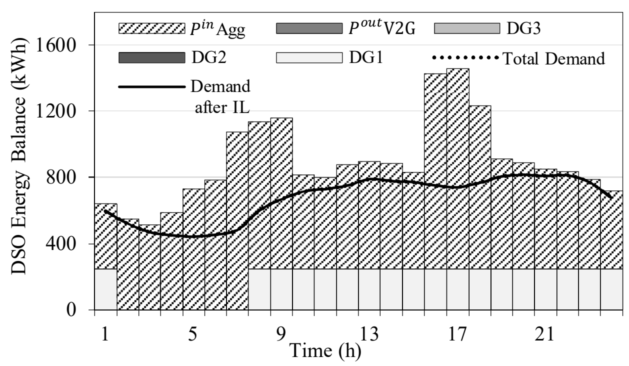

Fig. 10. Energy balance of system in Case I.

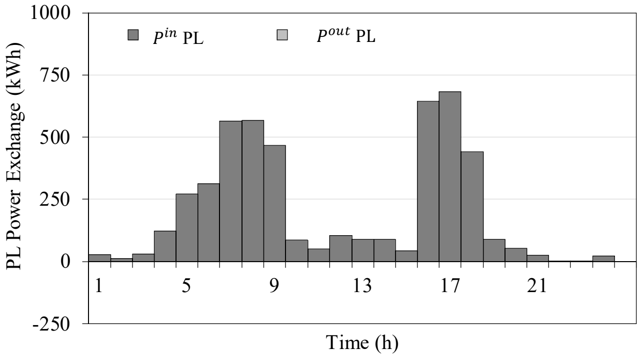

Fig. 11. PL's power exchange in Case I.

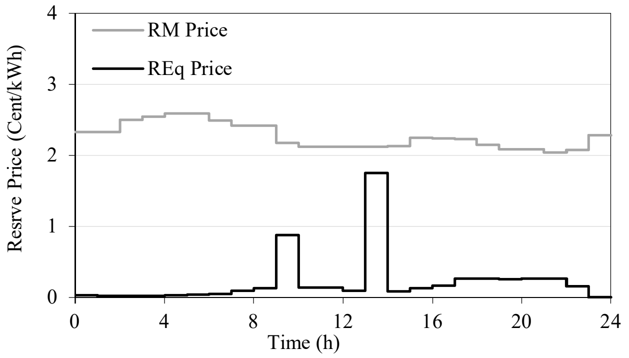

Fig. 12. Upstream reserve market and LL reserve equilibrium prices in Case I.

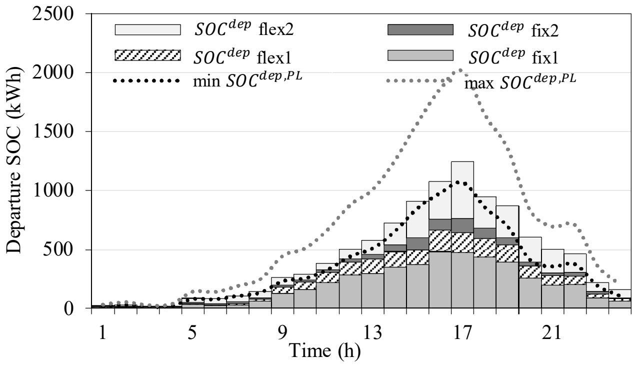

Fig. 13. PL's state of charge for various categories of PEVs in PL in Case I.

The most challenging resource in this model is PL. In this case as shown in Fig. 9, the price for PL's energy trade is a constant value for the whole 24 hours. This price is the equilibrium price derived from the behavior of the PL and the aggregator considering other resources available to the aggregator. In other words, if the PL changes its behavior, the price will also change.

However, both the PL's behavior and the price are propelled to the equilibrium price as in this price the optimum profit is obtained. During the early hours of the day (hours 1-9) the PL starts to charge the PEVs in the PL because the energy price is low. The PL can make profit from selling energy to the PEVs, however the preferences of PEVs on requiring a fixed amount of departure SOC limits the charging behavior of the PL.

