A Power Monitoring and Control System to Minimize Electricity Demand Costs Associated With Electric Vehicle Charging Stations

Nicholas Jewell, John Naber, Michael McIntyre and Matthew Turner
Department of Electrical and Computer Engineering
University of Louisville
Louisville, KY, USA
Nicholas.Jewell@louisville.edu

Abstract— **The impact of Battery Electric Vehicle (BEV) charging on the electrical demand of a commercial / industrial energy consumer is examined. A Power Monitoring and Control System (PMCS) is introduced as a method to limit the disincentive to large scale BEV adoption resulting from increased demand costs associated with uncontrolled BEV charging. Reductions in added costs of up to 90% are possible with the incorporation of an intelligent charge control system. Additionally, the PMCS enables transformative charge sharing topologies, including Vehicle to Grid (V2G) and Vehicle to Vehicle (V2V), as solutions for peak shifting and demand response techniques during high demand periods.**

Index Terms-- **Electric Vehicle, EV, BEV, Charging System, Energy Demand, PMCS, Vehicle to Grid**

I. INTRODUCTION

The introduction of Electric Vehicles (EVs) to the US automobile market has generated a number of new issues with respect to the power grid, such as: impacts to system power quality [1], stresses to distribution system equipment [2], and limits to generation capacity [3]. A commonly overlooked concern, that can impact future large scale deployment of commercial EV charging stations is the excessive electric demand cost for Commercial and Industrial (C&I) users of electricity. C&I rate payers consume approximately 61% of the electricity generated in the USA as shown by the DOE pie chart in figure 1. These C&I rate payers are charged for electricity usage through a peak kVA demand billing structure that differs from the common residential customer kWh rate structure [4]. The peak demand charge for a C&I consumer can easily reach 50% or more of the monthly electricity bill dependent on the type of load connected. For example, the peak demand charge was over 50% of the total monthly electric bill for multiple months in 2010 at the University of Louisville [5].

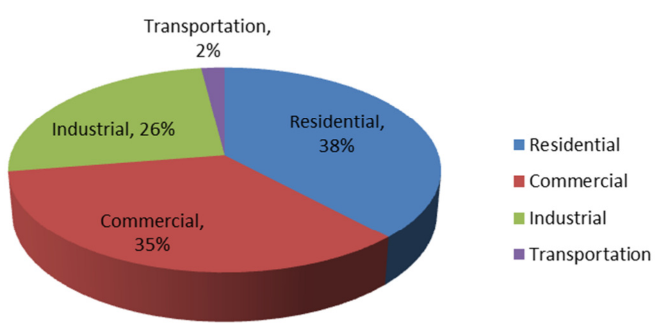

Figure 1: Electricity usage by major consuming sectors (2010) [6]

An EV charge forecasting algorithm has been proposed in [7] that can help limit or eliminate the effects that EV adoption would cause in C&I environments. The algorithm is to be implemented into a Power Monitoring and Control System (PMCS) that will provide the ability to control when EV charging stations can be used, so that the EV electricity demand will not increase the maximum overall kVA demand for the customer. In addition, the PMCS proposed here provides a platform to enable other strategies such as Vehicle to Grid (V2G) [8] and Vehicle to Vehicle (V2V) charge sharing topologies. The PMCS provides a communication link between EVs, charging stations and utility meters so that all system components form a smart grid of intelligent electrical devices.

