Deploying Power Grid-Integrated Electric Vehicles as a Multi-Agent System

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ABSTRACT

Grid-Integrated Vehicles (GIVs) are plug-in Electric Drive Vehicles (EDVs) with power-management and other controls that allow them to respond to external commands sent by power-grid operators, or their affiliates, when parked and plugged-in to the grid. At a bare minimum, such GIVs should respond to demand-management commands or pricing signals to delay, reduce or switch-off the rate of charging when the demand for electricity is high. In more advanced cases, these GIVs might sell both power and storage capacity back to the grid in any of the several electric power markets — a concept known as Vehicle-to-Grid power or V2G power.

Although individual EDVs control too little power to sell in the market at an individual level, a large group of EDVs may form an aggregate or coalition that controls enough power to meaningfully sell, at a profit, in these markets. The profits made by such a coalition can then be used by the coalition members to offset the costs of the electric vehicles and batteries themselves. In this paper we describe an implemented and deployed multi-agent system that is used to integrate EDVs into the electricity grid managed by PJM, the largest transmission service operator in the world. We provide a brief introduction to GIVs and the various power markets and discuss why multi-agent systems are a good match for this application.

Categories and Subject Descriptors

I.2.11 [**Distributed Artificial Intelligence**]: Multiagent systems

General Terms

Algorithms, Design, Performance, Experimentation

Keywords

Coalition formation, Vehicle-To-Grid, Grid-Integrated-Vehicle, Power Regulation

1. INTRODUCTION

Cite as: Deploying Power Grid-Integrated Electric Vehicles as a Multi-Agent System, Sachin Kamboj, Willett Kempton and Keith S. Decker, *Proc. of 10th Int. Conf. on Autonomous Agents and Multiagent Systems – Innovative Applications Track (AAMAS 2011)*, Tumer, Yolum, Sonenberg and Stone (eds.), May, 2–6, 2011, Taipei, Taiwan, pp. 13-20.

Plug-in Electric Drive Vehicles (EDVs), i.e. vehicles that use electricity to power at least part of their drivetrains, are becoming increasingly popular and offer some distinct advantages over their gasoline counterparts: they are cheaper to drive per-mile, produce fewer tailpipe emissions and have lower maintenance costs when compared to conventional gasoline vehicles. Grid-Integrated Vehicles (GIVs) are plug-in Electric Drive Vehicles (EDVs) with power-management and other controls that allow them to respond to external commands sent by power-grid operators, or their affiliates, when parked and plugged-in to the grid. Electric utilities and grid operators are interested in integrating EDVs into the electricity grid, instead of treating them as traditional dumb loads, because:

1. Since EDVs run on electricity, a large penetration of EDVs in the market is likely to increase the demand for electricity. Grid operators are concerned that this increased demand might result in an increase in the peak load, which would require them to add additional power generation capacity to the grid [5, 7]. However by using Demand-Side Management commands or pricing signals the grid operators might be able to delay, reduce or switch-off the rate of charging when the demand for electricity is high and push the EDVs to charge during non-peak hours [18]. This would not only reduce the need for new investments but also result in better utilization of the existing power grid.
2. Electric utilities are increasingly diversifying their generation portfolio by adding large quantities of renewable energy resources in order to mitigate climate change and to reduce our dependence on fossil fuels. These resources of electricity, like wind and solar power, are "intermittent" in that the instantaneous power output of these resources depends on the environmental conditions, such as wind speed, at any given time. To match the instantaneous power output of these resources with the instantaneous power demand, the electricity grid needs some form of storage capacity. However, our current electricity grid has a negligible amount of storage capacity, primarily associated with hydro-electric facilities.

   Since most vehicles are parked over 90% of the time, these EDVs can be used as a large distributed battery and can provide power storage and ancillary services to the electricity grid when they are not being driven. This concept is known as Vehicle-To-Grid power or V2G power [11, 12]. Although individual EDVs control too little power to sell in the market at an individual level, a large group

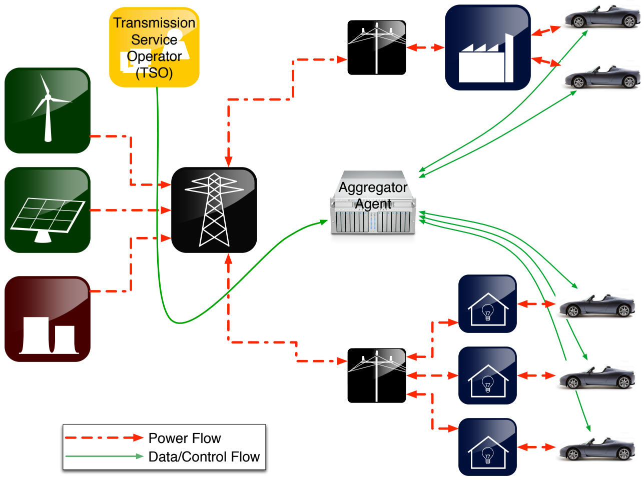


Figure 1: A simplified schematic of the power flow and data flow amongst the entities and agents in our implemented system

of EDVs may form an aggregate or coalition that controls enough power to meaningfully sell, at a profit, in the various electricity markets (See Section 2).