Meanwhile, the aggregator wants to increase its profit from selling energy to the PL; as a result, it will encourage the PL to charge its PEVs by increasing the price of reserve at hours 10 and 14 (see Fig. 12). The price of reserve is increased by the aggregator so that the PL will be motivated for charging; however, the preferences of the PEVs limit the maximum charging of PL.

In fact, noting Fig. 13, it is shown that the PEVs are charged almost the same as their minimum requirement of departure SOC. The reason is that from hour 16, the PEVs departure from the PL increases. As a result, in order to meet the PEV's preferences the charging of PL is limited.

For the reserve provision, except where the reserve price faces a spike at hour 15, in other hours the price is almost equal to the marginal price of PL for providing reserve.

B. *Case II: Uniform Pricing*

In this case, all the resources on the LL trade with the aggregator with a uniform price which is the equilibrium price. As a result, the LL resources can have more flexibility on their transactions with the aggregator comparing to Case I.

As can be seen in Fig. 14, the LL energy equilibrium (EEq) price has significant differences from the EM price and the pay as bid case.

Moreover, Fig. 15 shows the contribution of all resources in the system. In contrary to Case I, in this case all the resources (i.e., DG, PL's V2G mode, and IL) take part in the schedule. The reason is that one equilibrium price concerning all the constraints and objectives of various components is calculated and hence more flexibility for the aggregator to compromise between the various objectives is provided.

From another point of view, the reserve price in this case in Fig. 16 is higher than the first case and in some hours the aggregator is persuaded to increase the reserve price up to the upstream reserve market price. As a result, the LL resources will be encouraged to participate more effectively in the market.

In Fig. 16, it is shown that in the reserve price experience a spike from hour 19 to 23.

At hours 19 to 23 the aggregator increases the reserve price to encourage the PL to charge its PEVs. In fact, the equilibrium price is a compromise between the lowest amount of EM price and RM prices.

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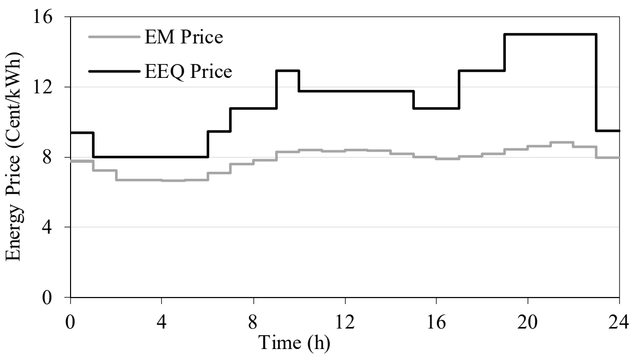

Fig. 14. Energy Market and Energy Equilibrium prices in Case II.

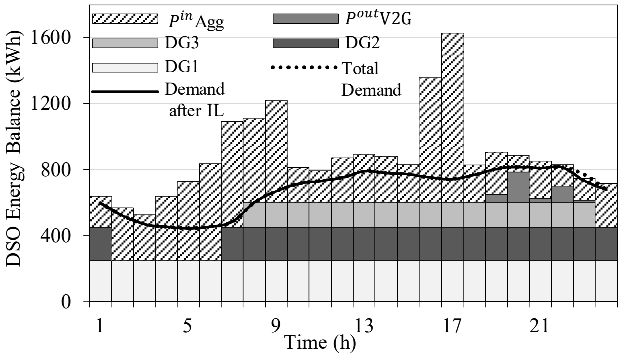

Fig. 15. Energy balance of system in Case II.

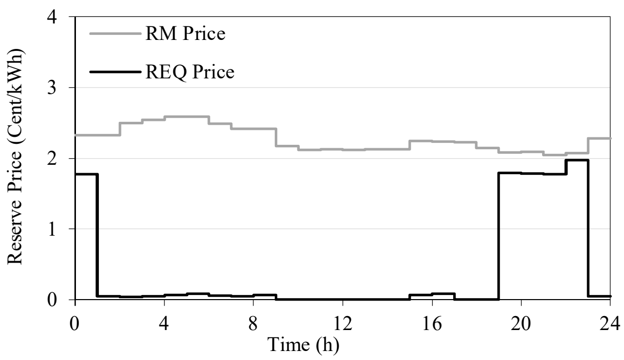

Fig. 16. Reserve Market and Reserve Equilibrium prices in Case II.

