Vehicle-to-grid power system services with electric and plug-in vehicles based on flexibility in unidirectional charging

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(Invited)

***Abstract*—With proper power scheduling and dynamic pricing, a unidirectional charger can provide benefits and regulation services to the electricity grid, at a level approaching that of bidirectional charging. Power scheduling and schedule flexibility of electric and plug-in hybrid vehicles are addressed. The use of electric vehicles (EVs) as flexibility resources and associated unidirectional vehicle-to-grid benefits are investigated. Power can be scheduled with the EV charger in control of charging or via control by a utility or an aggregator. Charging cost functions suitable for charger- and utility-controlled power scheduling are presented. Ancillary service levels possible with unidirectional vehicle-to-grid are quantified using sample charging scenarios from published data. Impacts of various power schedules and vehicle participation as a flexibility resource on electricity locational prices are evaluated. These include benefits to both owners and load-serving entities. Frequency regulation is considered in the context of unidirectional charging.**

***Index Terms*—Demand response, electric vehicles, plug-in hybrids, unidirectional battery charging, utility dynamic price control, vehicle-to-grid.**

I. INTRODUCTION

BIDIRECTIONAL charging offers limited benefits to owners of plug-in electric vehicles compared to simpler unidirectional chargers. Bidirectional chargers add cost and metering complexity, and expose batteries to extra wear and tear. Presumably utility grid operators would support them, but the extra costs are hard to quantify and the benefits to the grid are not always clear. In this paper, it is shown that flexible scheduling applied to unidirectional chargers offers most of the same grid benefits without the extra costs. The term "vehicle-to-grid" (V2G) is used for these interactions. The presentation is based on an associated conference paper [1], combined with some operational details presented in [2]. For purposes of the paper, fully electric vehicles and plug-in hybrid vehicles are considered together as grid-interactive electric vehicles (EVs).

Flexible demand is relatively well understood for grid operations [3]. Even though V2G unidirectional equipment offers extensive benefits, most research has focused on bidirectional power flow as a means of deriving V2G benefits. These include active power regulation (frequency regulation), reactive power support (voltage regulation), and tracking the output of renewable energy sources [4-6]. Electric vehicles equipped with bidirectional flow capability have been demonstrated to provide ancillary services, including regulation, to the grid in real time. It is often asserted that bidirectional charging is a necessary capability for the full range of V2G services [7-8]. Kempton [9-10], used an EV to provide regulation services using real-time dispatch signals from the Pennsylvania-New Jersey-Maryland Interconnection (PJM). Depending on the type of signal received, the battery either charges or discharges. A team at the Technical University of Denmark [11] validated a range of ancillary services with a production Nissan Leaf charger. Although bidirectional capability is mentioned, the actual test results modulated unidirectional chargers. In [12], distributed controls are evaluated for high-performance grid regulation.

Bidirectional power flow is supported by many topologies and is not a technical barrier (see, for example, [13]), but in the context of vehicle charging it must overcome the following challenges:

1. The extra costs and safety management attributes associated with bidirectional grid-interactive chargers.
2. Battery degradation caused by stochastic bidirectional cycling [14].
3. Metering issues, protection, and bidirectional power flow management at the distribution level.
4. Hardware upgrades and bidirectional communication links.
5. Energy guarantees: the requirement that the end user ends a time sequence with a contractually obligated energy level in a battery pack.

In a unidirectional charging system, charger operation can respond to one-way grid signal such as real-time prices or specific economic incentives for flexibility. In the above list, only the energy guarantee remains, and it is simplified because

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energy will not be extracted during a charging sequence. The extra requirements imposed on bidirectional power flow are hard to overstate. Bidirectional chargers become distributed generators subject to interconnection standards [15], with requirements for anti-islanding, shutdown outside a narrow frequency and voltage range, and other attributes. Even though these challenges are well understood and have been resolved for distributed renewable energy [16], such chargers carry a cost premium.

With reasonable penetration of EVs, and active control of charging current, a unidirectional charger can meet almost all desired V2G benefits while avoiding cost, performance, standards, and safety concerns associated with bidirectional chargers. Even though work such as [17] discusses strategies to address battery pack energy demands in the context of bidirectional flow, an energy constraint means that full power control offers little advantage over unidirectional flow, as will be seen in this work. An EV charger with unidirectional power flow can participate in the electricity market as both a buyer of electricity and seller of flexibility or load curtailment. Load curtailment is a well-established market mechanism that can be extended. Research on unidirectional charging has involved developing optimal charging strategies by maximizing aggregator profits and investigating the impact on distribution networks [5], [18]. There have been a few publications exploring comprehensive benefits from coordinated unidirectional charging [19-20].

To quantify strategies that obtain V2G benefits with unidirectional power, this paper tests a few charging scenarios and penetration levels. One broad version of an optimization problem is explored. A positive charging-cost coefficient, by which an EV owner has incentives to charge at a relatively low power, is emphasized. Ways to enable vehicle owners to offer load flexibility are discussed. Charging scenarios are simulated based on a dataset of locational marginal prices (LMPs) from the New England Independent System Operator (ISO) [21]. EVs used for daily commuting are likely to be connected to the utility grid during work hours at a workplace, and via a home connection overnight [5].

II. EVs AS ENERGY LOADS WITH TIME FLEXIBILITY

A load with a specified energy need with no flexibility in quantity can be termed an "energy load." For bulk commercial loads and energy interchanges, it is common for the load-serving entity (LSE), in the form of a utility, to contract with a customer to support such a load. This is termed *firm demand* by regulators [22]. The LSE has an obligation to meet firm demand without a shortfall – the alternative is essentially a blackout or equivalent emergency situation in which total demand cannot be met. Conventional flexibility at the bulk level takes the form of a customer contract for *interruptible load* [22]. EV owners often express concern that this type of flexibility will lead to energy shortfall, but this should not be an issue if EV charging is linked to firm demand contracts instead.

The distinction of EVs compared to conventional load is *time* flexibility. During routine charging overnight or at work – with a long duration of grid connection -- an EV owner is likely to specify a certain amount of energy to be delivered by the end of a designated interval to meet driving energy needs. From the utility's perspective, no flexibility exists in the energy amount, but the inherent time flexibility can support ancillary services. In this paper, firm demand becomes an energy guarantee, and this is emphasized in the power-draw scheduling strategies presented. Time flexibility is plausible for unidirectional chargers.

Time flexibility has exceptions, but in practice none of these exceptions benefits from bidirectional power. One example is short-term *opportunity charging*, when a vehicle is connected for short intervals during a driving sequence. Often this can be linked to predictable locations, such as rest areas along major highways, or coffee shops offering charging services. In these cases, the driver seeks the highest possible energy transfer during a relatively brief stop. However, opportunity charging can command premium energy pricing and in many cases locations are predetermined. This combination is a benefit to utility operators and planners, since the extra cost of meeting this substantial point demand can be linked to local pricing. Bidirectional chargers would defeat the need for high energy exchange in a constrained time interval.

Another exception is fast charging (identified as *Level 3 charging* in the literature [2]). This represents the "electric filling station" application in which a vehicle seeks substantial energy in a very short time interval. This situation is fully constrained with respect to location – such stations would be located and provisioned according to utility best practice for intense local loads – and subject to special pricing. In fast charging, bidirectional power flow is counterproductive, so Level 3 chargers would not justify the extra costs of high-power multi-quadrant interfaces.