In exchange for integrating with the power grid, the EDV owners would be paid for the power services that they provide and this money can be used to offset or partially subsidize the high cost of the batteries in these EDVs. This in-turn might help to accelerate the adoption of EDVs by price conscious consumers.

In this paper we describe an implemented and deployed multi-agent system that is used to integrate EDVs into the electricity grid managed by PJM. PJM is a Transmission System Operator (TSO)[1] that is responsible for (a) maintaining the security, integrity and reliability of the power grid; and (b) operating wholesale energy markets that enable the transfer of power between the market buyers (consumers) and market sellers (providers). PJM is the largest TSO in the world, servicing 13 states and 51 million customers in the northeastern and midwest United States.

We decided to use a multiagent system because

1. In this system we are dealing with different individuals, systems and entities all of which are self-interested and often have conflicting goals. For example, the TSOs are primarily concerned with the stability and integrity of the grid, while the drivers of the cars are more interested in ensuring that there is sufficient charge in their batteries for whatever trips they are planning to take. These two goals might conflict with each other.
2. Various research topics in multiagent systems, like coalitions, auctions and electronic markets are directly applicable to this problem and offer a way of modeling the EDVs and the power markets that they can operate in.

Our implemented system is able to successfully integrate a group of EDVs into the power grid and is able to provide both demand-side management and V2G services. We have tested the first phase of the system with 5 EDVs in the PJM TSO providing services in the regulation market. In the next phase, we are using what we have learned to integrate an additional 20 EDVs with plans for an additional 50 EDVs in Phase III.

The outline of the rest of this paper is as follows. In Section 2, we describe the different types of power markets and their suitability for EDVs. Then in Section 3 we describe the agents that form our multiagent system and discuss implementation details. Section 4 describes how coalition formation for EDVs is different from the existing work on the topic and Sections 5 and 6 discuss our evaluation, conclusion and future work.

2. POWER MARKETS

There are a large number of different power markets run by the TSOs, each with a different set of rules and minimum requirements for participation. But generally, power markets can be classified into four distinct types based on the kind of power provided:

1. **Baseload Power:** The baseload power market is for the power that must be provided round-the-clock, usually at low costs per kWh. This kind of power is usually provided using large nuclear, coal-fired, hydroelectric and natural-gas power plants. EDVs are unsuitable for providing baseload power because (a) EDVs have very limited battery and power capacities; and (b) most EDVs are net consumers of power, i.e. they don't actually produce electrical power — they simply store power in the batteries.
2. **Peak Power:** Peak power is generated and purchased at times of exceptionally high demand, usually on hot summer afternoons. Peak power is typically provided by gas generators that can be switched on and off for shorter periods of time, usually 3–5 hours. Whereas EDVs with V2G capabilities might be able to provide peak power, the battery capacities might limit the amount of power that can be economically provided. See [10] for more details.
3. **Spinning Reserves:** Spinning reserves refers to generators that are available to serve the load in case of unplanned events like generator or transmission line failures. They are called spinning reserves because the generators are kept "spinning" and synchronized to the grid so that they are readily available when needed. Since spinning reserves are designed for contingencies, they are rarely used. They might be used 10–20 times a year and even then for durations ranging from 10 minutes to an hour. Furthermore, spinning reserves are paid for the duration they are available even if they are never used.

   EDVs with V2G capabilities are highly suited for providing spinning reserves because (a) EDVs can react quickly to contingencies when needed — they can provide power within a couple of seconds when requested and do not need to be kept "spinning" like traditional generators. They just need to be parked and plugged into the grid; and (b) since spinning reserves are rarely called into operation, it does not affect the battery lifetime as much participating in some of the other markets might do.
4. **Regulation:** Regulation power is used to regulate frequency and voltage on the grid by matching the instanta-

[1]Alternatively known as an Independent System Operator (ISO) or a Regional Transmission Organization (RTO). We use the term TSO throughout this paper but other papers might use ISO or RTO to refer to the same entity.

neous power supplied by the grid with the instantaneous power demand. To provide regulation services and to participate in the regulation market, the participants (typically generators, but in our case, EDVs) must respond to a frequent real-time AGC (Automatic Generation Control) signal sent by the TSO every 2–4 seconds.

There are two types of AGC or regulation signals — (a) *Regulation-Up* signals are sent whenever the demand for power exceeds the supply and are used either to request additional power from the generators/EDVs (i.e. increase the supply) or to switch off some load (i.e. reduce the demand); and (b) *Regulation-Down* signals are sent whenever the supply for power exceeds the demand and are used either to decrease the output of the generators or to increase the load.

