PEV-Based Combined Frequency and Voltage Regulation for Smart Grid

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***Abstract*—With the increasing popularity of plug-in electric vehicles (PEVs), they will be able to help the power grid by providing various ancillary services. In fact, recent studies have suggested that PEVs can participate in frequency regulation. In this paper, we consider offering both, *i.e.,* combined, frequency and voltage regulation by PEVs. In this regard, we first investigate a set of constraints that need to be taken into account on PEVs' active and reactive power flow to offer ancillary services. Next, we formulate two joint optimization problems, based on different pricing and contract scenarios, that can be solved for optimal combined offering of frequency and voltage regulation by PEVs. They address both *day-ahead command-based* and *day-ahead price-based* models. Simulation results show that the proposed designs can benefit both users and utilities.**

***Index Terms*—Smart grid, plug-in electric vehicles, demand side management, reactive power compensation, ancillary services, frequency regulation, voltage regulation, optimization.**

I. INTRODUCTION

For proper operation of the grid, the grid operator must constantly balance production and consumption of both *active* and *reactive* power, in order to maintain the frequency and voltage amplitude close to their nominal values [1]. In this regard, *frequency regulation* is used to balance supply and demand for active power. Similarly, *voltage regulation* is used to balance supply and demand for reactive power. In general, since most reactive power consumption is inductive, reactive power compensation usually involves adding capacitors, *e.g.,* switched shunt capacitors [2] to the grid. Optimal sizing, placing, and switching of switched shunt capacitors for reactive power compensation have been extensively studied in the literature, *e.g.,* in [3]–[5].

At each time instance, such balance can be achieved by either adjusting supply or changing demand. While various *demand side management* programs have used to help frequency regulation [6], [7], voltage regulation and reactive power compensation traditionally do *not* involve end users as capacitor switching is done by regional grid operators [8]–[10]. However, recent studies have shown that the power electronics AC/DC inverters used for charging PEV batteries can potentially contribute to reactive power compensation and voltage regulation [11]. While the use of PEVs for frequency regulation has been well-studied in the literature (*e.g.,* in [7], [12], [13]), to the best of our knowledge, there is no analytical study of PEV-based simultaneous active and reactive power compensation. Unlike frequency regulation that can reduce the PEV batteries' lifetime due to frequent charging and discharging, reactive power compensation for voltage regulation has minimal degradation effect on the batteries, making it desirable for the users to make profit for providing voltage regulation service [14].

Reactive power compensation not only can help the grid to maintain power quality and reliability [15], but also increase the active power transfer limits [16]. Currently, in the United States, as per the NERC Operating Policy - 10 [17], only the reactive power provided by synchronous generators is considered as an ancillary service to receive financial compensation [8]. However, the reactive power market is foreseen to grow and become more diverse, mainly due to the increase in the number and capacity of PEVs and renewable energy sources connected to the grid [18]–[20].

Reactive power compensation and voltage regulation have different characteristics compared to demand side management and frequency regulation. In particular, generation of real power requires energy conversion from some other energy resource (such as fossil / nuclear fuel, sunlight, wind power or water flow), whereas reactive power does not. The cost of common reactive power compensators such as shunt capacitors mainly comes from their capital installation (equipment) and operating cost. For the case of PEV-based reactive power compensation, operation can be coordinated by the same charging and discharging scheduling software agents that are foreseen to be used by residential consumers for demand-side management *with low additional cost* [14].

Therefore, different from most of the literature on resource management for electric vehicles that exclusively focus on offering frequency regulation services, in this paper we study optimal combined frequency and voltage regulation by controlling both active and reactive power flows of the PEVs. Our work leads to better understanding of trade-offs involved in offering such combined services. The rest of this paper is organized as follows. The system model is given in Section II. The joint reactive and active power compensation optimization problem is formulated in Section III. Simulation results are

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This work was supported in part by the new faculty startup support by Texas Tech University, the National Basic Research Program of China Grant 2007CB807900, 2007CB807901, and the National Natural Science Foundation of China Grant 61033001, 61061130540, 61073174.

