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Experimental Demonstration of Smart Charging and Demand Response for Plug-in Electric Vehicles Based on SAE Standards

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Abstract

In this paper, we present an implementation of smart charging systems for plug-in electric vehicles based on off-the-shelf communication protocols for smart grids including SAE J2836/2847/J2931 standards and SEP 2.0. In this system, the charging schedule is optimized so that it supplies sufficient electricity for the next trip and also minimizes the charging cost under given time-of-use rate structures while it follows demand response events requested by a utility. Also, users can control charging schedule and check the current status of charging through application software of tablet computers. To validate the effectiveness of the developed smart charging system, we conducted experimental demonstration in which a total of 10 customers of Duke Energy regularly used our developed system for approximately one year with simulated time-of-use rate structures and demand response events. We show the users' acceptance for the system usability and demand response events, the cost benefits for users without forcing their patience, and the impact on peak demand shift by the user-friendly system.

Introduction

Plug-in electric vehicles (PEV) provide better fuel efficiency and economic benefit and also they reduce the dependency on fossil fuel, greenhouse gas emission, and air pollution, rendering a society more environmental and sustainable over petroleum-powered vehicles. In this paper, we use the term "PEV" as a general term that includes battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), and extended range electric vehicles (EREV). Owing to the favorable views of PEV, they are becoming increasingly popular and they may achieve significant market penetration in the next few decades. However, as the market penetration of PEV increases, PEV may further increase peak demand and require more electricity generation and transmission capacity, resulting in additional costs for utilities and consumers. Therefore, it is crucial to consider solutions for reducing the increased peak demand without impairing users' convenience on PEV charging. Particularly, this would be significant in certain states or areas such as California where the Zero Emission Vehicle (ZEV) program is mandated [1], and at the same time the grid condition appears to be critical. One of promising solutions for the problem is demand response (DR) [2].

DR is a mechanism to reduce peak demand for electricity by encouraging consumers to reduce or shift their power consumption, i.e., peak demand cut/shift, through price-based DR programs and/or incentive-based DR programs operated by utilities or aggregator. In price-based DR programs, a utility offers customers a time-varying tariff based on wholesale electricity costs. Consumers can save their electricity cost by reducing the energy usage during peak periods and/or by shifting the time of the energy usage to off-peak periods. This type of programs includes time-of-use (TOU) pricing, critical peak pricing (CPP), and real time pricing (RTP). In incentive-based programs, a utility pays incentives to consumers if the consumers reduce their power consumption as per the utility's requests. This type of programs includes direct load control (DLC) and peak time rebate (PTR). By employing DR programs above, both consumers and utilities gain cost benefit, i.e., consumers can reduce the electricity cost and utilities can also reduce their investment cost for increasing the capacity of power generation and transmission systems to deal with

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increased peak demand. Commercial and industrial DR has been in use for decades, whereas residential DR is still emerging but gaining much attention as advanced metering infrastructure (AMI), through which DR information is sent to consumers, is increasingly deployed. With AMI, utilities can also gather real-time or near real-time metering information and understand the real-time grid condition, which will be utilized to decide the time and duration of DR events. One of the issues when we operate DR programs is that customers' behavior to DR is somewhat unpredictable because they respond passively and manually. Therefore, there is no guarantee that customers will participate in DR events nor that the DR events will be effective. Additionally, manual DR requires the decision and actions of consumers within a limited time frame to achieve effective DR. Another issue is that DR events are different by utilities and changeable.

In recent years, automated demand response (ADR) has gained much attention and is considered as one of the key components of smart grids [3] because it realizes DR automatically by utilizing two-way digital communication such as AMI and the Internet between a utility and consumers. In ADR, a utility sends DR signals to consumers' control systems or devices and directly controls the load of their devices. Since ADR is done automatically without human intervention, it is easier for utilities to predict the impact of ADR on peak demand cut/shift and also easier for customers to cut or shift power consumption because the customers do not need to react to DR events by themselves. ADR also increases the speed and reliability of the response from devices. Also, it is important that ADR programs allow consumers to have an option to override or opt-out of DR events when the consumers do not want to cut or shift their electricity demand during the DR events.

To realize ADR for PEV charging, we require communication protocols between PEV and grids. So far, various standard communication protocols have been developed such as Smart Energy Profile (SEP) 2.0 [4], OpenADR 2.0 [5], the Society of Automotive Engineers (SAE) J2836/J2847/J2931 [6], and ISO/IEC 15118 [7]. SEP 2.0 specifies an application-layer protocol for use in smart home energy management based on a representational state transfer (REST) architecture over the HTTP and TCP/IP stack. SAE J2836/J2847/J2931 is a suite of standards developed by the automotive industry for the two-way digital communication between PEV and a grid. Their standardization was done and is already available. Those standard protocols are inherently designed to support ADR and coordinate with each other, and thus they enable ADR effectively without human intervention and also ensure the interoperability between different manufacturers' equipment.