II. PROBLEM: PEAK DEMAND COST OF ELECTRICITY FOR C&I CHARGING STATIONS

A. *Industrial / Commercial Electric Billing Structures*

Both residential and C&I customers pay a combination of electricity consumption (kWh) and demand charges (kVA or kW) for energy consumed. However, since energy consumption and demand vary greatly among C&I customers, those customers pay for energy usage by means of a different billing structure than residential customers as shown in Equations 1 and 2. These equations are representative of billing structures found in the southeastern USA where coal serves as the primary source of electricity.

$$Total\ Cost_{Residential} = kWh * \$0.0890 \quad (1)$$

$$\begin{aligned} Total\ Cost_{Commercial} = {} & kWh * \$0.03226 \\ & + MaxkVA_{Peak} * \$5.70 \\ & + MaxkVA_{Int} * \$4.40 \\ & + MaxkVA_{Base} * \$2.64 \end{aligned} \quad (2)$$

Many utilities across the US charge a single specified rate per kWh, which includes a built-in demand charge for residential customers (Eq. 1). On the other hand, C&I energy consumers commonly pay a combination of separate charges (Eq.2), one for energy consumption (measured in kWh) and others based on energy demand. The demand charge is calculated based on monthly 15-minute time averaged kVA data. As shown in Eq. 2, this demand charge is divided into 3 portions each having its own specified time interval during the day. This Time Of Use (TOU) rate structure, with three separate rates for peak, intermediate, and base periods, penalizes the consumer for energy use during high demand periods. The total demand charge is determined by taking the maximum 15-minute time averaged kVA demand for each demand window (Peak, Intermediate, and Base) and multiplying it by its respective charge rate and then accumulating the results. Also, note that C&I consumers are commonly billed for demand based on kVA instead of kW which penalizes consumers having a poor power factor.

Additionally, the TOU rate structure varies the hours of the three demand periods seasonally. For example, during summer months, the peak demand window may occur between 1:00pm and 7:00pm. In the winter this peak period may be between 6:00am and 12:00pm. This poses a serious issue in that uncontrolled EV charging can cause peak level increases in these demand windows since charging activity would coincidentally fall directly into these periods. Therefore, a system such as the PMCS proposed in this paper is essential to prevent the negative effects of uncontrolled charging. Additionally, such a system may be optimized to perform services such as load shifting or shoulder extension, resulting in positive economic benefits.

B. *Effects of EV Chargers*

A simple calculation, shown in table 1, demonstrates the effects that uncontrolled EV charging can have on the energy cost paid per month for C&I consumers using the rate structure shown in Eq. 2. For a worst case scenario, where EV charging is uncontrolled and the resultant increase in demand occurs during the peak demand window, cost increases were calculated for various numbers of EVs introduced to the University of Louisville microgrid. This figure is an estimate only and will vary for specific communities. However, it proves the impact EV charging can have on C&I consumers. 90% of the increase in total cost is due to the increase in overall system demand creating a great disincentive for large scale EV adoption. The PMCS proposed here will eliminate this increase in demand cost by limiting EV charging when the peak demand is experienced, based on all other loads on the micro grid. Therefore EV charging loads will not drive the peak demand for the consumer, due to intelligent load shifting and adaptive charge control.

Table 1: Effects on energy and demand charges for various penetration levels of EVs on UofL campus.

Number of Evs	Energy cost per Month	Peak Demand cost per Month	Total cost per Month
1	$5.16	$46.40	$51.56
10	$51.62	$463.98	$515.60
100	$516.16	$4,639.80	$5,155.96
1000	$5,161.60	$46,398.00	$51,559.60

Assumptions:
- EVs require average of 50% charge
- Charging occurs during peak demand window
- University of Louisville billing structure used
- Chevy Volt used to determine added load

III. Solution: Power Monitoring and Control System (PMCS)

In an effort to reduce or eliminate the substantial demand charge increases, the following charging control system is proposed [9].

A. *System Design*

The implementation of an accurate control system for EV charging requires the measurement of a number of variables. These include: real-time energy usage and demand readings for the consumer, instantaneous state of charge of the EVs connected to the system, number of EVs requiring charge, and number of charging stations available for use. The PMCS proposed here will assure that all devices will intelligently work together to provide the optimal energy footprint for the consumer while assuring that all EVs receive a complete charge in a reasonable time. The overall system design is comprised of few elementary modules. These are shown in figure 2.