Active roadbed charging is another example in which bidirectional power is counterproductive, but in this application flexibility is more plausible. A driver is likely to seek a certain amount of stored energy at a specified location during a long trip, such as a destination highway exit. Both the power and time requirements may have some flexibility as the real-time power demand changes during an active drive cycle. The combination of unidirectional flow and limited flexibility for active roadways has been suggested in the literature [23].

The overall result is that flexibility for firm demand in EVs applies primarily to routine long-term connections at work, when parked overnight, or in urban daytime parking garages. These are associated with Level 1 and Level 2 charging scenarios [2]. Typically, Level 1 chargers are designed to support opportunity charging, and only Level 2 chargers are discussed for bidirectional operation. However, both levels can offer time flexibility. It is interesting to consider the impact if a vehicle-embedded unidirectional Level 1 or Level 2 charger is provided with operational intelligence. Such a charger could manage metering and seek out utility pricing and operating information. It could even negotiate billing. The vehicle itself could turn any electrical outlet into intelligent flexible infrastructure. This gives rise to the concept of *ubiquitous charging infrastructure* [24-25] since charging at any location and conventional electrical outlet would offer flexibility and energy delivery. Given constraints on distribution networks, this capability is not possible in general with bidirectional charging.

III. Charger-Controlled Power Scheduling

One suitable objective for a charger-controlled power-draw strategy is to minimize user energy costs. In the simplest case, a charger-controlled strategy can be based on price, subject to an energy guarantee. In more sophisticated strategies, the EV driver can alter priorities based on relative importance of a full battery pack and low energy cost. There are at least three forms of charger-controlled power draw scheduling strategies. In the first, the charger obtains cost from the utility – ideally for the next few hours – and adjusts to deliver the requested energy amount over the allotted time at the lowest total cost. This is useful only if real-time prices are communicated in advance. If not, the charger must use historic data or other information to predict expected prices, and can only minimize *expected cost* rather than actual cost. In the second, a more comprehensive cost function is formulated and used as the basis for charge optimization. In this case, the energy target can be weighted along with cost, thermal management, and other factors, and the charger can operate to minimize the total function. A third method is price-sensitive energy bidding. In this case, an EV owner with extra flexibility can bid for energy in a day-ahead market or a spot market. The amount of energy drawn depends on the price the EV owner is willing to pay. In the day-ahead case, the charger would follow an agreed schedule. Two of these strategies are developed in more depth below.

In these scenarios, flexibility is not being offered as a resource. The charging process instead is reactive to price, and price adjustment is the only means by which a utility can influence EV loads. Control capability is therefore limited. For example, a rate concept was tested in California with a low energy rate offered between midnight and 5:00 am for EV charging [26]. The result was an abrupt load increase at midnight that extended through 5:00 am. This can be a useful demand shifting strategy but does not address ancillary services.

A. Cost function-based charge operation

Cost function scheduling strategies make a grid-connected vehicle completely responsible for its power draw management, with only one-way pricing communication from the utility. With this strategy, the utility broadcasts pricing information, and the connected vehicle will schedule and implement its power draw in response. Typically, the cost function settings mean that a connected vehicle will charge at its maximum possible rate when electricity is cheapest. With significant penetration of EVs, the power draw seen by the grid could become large at times when electricity prices otherwise are lowest. Even with enough grid capacity to handle this aggregated load, there could be local feeder overloading issues. To avoid these issues, one alternative is highly localized price signaling. Another alternative is to augment pricing information with a demand charge, such that vehicles have economic incentive to limit the charging power accordingly. Adding a demand charge into an EV pricing structure can encourage time flexibility while still allowing the EV owner to recharge as desired.

To set up a cost function approach, an optimization procedure runs at the time of connection to determine an expected schedule. The optimization problem, when only energy cost is to be addressed, is given by

$$J = \min \sum_{k=h}^{H} C(P_k) \times (P_k \times \Delta t)$$
$$\text{such that } \sum_{k=h}^{H} P_k \times \Delta t = E_{des} \tag{1}$$
$$0 \le P_k \le P_{\max}$$

based on linear weightings

$$C(P_k) = C_k^{\,0} + \alpha_k \times P_k \tag{2}$$

and a retail rate

$$CC = C_k^{\,0} + \theta(P_k - P_0), \quad \{\theta = 0 \ \ \forall P_k \le P_0\} \tag{3}$$

Where:

J is the charging cost function;

α_k is the weight on hourly power draw at time k with units of cost per kilowatt;

C_k^0 is the base hourly price of electricity;

P_k is the scheduled power draw at time k;

P_0 is a utility-enforced charging rate threshold above which there is a demand charge;

Δt is the length of charging sub-period in hours;

P_{max} is the maximum charger power permitted (based on the outlet, a rating limit, or other predetermined limit);

h is a connection interval index;

H is the user set time for charging completion;

E_{des} is the desired total charger energy draw from the grid;

θ is the retail rate demand charge factor when $P_k > P_0$.

Notice that (1) is only causal if hourly prices are set in advance. If instead prices are adjusted at the beginning of each interval, the cost function must start with expected values for C(P) and θ, updated them with actual values as they become available. The constraints in (1) guarantee energy E_{des} subject to the maximum power transfer capability of the charger or outlet. Depending on electricity prices and load levels, charging can be done according to the cost function J given by (1). The cost function weight α in (2) will be set by the charger as a means of regulating its power demand at prevailing hourly prices. The factor θ in (3) penalizes power demand above a utility-enforced threshold. It should be noted that setting $\alpha=0$ in (2) implies no penalty for high charging rates, thus permitting the charger to draw maximum power at periods when the price of electricity is lowest.

Hourly pricing is emphasized as it is considered an efficient pricing strategy [27], and is conventional. This will allow an EV charging profile to align with prevailing system conditions resulting in economic benefits for the power system. Fig.1 illustrates a sample LMP profile, taken from an ISO New England location (4123) on July 21, 2016 [28]. The average is US$0.0282/kWh. A suitable EV pricing structure might use this LMP plus an extra markup to cover other costs. To make EV loads more predictable, a utility can compute hourly prices and demand charges or a day-ahead basis, and can simulate how chargers will respond to such signals.

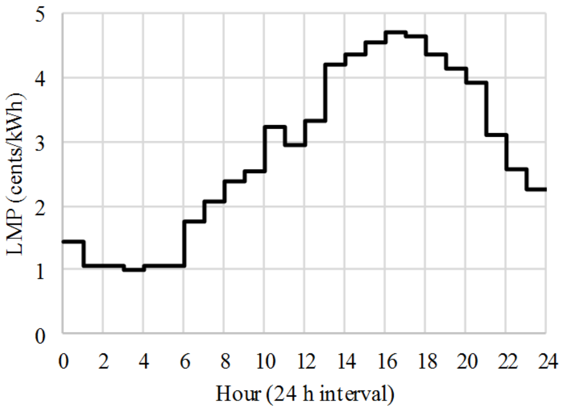

Fig. 1. Sample LMP profile, data from [28].