One of the most important things when we apply ADR to PEV charging is to ensure users' convenience while following DR events. To this ends, it is required to develop smart charging control systems that lean the user's usual driving habit and based on that they react to DR events while ensuring the user's convenience. Compared with other appliances, PEV are suitable for realizing peak demand shift because for typical appliances, the period of power consumption and the period of use are the same, whereas the period of charging a PEV and the period of driving it are different. This fact provides us the flexibility of charging scheduling without impairing users' convenience so that we can obtain a charging schedule that satisfies both the utility's demand and user's demand. Currently, the most common way of charging is immediate charging, i.e., charging is started immediately when a PEV is plugged in. Another common way is timer charging, in which the user manually sets the charging timer based on tariff information. On the other hand, smart charging is a sophisticated way of charging that enables users or a charging control system to control and monitor PEV charging remotely and/or automatically by utilizing the two-way digital communication between PEV and a smart grid. This allows users to charge PEV for the best available price by avoiding the duration of higher prices when the load is at its peak.

In [8], optimal charging scheduling taking into account TOU rates but without DR events was proposed and analyzed through numerical simulations. In [9], optimization problems of coordinated charging among multiple vehicles was formulated and analyzed to minimize the power losses in a distribution grid.

In this paper, we present an implementation of smart charging systems for plug-in electric vehicles based on SAE J2836/2847/J2931. In this system, the charging schedule is optimized so that it supplies sufficient electricity for the next trip and also minimizes the charging cost under given time-of-use rate structures while it follows demand response events requested by a utility. Also, users can control charging schedule and check the current status of charging through application software of tablet computers. To validate the effectiveness of the developed smart charging system, we conducted experimental demonstration, in which a total of 10 customers of Duke Energy regularly used our developed system for approximately one year with simulated time-of-use rate structures and demand response events. We show the users' acceptance for the system usability and demand response events, the cost benefits for users without forcing their patience, and the impact on peak demand shift by the user-friendly system. In [10], we presented initial results of our experimental demonstration, particularly focusing on users' behavior for DR events. Also, in [11], we analyzed the theoretical aspect of optimal charging scheduling by formulating an optimization problem of smart charging scheduling. In this paper, we present more detailed and comprehensive results of our smart charging system.

SAE J2836/J2847/J2931 Standards and SEP2.0

In this section, we briefly introduce SAE J2836/J2847/J2931 standards and SEP 2.0, which were used in our experimental demonstration.

SAE J2836/J2847/J2931

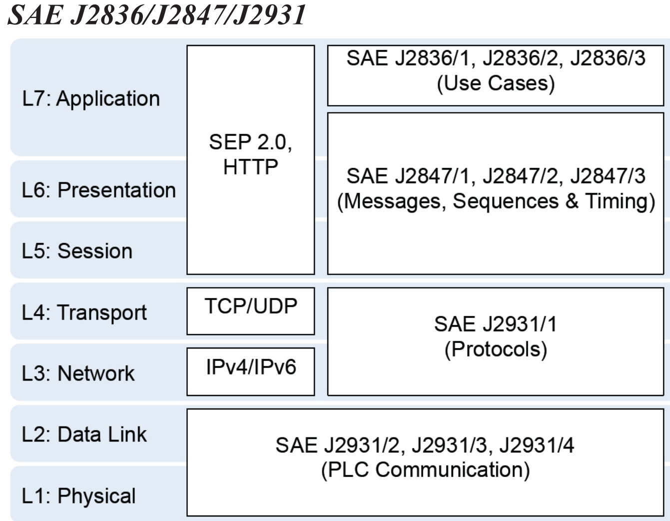

Figure 1. Protocol stack of SAE J2836/J2847/J2931 Standards and SEP 2.0.

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Table 1. SAE J2836/J2847/J2931 Standards.