To participate in the regulation market, the regulation service providers must first advertise a regulation capacity. This advertisement usually takes the form of a bid in an hourly auction. If the bid is accepted, the regulation providers must respond to the request for specific amounts of power from the TSO.

Some TSOs have separate markets for regulation-up and regulation-down and generators may bid in either one or both of these markets at the same time since the two will never be requested simultaneously.

EDVs are particularly suited to provide regulation power because (a) the batteries in the EDVs can respond very quickly to changes in the regulation request — much faster than traditional generators; and (b) EDVs can participate in the regulation market even if back-feeding of power (i.e. discharging the batteries and providing power back to the grid) is disallowed, by varying the rate at which the batteries are being charged (i.e. by varying the demand.)

For our system, we decided to focus on the regulation market because (a) regulation services command the highest value in the market when compared to other ancillary (for example, spinning reserves) and non-ancillary (for example, peak power) services; (b) EDVs are particularly suited for providing regulation services as discussed above; and (c) the size of the regulation market is larger than the size of the spinning reserve market, so even a large number of EDVs are unlikely to saturate the market.

We worked closely with PJM Interconnection to allow our EDVs to provide regulation services in the PJM TSO. PJM requires a 1MW minimum capacity to bid in the regulation market and requires symmetric advertisements. See Section 3.2 for more details about fulfilling these market requirements. For more information about the PJM market rules, see [3, 19].

3. IMPLEMENTATION

Our agents have been implemented using the JADE (Java Agent DEvelopment Framework) open-source framework [2]. Our system consists of the following agents:

3.1 VSL Agents

The VSL agents run on an embedded linux computer, called the Vehicle Smart Link (VSL), inside the cars. *The VSL agents look after the best interests of the owner or driver of the car.* Since the primary purpose of an EDV is to be driven, the primary goal of a VSL agent is to ensure that there will always be sufficient charge in the EDVs for whatever trips the driver might want to take. The secondary goal of the VSL agent is to integrate the EDV into the power grid, sell grid services and make money for the driver. We will look at both of these goals below.

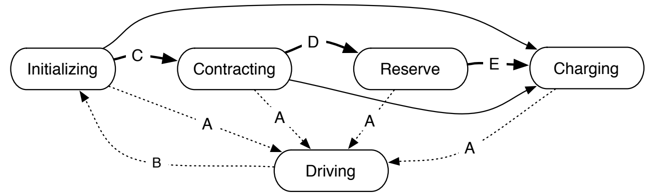


Figure 2: A simplified finite state machine for the VSL agent. The dotted arrow are actions performed by the driver of the EDV and are outside the control of the VSL agent. The dark arrows show the usual progression of state transitions.

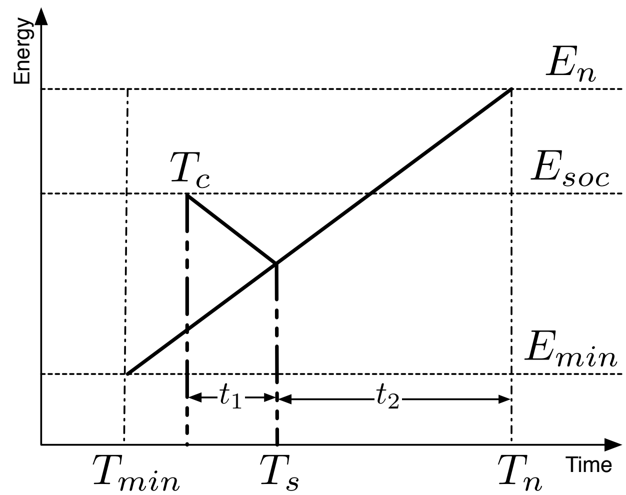


Figure 3: Computing T_s, the time to switch to V2G-monitoring mode

The operation of this VSL agent is based on the simplified finite state machine (FSM) shown in Figure 2. In this FSM, the dark arrows show the usual progression of state transitions.

The VSL agent starts out in the *Initializing* state — in this state the VSL agent tries to discover coalition servers servicing the geographic location where the EDV is plugged in. It also predicts the next trip, either by looking it up in the owner's calendar or by predicting it based on the past driving behavior[2].