B. Price-sensitive energy bidding

In price-sensitive energy bidding, the EV owner (actually, the intelligent charger as a surrogate) bids for energy in the day-ahead market and locks in a price based on a preset schedule. This hedges against uncertainties in real-time spot markets, although it can be hard for an owner to predict energy needs even on a day-ahead basis to the extent that driving cycles are stochastic. In the nominal case, an EV owner bids for a price-energy schedule detailing the desired amount of energy to be purchased at specific price ranges and hours, similar to bulk industrial buyers. If the bid is higher than the market clearing price (MCP), the bid will be accepted and the vehicle will charge as planned and be billed as agreed; otherwise the bid will be rejected. An EV owner could choose to bid in subunits to reduce the chance of all bids being completely rejected, or could bid at an open price and accept whatever MCP emerges. The latter provides for an energy guarantee. The former methods offer possible lower costs in exchange for energy risk. At worst, an EV owner whose bids are rejected could accept the prevailing retail rate, which becomes a maximum price in Fig. 2, or draw based on real-time spot market prices.

The incentive for EV owners is that the day-ahead MCP is likely to be lower than spot market or retail rates. A successful bidder keeps the day-ahead prices even if spot prices in the real-time market are higher. An example is PJM's two-market settlement process [29], which could be applicable to EVs. Day-ahead bidding gives an EV owner complete responsibility for the quantity and price at which energy is bought. The flexibility attribute, as above, only exists in the sense of utility set points on prices and does not include ancillary services.

Fig. 2 shows a potential bid profile for an owner managing a cost-sensitive charging application from [1]. Here, ρ_{max} is the EV owner bid limit above which no energy would be delivered (ρ_{max} could be the retail price of electricity, for instance), E is the quantity of energy requested at ρ_{max}, E_{max} is the maximum energy request, and E_s is the energy shortfall when MCP = ρ_{max}. If the MCP is less than or equal to ρ_0, the maximum energy requested will be purchased. A price-sensitive bid process carries delivery risk and is relatively complicated for an individual vehicle owner. More likely, such a method would be employed by an aggregator, who would need to find other ways

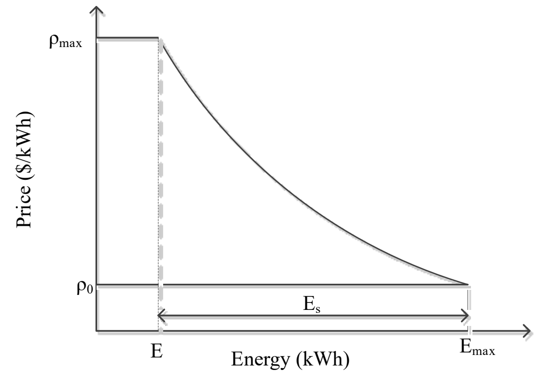

Fig. 2. Sample EV energy bid function [1].

to mitigate delivery risk. For an individual owner, the strategy is likely to become a "market price" bid in which the MCP is accepted when set, regardless of the amount. The vehicle itself will need sufficient intelligence to track bidding and anticipate energy requirements that would support a suitable day-ahead bid. In a real application, the charger will need to learn patterns and address day-by-day requirements. This is plausible given advances in machine learning, but is beyond the scope of this work.

IV. Gaining Ancillary Service Benefits

For suitable plug-in vehicles, energy usage is on the order of 200 W-h/mile [30]. However, the actual input power based on standardized tests and accounting for input-output battery inefficiencies is typically about 350 W-h/mi for present production vehicles [31]. Survey data indicate average daily driving (in the U.S.) of 29.2 miles (47.0 km) [32], typically split into at least two discrete trips, so the average daily usage is just over 10 kWh. This is substantial for a household load. For a dedicated 240 V, 30 A circuit loaded at 80% and with a tapering current to protect the batteries, 10 kWh recharge could be accomplished in as little as three hours. Even a 120 V, 20 A circuit loaded at 80% can draw this energy in less than eight hours. Since a majority of vehicles are parked most of the time [33], there is an opportunity for them to be connected from 8 to 15 hours a day. The difference between the time needed for recharging and the connection time is available for flexibility.

For the discussion here, the expectations is that the following are available:

1. The vehicle charger is adequately self-metered and can report its usage regardless of the location of the connection.

2. There is unidirectional real-time data, although intermittent and with limited bandwidth, from the utility.

3. There is non-real-time bidirectional communication between the vehicle and the utility, for usage, billing information, market information, and transaction requirements.

4. The charger is able to adjust its power draw to any positive level consistent with the local connection capacity, provided

the battery is not full.

5. The charger can adjust its reactive power demand, at least over a limited range.

6. The charger and connection meets power quality, safety, and other standards requirements.

Even though reactive power control implies two-quadrant operation in general, the system impact is distinct compared to a full four-quadrant bidirectional charger. Actually, it has been established that a modest reactive power control range is possible within power quality limitations even with a one-quadrant charger [2]. In [2], current harmonic distortion below 5% allows phase shifts up to ±8°. Since sin(8°) = 0.139, this means reactive power adjustment at almost 14% of the charger rating is possible even with a one-quadrant circuit.

A. Active power regulation

Active power regulation can be performed with a unidirectional charging EV by modulating its charging rate about a "preferred operating point" (POP) [5], [34] determined from (1). By varying the charge rate about this point, *regulation-up* and *regulation-down* service, the amount by which an EV can increase or decrease its charging rate from the POP can be performed. Regulation-up and-down dispatch signal should average zero over each charging sub-period [3] since an energy guarantee is to be enforced. A sample charging profile of an EV performing regulation services is illustrated in Fig. 3, from [1],

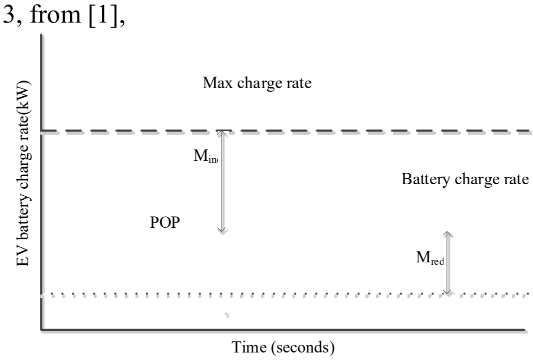

Fig. 3. Sample EV charging profile with power regulation [1].

Where M_{inc} is the contracted regulation-up capacity, M_{red} is the regulation-down capacity, and POP is the optimal scheduled charging rate for a given sub-period. The dashed lines must not exceed the maximum charge rate or fall below the POP while the dotted lines cannot exceed the POP or fall below zero. A negative power implies injection of power back into the grid and it explicitly avoided.

Obviously, a profile as in Fig. 3 is only possible when the battery is not full. This need for energy headroom is a requirement if a unidirectional charger is to provide active power regulation services. The LSE can adjust the total energy schedule to maintain headroom until near the end of the owner-specified interval, or can make use of load diversity among many connected vehicles to obtain headroom. In any case, an intelligent charger should be able to report its remaining energy requirement, and the headroom is predictable to the LSE.

Active regulation capacity is a factor in many utility markets. Regulation capacity payments can be considered as a revenue source to the customer when computing the net energy costs to a unidirectional charger. The active regulation total revenue is given by

$$r = \sum_{d=1}^{n} \sum_{k \in H} \rho^{d}_{cap,k} P^{d}_{reg,k} \Delta t \qquad (4)$$

Where $\rho^{d}_{cap,k}$ is the regulation market clearing price (RMCP) at hour k and on day d, $\rho^{k}_{reg,k}$ is the regulation capacity, n is the number of days considered (set to 365), H is the charging period and Δt is the time interval (one hour). For instance, with RMCP of \$0.02/kWh, an EV providing a 3 kW hourly active regulation capacity for a daily interval of five hours can generate annual customer-side revenue of almost \$110 [33].