SAE J2836/1	Use Cases for Communication Between Plug-in Vehicles and the Utility Grid
SAE J2836/2	Use Cases for Communication between Plug-in Vehicles and Off-Board DC Charger
SAE J2836/3	PEV Communicating as a Distributed Energy Resource
SAE J2847/1	Communication for Smart Charging of Plug-in Electric Vehicles using Smart Energy Profile 2.0
SAE J2847/2	Communication Between Plug-in Vehicles and Off-Board DC Chargers
SAE J2847/3	Communication for Plug-in Vehicles as a Distributed Energy Resource
SAE J2931/1	Digital Communications for Plug-in Electric Vehicles
SAE J2931/4	Broadband PLC Communication for Plug-in Electric Vehicles

SAE J2836/J2847/J2931 [6] is the family of standards for the two-way digital communication between PEV and a smart grid. Figure 1 shows the architecture of SAE J2836/J2847/J2931 mapped to the OSI reference model and the list of the standardized specifications is shown in Table 1. SAE J2836 defines various use cases for two-way digital communications between PEV and a grid for energy transfer and other applications. SAE J2847 defines communication for smart charging using SEP 2.0 to implement the functionality defined in SAE J2836. SAE J2931/1 defines the architecture and general requirements for digital communications between PEV and electric vehicle supply equipment (EVSE). SAE J2931/4 defines the specifications for physical and data-link layers using broadband PLC (HomePlug Green PHY [12]) between PEV and EVSE. SAE J2836/J2847/J2931 comprises different parts addressing specific charging options.

SEP 2.0

SEP 2.0 [4] is an application-layer protocol that enables home energy management in home area networks (HAN), including controls of PEV charging. SEP 2.0 was standardized by ZigBee Alliance and HomePlug Powerline Alliance and it was included by the U.S. National Institute of Standards and Technology (NIST) in 2010 for smart grid applications [13].

SEP 2.0 is based on RESTful architecture over the HTTP and TCP/IP stack as shown in Fig. 1, in which a stateless server exposes resource representations to clients and the clients request resources that they want to the server by using four request methods: GET, POST, PUT, and DELETE. Since SEP 2.0 is designed to work over TCP/IP, it is MAC/PHY agnostic, i.e., we can use any MAC/PHY technologies such as IEEE802.11b/g/a/n, IEEE802.15.4, Ethernet, and power line communication (PLC).

SEP 2.0 defines several function sets, which represent a set of device behaviors to realize a particular functionality, such as time synchronization, metering, pricing, demand response and load control (DRLC), billing, pre-payment, and distributed energy resources. SEP 2.0 is designed to support several devices such as metering devices, thermostat, in-premise display, PEV, distributed energy resource (DER), and smart appliance. By using these function sets and device profiles, we can manage and control smart devices in HAN. A brief description of main function sets is as follows: The time function set allows devices to synchronize their time by acquiring time from a time source. Time synchronization is important because it is essential to support time-related functionalities such as metering, pricing, DRLC, and so on. The metering function set provides interfaces to exchange meter readings between HAN devices. The pricing function set provides interfaces to send tariff information to HAN devices. This supports various tariff types, including flat-rate pricing, TOU pricing, RTP, CPP, consumption-based pricing, and application-specific tariffs for smart devices (e.g., smart PEV). The DRLC function set allows energy management systems to send DR information to HAN devices and also control them.

Smart Charging System Based on SAE Standards

In this section, we present our developed smart charging system based on SAE J2836/J2847/J2931 standards. The basic principle of this smart charging system is to provide easy and intuitive customer experience. Therefore, we designed the system as simple as possible for users. Basically, all the user has to do is to just plug in the vehicle, then the vehicle communicates with the utility and the charging management system and the system automatically sets the best charging schedule to the vehicle. The charging schedule is tailored to the user's habits by learning the past driving and charging history. Also, if the user wants to change the charging schedule or control charging, the user can command it directly with a developed mobile application.

System Overview

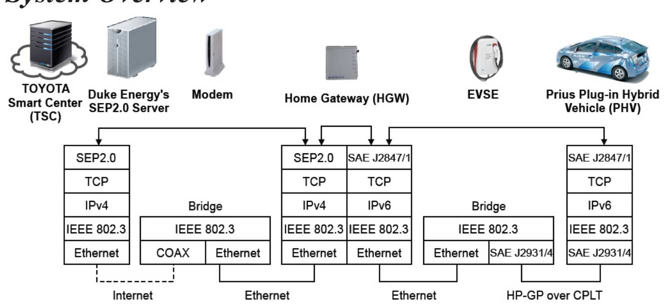

Figure 2. Network architecture of developed smart charging system.

The network architecture of our developed smart charging system is depicted in Fig. 2. This system comprises a Prius Plug-in Hybrid vehicle (PHV), EVSE (AC Level 2), home gateway (HGW), broadband modem, and Duke Energy's SEP 2.0 server, TOYOTA Smart Center (TSC), and tablet computer. A developed HGW, EVSE, and PHV are shown in Fig. 3. PHV is connected with HGW using PLC (SAE 2931/4) between PHV and EVSE and Ethernet between EVSE and HGW, where EVSE acts as a bridge. Duke Energy's SEP 2.0 server provides TOU rates and DR events to PHV via HGW. HGW is a gateway between Duke Energy's server and PHV as well as one between PHV and TSC. TSC periodically collects the usage information of PHV as well as the current battery status, and based on them, TSC calculates a charging schedule and controls the charging of PHV automatically. With the tablet computer, users can remotely monitor the charging status and change the charging schedule as needed. In real deployments, either a cloud management system used in this experiment or an on-board management system is possible as long as good-enough performance is secured.

