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Smart Electric Vehicle Charging Infrastructure Overview

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***Abstract*—WINSmartEV™ is a smart electric vehicle charging system that has been built and is currently in operation. It is a software and network based EV charging system designed and built around the ideas of intelligent charge scheduling, multiplexing (connecting multiple vehicles to each circuit) and flexibility. This paper gives an overview of this smart charging system with an eye toward its unique features and capabilities.**

***Index Terms*—EV, PEV, charging, smart grid, multiplexing.**

I. INTRODUCTION

The demand for charging infrastructure, including charging stations in parking structures and garages is more important as the EVs on the road multiply. For long distance commuters, an available charging station may be a critical requirement to ensure the ability to finish the round trip and make it home. Even when charging is not critical, many EV drivers may plug in to alleviate range anxiety or to shorten the charge discharge cycle and decrease battery wear. A scarcity of charging stations may make EVs less convenient and contribute to range anxiety resulting in less people embracing the use of electric vehicles. Furthermore, if charging infrastructure is available at work, smaller batteries and therefore less expensive vehicles are required to meet consumer's needs [1]. Beyond the physical existence of charging stations, several critical needs must be filled to meet the increasing demand for charging infrastructure, including the grid capacity and the electrical circuits that make charging possible. One solution is charging stations that service multiple vehicles at the same time with a given infrastructure. Multiple parts of the infrastructure need to be shared in order for a charging station to truly service multiple vehicles simultaneously. The charging system needs to share the plug port by safely plugging in multiple vehicles at once, it needs to share the circuit by rationing the available power in order to not overload the circuit, and it needs to share the grid capacity by intelligently scheduling charging in order to avoid peak consumption. To meet this demand, an EV charging system has been developed that safely multiplies the number of EVs that can be connected to a circuit by rationing the power allotted to each EV.

Current EV charging systems include charging networks such as DBT[1], ChargePoint [3], and ECOtality [4]. These EV charging networks focus on providing EV chargers with the ability to identify users and take payments for public charging. Intelligently sharing grid infrastructure resources has not been emphasized in these networks. Work has been done in modeling and algorithms for smart EV networks [5]-[7]. Moving beyond modeling, WINSmartEV™[8][9] is a demonstration EV charging network currently in operation. It is a software and network based EV charging system designed and built around the ideas of intelligent charge scheduling, multiplexing (connecting multiple vehicles to each circuit) and flexibility. The system is neutral about the hardware, the control center and network that interconnect it with all the parts of the system. Much of the design for the system has been described [10]-[13]. However, no summary or commentary of the current embodiment of the system has been published that would provide a convenient reference in understanding this system. This paper gives a summary and commentary of this smart charging system with an eye toward its unique features and capabilities. This paper begins by briefly describing the control system and its basic requirements for the system to function. Then it describes the EV chargers, how they operate and how they connect to the control system. Then, this paper describes the control system in more depth before commenting on its capabilities for configuration and extension.

II. CONTROL SYSTEM

A. Control System Overview

To obtain the full benefits of intelligent EV charge scheduling, decisions need to be made at a central location that will optimize the overall system. Other decisions may need to be made locally, without a server wait time, such as when safety is a concern. A

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software based system will allow the intelligence to be upgraded (as needed) and the system integrated with other devices and networks as network of devices as shown in Figure 1. The server may communicate with any entity interested in the charging of EVs, including the user, the vehicle, the EVSE (Electric Vehicle Supply Equipment), grid devices, and relevant external entities. The data may include critical information required for initializing the charging process such as the user/vehicle account ID, payment information, and the port or device where the EV is connected. Data may also include information that is not critical to charge initialization but may be helpful to optimize the charge scheduling, such as the state of charge of the battery, the power availability, weather and power consumption forecasts, condition of the power transformer used by an EV charger, and demand response or price signals from the grid.