B. Reactive power support and voltage regulation

Two-quadrant chargers, even when constrained to unidirectional power, can control current flow almost as desired, subject only to a modest local energy buffer resource. Typically, the buffer takes the form of a bus capacitor within the charger topology. A charger of this type can provide reactive support even if the batteries are full, provided only that the vehicles is connected. In the literature, the control issues have been studied in depth for bidirectional chargers [35], even though reactive power support can be controlled independent of power flow.

Given that even a one-quadrant charger can support some range of reactive power control, there are several ways in which conventional power-factor-corrected unidirectional chargers can participant in reactive power support. One of the simplest is a time-scheduled reactive power process, such as a charger supplying reactive power if connected during daytime hours and absorbing reactive power at night. Almost equivalently, the LSE could set up a desired power factor schedule on an hour-by-hour basis. A more sophisticated approach could have the LSE set up a voltage droop characteristic range for reactive power adjustment, or define an active local voltage regulation objective. The challenge in this context is that the nominal voltage is uncertain at the EV connection location, so the set point for zero reactive support is not clear. In any event, reactive power can be adjusted rapidly whenever a charger is connected and a battery pack is not full, so a unidirectional charger provides a fast-acting reactive power resource given suitable communication and control.

C. Market opportunities for energy flexibility

In addition to active regulation, unidirectional-charging EVs can participate in day-ahead markets the DAM by offering some energy flexibility in the form of load curtailment. For instance, an EV owner might be willing to accept 75% recharge on a particular day, especially if the LSE has requested support or reported an interval of high prices. The EV owner can request 100% recharge and offer 25% curtailment in the market at a particular price. If the offer is below the MCP, it is accepted and the EV becomes a demand-response resource (DRR). If the offer is rejected, then the full charge is delivered. Since the MCP in such a situation is linked to the most expensive generating unit used to meet demand in a particular interval, the owner may be able to save money with this strategy. During periods of high demand, the LSE could encourage this type of energy flexibility and create situations in which substantial numbers of EVs offer curtailment. In effect, this approach allows some energy to be shifted by a day or more if EV battery packs have adequate capacity.

The offer for an EV participating as a DRR in a sub-period k can be represented as a price-quantity pair (η, d). If the EV offering price η for load curtailment d is less than the MCP $(\eta < p_k^{'})$, the offer is accepted. The utility operator uses the supply curve to meet a new load $(D_k - d = D_k^{'})$ resulting in a price reduction of $p_k - p_k^{'}$, as shown in Fig. 4 from [1]. The total savings to the LSE is given by $(p_k - p_k^{'}) \times d$ and the DRRs are paid $d \times p_k^{'}$ for their curtailment efforts. Therefore, each kilowatt of demand pays an additional amount given by

$$\frac{p_k^{'}}{D_k^{'}} \times d \tag{5}$$

and the price to the LSE load is given by

$$\hat{p}_k = \left(p_k^{'} + \frac{p_k^{'} \times d}{D_k^{'}} \right) \$/_{kWh} \tag{6}$$

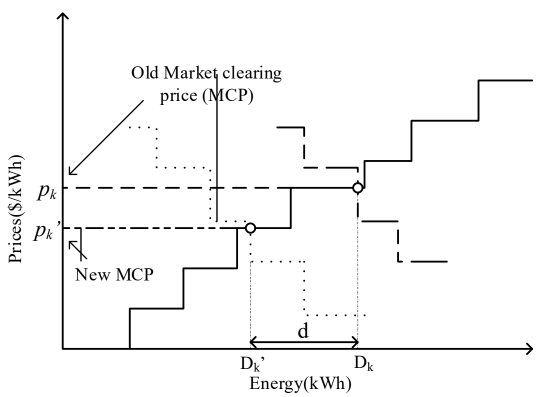

Fig. 4. Illustration of price decrease with load curtailment [1].

The impact of EVs offering partial curtailment in the day-ahead market can be strong when there is significant penetration, even though it the opportunity would not be expected to extend beyond a day or two. Thus, to study this impact, the EVs are treated in the aggregate and the combined load curtailment is bid into the day-ahead market with each vehicle sharing the revenue according to the magnitude of its curtailment.

V. Results

Scenarios simulated to show V2G benefits obtainable from an EV with a unidirectional charger are given below. The recent hardware validation in [11] is especially valuable here, since the authors of that work have tested many of the concepts directly.

A. Benefits of power flexibility to EV owners

To explore how a power-based pricing strategy can set up economic benefits for an EV owner, the annual charging cost for an EV whose charging-cost function is governed by (1) and (2) was explored based on a price profile scaled from the LMP profile in Fig. 1 and a flat retail rate of \$0.12/kWh. Each EV charging parameter is taken from Nissan Leaf specifications with a 24 kWh battery [36] that requires 20 kWh of energy each day. The maximum charging rate is set at 6.6 kW. For the purpose of this simulation, the ac current draw is limited to 27.5A. For the pricing structure, the coefficient α in (2) is adjusted from 0 to 100%, with α = 1 scaled into the cents per kilowatt range. Retail rate is charged when the demand is above 3.3 kW. The vehicle is connected daily from 9:00am to 5:00pm and from 9:00pm to 7:00am. The vehicle seeks 10 kWh during each of these intervals. In this case, no current tapering is considered, but instead energy is purchased in one-hour blocks adding to 10 kWh.

Fig. 5 shows the results for the daytime charging profile. The case α = 0 is equivalent to considering a pure hourly energy rate, with no pricing incentive to adjust power flow. As α increases, the EV owner has incentive to shift power draw to reduce costs. When α = 0, recharge cost is minimized simply by drawing power at the 3.3 kW threshold during the cheapest hours – in this case, 9am to noon – plus the final 0.1 kWh drawn between noon and 1:00pm. As α increases, the owner benefits by reducing the power during the cheapest hours and shifting it in time to other intervals. For instance, a small value of α = 0.25 cents/kW shifts energy from the 10:00am and 11:00am hours to the noon hour, with the degree of shift chosen to minimize total cost. When α = 1 cent/kW, there is economic incentive to spread out the energy draw much more; in this case the minimum energy draw is taken during the most expensive hour, 4:00pm to 5:00pm. The LSE has control over the coefficients in (2) and therefore the sensitivities of the charging action.

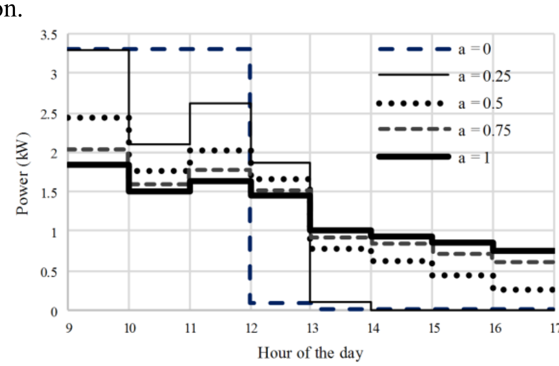

Fig. 5 EV daytime charging profile based on LMPs in Fig. 1.