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Figure 3. Pictures of a developed HGW, EVSE, and Prius PHV.

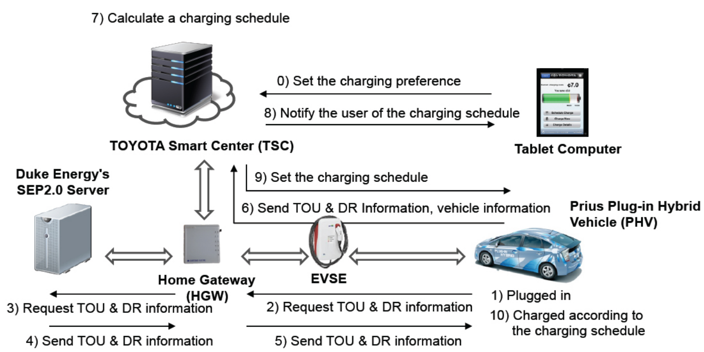

Figure 4. Data flow of developed smart charging system.

The data flow of our developed system is depicted in Fig. 4. First of all, when a PHV is plugged in, the PHV obtains tariff information and DR events from Duke Energy's server by using the two-way digital communication through PLC and the Internet. The PHV aggregates the information from Duke Energy's server and the vehicle information, including the vehicle ID, the current SoC, the battery capacity, the maximum voltage value, the maximum current value, and so on, and then The PHV sends them to TSC. Based on the information provided by Duke Energy's server and the PHV, TSC calculates a charging schedule and sends it back to the PHV. Finally, the PHV is charged according to the charging schedule.

Mobile application software for smart charging

In this project, we also developed mobile application software that allows users to check the current status of charging and the charging schedule and also manage their charging such as starting and stopping charging. Figure 5 shows some example views of the developed application. With this application, users can:

- Check the current status of charging and battery
- Start and stop charging
- Check the charging schedule
- Receive a push notification when charging is completed
- Set the charging mode (immediate charging or smart charging)
- Set the DR mode (DR priority or not)
- Set the target SoC and the departure time

In the charging mode setting, if the user selects the immediate charging, charging is started immediately when PHV is plugged in. On the other hand, if the user selects the smart charging, the charging schedule is calculated based on our smart charging scheduling.

Figure 5. Mobile application software for smart charging.

In the DR mode setting, if the user selects the DR priority mode, the calculated charging schedule always follows the DR events (i.e., opt-in to the DR program). On the other hand, if the user selects the user priority mode, the charging schedule is calculated as if there is no DR event (i.e., opt-out from the DR program).

Smart Charging Scheduling

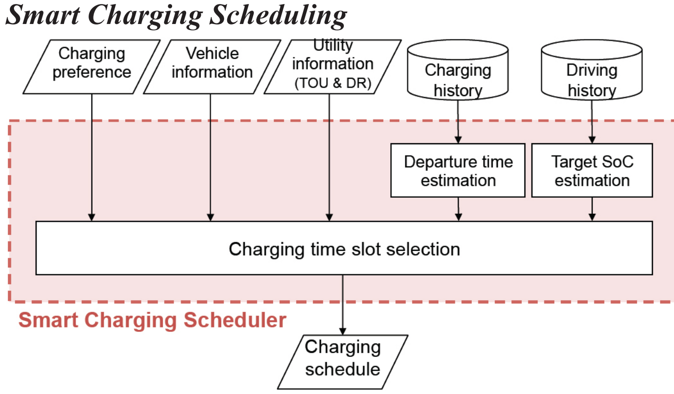

Figure 6. Basic architecture of smart charging scheduling.

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In this section, we present smart charging scheduling that can take into account both the user's preference and utility's request. Figure 6 shows the basic architecture of the smart charging scheduling. The user has the charging preference, including the target SoC and the departure time when PEV is expected to depart. The PEV provides the vehicle information, including the vehicle ID, the current state of charge (SoC) of the battery, the battery capacity, and the charging rate. The utility also provides the tariff information, i.e., TOU rates, as well as the information of DR events, i.e. DLC, to a PEV. Based on the information provided by the user, the PEV, and the utility, the charging scheduler calculates the optimal charging schedule that minimizes the charging cost while it satisfies both the utility's demand and user's demand. For that purpose, we impose some requirements on smart charging scheduling that are summarized as follows:

1). Comply with DR events if the user selects the DR priority mode
2). Under 1), satisfy the target SoC by the departure time
3). Under 1) and 2), select the cheapest time slots for charging
4). Under 1)-3), select earlier time slots for charging as long as the charging cost is the cheapest

In addition, our smart charging system can learn the past charging history and driving history so that PEV is charged enough for the next drive by the departure time. More specifically, TSC estimates the departure time based on the past charging history. We use the estimated result to determine by which time PEV should be ready for departure. Also, TSC estimates the target SoC based on the past driving history. This estimated result is used for ensuring that PEV is charged enough for the next drive. Also, the user can set the departure time and target SoC manually through the developed mobile application if desired. More detailed and theoretical aspect of our developed smart charging algorithm can be found in [11].

Figure 7 shows an example of the smart charging scheduling. In this example, charging is done in earlier time slots with a cheaper TOU rate, while the charging schedule follows the DR events. Also, this charging schedule ensures that the target SoC is satisfied by the departure time.

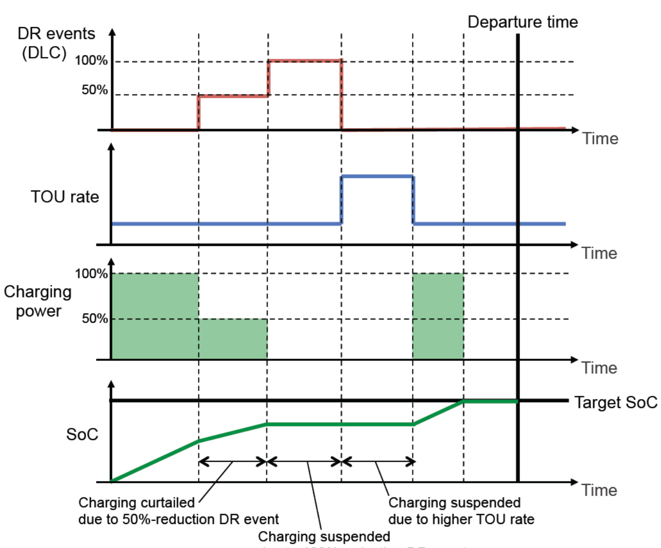

Figure 7. Example of smart charging scheduling.

Experimental Demonstration

Pilot Project Overview

We conducted demonstration experiments in Indianapolis, IN, USA, in cooperation with Duke Energy and Energy Systems Network (ESN). This project was done as part of the Project Plug-IN initiative, led by ESN. This project ran for one year from January 2013 to January 2014. In this project, we provided a set of PHV with 4.4 kWh batteries, EVSE, HGW, and tablet computer with the developed application software for each participant. Duke Energy selected a total of 10 customers of Duke Energy as the participants of this project. 5 PHVs were driven by 5 employees of Duke Energy for the first half of the one-year period (Phase 1) and another 5 general customers for the second half of the year (Phase 2). Each customer drove PHV and also used our developed smart charging system on a daily basis. Duke Energy simulated TOU rates and DR events during the pilot period. The objectives of this pilot project are summarized as follows:

- To test and validate the effectiveness of SAE J2836/J2847/J2931 standards for effectively managing PEV charging while coordinating with utilities
- To evaluate the users' acceptance of our developed system and the users' behavior for DR events

Simulated Time-of-Use Rate Structures and Demand Response Events

In this pilot project, Duke Energy set virtual TOU rate structures as shown in Table 2. During the pilot period, two different TOU rate structures (two-tier and flat rate structures) were used. It should be noted that although we focused on TOU pricing in this pilot project, our developed smart charging system also works for other dynamic pricing such as CPP and RTP. This is because in this system, the PHV periodically communicates with Duke Energy's SEP 2.0 server and TSC and updates its charging schedule based on the updated pricing structure and DR events.

In this simulated DR program, Duke Energy called 4 DR events every month during the pilot period, as shown in Table 3. All of the DR events were 3-hour DLC requesting 40% power reduction, i.e., reduction of a current value from 10 A to 6 A. Duke Energy provided customers 24-hour advanced notifications of when to start and end a DR event through e-mail or SMS. This allowed the customers to prepare in advance for a temporary reduction in their charging capabilities. As an incentive, the customers got rebates from ESN on a monthly basis if they followed all of the DR events in a corresponding month. In this pilot, we set the rebate at $5 per month.

Table 2. Simulated Time-of-Use Rate Structures.

Periods	Time	Rate	Type
2013/05/01 – 2013/06/23, 2013/07/11 – 2013/09/30, 2013/11/15 – 2014/01/08	12am – 2pm	6.3 ¢/kWh	Off-Peak
	2pm – 7pm	29.5 ¢/kWh	On-Peak
	7pm – 12am	6.3 ¢/kWh	Off-Peak
Other	All hours	6.3 ¢/kWh	Off-Peak

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Table 3. Simulated Demand Response Events.