1) DGs' behavior

During hours 2 to 6, the EM price is in its lowest amount; however, during those hours DG1 is committed for the energy generation but two of the DGs cannot compete and are not operating. At hour 7, DG2 is committed and after that all DGs are participating in the energy production of the system. This happens because of the EEq price increase on that hour. The reason is that from hour 7 the arrival to the PL is increasing; as a result, the PL will be able to charge the batteries of arriving PEVs, increase its potential of reserve provision and consequently increase its own profit.

2) Load Retailer's behavior

The aggregator's decision making on operating its resources impose significant changes on the EEq price during 24 hours. However, these changes are not tempting enough for the load retailer to activate its IL until hours 19-23 when the end users' demand is on its peak amount. As a result, the load retailer will use the IL to reduce its costs.

3) PL's behavior

During early hours of the day, the PL is encouraged to charge the PEVs due to low energy prices. After hour 6 up to 9, although the EEq price is increased, it is still maintained in low amount; therefore, the PL keeps charging the batteries. In other words, in these hours the aggregator holds the EEq price relatively low so that the PL continues on its behavior of charging.

In hour 10, the price of the EM increases and consequently the aggregator increases the price to make benefit from selling energy to load retailer and PL.

Referring to Fig. 8, it is observed that from hour 10 most of the PEVs that enter the PL are those who need to stay in the PL for a short stay. As a result, the EEq price is reduced and the energy trade is reduced (Fig. 14 and 16). Consequently, from hours 10 to 15, the PL changes its strategy.

Although the EEq price is reduced at hour 11 comparing to hour 10, the PL is not motivated to increase its charging. During this period, the PL will charge mostly the PEVs that only take part as G2V mode. The reason is that the price reduction is up to the G2V2 price considering the efficiency of the station charger. In other words, the *Fix2* contracts are the most preferred contracts for both PL and the aggregator, because the aggregator benefits from selling energy to PL and the PL benefits from selling to the PEVs.

After that in hours 16 and 17, the EEq price is decreased. The reason is not only due to the price reduction in the EM, but also due to the fact that from hour 16, the number of PEV departure increases. Hence, the PL needs to charge the batteries, especially the flexible ones, to increase its own profit. As a result, the aggregator decreases the EEq price so that the PL is encouraged to charge the PEVs which are about to depart the PL. This increase in the SOC can be seen in Fig. 17.

Unlike Case I, in this case the V2G power is injected into the grid (see Fig. 18). The reason is that in hours 16 and 17 the PL charges the PEVs but from hour 19, it has to discharge the batteries because it gets near to the ending hours and the PEVs leaves the PL. As a result, in order to meet the requirements imposed to the PL by PEVs' categories, it will inject the excess power to the grid. Consequently, the price of energy spikes in hour 19 and remains high after that, both due to this reason and the fact that the demand peak is also during those hours.

Although the strategy of PL from hour 19 to 24 is to discharge most of the energy stored in PEV batteries, the aggregator will equilibrate the situation by increasing the reserve up to the upstream reserve market (see Fig. 16). The total departure SOC of PL for Flex2 contracts in this case is shown in Fig. 17. As shown, the difference of SOC in the PL with the minimum requirement of PEVs' departure SOC is higher in hours 17-22 which is due to higher reserve price encouraged by the aggregator. For other hours the PL tends to keep the PEVs on their minimum requirement. Figure 19 shows the total PL's SOC and capacity and the reserve provision of the PL.

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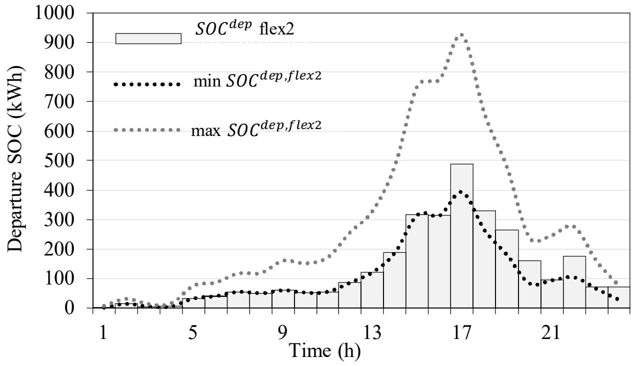

Fig. 17. The behavior of PL in charging Flex2 contracts in Case II.