Fig. 6 shows the night profile. As in the daytime case, a value of α = 0 means the lowest charging cost is accomplished by drawing the threshold power value during the cheapest hours. In this example, power will be drawn at 3.3 kW from 2:00am to 5:00am, and the final 0.1 kWh will be drawn between 5:00am and 6:00am. Since the price profile at night is flatter than during the day, higher values of α spread recharge energy across most of the night, and the α = 1 cent/kW case leads to a long duration of charging at about 1.3 kW. The scenarios in Figs. 5 and Fig. 6 correspond to vehicle use at roughly double the U.S. average, and therefore corresponding to about a 94 km one-way commute. The LMP profile in Fig. 1 shows that a customer with average needs (10 kWh total instead of 20 kWh) will have strong incentive to charge only at night. In both intervals, even an LMP with markup is likely to be cheaper than the retail electricity cost, so owners have incentive not to exceed the defined threshold power draw. The communication requirements are limited: hourly information on the base price and price coefficients.

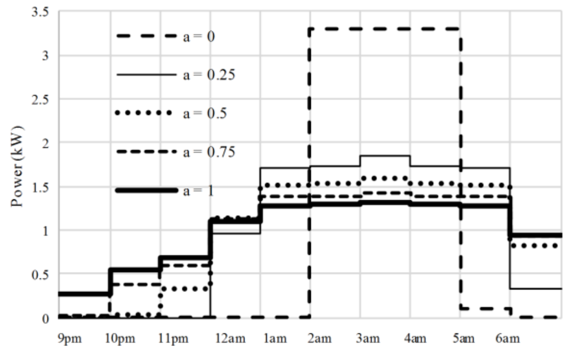

Fig. 6. Nighttime charging profile with power-sensitive pricing.

B. *Benefits to LSEs from EV power pricing*

The IEEE 118-bus system [37] is used as a power system test bed, with scaled EV loads added. It is tested here against an annual load profile shape shown in Fig. 7, which is scaled from 2009 data available on the New England ISO website [21]. In the test scenario, there are 118 aggregated sets of EVs with one set connected at each bus. EV penetration is evaluated at levels of 5%, 12% and 20% relative to the load energy at each bus. The EVs are connected at 9:00 am and disconnected at 5:00 pm every weekday throughout the year. Similarly, they are connected at 9:00 pm and disconnected at 7:00 am every weeknight throughout the year. Each EV requests 20 kWh daily (10 kWh during each charging interval). The optimal power flow formulation given in [38] and the power draw scheduling formulation given in (1) are used to find market clearing prices over the simulated year.

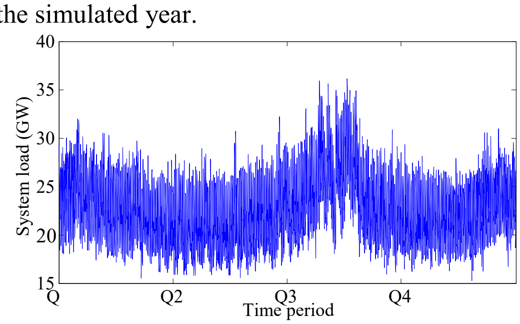

Fig. 7. System load over a full year, based on data from [21].

The MATPOWER OPF solver [39] is used to solve the optimal power flow problem to give the market clearing prices and load quantity. A value α = 0.1 cents/kW in (2) is set as a baseline. Fig. 8, from [1], illustrates the reduction in weighted LMPs to meet the total demand for the 118-bus power system model during each quarter of the simulation year for values α = 0.5 and 2 cents/kW. The LMP reduction represents potential system-level cost savings, as suggested in the figure. The magnitude highlights the impact of a power-sensitive charging schedule with substantial penetration of EVs as α increases above the baseline. In the third quarter, for instance, α = 2 cents/kW reduces the combined costs by about 7%.

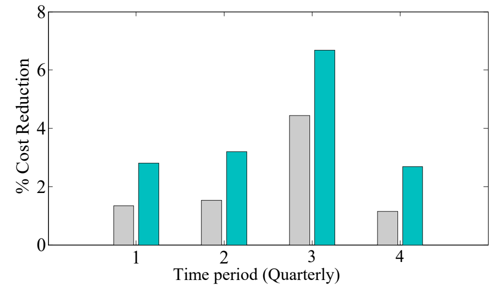

Fig. 8. Quarterly cost savings to LSEs with 20% penetration of EVs [1].

C. *Benefits to LSEs from EV energy flexibility*

If an EV owner can accept an energy shortfall in return for extra economic benefit, the LSE also benefits. Here, the impact on system combined LMP is investigated for various levels of curtailment. This case study considers only daytime charging from 9:00 am to 5:00 pm for a particular summer day, since load curtailment is likely to be more valuable under such a circumstance. Fig. 9, from [1], shows the impact of energy flexibility on system LMP at an EV penetration of 20% with daily curtailment levels of 10%, 20%, and 30%.

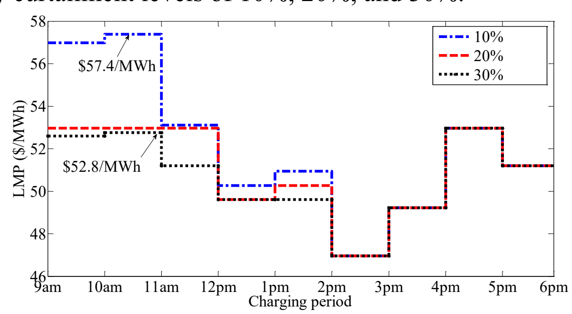

Fig. 9. Impact on LMPs at a 20% penetration [1].

From Fig. 9, a 30% load curtailment with a 20% EV penetration yields a 9% decrease in LMP, from $57 to $52 between 10: 00 am and 11:00 am, for this particular day. This is substantial given that it leverages 6% of the load. Notice that in this case, there is no impact after 2:00pm. In the scenario, the batteries have reached the intended state of charge by about 2:00pm, and further flexibility is not available. This can be remedied by increasing the value of α to spread charging more.

D. *Benefits to EV owners from energy flexibility*

A scenario in which an owner requests energy in two 10 kWh blocks each workday, all year (to support about 94 km per day) implies weekly consumption of 100 kWh and annual consumption of 5.2 MWh. Annual driving is about 24,400 km (about 15,000 miles). The relationship between LMPs and billing is complex, and varies daily. The LMP variation in Fig. 1 suggests that the utility might associate α = 0 with a daytime rate of about $0.10/kWh and a nighttime rate of about $0.05/kWh. To provide incentive, a value of α = 1 cent/kW might be set up by the LSE to result in approximately 20% savings below these values. Since half of the recharge is at night and half during the day, the end result is an annual usage of 2.6 MWh at $0.08/kWh and 2.6 MWh at $0.04/kWh. The total is US$312. For comparison, a similar vehicle attaining 24 miles/gallon in this commuting duty, with a fuel price of $2.50/gallon, costs US$1563 annually for fuel. The annual $312 energy cost provides a baseline for any additional savings or benefits.

An owner who does not require the full 20 kWh each day, and either can offer curtailment or can move some portion of charging from day to night, ultimately provides the LSE benefits shown in Fig. 9. By sharing these benefits between LSE and consumer, an additional savings of about 5% (in addition to any cost reduction either from reduced energy use or from shifting from day to night) can be attained by a customer with some energy flexibility.