02/05/2013 6am – 9am	08/16/2013 4pm – 7pm
02/14/2013 6am – 9am	08/21/2013 5pm – 8pm
02/19/2013 6am – 9am	08/29/2013 6am – 9am
02/28/2013 6am – 9am	09/03/2013 4pm – 7pm
03/05/2013 4pm – 7pm	09/14/2013 11am – 2pm
03/11/2013 4pm – 7pm	09/16/2013 5pm – 8pm
03/22/2013 4pm – 7pm	09/27/2013 3pm – 6pm
03/25/2013 4pm – 7pm	10/02/2013 5pm – 8pm
04/02/2013 5pm – 8pm	10/11/2013 4pm – 7pm
04/11/2013 4pm – 7pm	10/15/2013 4pm – 7pm
04/18/2013 4pm – 7pm	10/26/2013 1pm – 4pm
04/23/2013 5pm – 8pm	11/01/2013 5pm – 8pm
05/07/2013 5pm – 8pm	11/06/2013 5pm – 8pm
05/16/2013 4pm – 7pm	11/21/2013 4pm – 7pm
05/23/2013 4pm – 7pm	11/27/2013 2pm – 5pm
05/28/2013 5pm – 8pm	12/05/2013 9am – 12pm
06/11/2013 4pm – 7pm	12/11/2013 6am – 9am
08/07/2013 9am – 12pm	

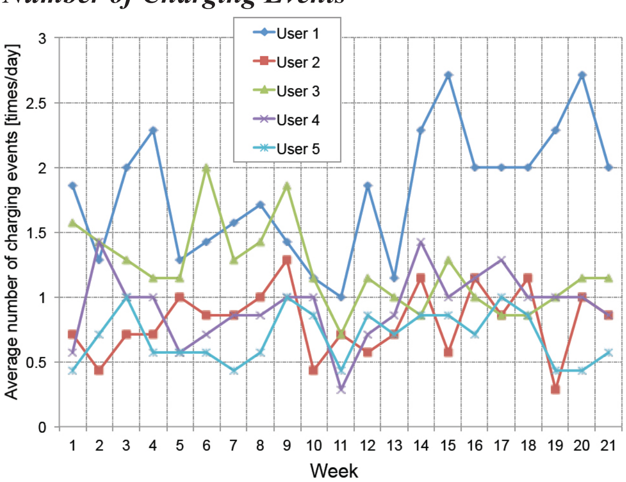
For the Phase 1 experiment, we mainly verified the effect of DR events with the flat rate structure and also verified the system function for the two-tier TOU rate structure. On the other hand, for the Phase 2 experiment, we verified the combined effect of DR events and the two-tier TOU rate structure.

Experimental Results

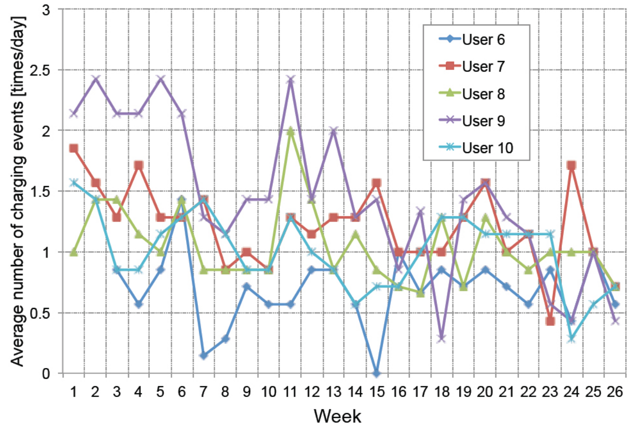
In this section, we present various results of our demonstration experiments to show the users' charging behavior and the users' acceptance for DR events and our smart charging system, including:

- Number of charging events
- User's acceptance for DR events
- User's acceptance for smart charging systems
- Charging cost
- Energy consumption of charging
- Duration of charging in DR events

Number of Charging Events



(a). Phase 1



(b). Phase 2

Figure 8. Average number of charging events.

Figure 8 shows the average number of charging events per day, in which the number of charging events are weekly-averaged. From the figure, we observe that every user charged the vehicle daily and some of them charged the vehicles more than two times per day. So, we can say that their interest for charging had been maintained without getting tired of charging.

User's Acceptance for Demand Response Events

Figure 9 shows the users' acceptance ratio for DR events. We can see that all the users accepted more than 80% of the DR events (17 events for the Phase 1 users and 18 events for the Phase 2 users) and particularly 7 users accepted all the DR events.