The VSL agent then computes various times for switching between the *Contracting*, *Reserve* and *Charging* states, shown by the transitions *C*, *D* and *E* in Figure 2. These times are computed based on the graph shown in Figure 3. In this figure:

[2]The prediction algorithms are outside the scope of this paper

E_{soc} = current amount of charge in the battery
E_n = expected charge required for the **next** trip
E_{min} = minimum reserved charge
T_c = current time
T_n = scheduled time for **next** trip
T_{min} = time needed to charge from minimum charge
T_s = time to switch to straight charge mode
t_1 = time difference between T_c and T_s
t_2 = time difference between T_s and T_n
P_{max} = maximum rate of charging
f_c = charge factor, to account for transmission losses

Based on the above, T_{min} is the time at which charging **must** start if the battery is at its minimum charge, E_{min}, and if we are charging at the maximum possible rate, P_{max}. If $T_c < T_{min}$, the VSL agent can safely participate in V2G regulation without worrying about the next trip since there will always be enough time to charge for the next trip. Hence, whenever $T_c < T_{min}$, the VSL agent is in the *Contracting* state and making contracts with the coalition server.

If $T_c > T_{min}$, the VSL agent switches to the *Reserve* state and will still participate in V2G regulation. However, the VSL agent won't make any contracts and may switch to the *Charging* state at any time depending on the current time, T_c, and the current state of charge, E_{soc}. To determine the time at which the VSL agent should switch to *Charge* state, T_s, the VSL continuously monitors the current state of charge and computes either t_1 or t_2 as shown in Equations 1 and 2.

$$t_1 = \frac{f_c(T_n - T_c)}{(1 + f_c)} - \frac{(E_n - E_{soc})}{[P_{max}(1 + f_c)]} \quad (1)$$

$$t_2 = \frac{(T_n - T_c)}{(1 + f_c)} + \frac{(E_n - E_{soc})}{[P_{max}(1 + f_c)]} \quad (2)$$

In order to sell grid services, the VSL agent must join a coalition with other VSL agents, make contracts with an aggregator agent and dispatch regulation power based on requests received from the aggregator agent. The coalition formation process is described in Section 3.2.1 and the advertisement and dispatch algorithms are described in Section 3.2.2

3.2 Aggregator Agents

The aggregator agent (also known as a coalition server) is responsible for aggregating a group of EDVs, for abstracting away the details about the individual vehicles and for presenting them as a single resource to the TSOs. The aggregator agent is needed because:

1. Individual EDVs command too little power to sell in the power markets and TSOs have minimum requirements for participation in the power markets that they run. For example, the PJM TSO requires a service provider/generator to have a minimum power capacity of at least 1MW to bid in the regulation market. A single EDV, even if it is connected to the grid using a high capacity 240V/80A power line, can only provide a maximum of 19.2kW [13]. Furthermore, EDVs can only store power and can not generate power. This means that the amount of power they can provide to the grid is limited by the total capacity and the amount of charge that can be stored in their batteries. Hence, a group of EDVs need to aggregate and form a coalition if they are to participate in these power markets.
2. Even if the minimum power requirements could be relaxed, TSOs have traditionally been set up to control large power plants that have an output of several hundred megawatts. To shift from controlling 100 MW power plants to 5 kW cars would require an increase in controlled nodes of 5 orders of magnitude and would require a significant upgrade in the existing software and control systems operated by the TSOs. Therefore, most TSOs[3] want a smaller operator to manage the EDVs, and to sell them power in 1 MW to 10 MW blocks. An aggregator agent would represent the best interests of this smaller operator.
3. TSOs require the power resources that bid in their markets to be predictable and reliable. A single EDV, on the other hand, is a very dynamic and unpredictable power resource — since a car may be unplugged and driven at any instant. An aggregator agent is needed to convert a group of dynamic EDVs into a reliable power resource that can bid a predictable amount of power in the power markets.
4. Finally, participating in the PJM regulation market requires an organization to sign a contract with PJM and become a PJM member. The aggregator agent would be operated and controlled by this organization and would be responsible for complying with all the TSO market rules and regulations.

The aggregator agent is responsible for answering questions such as:

- How can a group of vehicles come together to form a coalition?
- How much capacity can a coalition of EDVs report to the grid operators?
- Which vehicles within the coalition should be used to service the power requests?
- How can the money be fairly distributed amongst the coalition participants?

In our deployed system, we have takes steps to address each of these questions, which are described below. However, the problem of integrating EDVs into the electricity grid is a novel problem that opens up new avenues of research within the multiagent community. See Section 4 for more details.

3.2.1 Coalition Formation

To enable coalition formation, the aggregator agent registers with a Directory Facilitator (DF) agent in the JADE framework, which provides the yellow pages service. To join a coalition, the VSL agents first contact the DF agent and request a list of aggregator agents that provide aggregation services for the geographic area in which the EDV is currently located. The DF agent responds with a list of aggregator agents. The VSL agent then contacts each of the aggregator agents in turn and sends a *request-for-contract-terms*

[3]We have discussed this with PJM, CAISO, NEISO and a TSO in Germany.

message containing, among other information, the identity of the VSL agent, the maximum regulation-up power, the maximum regulation-down power and the battery energy capacity of the EDV. The aggregator agents then verifies the identity of the VSL agent[4] and then responds with a *contract-terms* message containing an estimate of the expected amount of money the VSL agent might hope to earn during a 24 hour period. The VSL agent then picks the aggregator agent with the best offer and sends it a *join* message.