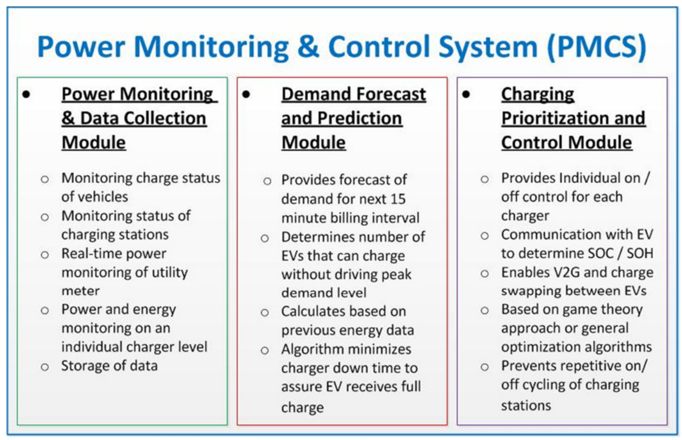

Figure 2: Proposed functionality of the Power Monitoring and Control System (PMCS)

The first module of the PMCS is responsible for real-time data collection from a variety of sources. This module communicates with the customer's utility meter to collect energy and power data, the charging stations to determine energy usage and charging status, and the vehicles to determine State Of Charge (SOC) and State Of Health (SOH) of the vehicle's battery system. Data storage is provided by the data collection module for historical data trending that is used to further refine the operation and performance of the PMCS throughout its lifetime.

One primary obstacle that must be overcome for this system to work properly is the unpredictability of the consumer's energy load profile and the associated demand peaks. These peaks must be forecasted in advance through processing of historical data and current demand trending since they do not occur regularly, which is the nature of electrical loads on a large microgrid. The second module provides peak prediction and forecasting which is utilized to determine the number of EVs that are allowed to charge during the next 15 minute demand interval. Several forecasting algorithms have been studied in [7] including a simple extrapolation model, a previous week extrapolation model, and a regression forecasting model. Each model was simulated using historical energy data from the University of Louisville. The eventual goal of these algorithms is to minimize charging outages and eliminate demand peak increases. By limiting charging outages it can be assured that all vehicles will receive a full charge assuming the vehicle is connected for an adequate amount of time (i.e. slightly longer than the normal vehicle charge time of 2-4 hours.) Figure 3 plots the performance of the three algorithms tested in [7]. Ongoing research is refining the algorithm to optimize the forecasting performance.

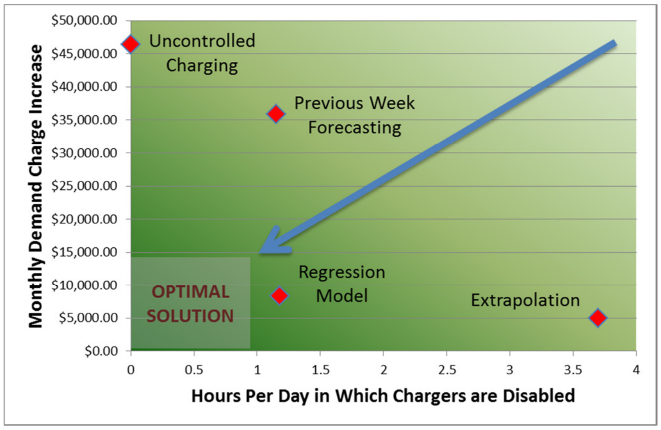

Figure 3 - Plot showing tradeoffs between various forecasting algorithms tested.

In the event that the forecasted number of vehicles allowed to charge in the subsequent demand window is less than the number of vehicles connected, a charging priority is determined and specific charging stations are temporarily disabled until the forecast allows for more vehicles to charge. The third module of the PMCS provides this capability. Charging priority is given to EVs with lower SOC over vehicles with higher SOC in an attempt to create a fair and impartial charging environment. In addition, control limits are provided to prevent cycling of charging stations on / off during successive 15 minute intervals as this cycling could be harmful to the EV's batteries and the charging infrastructure.