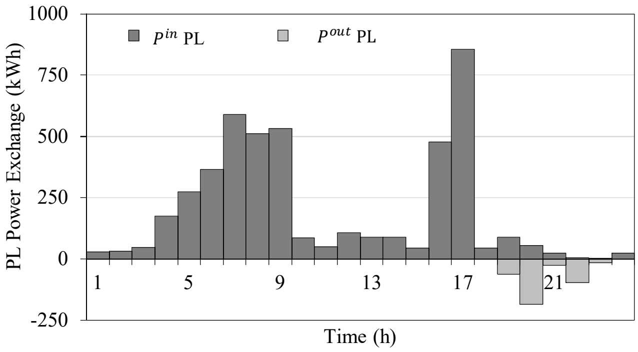

Fig. 18. PL's power exchange in Case II.

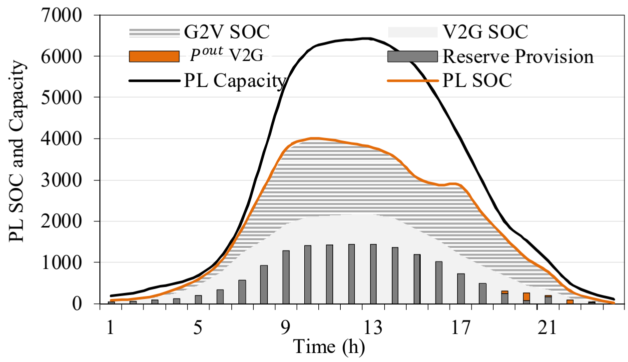

Fig. 19. Comparison of PL's capacity and SOC divided by G2V and V2G PEVs in Case II.

VII. The Role of PEV Preferences on Aggregator Equilibrium

In this paper, the PL as the main concern of the study changes its behavior based on its trade with the PEV owners and the aggregator. As a result, the tariffs that are implemented to the PEVs can significantly change the strategy of the PL in the market. The variation of the behavior also leads to different levels of profit gain for the PL and aggregator.

In this study, PL is a complicated resource in the system which can act as a flexible demand and as a resource as well. Therefore, the aggregator can benefit the most from the PL's potential to act as the flexible load. However, the aggregator needs to manage the market wisely to encourage the PL to show more flexibility.

In this regard, in Figs. 20 and 21 the profits of the aggregator and PL for the variation of G2V2 and G2V3 prices in case II are shown, respectively. For the aggregator in Fig. 20, the total profit is reduced constantly with the reduction of the G2V prices. The reason is that as the prices decrease, the tendency of the PL to charge its PEVs will decrease and consequently the aggregator's profit will decrease. However, it can be seen that when the G2V2 price goes less than 11 cents, the aggregator's profit decreases drastically. It is due to the fact that G2V2 price is for those PEVs that only participate in G2V mode, but they agree to have flexible departure SOC (i.e., *Flex1* contract). In this case, the PL's choice of profit is only through charging these PEVs and no encouragement for charging the PEVs to take benefit from them in the reserve market does not exist. As a result, the PL reduces its flexibility and considerably affects the aggregator's profit.

In Fig. 21, it is observed that the total profit of the PL can have significant changes with the changes in G2V2 and G2V3 prices. These prices are the incentives that the PL determines for its trade with those PEVs that agree to have flexible departure SOC requirements. It should be noted that these tariffs can considerably affect the role of the PL as a flexible load or as a resource. In other words, these two prices can change the marginal price of the PL and change its behavior in contact with the aggregator.