The EV charging systems software based controls may be in the cloud, or on a specific server with internet access. The system is network neutral, it can communicate with the routers that control the EVSEs through Ethernet, WiFi or cell phone data network such as 3G. The router communicates with the relays through Zigbee so that only one router can control multiple charge boxes. The J1772 EVSE device communicates with the EV through the charge cable. The user and vehicle identification are communicated through an internet enable device such as a smart-phone. It is also able to connect other devices to the network in order to accomplish tasks such as inputting user/vehicle ID and charge port ID through RFID or other type of scan and communication systems. The central controller for the current implementation of this system is located on a server connected to the internet. Users communicate with the system through internet connected devices such as a smartphone or computer. The EVSEs also communicate with the server through the internet. This deployment has devices connected directly to the internet through Ethernet, WiFi, and 3G. It also has devices that connect to the internet through local communication to other devices with direct internet connections. The local communication systems in this deployment include WiFi, Zigbee and PLC (Power Line Communication).

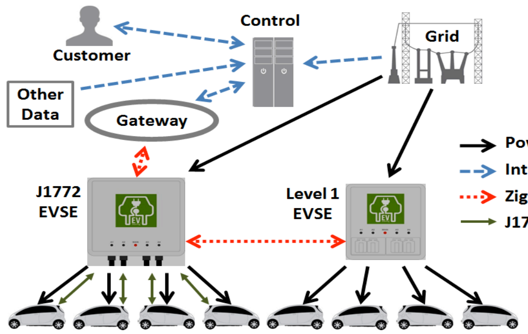

Figure 1. Network Architecture

B. Charging System Communication Requirements

In an intelligently controlled EV charging system, the controller must obtain basic information to make decisions and fulfill the required tasks such as track users, queue charging, take payment, track power consumption, allocate resources, etc. The first piece of data that the control center requires to begin a charge sequence is user/vehicle identification and the charge point that the EV is connected to. Correct mapping of each user/vehicle ID with the ID of the charge point it is connected to, is critical. This ensures that the proper charge point is energized and provides power to the customers EV. Correct mapping also facilitates accurate payment transactions, optimal resource allocation, and statistics tracking to enhance the system. The current implementation of the EV charging system requires the user to have signed up for an account. When the user arrives at a charge port, the vehicle must be connected to an EVSE port and the port ID must be noted in order to relay that information to the control server. Users log into the EV charging system's control website with an internet enabled device such as a smart phone or a computer, identifying oneself or the vehicle, then choosing from the menus the identification of the charging station and the charge port the vehicle is plugged into. In this way the control server has associated the vehicle or user with a given charge port and charging can be initialized. This method works, but has a few shortcomings. It requires the user to have an account, and the user may find the process cumbersome. These issues can be overcome by adding features such as accepting credit cards and automatic user identification.

SAE J1772 is a North American standard for connecting EVSEs to EVs. This standard includes the cables, the communication interface and the safety system requirements. The communication between the EVSE and the EV through the J1772 system is limited to the state of cable connection, whether devices are ready to power up, the electric voltage and current available to the vehicle to charge. No vehicle ID or battery charge information is communicated through the J1772 cable. In order to obtain a vehicle ID or battery state of charge, other communication channels must be implemented. Once the control server has the vehicle/user ID and the ID of the charge port the vehicle is connected to, the server can put the vehicle into the charging queue and initiate charging as appropriate. The charge sequence and queuing will depend on the algorithms implemented in the server. How the EVSE reacts to charge instructions depends on the type of EVSE. There are two types of EVSEs in the deployed charging system. The first is a level 1 only, trickle charge device that that turns 120V household outlets on and off while allowing the 120V EV cable provided with each EV to fulfill all the J1772 communication protocols and safety requirements regarding EV charging. The second is a level 1 or 2 box that uses J1772 cables to connect directly with the EVs. This EVSE fulfills all the standard J1772 communication and safety requirements.

III. EVSE DEVICES

A. Trickle Charge EVSE

The level 1, trickle charge, EVSE does not connect or communicate with the EV directly. Each EV comes with the portable, 120V, trickle-charge cable that plugs into standard household 120V plug (NEMA 5-15). The other end of the trickle charge cable has a standard EV charging plug (SAE 1772) plug that connects to the EV. On the cable, in between these two plugs, is a box that contains the electronics required to communicate with the EV and initiate the charging protocol. The electronics in the cable box automatically initializes the charging protocol whenever power is provided to the 120V plug, and disengages when power is removed. Therefore, the action of this cable can be ignored and when power is provided to the cable, it can be considered provided directly to the EV. When multiplexing power to EVs connected through these cables, if an EV is plugged in to the outlet, charging can be started and terminated by simply providing and removing power from the outlet.