Once enough VSL agents have joined an aggregator agent to allow it to place a minimum bid in the PJM regulation market, the aggregator agent submits its bids. If a bid is accepted, it dispatches the cars by dividing the received AGC (regulation) signal amongst the VSL agents in the coalition.

Currently we only have 5 EDVs and do not have enough capacity to bid independently in the regulation market. When connected to the grid using a high capacity 240V/80A plug, our EDVs can potentially provide 19.2 kW of power in the regulation market. If the EDVs were permanently connected to the grid, we would need 53 EDVs to meet PJM's 1MW minimum requirement. We have used simulations to empirically determine that we need 230–300 EDVs before an aggregator can reliably provide 1MW of power [9]. To allow us to still participate in the PJM regulation market, we have partnered with a 1MW stationary battery trailer operated by AES Corp. AES Corp. bids 1MW in the regulation market and the received AGS signal is divided proportionally amongst the battery trailer and whatever EDVs are currently connected to the aggregator agent. The aggregator agent is paid according to the Regulation Market Clearing Price (RMCP) for total capacity advertised during a particular hour.

3.2.2 Capacity Advertisement and Vehicle Selection

The amount of capacity that can be advertised by an aggregator agent depends on the makeup of the EDVs that have joined the coalition. Specifically this depends on (a) the plug size used to connect the EDV to the grid; (b) the size of the EDV's battery; and (c) the predictability of the EDV (or the probability the the EDV will actually be parked and plugged in during the hour in which a bid is placed.)

Hence, the job of the aggregator agent is to map a population of VSL agents ($P = \{a_1, a_2, ..., a_n\}$) defined by the tuple $a_i =< l, P_{max}, P_{min}, E_{cap}, E_{soc}, E_{min}, \rho >$ to a coalition defined by the tuple $C =< A, R_{up}, R_{down} >$, where:

- l is a label identifying a VSL agent
- P_{max} is the maximum rate of *discharge*, in kW, permitted by the plug size and the specific EDV model. We define this quantity as the maximum rate of discharge in order to comply with the generator conventions that denote positive power as that flowing from the generator/EDV to the grid and negative power as flowing from the grid to the EDV batteries. If this value is 0, the EDV is not allowed to back-feed power back to the grid (i.e. the EDV is not permitted to discharge power back to the grid.)
- P_{min} is the minimum rate of *discharge* permitted, in kW. The quantity will almost always be negative since EDVs are primarily meant to be *charged* from the grid.
- E_{cap} is the battery capacity of the EDV, in kWh.
- E_{soc} is the current state of charge (SOC) in the battery, in kWh.
- E_{min} is the minimum amount of charge needed to maintain a minimum driving range in the EDV and allow the driver to take unscheduled trips.
- $\rho \in R$ is a real number between 0 and 1 denoting the aggregator agent's measure of the predictability of this car.
- $A \subseteq P$ is the set of agents selected for participating in the coalition.
- R_{up} is the amount of regulation up power being advertised by the coalition.
- R_{down} is the amount of regulation down power being advertised by the coalition.

Since the PJM TSO requires symmetric advertisements/contracts, R_{up} must always equal R_{down}. To allow for symmetric contracts we first define a term, Preferred Operating Point (POP) for each individual EDV. To get an intuitive sense for the POP, think of the POP as the *rate of discharge when the regulation request is zero.* (Again we define POP as the rate of *discharge* to comply with generator conventions in which positive quantities indicate power flow from the EDVs to the grid.) For example, if the POP is defined to be -2kW, in the absence of a regulation request, the EDV would be *charging* by drawing 2kW of power from the grid. Now if the TSO sends a regulation request for -3kW (i.e. regulation-down or drawing of power from the grid), the EDV would set its charge rate to -5kW $(-3 + (-2))$, i.e. it would draw 5 kW of power from the grid to charge its batteries.) If instead the TSO sets the regulation request to 1 kW (i.e. regulation-up or providing power to the grid), the EDV would set its charge rate to -1kW $(1 + (-2))$, i.e. the EDV would still charge at 1kW and draw power from the grid, despite providing regulation-up.)

We determine the POP by using the *effective* maximum and minimum rates of discharge, where the effective rate is determined by both the plug size and the state of charge in the battery. We define the POP as follows: (Note in the following description, we assume that δt is the amount of time for which a coalition is required to provide the advertised regulation request.)

$$POP = \frac{E(P_{max}) + E(P_{min})}{2} \tag{3}$$

$$E(P_{max}) = \min\left(\frac{E_{soc} - E_{min}}{\delta t}, P_{max}\right) \tag{4}$$

$$E(P_{min}) = \max\left(\frac{E_{soc} - E_{cap}}{\delta t}, P_{min}\right) \tag{5}$$

Note in Equation 4, if the SOC is at a minimum (i.e. $E_{soc} = E_{min}$), the effective maximum rate of discharge, $E(P_{max})$, will be set to zero and the EDV will only be charged. To see how $E(P_{max})$, $E(P_{min})$ and the POP varies with the SOC, $E(P_{soc})$, see Figure 4. Now to compute the amount regulation-up and regulation-down power that can be advertised by an individual EDV, we define

[4]We use the Transport Layer Security (TLS) to allow the VSL agents and the aggregator agents to mutually authenticate each other. Hence, for security and reliability reasons, we only allow communication between known and trusted aggregators and VSL agents.