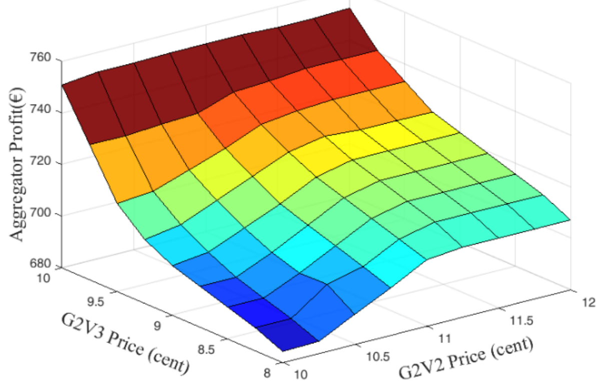

Fig. 20. Aggregator profit in Case II for various G2V2 and G2V3 prices.

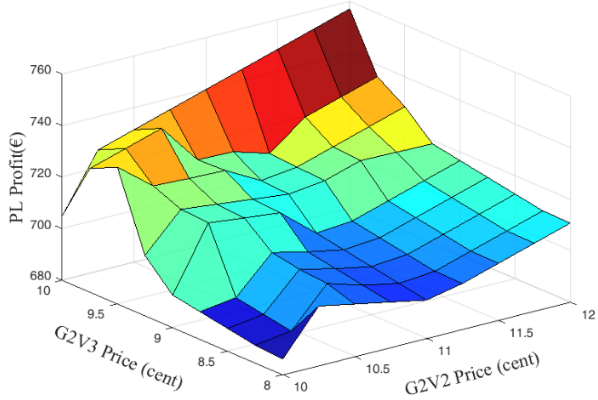

Fig. 21. PL profit in Case II for various G2V2 and G2V3 prices.

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VIII. Conclusions

In this paper a comprehensive bilevel model to derive the equilibrium price of energy and reserve trade of PL has been proposed considering the preferences of the PEV owners. It is obvious that a critical influence is put on the manipulation of the electric vehicles in future systems by their owners. The behavior of the PEV users can significantly change the process of the system operator. On the other hand, in such environment with various components and complicated interactions, an organized inter-relation should be defined so that all the involved parties in this system could assure their own profit. In this regard, this paper intended to propose a model for such situation. The main characteristic of this model is that in the upper level the price was specified while the lower level determined the quantity. This was accurately compatible with the reality of PL operation. In fact, the main role of PL as a flexible load is to add the potential of possible load increase or decrease.

Considering the results obtained from this study, several influential conclusions can be deduced which are listed below:

- It is shown that in the uniform pricing model where the LL components can have more flexibility the model is more effective and the equilibrium point is found in a more suitable way for all parties' profit. On the other hand, it is shown that in an environment with mixed resources, the model can provide the solution to compromise between all the potentials in the system.
- It is shown that the equilibrium price is affected by various factors that may change the behavior of the players in the model. When the behavior is changed, the equilibrium price is going to be changed; however, the bilevel model is designed in a way that the optimum solution is found in this compromising situation.
- Although the PL can be considered as a resource in the system, the compromise between the competitiveness of other resources in the system such as DGs and the expenses of V2G vehicles will lead to less tendency towards V2G mode operation. However, it was deduced from the study that the PL can provide various opportunities for the aggregator in terms of flexibility and increase the total profit. The aggregator can decrease the equilibrium price to increase its own share of the local market, triggering the load flexibility potential of the PL (increasing the quantity in lower level) which causes higher profit for both aggregator and PL.
- It is deduced that the reserve price also had a critical role with which the aggregator controls the input energy to the PL and encourages the PL for purchasing more energy. From another point of view, other local resources have proved that they influence the problem. With higher levels of local resources penetration in the system, the equilibrium price can go as low as the marginal price of these resources, which affects the charging status of the PL as well.

In final words, this study proposed a model for the combination of future system components with high penetration local resources considering the two-fold role of the PL. The inherent nature of the bi-level interaction of the PL with the grid is coordinated with the inevitable effect of the PEV owners' preferences. The outcomes of this model can be useful for future tariff determination or incentive calculations for further deployment of PLs in the system. The relation of multiple PLs, as the commute between two PLs in one zone can affect the total SOC and capacity of each PL and make it dependent to the other PL's behavior in charging its vehicles, will be a subject of future work.

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