Additionally, PMCS communication capabilities will allow for other smart grid technologies to be implemented such as Vehicle to Grid (V2G) and Vehicle to Vehicle (V2V) charge sharing topologies [9, 10]. In periods where a peak demand is measured, V2G can be used for peak shifting or shoulder extension assuming adequate energy is available in the combined BEV storage of the charging system. Also, V2V can be used for charge equalization between BEVs when charging is halted during peak demand windows to create a fair charging environment. The PMCS in conjunction with the power electronics required for injecting charge back onto the grid will work together to enable these valuable technologies (Fig. 4).

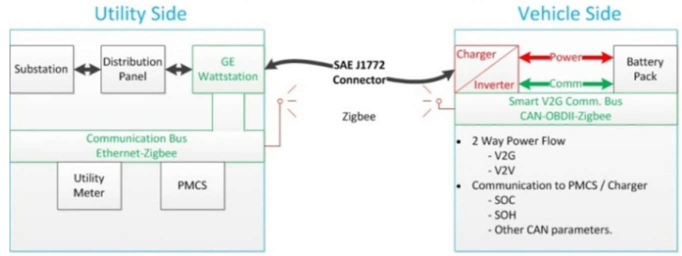

Figure 4: Smart V2G / V2V integrated system

B. Control Algorithms

Advanced control algorithms are required to accomplish the required tasks for both charge control and V2G / V2V topologies. The control algorithms used are divided into two major components. The first provides demand forecasting and the second provides agent based charging control. Ongoing research at the University of Louisville [7] has studied various forecasting models used to determine the number of EVs allowed to charge during each demand interval throughout a day without increasing the overall system demand. Of these algorithms, it was found that a regression model provided the best behavior (Fig. 3) by minimizing the increased demand and maximizing charging time per day. Additional forecasting models such as game theory, reference class forecasting, neural networks and consensus forecasting are also in consideration for the final PMCS design.

The second major component of the control algorithm is responsible for managing charging stations in the event that the forecast provided does not allow 100% charging. This algorithm assigns a priority to vehicles based on their state of charge and other factors including battery state of health, and time constraints required for charging. Additionally, this algorithm also determines when it would be beneficial to enable V2G or V2V charge transfer topologies. The process of demand forecasting and charging station control repeats every demand interval. Figure 5 represents the generalized decision diagram traversed by the control algorithms implemented with the PMCS.

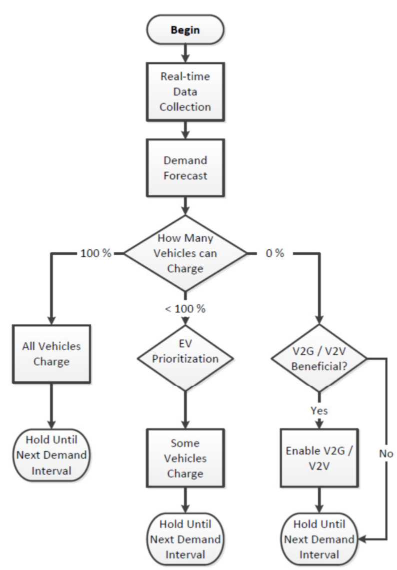

Figure 5: Control system decision diagram.

C. Communication Capabilities

A wireless Zigbee mesh network links the various system components connected to the smart charging system. A link between the PMCS and charging station allows intelligent control of power flow operations with regard to peak demand decisions at a system level. The charging station can also pass its measured data to the PMCS for better system awareness. On the BEV side, a Zigbee to CAN translator is under development for the OBDII connector standard to pass information regarding vehicle information to the charger and PMCS [10]. Information from the BEV such as State of Charge (SOC) and State of Health (SOH) of the battery pack are used to facilitate the systematic charging control. In addition, a link with the utility power meter is required for measuring real-time energy demand for the micro grid. With these communication links in place, the PMCS system is aware of the SOC of each member of the network and is capable of making control decisions about each BEV's charging in light of current utility demand levels, providing a systematically smart implementation.