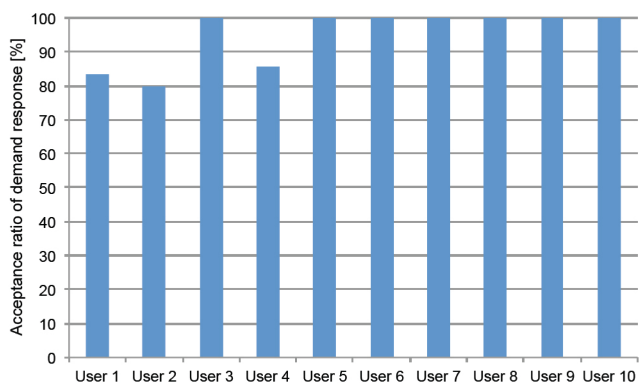


Figure 9. User's acceptance ratio of demand response events.

User's Acceptance for Smart Charging System

Figure 10 shows the acceptance ratio that each user charged the vehicle according to charging schedules calculated by our smart charging system (i.e., the ratio that the user did not manually override the calculated schedules.). From the figure, we observe that the acceptance ratio is increased over time. This is because they become familiar with the smart charging system and satisfied with suggested charging schedules. The reason why the acceptance ratio of some of the Phase 2 users drops around the 17th week is because system failure happened and the users selected to use the immediate charging mode.

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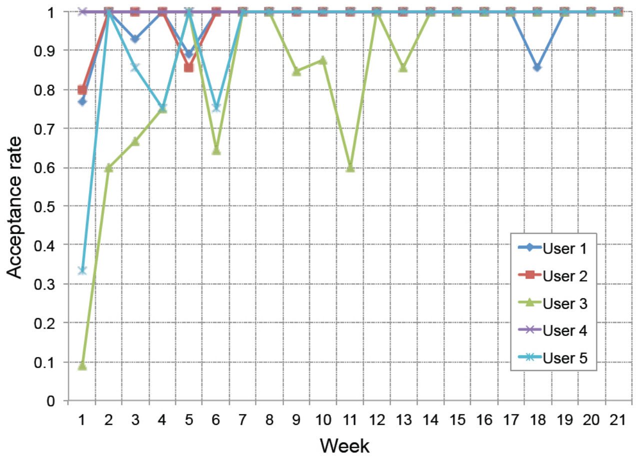
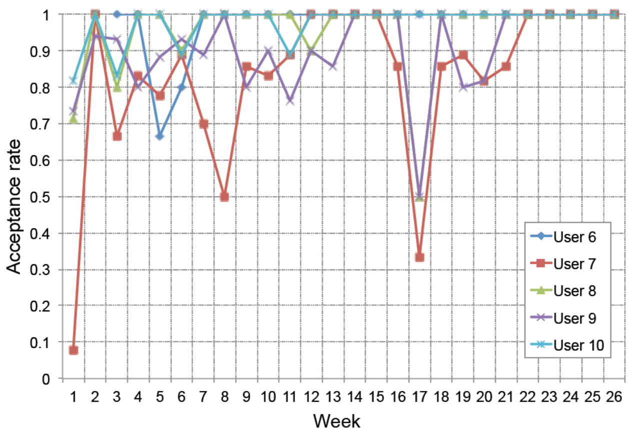


(a). Phase 1



(b). Phase 2

Figure 10. Users' acceptance ratio for smart charging scheduling.

Charging Cost

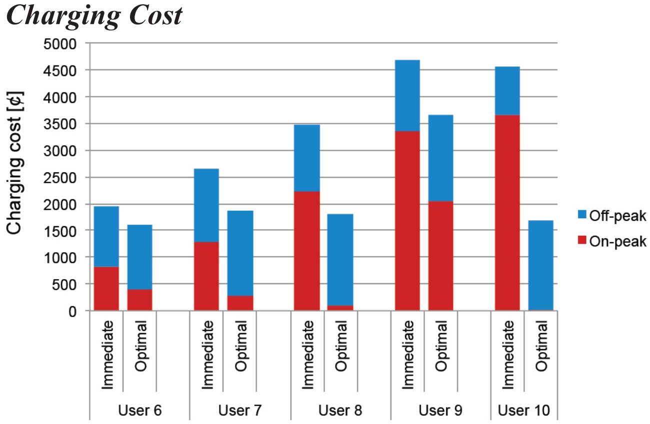


Figure 11. Charging cost for immediate charging and optimal charging in Phase 2.