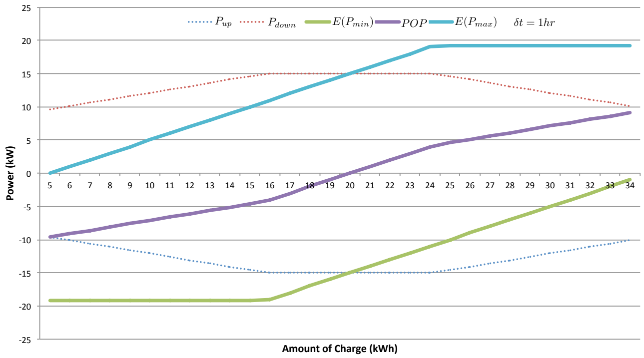


Figure 4: Graph showing the change in Preferred Operating Point (POP) and Advertised Regulation Capacities, P_{up} and P_{down} with the amount of charge in the EDV battery. Note that $E_{cap} = 35kWh$, $E_{min} = 5kWh$ and $\delta t = 1hr$.

$$P_{up} = E(P_{max}) - POP \quad (6)$$
$$P_{down} = E(P_{min}) - POP \quad (7)$$

Again the dotted lines in Figure 4 show how the advertised regulation-up (P_{up}) and regulation-down (P_{down}) power varies with the SOC. Now for the whole coalition, the advertised capacities are calculated as follows:

$$R_{up} = \sum_{a_i \in A} \rho(a_i) \times P_{up}(a_i) \quad (8)$$
$$R_{down} = \sum_{a_i \in A} \rho(a_i) \times P_{down}(a_i) \quad (9)$$

where $\rho(a_i)$ is the availability of agent a_i. Defining the advertised capacity in this way ensures that R_{up} is always equal to R_{down} and allows us to consume all the available capacity while bidding in symmetric markets.

Two questions remain, how do we select the subset of agents to use for the coalition and how do we measure $\rho(a_i)$. Currently, we use all the available agents to form the coalition (that is, we always form a grand coalition). To determine $\rho(a_i)$, we maintain a discounted history of the availability of each EDV, a_i for every hour of the day. Intuitively, we want $\rho(a_i)$ to equal to the probability that a car will be available for a given hour, when it has contracted with the aggregator agent for that particular hour. After every contract hour, we update the value of $\rho(a_i)$ by using the formula

$$\rho(a_i)^{j+i} = \alpha \rho(a_i)^j + (1 - \alpha) \frac{\text{car's availablity in min}}{60} \quad (10)$$

3.2.3 Fair-Payoff Division

The traditional solution concept for calculating a fair payoff for a coalition game is the Shapley Value [17]. Given the characteristic function $v(C)$ and the coalition C, the Shapley Value of agent a_j can be calculated by Eq. 11:

$$\phi_j(C, v) = \frac{1}{|C|!} \sum_{S \subseteq C \setminus \{a_j\}} |S|! \, (|C| - |S| - 1)! \, [v(S \cup \{a_j\}) - v(S)] \quad (11)$$

As is typical in a large realistic system, calculating the Shapley Value for each agent in this way for any feasible coalition (i.e. a coalition with R_{up} and $R_{down} \geq$ 1MW) is clearly intractable, since even the minimal sized such coalition would have 53 EDVs (at 19.2 kW power each) and require computing over 2^{53} subsets of C.

In practice, due to the symmetry axiom of Shapley Values, we might not need to consider every agent as unique and can divide the agents into a set of equivalence classes. However, the number of equivalence classes might still be very large since the number of equivalence classes would depend on (a) the model of the EDV and its battery size; (b) the plug size used to connect the EDV to the grid; (c) the amount of charge in the EDV's battery when contacted out; and (d) the predictability of the EDV.

Given our chosen way of advertising capacities and making contracts, the Shapley value payoff vector will not necessarily be in the core. Consider for example a grand coalition of 54 EDVs where the 54th car has a slightly smaller plug size. While no individual car may have veto power (i.e. any 53-car subset will gain a positive payoff), the 53 cars with the larger plug size would be better off forming their own coalition. Instead, the core is non-empty and contains at least the payoff vector where each car gets a payoff proportional to its own contribution, provided that there are no veto players (cars that can scuttle the coalition on their own) and that the coalition is feasible (meets the minimum requirements). The experimental tendency is that the Shapley value grows closer to the simple proportional payoff as the number of vehicles becomes large (diminishing the effect of the minimum power restriction). Hence, we decided to use a proportional payoff for the EDVs in our system (i.e. each EDV is paid a share proportional to its contribution in the coalition.)