The level 1 multiplexing EVSE for current implementation consists of a box with 4 outlets attached to the outside where customers can plug in the 120V EV portable trickle-charge cable. Above each of 4 outlets there is an indicator light that indicates which outlet is provided power. There is a fifth light that indicates whether or not the charging box has power and is in service. Inside the box, there are 4 relays with metering capability that both turn the power on and off to each outlet and measure the current to ensure that the device is truly off. A router inside the box communicates between relay/meters and the control server.

The main function of multiplexing is to share the available power among multiple EVs. Since the level one box does not communicate directly with the EV, the amount of power that an EV pulls cannot be controlled. Therefore, to ensure that the circuit does not overload, the control algorithms dictate that only one EV (at a time) can charge per circuit. A redundant system first turns off the power to any charging EV, and then checks the current flowing through each relay to ensure that no current is flowing before proceeding to engage power to the next EV in the queue. This redundant system ensures that the circuit is never overloaded. Because software controls the turning off and on the charging, many different algorithms can be explored for scheduling the EV charging. These algorithms can take into account time of arrival, state of charge, end charge time, grid stability, price and any other factor relevant to EV charge scheduling.

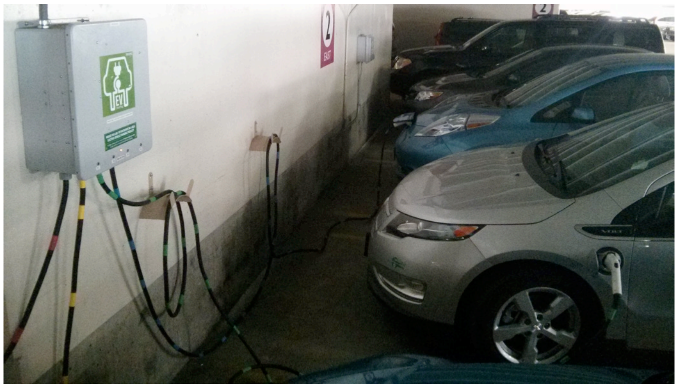

Figure 2. Level 2 J1772 EVSE

B. J1772 EVSE

The multiplexing J1772 EVSE must incorporate all the J1772 standards, cables, and protocols. In addition, it must connect multiple EVs at once and safely provide optimal charging. To accomplish this, the J1772 charging device incorporates all of the capabilities of the trickle charger including the communication router, 4 relays for control power and electrical metering. Furthermore, it includes systems that communicate with the EV to let the EV know it is connected and how much power is available, shut power off if the cable is disconnected and provide ground fault protection (GFCI) capabilities that shut power off if a fault is detected. A picture of a deployed J1772 multiplexing EVSE charging multiple EVs at once is shown in Figure 2. The J1772 standard was developed to provide a high level of consumer safety. The standard requires that no part of the interface between the charging station and the EV should be electrified until the charge cable has been properly connected to the EV – a precaution against the possibility of the user getting shocked. The EV can detect the presence of the J1772 connector and the charging device can detect the presence of the EV. Only when a J1772 cable is connected does the charge procedure begin, and only after the charge procedure has started is the cable electrified. If the cable is disconnected while charging, the EV and the EVSE will immediately detect the change in state and disconnect power to the cables at their respective ends thereby de-energizing the cables and rendering them safe.

A pilot signal is used to allow communication between the EV and EVSE. The pilot signal is in the form of a PWM signal created by the EVSE. Both the EV and the EVSE can detect changes in the pilot signal. When no EV is connected to the EVSE, the EVSE detects no changes to the pilot signal. When the J1772 cable is plugged into the EV, a circuit in the EV creates a resistance between the pilot signal and ground that changes the amplitude of the square wave. This change in amplitude signals to the EVSE that an EV is present. In order to begin charging, the EVSE energizes the charge cable and changes the duty cycle of the PWM signal to indicate to the EV the amount of power available. Only once the EV receives this information, does it activate its charging equipment to begin charging.