E. Ancillary service for frequency regulation

Considering a charging profile on a typical day as illustrated in Fig. 3, the amount of regulation-up and -down capacity for different charging profiles can be evaluated. In this case study, three scheduled charging profiles corresponding to a plug-in hybrid with about 5 kWh of daily use, a small electric car with 20 kWh of daily use, and a heavily used electric delivery vehicle requiring 50 kWh each day. The daily usage does not necessarily reflect the battery size. The largest batteries in modern EVs do not require recharge energy much more than 10 kWh in average commuting duty. The vehicle-energy request parameters and charging levels are summarized in Table I. In this scenario, the vehicles are plugged in at 9:00 pm and are required to complete charging by 7:00 am the following day, allowing a 10 h charging period. The goal is to quantify the regulation capacity levels possible with these EV models. Dynamic regulation signals from PJM [29] are used to command the charger to increase or decrease its charging rate from the scheduled POP.

TABLE I
SAMPLE VEHICLE PARAMETERS

Vehicle type	Battery capacity	Maximum recharge rate	Workday energy request
Plug-in hybrid, short commute	8 kWh	1.5 kW	5 kWh
Electric car, long commute	24 kWh	6.6 kW	20 kWh
Delivery truck	60 kWh	14 kW	50 kWh

The charge schedule is obtained using the formulation of (1) with $\alpha = 2$ cents/kW. This is done to encourage flexibility in the charging duration, increasing the charge duration and the time when some battery capacity remains to support frequency regulation. Fig. 10, adapted from [1], shows a sample night profile on a day when the LMP is lowest between 1:00am and 2:00am (not the same as Fig. 1), for the 5 kWh need of the plug-in hybrid. The actual profile is derived from sample PJM regulation signals [29]. Obviously, a unidirectional charger can support power-based regulation only when the charger is active. For this vehicle, the LMPs between 9:00am and 11:00pm are too high to justify active charging during that interval. Also, during the cheapest hour there is little headroom below the specified 1.5 kW charge rate limit.

Fig. 11 shows a sample profile for the 20 kWh case from [1]. In this case, the value of α has been sufficient to spread out the charging process, and substantial regulation capability is attained through most of the connection time. Notice that the allowed variation declines noticeably after 5:00am, as the battery approaches full state of charge. The 50 kWh process result is not shown since it is similar, except in magnitude, to Fig. 11, plus somewhat more headroom in the last two hours.

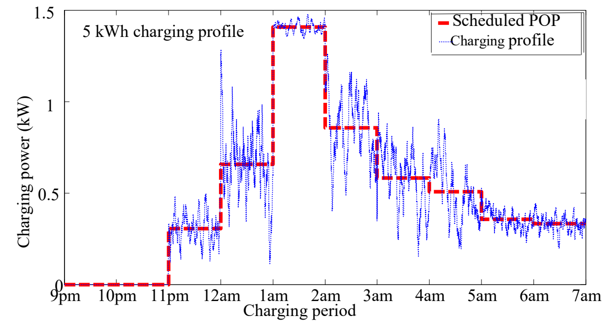

Fig. 10. Sample regulation profile during 5 kWh night recharge process [1]

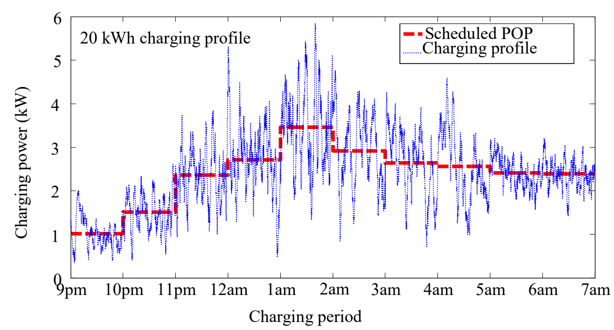

Fig. 11. Sample regulation profile during 20 kWh night recharge process [1].

It should be emphasized that the capacity of a unidirectional charging EV to perform regulation services depends on the magnitude of its energy request during each charging sub-interval and its charging power limit. Once fully charged, there is no power headroom to support frequency regulation services. Even so, as in Fig. 11, a suitable charge profile ensures that some capacity is available over the entire charging interval for regulation services. Notice that each profile avoids negative power values, but even so, a unidirectional charger can be used to support dynamic regulation. The communications aspects of frequency support are more complicated, even though in principle the charger can respond to local frequency fluctuations. It is essential to maintain the POP on average such that the intended total energy is delivered as required.

It is also important to recognize that power-based pricing is an important strategy. If the coefficients are set such that $\alpha = 0$, an EV owner has incentive to draw power at the limit during the cheapest hours, with no headroom for regulation, and with a charger that shuts down when it has drawn the intended energy. Fig. 12 shows a 20 kWh scenario with $\alpha = 0$, in which the charger is permitted to operate right up to its 6.6 kW limit. Only the last hour has any headroom for regulation services, in contrast to Fig. 11 for the same vehicle and energy requirement.

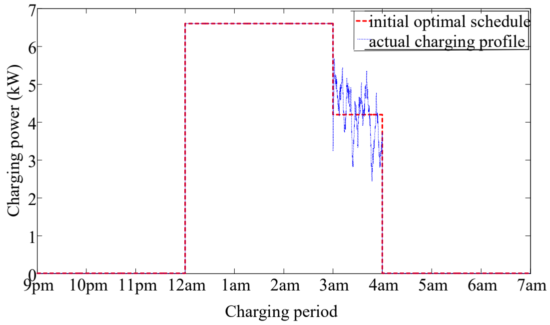

Fig. 12. Scenario with 20 kWh charging and α = 0.

F. Revenue from ancillary services

End-user revenue obtained from regulation services can be quantified by using published regulation capacity prices against the simulation scenarios in the previous section. For this purpose, four combinations of power limits and energy requests were considered. This case study is summarized in Table II. A simulation was run over an entire year, mapping LMPs and market regulation prices with charging operation based on α = 2 cents/kW. Eq. (4) was used to compute capacity payments to EV owners. Historical regulation capacity prices are obtained from the PJM interconnection [29]. Fig. 13, from [1], quantifies the annual revenue generated by the EVs for this simulation scenario. The result is not linear relative to the energy need – the 1.5 kW charger has less flexibility than the 6.6 kW charger and values of α have less impact at lower power. However, the 20 kWh case results in annual benefit of about US$140. Compare this to the estimated annual cost of US$312, and it represents a 45% decrease in outlay. The test cases for TABLE II do not include any energy risk: every day, the pack is charged fully as requested.

TABLE II
SAMPLE VEHICLE PARAMETERS

	E_{req}[kWh]	P_{max}[kW]	Time in	Time out
A	5	1.5	9pm	7am
B	10	3.3	9pm	7am
C	15	6.6	9pm	7am
D	20	6.6	9pm	7am

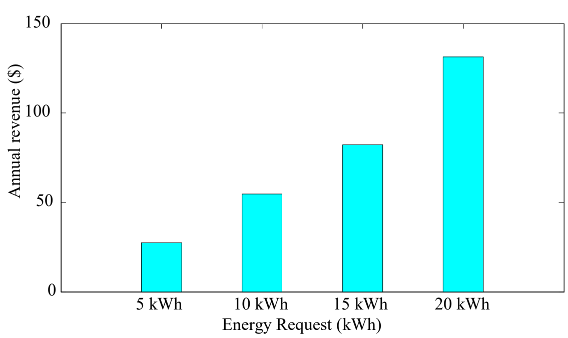

Fig. 13. Annual revenue from frequency regulation services, simulated scenario [1].