Figure 11 shows the total charging cost of the optimal charging scheduling for the Phase 2 users in the period of the two-tier rate structure, and we also show the simulated charging cost of the immediate charging for comparison. Note that those charging costs do not include the amount of incentives. In this figure, we show the proportion of off-peak and on-peak charging in the total charging cost. From this figure, we observe that the optimal charging scheduling significantly reduces the charging cost; specifically the charging cost is reduced by 38.7% on average by employing the optimal charging scheduling compared with the immediate charging. This cost reduction comes from shifting the time of charging from on-peak periods to off-peak periods.

Energy Consumption of Charging

Figure 12 shows the total energy consumption of the optimal charging for the Phase 2 users in the period of the two-tier rate structure, and we also show the simulated energy consumption of the immediate charging for comparison. In this figure, we show the proportion of off-peak and on-peak charging in the total energy consumption. From this figure, we observe that we can successfully shift the charging time from peak periods to off-peak periods by using the optimal charging scheduling for the given TOU rate structures.

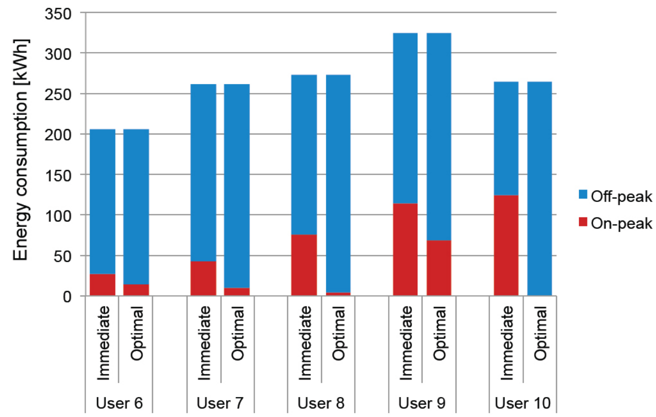


Figure 12. Energy consumption for immediate charging and optimal charging in Phase 2. Duration of Charging in Demand Response Events

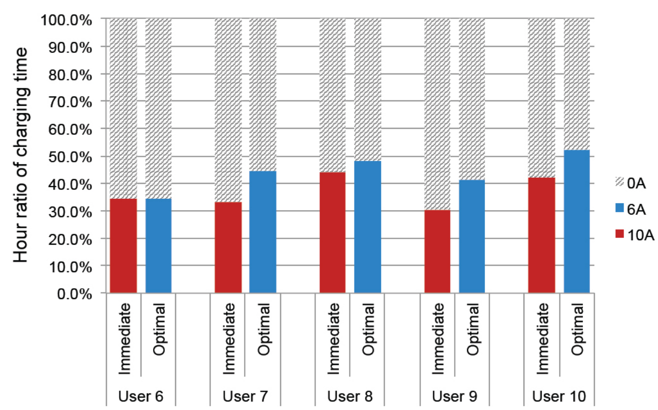


Figure 13. Duration of immediate charging and optimal charging in demand response events in Phase 2.

Figure 13 shows the total hours of uncharging and charging in the DR events for the Phase 2 users, where the total hours of uncharging and charging are normalized by the total hours of the DR events in which a PHV is plugged-in. In this figure, we also show the simulated performance of the immediate charging for comparison. From this figure, we observe that all the users accepted all the DR events, and hence, the charging current of 10 A is successfully decreased to 6 A during the DR events when the optimal charging scheduling is employed. Since charging with 6 A takes more charging time than that with 10 A for the same amount of charge, the total charging time of the optimal charging is longer than the immediate charging in DR events. This is favorable to utilities because utilities prefer reducing

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or shifting peak demand rather than short time charging with higher charging power in the period of peak demand. Therefore, we can successfully achieve peak shift with optimal charging and DR events.

Conclusions

In this paper, we presented an implementation of smart charging systems for plug-in electric vehicles based on off-the-shelf smart grid standards including SAE J2836/2847/J2931 standards and SEP 2.0. In this system, the charging schedule is optimized so that it supplies sufficient electricity for the next trip and also minimizes the charging cost under given time-of-use rate structures while it follows demand response events requested by a utility. We showed the results of experimental demonstration in which a total of 10 customers of Duke Energy regularly used our developed system for approximately one year with simulated time-of-use rate structures and demand response events. We showed that the users' acceptance for the system usability and demand response events, the cost benefits for users without forcing their patience, and the impact on peak demand shift by the user-friendly system, which ease the burden of users from checking tariff information by themselves. From the results above, we can conclude that *SAE J2836/J2847/J2931 standards with SEP 2.0 are good solutions for dealing with DR events and also technically ready for real deployments*.

Future works are to develop fleet charging management algorithms for jointly optimizing charging schedules of multiple vehicles and implement them with standard communication protocols over AMI.

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