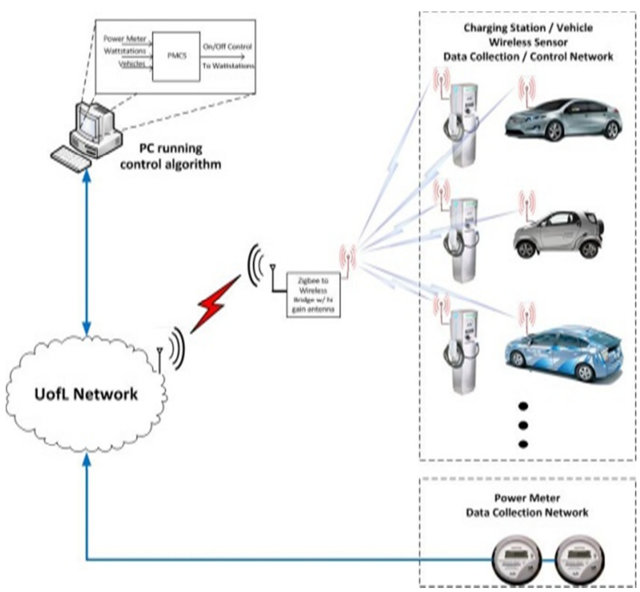

Figure 6: Intelligent BEV charging system network showing communication between system components.

IV. Conclusions and Future Directions

The systems described here are currently under development and will soon be implemented into the University of Louisville EV charging test bed shown in Figure 7 to prove their practicality. The University of Louisville currently has 6 GE Level II Durastation charging stations installed for use in this study, with intent to install 9 more. In addition, UofL owns 3 electric vehicles including a GEM, Wheego Whip, and a Toyota Prius (converted for PHEV use) to be used in the pilot study. As EVs become available in the Louisville area market, university employees and students will be invited to participate in the EV charging test bed as shown by the Chevy Volt in Figure 7. Measured results will be collected and presented proving the benefits of such a system after all system components have been fully developed and tested.

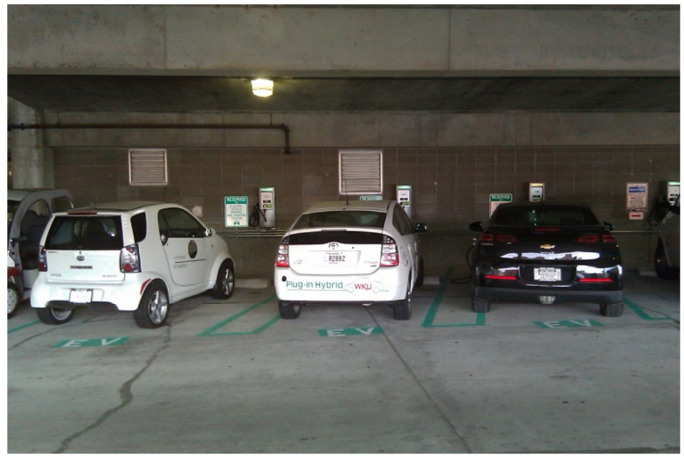

Figure 7: University of Louisville EV charging test bed showing a GEM, Wheego, Prius plug-in and a Volt being charged (L-R).

In addition to the charging infrastructure that is currently in place at the University of Louisville, present work is focusing on developing a universal zigbee interface for vehicle data collection through the standard OBDII vehicle port [10]. Also, a modular interface for reading real-time energy pulses and communicating with the incoming power meters for the campus is under development. This system is currently being implemented using Matlab and Simulink software packages for evaluation purposes and a LabView interface has been developed as well. A screenshot of the initial LabView power meter interface is shown in Figure 8 and some sample data collected in Matlab is shown in Figure 9.