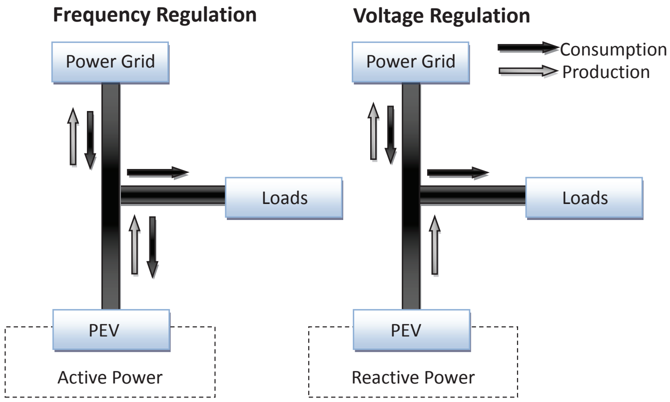

Fig. 1. System model for PEV-based combined frequency and voltage regulation.

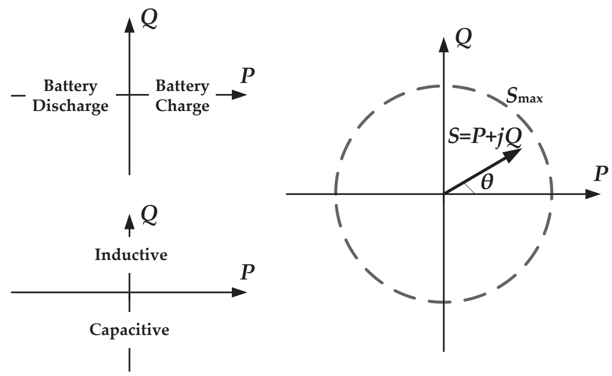

Fig. 2. Four-quadrant power response of a PEV [1].

presented in Section IV. The paper is concluded in Section V.

II. System Model

In this section, we introduce the system model to study combined offering of frequency and voltage regulation by PEVs. Consider the block diagrams in Fig. 1. A PEV participates in frequency regulation by charging or discharging its battery. In case of discharging, the portion of power that is not used by local load (*e.g.,* household appliances), will be injected into the grid. In the meanwhile, a PEV can participate in voltage regulation and compensate inductive or capacitive reactive power by properly selecting the phase angle difference between charging/discharging current and grid voltage. There are three very important operating constraints related to *maximal apparent power*, *charging deadlines, and battery capacity*. They will be explained next.

A. Maximal Apparent Power Constraint

Consider a PEV charger containing a power electronics AC/DC inverter which can adjust reactive power consumption. Let P and Q denote the active and reactive power flow from the grid to the PEV. We have [14]:

$$P = V_s \times I_c \cos\theta, \tag{1}$$
$$Q = V_s \times I_c \sin\theta, \tag{2}$$

where V_s is the grid voltage, I_c is the charger current, and θ is the phase difference between the voltage and current. In practice, the current and phase variables I_c and θ can be controlled by the charger invertor's power electronics circuits, leading to changes in active and reactive power flows based on (1) and (2). Next, let S denote the PEV-charger systems's *apparent power*. We have

$$S = V_s \times I_c \le S_{\max}, \tag{3}$$

where $S_{\max}$ is the system's maximum supported apparent power. From (1)-(3), we are now ready to formulate the following *nonlinear* maximum apparent power constraint on the PEV's active and reactive power flows:

$$P^2 + Q^2 = S^2 \times (\cos^2\theta + \sin^2\theta) = S^2 \le S^2_{\max}. \tag{4}$$

The geometrical representation of constraint (4) is shown in Fig. 2. We can distinguish four different operating regimes for the PEV-charger system's power response to the grid:

- I: charging ($P > 0$) with inducting load ($Q > 0$),
- II: discharging ($P < 0$) with inductive load ($Q > 0$),
- III: discharging ($P < 0$) with capacitive load ($Q < 0$),
- IV: charging ($P > 0$) with capacitive load ($Q < 0$).

The exact regime of operation at each time can be controlled by properly adjusting current I_c and phase θ. Note that, in this case, we assume V_s is fixed, and thus, the maximum apparent power S_{max} depends on the maximum supported charging current. The maximum supported charging current and other operational characteristics for the existing charging technologies are summarized in Table I.

TABLE I
Charging Methods in North America [14].

Charging method	Nominal supply voltage	Maximum current	Continuous input power
AC Level 1	120 V	12 A	1.44 kW
AC Level 2	240 V	32 A	7.68 kW

B. Charging Deadline Constraint

Due to their flexible load, PEVs can offer various ancillary services [7], [21]–[28] or participate in demand side management as controllable loads [29]. However, for each PEV user, the first priority is to assure finishing the charging task by a certain *charging deadline* [30]. For example, once plugging in the car at work in the morning, a user may expect a full charge of his/her PEV by 6:00 PM when he/she wants to drive the car to home. Therefore, it's important to define a feasible range of acceptable charging schedule for each PEV.