G. Reactive power services

Reactive power service valuations vary widely among system operators and utilities. The degree to which reactive power can be supported is linked to the charger topology and implementation details. For purposes of discussion here, consider an ideal power-factor-corrected one-quadrant charger. Even though in principle such a circuit is optimized for no phase shift between current and voltage, there is a tradeoff between phase shift and distortion as detailed in [2]. Per the discussion in section IV above, the practical limit is about 8°. Fig. 14 shows the reactive power capacity based on a maximum 6° phase shift (to allow some headroom) for the same charge profiles as for Figs. 9 and Fig. 10. For the 20 kWh case, the values are modest, but they do represent full control up to the limit shown. A two-quadrant charger with unidirectional power flow would not be subject to these limits, and the process could be more comprehensive [40].

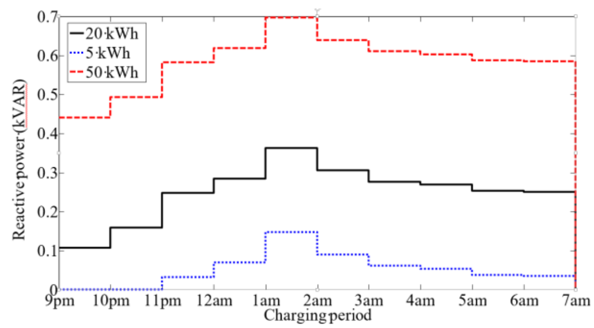

Fig. 14. Limits on reactive power capability based on power-factor corrected charger with a 6° phase shift limit.

VI. DISCUSSION

The results in this work suggest substantial V2G benefits to LSEs and EV owners with suitable power and energy scheduling. Even a basic linear power-aware pricing structure supports a range of capabilities, with the local charger able to carry out schedules with only basic cost information from the utility. The utility can encourage EV owners to participate in V2G programs in exchange for energy price breaks. Perhaps this is best accomplished with an aggregator having a contractual agreement stipulating terms and conditions to each EV owner, but price-aware chargers can perform the basic processes in the absence of an aggregator.

A. V2G Benefits: Unidirectional vs. Bidirectional

A bidirectional charger must support an energy guarantee (since EVs are energy loads) and the charging rate is limited by the battery. V2G ancillary services from bidirectional flow should be performed under optimized state of charge conditions, but in principle can be obtained whenever a vehicle is connected. Unidirectional V2G benefits are only obtainable from a charging battery, although it was shown that suitable power-linked pricing structures extend the charge duration. In the scenarios above, the 20 kWh unit with 6.6 kW limit presumably has maximum regulation capacity of 6.6 kW—the maximum allowed rate—when connected through a bidirectional charger. A summary from Fig. 11 suggests that a unidirectional charger and 20 kWh energy request has a maximum hourly regulation capacity of about 3 kW. This means that unidirectional EV charging penetration about twice the level of bidirectional EV penetration would be needed to match all of the ancillary service levels. Such an analysis is pessimistic, however. For a 20 kWh battery, a 6.6 kW regulation limit is a "three-hour" battery rate and relatively aggressive in terms of battery wear and tear. A limit on the order of six hours is much less stressful on typical batteries.

To account for the cost of battery degradation, a lithium-ion battery is expected to achieve up to one million cycles at 3% depth of discharge (DOD) [33]. According to [33], 3% DOD would be typical for regulation services. With a conservative cost estimate of $200/kWh, battery degradation can be estimated using cost equations in [33] to be $0.007/kWh. This results in about $165/year in degradation cost, offset by the income in Fig. 13. Even if the income can double with heavier use of a bidirectional charger, the battery degradation cost is more than the extra income. The "benefits" of a birectional charger become even more negative when extra metering and installation issues are considered. It should also be emphasized that bidirectional power flow on its own adds little economic benefits to the LSEs. During the charging phase, a bidirectional charger is subject to the same power draw scheduling schemes discussed previously with the same cost savings as that achieved with a unidirectional charger. Any discharge must be made up with additional load power. In summary, bidirectional power flow is not a necessary requirement to support V2G services, and unidirectional chargers are generally sufficient.

B. Additional validation

The discussion here emphasizes simulation studies, but developed from actual load and LMP data from independent system operators. The work in [11] provides ancillary service validation. The public database in [41], used extensively in [42] and [43], offers an opportunity to extend this work. There is additional discussion in [44].

VII. Conclusion

In this paper, power-based pricing and scheduling strategies, and potential V2G benefits that can be obtained from unidirectional EV chargers were explored. The use of an efficient price schedule to incentivize owners to respond according to prevailing power system conditions in the simulation model shows significant cost savings that would encourage V2G participation. From the LSE's perspective, an appropriate scheduling strategy results in significant cost savings to serve the system load. Key aspects are the development of a scheduling strategy and quantification of the ancillary service levels available to vehicles with varying battery capacity. The results showed significant regulation service capacity over long periods when charging is spread over time. This was enforced using the charging cost function and pricing strategy. An EV requesting to charge at its maximum for a short time has a significantly less ancillary service capability than one willing to offer some flexibility in the charging schedule. The cost savings associated with offering charging flexibility would encourage EV owners to do so.

References

[1] M. A. Fasugba, P. T. Krein, "Cost benefits and vehicle-to-grid regulation services of unidirectional charging of electric vehicles," *in Proc. IEEE Energy Conversion Congress*, 2011, pp. 827-834.

[2] M. A. Fasugba, P. T. Krein, "Gaining vehicle-to-grid benefits with unidirectional electric and plug-in hybrid vehicle chargers," *in Proc. IEEE Vehicle Power and Propulsion Conference.*, 2011.

[3] A. Brooks, E. Lu, D. Reicher, C. Spirakis, and B. Weihl, "Demand dispatch," *IEEE Power and Energy Magazine*, vol. 8, no. 3, pp. 20 –29, May-June 2010.

[4] S. B. Peterson, J. F. Whitacre, and J. Apt, "The economics of using plug-in hybrid electric vehicle battery packs for grid storage," *J. Power Sources,* vol. 195, no. 8, pp. 2377–2384, 2010.

[5] E. Sortomme and M. El-Sharkawi, "Optimal charging strategies for unidirectional vehicle-to-grid," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 131–138, 2011.

[6] S. Han, S. Han, and K. Sezaki, "Development of an optimal vehicle-to-grid aggregator for frequency regulation," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 65–72, 2010.

[7] G. Buja, M. Bertoluzzo, and Christian Fontana, "Reactive power compensation capabilities of V2G-enabled electric vehicles," *IEEE Trans. Power Electronics*, to appear 2017.

[8] M.I. Milanés-Montero, M.A. Guerrero Martínez, Eva González-Romera, E. Romero-Cadaval, F. Barrero-González, "Active and Reactive Power Control Strategies for Electric Vehicles in Smart Grids," in *Proc. 2016 10th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, 2016, pp. 114–119.

[9] W. Kempton, J. Tomic, "Using fleets of electric-drive vehicles for grid support," *J. Power Sources,* vol. 168, no. 2, pp. 459–468, 2007.