Figure 8 - Screenshot of LabView interface for real-time power meter data collection.

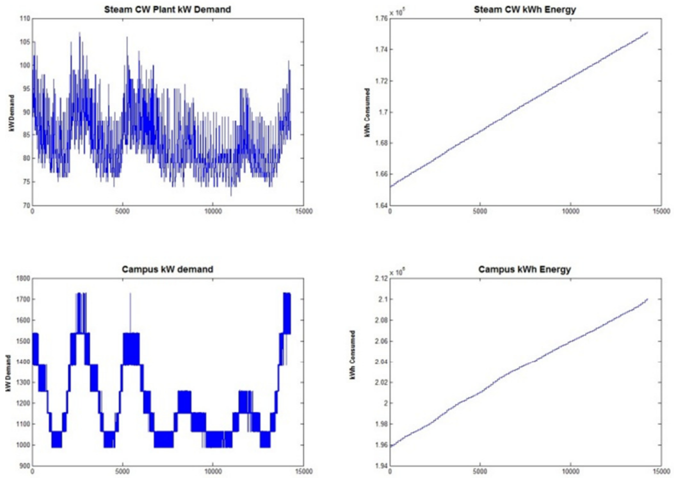

Figure 9 – Matlab plot of data collected from utility meter over 5 day span. This data is fed into Simulink for control and data manipulation.

Implementation of a control system such as the PMCS described in this work is essential to preventing the deleterious effects introduced when C&I energy consumers adopt EVs as replacements to their existing light duty vehicle fleet. It can be easily seen how uncontrolled charging and the resulting demand charge increase can be a vast disincentive for the large scale deployment of EVs, thus limiting the rollout of EVs into the US market. The PMCS proposed here will provide a means to limit or eliminate this disincentive.

V. References

[1] Putrus, G.A.; Suwanapingkarl, P.; Johnston, D.; Bentley, E.C.; Narayana, M.; "Impact of electric vehicles on power distribution networks," *Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE* , vol., no., pp.827-831, 7-10 Sept. 2009

[2] N. DeForest, J. Funk, A. Lorimer, B. Ur, I. Sidhu, P. Kaminsky, B. Tenderich. “Impact of Widespread Electric Vehicle Adoption on the Electrical Utility Business – Threats and Opportunities”. Center for Entrepreneurship & Technology, University of California Berkeley. August, 2009.

[3] C. Yang and R. McCarthy. “Electricity Grid-Impacts of Plug-In Electric Vehicle Charging”. EM Journal, Air and Waste Management Association, pp 16-20. June 2009.

[4] John L. Neufeld (1987). Price Discrimination and the Adoption of the Electricity Demand Charge. The Journal of Economic History, 47 , pp 693-709

[5] 2010 and 2011 electric bills charged to the University of Louisville by Louisville Gas and Electric Company.

[6] “Use of Electricity”. 22 July 2011. Retrieved 13 October 2011. http://www.eia.gov/energyexplained/index.cfm?page=electricity_use

[7] A. Halbleib, M. Turner, and J. Naber. “Control of Battery Electric Vehicle Charging for Commercial Time of Day Demand Rate Payers”. IEEE Power and Engineering Society Innovative Smart Grid Technologies Conference. Washington, DC. January 2012.

[8] "V2G : Vehicle to Grid Power". June 2001. Retrieved 13 October 2011. http://www.udel.edu/V2G/

[9] J.Naber, A. Halbleib, M. Turner, “Peak Power Monitor and Control for Shedding Load and Reducing Electric Demand Charges”, University of Louisville Patent Disclosure, May 2011.

[10] J. Naber, M. McIntyre, N. Jewell, “A Zigbee-Based Wireless Interface to the OBDII Automotive Port and an EV Charging Station”, University of Louisville Patent Disclosure, September 2011.