Let E denote the total charging capacity, in kWh, for the PEV's battery. For example, one typical value of E_n for an electric sedan is $E = 16$kWh [31]. Let α and β denote the beginning and the end of an acceptable scheduling time frame.

Here β refers to the charging deadline. Finally, let P^h and Q^h denote the PEV's scheduled active and reactive power consumption at each hour h. In order to assure reaching the charging deadline, the charging schedule needs to satisfy

$$\sum_{h=\alpha}^{\beta} P^h = E. \tag{5}$$

C. Battery Capacity Constraints

The feasibility of a charging or discharging decision P^h in time slot h critically depends on the scheduling plan in previous time slots, *i.e.,* $P^1, \cdots, P^{h-1}$. Let C denote the total charging capacity of the PEV battery and let C^{init} denote the initial charging level of the PEV battery at the beginning of the operation interval of interest. Thus, in addition to (5), we also need to satisfy

$$-C^{\text{init}} - \sum_{s=1}^{h-1} P^s \leq P^h, \quad \alpha \leq h \leq \beta, \tag{6}$$

$$C - C^{\text{init}} - \sum_{s=1}^{h-1} P^s \geq P^h, \quad \alpha \leq h \leq \beta. \tag{7}$$

At time slot h, from (6), the battery cannot be discharged more than it was initially charged at the beginning of that time slot; from (7), the battery cannot be charged more that its what was left to charge at the beginning of that time slot.

III. Joint Optimization Problem

In general, users would like to maximize their own profits by reducing the electricity costs or increasing the profits of providing ancillary services such as frequency and voltage regulations. However, the exact formulation of the profit maximization problem depends on the type of the contract between the grid and PEVs. Next, we will consider two different scenarios and formulate the joint active and reactive power compensation problems for each scenario accordingly.

1) Day-ahead Command-Based Model: Consider a scenario, where the grid sends commands to *each user* on the exact amount of the active power and reactive power that it expects each PEV to consume or generate for the purpose of frequency regulation and voltage regulation, respectively. These commands can be chosen by the utility company based on the imbalance between total supply and total demand in the power system. At each hour h, the grid's requested active and reactive power consumption levels are denoted by $\bar{P}^h$ and $\bar{Q}^h$. We assume that these commands are provided $H > 1$ hours ahead. Given these commands, the PEVs will then participate in frequency and voltage regulations on a *best-effort* basis as we explain later in this section. For notational simplicity, we first define

$$\bar{\mathbf{P}} = [\bar{P}^1, \cdots, \bar{P}^H], \tag{8}$$

$$\bar{\mathbf{Q}} = [\bar{Q}^1, \cdots, \bar{Q}^H], \tag{9}$$

and

$$\mathbf{P} = [P^1, \cdots, P^H], \tag{10}$$

$$\mathbf{Q} = [Q^1, \cdots, Q^H]. \tag{11}$$

Note that $\mathbf{P}$ and $\mathbf{Q}$ are decision variables which are decided by the user based on the optimal solution of the following joint active and reactive power compensation problem:

$$\begin{aligned} \underset{\mathbf{P},\mathbf{Q}}{\textbf{minimize}} \quad & \lambda_F \left\| P - \bar{P} \right\| + \lambda_V \left\| Q - \bar{Q} \right\| \\ \textbf{subject to} \quad & \sum_{h=\alpha}^{\beta} P^h = E, \\ & -C^{\text{init}} - \sum_{s=1}^{h-1} P^s \leq P^h, \ \alpha \leq h \leq \beta, \\ & C - C^{\text{init}} - \sum_{s=1}^{h-1} P^s \geq P^h, \ \alpha \leq h \leq \beta, \\ & (P^h)^2 + (Q^h)^2 \leq S_{\max}^2, \ h = \alpha, \cdots, \beta. \end{aligned} \tag{12}$$

where $\lambda_F \geq 0$ and $\lambda_V \geq 0$ are constant parameters set by the grid to indicate the *relative importance* of freuqency and voltage regulation, resepctvely. The objective function in (12) has two terms. In the first term, $\|P - \bar{P}\|$ provides a measure for the deviation of the active power flow from the frequency regulation commands provided by the utility. In the second term, $\|Q - \bar{Q}\|$ provides a measure for the deviation of the reactive power flow from the voltage regulation commands. The constraints are simply the same as those in (4)-(7). Note that, to formulate problem (12), it is required that $\alpha \leq \beta \leq H$. Also, note that, problem (12) is a per user optimization problem and the objective function is related to each end users' electricity costs. Thus, each end user will be interested to to achieve the minimum electricity costs by solving problem (12) individually.