The J1772 charger must shut down if a ground fault is detected. A ground fault is any stray current that is not passing through one of the power conductors. This current needs to ground somewhere; and potentially passing through a person poses a severe danger. Any difference in current through the two power conductors is a danger that is prevented by the ground fault circuit interrupter (GFCI). The GFCI detects a difference in the two conductors and quickly shuts off the power. This is accomplished in the J1772 box with a current transformer that outputs a small voltage in proportion to the current difference in the two hot wires. The voltage is then amplified and used to shut down the coil voltage to the power relay, shutting off power the EV [14].

C. EV Charge Device Configurations

With the average commute of 12.6 miles [15], and a Nissan Leaf getting 29kWh/100mi [16], the energy required to recharge the EV after the average commute is 3.7kWh. A dedicated, 30A (40A peak), 240V circuit supplying a level 2 charger can supply 7.2kW of power, which will translate into 6.6kW going into the battery after inefficiency losses. In this scenario, the average commuter's EV can be recharged in a little over ½ an hour. With 4 EVs sharing the circuit, it only takes 2 hours to recharge all the EVs. If the average commuter will stay at work for 8 hours, the circuit will provide much more power than what will be require to satisfy the customer. Not all situations have the same criteria; therefore, in order to optimally serve the customer's requirements within the limits of the grid resources, both EVSEs can be configured to work with different constraints depending on the available grid resources and charge requirements. A few scenarios will demonstrate the flexibility with which this system can be configured to suit a given situation.

Installations at malls or other public places where the commute may be longer than average and the EVs may be parked for shorter periods of time; sharing a 30A circuit may not fulfill the customer's requirements. If the level 2 EVSE has a 120A circuit, all 4 EVs can charge at full 30A each. If many chargers with this setup are connected to a single transformer, than the transformer could be a bottle neck. If each EV charges at 7.2kW, than a 100kVA transformer can handle a maximum of 13 of these. In this scenario, a group of 4 or more EVSEs, with 16 or more charge points can charge the first 13 EVs that arrive at maximum charging speed. The control system can run algorithms that limit the power consumed by the EVSEs as a group by putting the 14th EV into a queue or lower the power allotment for the other EVs to provide power to the 14th.

If splitting1.5kW (120V, 12.5A) 4 ways with the level 1 EVSE does not satisfy the given set of power requirements, then the EVSE can be configured to split 2 120V circuits between the 4 charge points. This leaves each circuit to be shared by only 2 plug points averaging 0.75kW each. If a 1.5kW level 1 circuit is too much power for 4 EVs, such as at airport parking lots where EVs may stay for long periods of time, multiple EVSEs may be safely connected to one circuit. The average charge required will determine the optimal number of EV plug points to circuit. A 1.5kW circuit can deliver 36kWh/day and 252kWh/wk. Since a Nissan Leaf's batter capacity is 24kWh, a 1.5kW circuit can charge 21 half discharged Leafs in a week. If the average parking time is a week, connecting 20 charge points per circuit would be appropriate. tThis would allow a very large number of EV charge points to be installed without major infrastructure upgrades, just a system configuration. The current implementation includes many level 1 trickle chargers with 4 charge points connected to one circuit. It also includes a number of J1772 chargers, some sharing 1 circuit between 4 EVs, others sharing 2 circuits between 4 EVs

D. System Network Topology

In order to provide the above mentioned flexibility, the central control system needs to be highly configurable. Because this EV charging system is network and hardware neutral, its controls can be any collection of processing and memory capability whether it is a server, a network of computing assets or cloud based. How intelligently the control system manages the EV charging with respect to fairness to the users[17], the stabilizing effects it has on the wider grid and amount of money it can save by optimally and dynamically scheduling EV charging is only limited by the capabilities of the software, the computing hardware and the network that support it. The system can be set up to aggregate demand and participate in the energy market, it can be set up to respond to DR (demand response) signals, or it can focus solely on meeting the customers demand. It also can be configured to work seamlessly with any microgrid controllers.