3.3 TSO Agents

The TSO agents communicate with the aggregator agents and provide a wrapper around the legacy systems used by the TSOs. The TSO agents have two main functions — (a) allow the aggregator agents to participate in the regulation market; and (b) send AGC power (regulation) requests to the aggregator agents. The TSO agents are responsible for converting between the legacy modbus data protocols used by the Arcom Director[5] and the FIPA agent communication language used by our agents.

3.4 EVSE Agents

EVSE is an acronym for *Electric Vehicle Supply Equipment* and is a fancy name for an EDV battery charger. The primary goal of the EVSE agent is to look after the best interests of the owner of the recharging station (which may be the same as the vehicle owner but might also be a completely separate entity like a commercial business or a municipality). Since EDVs are designed to plug into a wide range of power sources, including traditional Edison 125V/15A plugs, the EVSE agents are optional to the operation of the GIVs. When present, the EVSE agents communicate with the VSL agents over a special power + network connector (SAE J1772).

In our system, we define two levels of functionality for the EVSE agents:

[5]The Arcom Director is a remote terminal unit used by PJM.

1. At the basic level, the EVSE agent simply communicates with the VSL agent. The information sent by the EVSE can be very comprehensive and includes information about (a) the maximum charge rate; (b) the maximum discharge rate; (c) whether or not V2G (or backfeeding of power to the grid) is permitted at this charger; (d) meter id and transformer id of the circuit on which this EVSE is located[6]; (e) the network settings the VSL agent should use for internet access; (f) whether the VSL should provide emergency power in the case of a power disruption; and (g) error codes related to ground, control and pilot faults.
2. At a more advanced level, the EVSE can negotiate charging contracts with the VSL agents. This would be useful in situations where the EVSE are owned by a third party such as a business or a city. (For example, there are plans for installing EVSEs on our main street and in our interstate service centers.) In these situations, the EVSE agents would negotiate rates of charging and the corresponding costs with the VSL agents and, in some cases, might even allow the EDVs to charge for free as long as the VSL agents agree to forego the revenue earned by providing GIV services. These EVSE agents would also be responsible for keeping records of charging events and for billing customers appropriately for the services used.

At present we have only implemented the basic functionality in our EVSE agents and are working on incorporating the more advanced functionality into future releases.

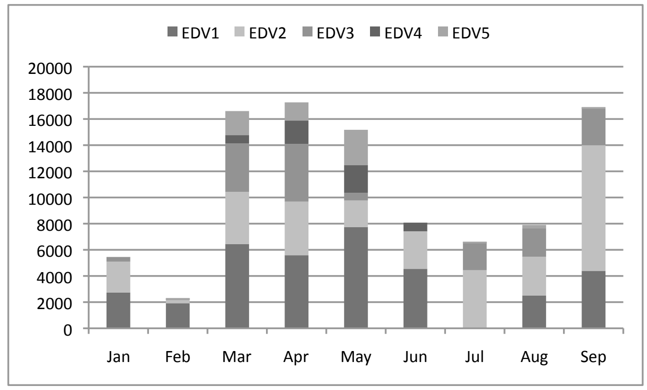
4. RESEARCH CHALLENGES

Coalition formation has been studied extensively in both game theory [8] and multiagent systems (see [16, 6, 8, 14, 1] for a small sampling) and has even been applied to power transmission planning [4] and open environments [15]. We believe there are some key differences between the existing research on coalition formation and the kind of coalition formation that we are interested in in this paper:

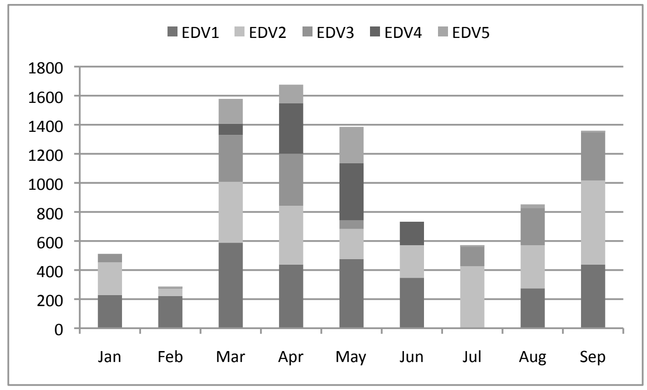
- Coalition formation for EDVs differs from iterative coalition formation games in that each game is not independent. Rather the coalition's ability to participate in the next game depends on the actions of the previous game. If we use up all the charge in the EDVs in game i, we won't have any charged EDVs available for use in game $i + 1$. Hence, what we do in one hour affects the kind of coalition that we can form in the next hour. Furthermore, the set of agents that form the coalition is highly unpredictable and varies from hour-to-hour.
- Most coalition games assume a fixed characteristic function that defines the payoffs received by the formed coalitions. However, in the case of coalition formation for EDVs the characteristic function is not fixed. Instead part of the problem is determining the amount of capacity to bid in the different markets which involves determining an appropriate characteristic function for the coalitions.