2) Day-ahead Price-Based Model: The day-ahead command-based model needs the grid operator knows the exact energy consumption pattern for each user so that the grid operator can distribute the target energy consumption profile to each end user. However, this may not be feasible in most cases. Therefore, we will introduce the day-ahead price-based model, which focuses on the aggregated behavior of all end users, instead of each single user. Using day-ahead pricing for active power is a common practice in certain regions. Fig. 3 shows an example for the day-ahead prices used by Illinois Power Company in Chicago area. In general, the price of electricity is higher at peak hours, encouraging users to shift their energy consumption to off-peak hours [32]. However, most existing reactive power pricing models are not on a day-ahead basis. Instead, they follow certain contracts between the grid and big commercial reactive power compensators. Nevertheless, day-ahead reactive power pricing has been considered in the literature, *e.g.,* in [33]. It also seems to be particularly promising to involve small reactive power providers such as PEVs. Such prices can be obtained using historical time-of-day data. Fig. 4 shows an example for day-ahead reactive power prices.

Next, let w_F^h and w_V^h denote the prices for active and reactive power at each hour h. Theoretically, the prices can take both positive and negative values. However, in practice,

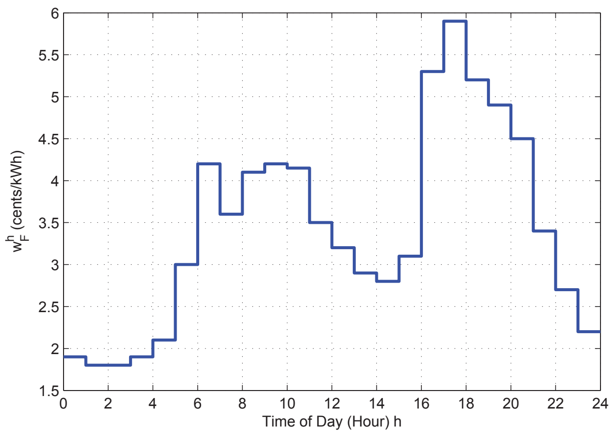

Fig. 3. Time-of-day prices for active power [30].

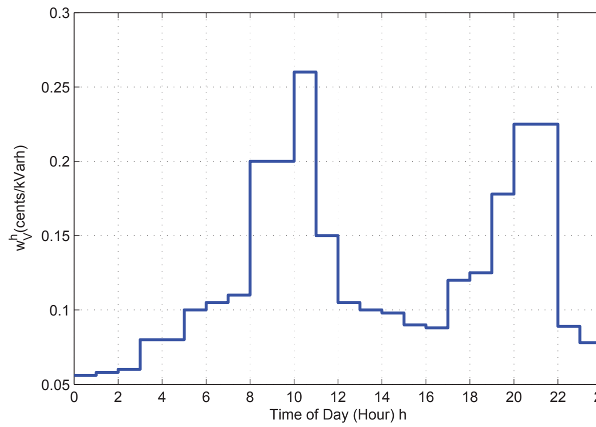

Fig. 4. Time-of-day prices for reactive power [33].

one would not expect to see negative prices for active power. Since reactive power compensation is mostly the matter of providing capacitor rather than inductor load, we can also assume only positive values for the reactive power prices as well. In this regard, the PEV-charger system operating is mostly limited to the two *lower* quadrants of the P-Q disc in Fig. 2. The day-ahead price-based joint active and reactive power compensation optimization problem can be formulated as:

$$
\begin{aligned}
\underset{\mathbf{P},\mathbf{Q}}{\textbf{minimize}} \quad & \sum_{h=\alpha}^{\beta} w_F^h\, P^h + \sum_{h=\alpha}^{\beta} w_V^h\, Q^h \\
\textbf{subject to} \quad & \sum_{h=\alpha}^{\beta} P^h = E, \\
& -C^{\text{init}} - \sum_{s=1}^{h-1} P^s \leq P^h, \quad \alpha \leq h \leq \beta, \\
& C - C^{\text{init}} - \sum_{s=1}^{h-1} P^s \geq P^h, \quad \alpha \leq h \leq \beta, \\
& (P^h)^2 + (Q^h)^2 \leq S_{\max}^2, \;\; h = \alpha, \cdots, \beta.
\end{aligned}
\tag{13}
$$

In this problem, the objective function is the user's total energy cost for both active and reactive power. Unlike the command-based model, in this case the utility's desired load or power injection are not directly indicated by the utility. Instead, utility chooses day ahead prices, and the user determines the power level accordingly. Finally, we note that both (12) and (13) are convex problems and can be solved using convex programming techniques such as the interior point method [34].