[10] W. Kempton, S. Letendre, "Electric vehicles as a new power source for electric utilities," *Transportation Research*, vol. 2, no. 3, pp. 157–175, 1997.

[11] K. Knezovic, S. Martinenas, P. B. Andersen, A. Zecchino, M. Marinelli, "Enhancing the Role of Electric Vehicles in the Power Grid: Field Validation of Multiple Ancillary Services," *IEEE Trans. Transportation Electrification*, to appear 2017.

[12] T. N. Pham, H. Trinh, L. V. Hien, "Load Frequency Control of Power Systems With Electric Vehicles and Diverse Transmission Links Using Distributed Functional Observers," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 238-252, 2016.

[13] N. Tashakor, E. Farjah, T. Ghanbari, "A Bidirectional Battery Charger With Modular Integrated Charge Equalization Circuit," *IEEE Trans. Power Electronics*, vol. 32, no. 3, pp. 2133-2145, 2017.

[14] S. B. Peterson, J. Apt, and J. F. Whitacre, "Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilzation," *J. Power Sources*, vol. 195, pp. 2385–2392, 2010.

[15] "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," IEEE Std 1547, July 2003.

[16] A. Brooks, S. H. Thesen, "PG&E and Tesla Motors: Vehicle to grid demonstration and evaluation program," *in Proc. 23rd Electric Vehicle Symp.*, 2007.

[17] H. Liu, Y. Yang, J. Qi, J. Li, H. Wei, P. Li, "Frequency droop control with scheduled charging of electric vehicles," *IET Generation, Transmission & Distribution,* vol. 11, no. 3, pp. 649-656, 2017.

[18] S. Acha, T. C. Green, and N. Shah, "Effects of optimized plug-in hybrid vehicle charging strategies on electric distribution network losses," in *Proc. IEEE Transmission and Distribution Conference and Exposition*, 2010.

[19] N. Z. Xu, H. Huang, C.Y. Chung, "A Comprehensive Framework for Unidirectional Vehicle-to-Grid Regulation Services," i*n Proc. 2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference*, 2014.

[20] N. Rahbari-Asr, M.-Y. Chow, J. Chen, R. Deng, "Distributed Real-Time Pricing Control for Large-Scale Unidirectional V2G with Multiple Energy Suppliers," *IEEE Trans. Industrial Informatics*, vol. 12, no. 5, pp. 1953-1962, 2016.

[21] The New England ISO 2010 [Online]. Available: http://www.iso-ne.com/marketshst_rpts/hstRpts.do?category=Hourly

[22] NERC Glossary. [Online] Available: http://www.nerc.com/files/glossary_of_terms.pdf.

[23] G. A. Covic, J. T. Boys, "Modern Trends in Inductive Power Transfer for Transportation Applications," *IEEE J. Emerging Selected Topics Power Electronics*, vol. 1, no. 1, , pp. 28-41, 2013.

[24] P. T. Krein, "Fundamental Challenges in Transportation Electrification, from Aircraft to Watercraft and Everything in Between," *presented at the IEEE Transportation Electrification Conference*, 2015.

[25] F. Pawlitschek, K. Hechtfischer, "Mobile Metering, Ubiquitous Smart Charging of Electric Vehicles Made Affordable," 9/1/2015, [Online] Available: http://aqtr.com/association/actualites/mobile-metering-ubiquitous-smart-charging-electric-vehicles-made-affordable

[26] N. DeForest, J. Funk, A. Lorimer, B. Ur, I. Sidhu, P. Kaminsky, B. Tenderi, "Impact of Widespread Electric Vehicle Adoption on the Electrical Utility Business – Threats and Opportunities," University of California Berkeley, Center for Entrepreneurship & Technology (CET), Technical Brief Number: 2009.5.v.1.1. Revision Date: August 31, 2009, p. 11.

[27] S. Braithwait, D. Hansen, and M. O'Sheasy, "Retail electricity pricing and rate design in evolving markets," Edison Electric Institute, Tech. Rep., 2007.

[28] ISO New England data, hourly LMPs by location, [Online], Available: http://www.iso-ne.com/isoexpress/web/reports/pricing/-/tree/lmp-by-node.

[29] PJM Interconnection 2010 [Online], Available: http://www.pjm.com/ -markets-and-operations/¬ancillary-services/-mkt-based-regulation.aspx

[30] Philip T. Krein, Timothy G. Roethemeyer, Robert A. White, Brandon R. Masterson, "Packaging and Performance of an IGBT-Based Hybrid Electric Vehicle," in *Proc. 1994 IEEE Workshop on Power Electronics in Transportation*, pp. 47-52.

[31] "GM tweaks battery materials, pack size, SOC window to increase 2013 Chevrolet Volt EV range to 38 miles" June 7, 2012, Green Car Congress, [Oline], Available: http://www.greencarcongress.com/2012/06/2013volt-20120607.html.

[32] "New Study Reveals When, Where and How Much Motorists Drive," April 16, 2015, AAA Foundation for Traffic Safety and the Urban Institute, [Oline], Available: http://newsroom.aaa.com/2015/04/new-study-reveals-much-motorists-drive/.

[33] W. Kempton and J. Tomic, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," J. Power Sources, vol. 144, no. 1, pp. 268–279, 2005.

[34] R. A. Alonso, "Impact assessment of plug-in electric vehicles in power system regulation and control," Master's thesis, University of Illinois at Urbana-Champaign, 2007.

[35] M. Kesler, M. C. Kisacikoglu, L. M. Tolbert, "Vehicle-to-Grid Reactive Power Operation Using Plug-In Electric Vehicle Bidirectional Offboard Charger," *IEEE Trans. Indus. Electronics*, vol.61, no. 12, pp. 6778- 6784, 2014.

[36] Nissan zero emission website 2011 [Online]. Available: http://¬www.nissanusa.com/¬leaf-electric-car/¬index#/¬leaf-electric-car/¬specs-features/¬index

[37] Data for the IEEE 118 bus test system ia, [Online], Available: http://www2.ee.washington.edu/research/pstca/pf118/pg_tca118bus.htm.

[38] A. S. Kowli, "Assessment of variable effects of systems with demand response resources," Master's thesis, University of Illinois at Urbana-Champaign, 2009.

[39] R. D. Zimmerman and C. E. Murillo-Sanchez, MATPOWER 4.0, Mar. 2011.

[40] W. Choi, W. Lee, B. "Sarlioglu, "Reactive power control of grid-connected inverter in vehicle-to-grid application for voltage regulation," in *Proc. 2016 IEEE Transportation Electrification Conference. (ITEC)*.

[41] "evCloud" public dataset, British Columbia, Canada, [Online], Available: http:/www.fleetcarma.com/evCloud/About.

[42] E. Yao, V.W.S. Wong, R. Schober, "Robust Frequency Regulation Capacity Scheduling Algorithm for Electric Vehicles", *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 984-987, 2016.

[43] E. Yao, V.W.S. Wong, R. Schober, "Optimization of aggregate capacity of PEVs for frequency regulation service in a day-ahead market," *IEEE Trans. Smart Grid*, to appear, 2017.

[44] M. Fasugba, "Power draw scheduling of electric and plug-in hybrid electric vehicles with unidirectioanl vehiucle-to-grid benefits," M.S. thesis. Technical Report CEME-TR-2011-4, and UILU-ENG-2011-2508, University of Illinois at Urbana-Champaign Engineering Documents Center, July 2011.

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