We believe these two issues need to be modeled and studied by the multiagent community in general and we would like to focus on modeling these issues in our future work.

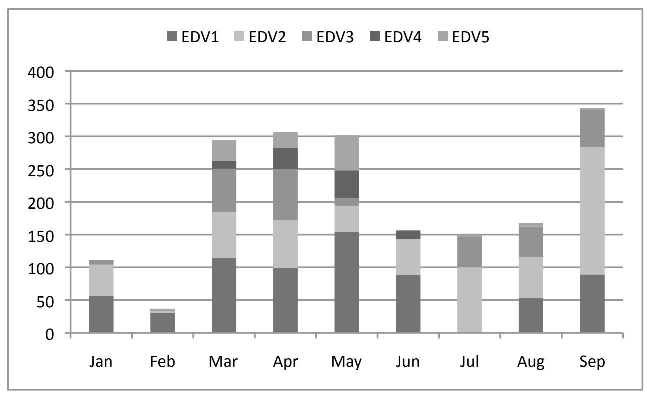
[6]This information together with the topology of the power grid can be used by the aggregator agent to limit the maximum load on an individual transformer.



(a) Regulation Capacity Offered (in kW-h)



(b) Total number of hours plugged in



(c) Amount of money earned by the EDVs (in US$)

Figure 5: Graphs showing the performance of our five EDVs for the first nine months of 2010.

5. EVALUATION

Since this paper describes an implemented and deployed system, we thought the best way to evaluate our system would be to describe its operation over the first nine months of this year. Figure 5a shows the total capacity bid by our EDVs in kW-h[7]; Figure 5b shows the number of hours that

[7]Since the regulation market pays for the bid regulation capacity and not for the actual power provided, the unit for regulation capacity is kW-h. One kW-h is a unit of power capacity meaning that one kW of regulation power capacity

each EDV was plugged-in and providing regulation services; and Figure 5c shows the amount of money earned by our EDVs, in US dollars, during the same period.

As can be seen, the amount of regulation capacity offered and the amount of money earned is directly proportional to the number of hours plugged in. (These EDVs were mostly plugged into 208V/50A plugs although occasionally an 80A plug was also used.) We started out with 3 EDVs in January and February. Since the winter months (especially February) were particularly severe in the northeast (in 2010), we chose to not participate in the regulation market in order to conserve the battery life of our EDVs. In March, we added two more EDVs to give us a total of 5 EDVs. The amount of regulation offered dropped significantly in the months of June, July and the starting of August because we were making significant upgrades to our system.

Extrapolating from our data, if an EDV is plugged-in and providing regulation services for 15 hours a day, it can expect to make a hundred dollars a month given the current Regulation Market Clearing Prices (RMCPs). Given that the RMCP was twice as high as what it is right now before the start of our current economic recession, EDVs owners can expect to make between 100 and 200 dollars a month or between 1,200 and 2,400 dollars a year by participating in the regulation market. This is a significant amount of money that can be used to offset the high costs of EDVs.

6. CONCLUSION AND FUTURE WORK

This paper describes an implemented and deployed system for integrating a group of EDVs into the electricity grid. We motivated the problem, described the various types of power markets and presented an implementation of a multiagent system that allows EDVs to participate in the regulation market. We have also deployed 5 EDVs in the PJM TSO that, in conjunction with a 1MW battery trailer operated by AES Corp., has been able to bid and earn money in the regulation market.

For our future work:

- We plan to deploy another 50 EDVs within the next two years. Our goal is to have enough EDVs so that we may participate independently in the PJM regulation market. We would also like to study the scalability of our approach to a couple of thousand EDVs.
- We would like to focus on each of the open research challenges presented in Section 4.
- We would like to lead the the effort to develop a standard set of protocols for (a) communicating between the VSL agents and the Vehicle Management Systems (VMSs) inside the EDVs; and (b) communicating between the aggregator agents and the VSL agents. This latter would involve defining a standard ontology for this application.

7. ACKNOWLEDGEMENTS

This work was supported by funding from the U.S. Department of Energy, Office of Electricity Delivery and Reliability (grant number DE-FC26-08NT01905, Willett Kempton, PI). We also acknowledge support on this aspect of the V2G project from Pepco Holdings, Inc., PJM Interconnection, AC Propulsion, Inc., and AES Corporation.

was available for one hour.

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