IV. Simulation Results

Next, we assess the performance of the proposed *combined frequency and voltage regulation* (CFVR) command-based and price-based methods introduced in Section III.

A. Day-ahead Command-based Model

As illustrated in Fig. 5, the sample target user active power consumption profile is obtained from [35] and the sample user's active power consumption without any scheduling is obtained from [32]. Note that in the sample user's active power consumption, there is a typical residential peak from 18:00 to 22:00. This is because people are back home and starting cooking or various recreation activities.

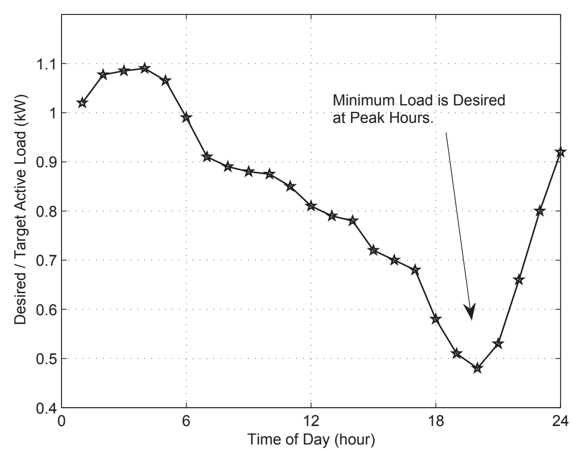

Fig. 5. An example target active power consumption level to be announced by utility / aggregator in a command-based CFVR system. The commands aim to push the load from peak hours to off-peak hours.

Fix $\lambda_F = 1$, then by solving problem (12), the trends between weight λ_V versus the minimum active power mismatch $\|P - \bar{P}\|$ and the minimum reactive power mismatch $\|Q - \bar{Q}\|$ are shown in Fig. 6. Obviously, by taking into account the real cost of handling the mismatch, based on Fig. 6 the grid operator can select λ_V properly to minimize the real cost.

B. Day-ahead Price-based Model

As references for comparison, to assess our proposed CFVR price-based method, we consider two different scenarios. First,

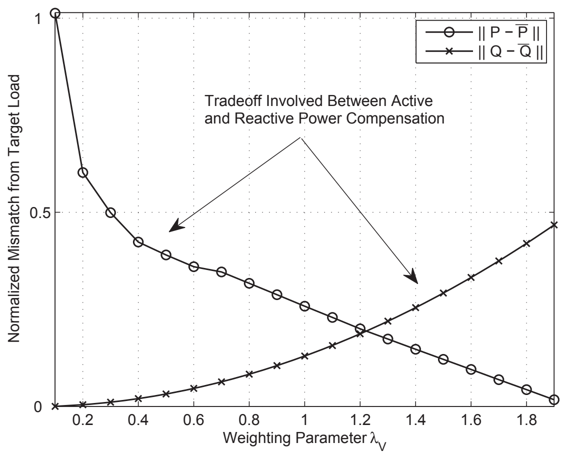

Fig. 6. Trends between λ_V versus the active power mismatch $\|P - \bar{P}\|$ and the reactive power mismatch $\|Q - \bar{Q}\|$.

the case where no voltage regulation is offered by PEVs, *e.g.,* as in [12], [13], [20]. We refer to this approach as *frequency regulation only* (FRO). Second, a heuristic *separate frequency and voltage regulation* (SFVR) method which works as we explain next. Assume that the optimal frequency regulation, obtained by [12], [13], [20] is given as P^h at each time slot h. The voltage regulation contribution in SFVR method is then simply obtained as

$$Q^h = \pm\sqrt{S_{\max}^2 - (P^h)^2}, \tag{14}$$

where the sign is set depending on whether the utility has asked for capacitive or inductive reactive power compensation. Note that the key difference between our proposed CFVR approach and the SFVR is that the former involves *joint* optimization of frequency and voltage planning while the latter only optimizes frequency regulation.