There are no constraints on how different local EV charger controllers communicate with each other. The network topology between charging systems can be optimized to match the given circumstance. These topologies may range from one central controller directly controlling all EVSEs, to local networks connected to a more centralized controllers that branch together making a tree like topology. The optimal topology depends on the goals of the system and how to best interact with the larger grid. There are some opposing motivations. A centralized controller may give the network more influence over the larger grid, making it a bigger asset in terms of DR and grid control. A centralized controller may not be as robust as more localized controllers. Furthermore, a localized controller that directly communicates with the local grid may better respond to the local needs of the grid in terms of power quality and response to local shortages and outages. The current setup uses one central server connected to a network and controls all the EVSEs on the network, regardless of where the EVSE is located. New, locally controlled networks will be setup to control independent charge systems. In the future, these independent networks could be connected with another central controller that allows the larger network that can influence the grid and respond to DR signals on mass.

E. Scheduling Algorithms

The basic functions of the control system is to map a EV (whether it is identified by the driver or the vehicle) to a charging station, then schedule and control the EV charging. Once a mapping is implemented, each charge schedule may be customized by the requirements of the consumer, the requirements of the EV charge device, the local circuit or the grid requirements. The level of sophistication required for the controller depends on the level of sophistication in which these duties are required to be executed. If all the EVSEs are the same, no multiplexing is implemented, and no users or usage is tracked, then the control system can be quite simple. This control system would only require a database of similar chargers mapped to temporary user IDs, all charging following a single algorithm. If each charge point has its own power capacity and rules of use, a more complex system is required. These rules of use may depend on what type of multiplexing is being implemented or the limits on the local grid. When accounts are used for frequent customers, a database for account holders is required. If consumption statistics are needed, a database for consumption statistics must be implemented. If higher level of charge scheduling is needed, then more intelligent systems can be implemented. These intelligent systems may include forecasting and sophisticated algorithms that balance both the grid and user requirements.

Beyond the critical requirements to keep the power usage within the safety requirements dictated by the local circuits, this EV charging system is neutral concerning the actual charge scheduling. Any relevant information can be used to influence any relevant type of algorithm to schedule the charging. Charge scheduling could be influence by user demands, power prices, and grid requirements in the form of price or DR signals, consumption or the availability of alternative energy resources. Highly developed algorithms may use the forecasting of all the above conditions to take the charge scheduling to another level. Therefore the scheduling algorithms will be constrained by available resources such as computing power, bandwidth capacity and data availability. Given its constraints, the algorithms should be customized to meet the local requirements or policies of a particular situation.

More complex charge scheduling may seek to optimize charging to meet different goals. Some goals may be to stabilize the grid, some may be to more fully meet consumer demands or to more fully utilize sustainable energy resources such as wind and solar. The optimization may be taken into account any collectable and relevant information. There are two general classes of information that may influence any charge scheduling, demand information and supply information. Demand information includes customer side such as state of battery charge, how much charge is required, the urgency in charging, price, priority such as PHEV vs. BEV, and preferences for sustainable energy or cheaper price. Supply preferences include all relevant grid power availability and grid stability information such as DR signals , spot market price for power, power limits on the local transformer, local power quality, and availability of sustainable energy such as wind and solar. In predictive models, weather predictions may be used to predict demand so that charging can be optimized to avoid charging during peak consumption. Because the control system is network neutral, it can gather this information by whatever communication method it is available, and use it to implement any desired optimal scheduling.

In the current deployment the server not only keeps a database of account holders to allow login in and charging, but tracks their usage such as connect time, leave time, amount of power used, weather the EV was fully charged, and the amount of current the EV used over time. The charging algorithms for the EVs are a simple round robin algorithm for the level 1 chargers that work on a first come first serve basis, and a current sharing algorithm for the J1772 chargers. As of yet, this system does not take advantage of its capabilities to respond to DR signals or participate in energy markets.

IV. CONCLUSION

In order to meet the need of an ever growing demand for EV charging infrastructure, a software based EV charging system has been built. It has the ability to optimally schedule charging in order to safely maximize the use available grid resources for charging EVs and thereby maximizing the number of EVs that can be connected to the grid while enhancing grid stability. The charging system consists of a controller connected through the internet to purpose built EVSEs that multiplex electrical circuits. The EVSEs allows multiple EVs to share a single circuit and available grid capacity. The control system is both network and hardware neutral and can connect to other devices and systems through the internet for data gathering and information exchange. Because of this flexibility, the system can grow and change as technology changes.

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