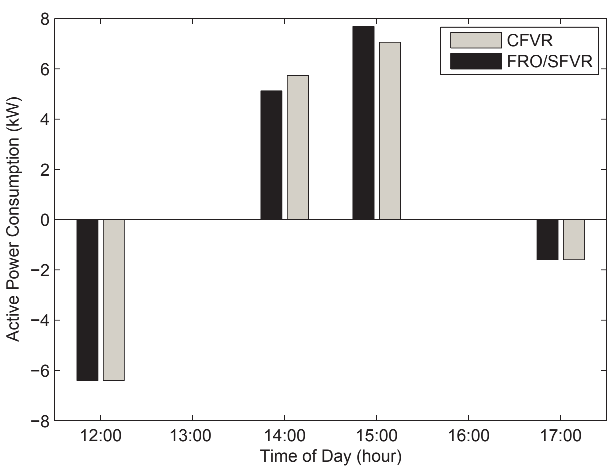

Fig. 7. Comparisons of active power scheduling profile among FRO, SFVR and CFVR using level 2 charging.

For the purpose of simulations, we consider a time frame of six hours from 12:00 to 17:00. Fig. 7 shows active power scheduling profile of FRO, SFVR, and CFVR using level 2 charging. Note that the charging levels are identical for FRO and SFVR methods. However, the results are very different for the proposed CFVR method. In fact, due to the proposed joint optimization approach, the CFVR sets the active power load such that the combined offering of voltage regulation in addition to frequency regulation service can lead to maximums savings in electricity charges as we will see next.

Recall that in a price-based scenario, The total electricity cost for the user is obtained as:

$$\sum_{h=\alpha}^{\beta} w_F^h \; P^h + \sum_{h=\alpha}^{\beta} w_V^h \; Q^h, \tag{15}$$

The detailed trend of the extra savings in the cost of electricity is shown in Fig. 8. We can see that in total using the proposed CFVR method can lead to saving an *extra* 16.4 cents per day due to *optimal* offering voltage regulation in addition to frequency regulation. This can accumulate to over \$5 monthly saving. Given the fact that offering voltage regulation regulation in the proposed setting has no depreciation impact on the PEV batteries and also since it does not require any major hardware implementation other than the same charging and discharging scheduling devices that are foreseen to be used by residential consumers for demand-side management, the observed savings are significant, suggesting that the proposed design can be of interest for many users in practice.

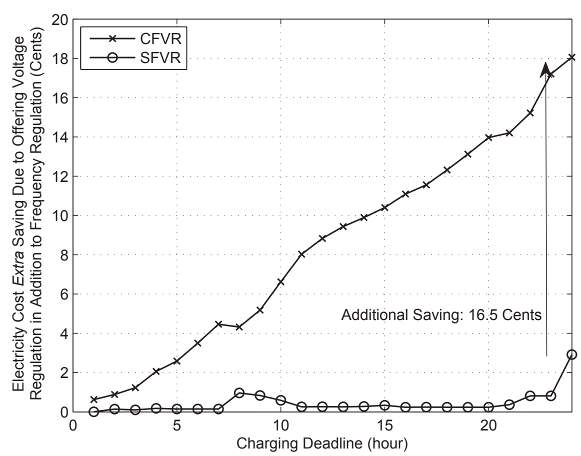

Fig. 8. Saved electricity costs v.s. charging deadline.

V. Conclusions

In this paper, we proposed two joint optimization problems, namely *day-ahead command-based* and *day-ahead price-based*, for combined offering of frequency and voltage regulation by PEVs. In this regard, three operating constraints with respect to the *maximal apparent power*, *charging deadlines*, and *battery capacity* were considered. The first constraint couples the active and reactive power while the latter two are applicable to active power only. The formulated optimization problems are convex and can be sloved via convex programming techniques. Simulation results revealed the trade-off involved and the advantages of combined frequency and voltage regulation offered by PEVs.

The results in this paper can be extended in several directions. For example, given the limited amount of reactive and active power that a PEV can contribute for frequency and voltagte regulations, the authors plan to study the more practical scenario where some aggregators [12] are deployed to coordinate the operation of several PEVs in terms of both active and reactive power compensation. In that case, the interactions among PEVs and the aggregator can be studied using game theory as in [7], [36], [37]. Finally, a better performance evaluation can be achieved via a testbed implementation such as the one in [35].

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