DESIGN OF FAIR CHARGING ALGORITHM FOR SMART ELECTRICAL VEHICLE CHARGING INFRASTRUCTURE

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Design of Fair Charging Algorithm for Smart Electrical Vehicle Charging Infrastructure

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***Abstract*—Smart charging infrastructure is required to meet the growing demand for Electrical Vehicle (EV) charging from ever more abundant EV owners. WINSmartEV™ is a software based smart charging infrastructure that can monitor, control and manage EV charging. It also can use multiplexing to share scarce charging resources among different EVs plugged in simultaneously. By default WINSmartEV™ uses a round-robin algorithm to schedule charging time between EVs charging on the 120V level one charging device. In order to enhance user acceptance of this technology, charge time allocation fairness is defined and an algorithm to enhance this fairness is proposed.**

Keywords—Electrical vehicle charging, power distribution control, smart grids, Wireless LAN, wireless mesh network, Zigbee

I. INTRODUCTION

As the popularity of Electric Vehicles (EV) shift the energy burden from the direct burning of fossil fuels to the electric grid, the electric grid must respond in order to adequately supply this increased demand. The increase in the number of EVs on the road will increase the demand for charging infrastructure of all types, from public fast chargers that will relieve range anxiety to home and garage chargers used for everyday charging. Long distance commuters may depend on charging infrastructure in parking lots and garages to make the return trip home.

They will now have to charge during on peak hours which will stress the grid. The electric grid can respond the increase of on and off peak demand of electricity for EVs by increasing capacity or more intelligently use the currently available resources. These resources include generation, distribution and infrastructure capacity. In order to more intelligently use available resources, an EV charging management system needs to be implemented to handle the peak demand of EV charging, regardless whether charging takes place in a parking garage or at home. The need for a reliable infrastructure for monitoring and controlling vehicle charging is of top priority. In response to this need, a software-based EV monitoring, control and management system, WINSmartEV™[1][2][3], was developed. This smart charging infrastructure is capable of providing power to several EVs from one circuit with multiplexing control. With this smart charging infrastructure, the shortage of energy in a local grid could be prevented by managing EV charging sessions.

The objectives of a smart charging infrastructure include: (1) Reducing overall energy cost to the society and the EV owner; (2) Making charging simple and convenient for the EV owner; (3) Improving monitoring and control of the local power system by managing charging operations of the EVs based on local grid conditions. Therefore, a smart charging infrastructure should include the ability to do the following: (1) Switch between auto and manual mode for EV charging control, (2) switch between charging algorithms, (3) scale the entire system including gateways, algorithm, and user accounts, from single parking structure to entire city (4) integrate station status onto commercial map systems such as Google map, (5) generate visual reports, (6) send Email notification to users for closing charging sessions, (7) Dynamically show available charging stations, (8) differentiate privileges for different levels of users and administrators, (9) keep system secure with features such as Secure Sockets Layer (SSL). A smart charging infrastructure should also have web-based application suitable for any mobile device.

Current commercial EV charging stations like Coulomb[4] and Blink[5] have their own proprietary networks to connect the charging stations in service. Coulomb provides a ChargePoint application programming interface (API) and an OpenCharge protocol for the developers. The current application uses their network to locate available charging stations for its users. It is possible to build the smart charging system by using the existing network with this API and protocols when they are obtained. Other commercial charging stations, Leviton[6] and Clippercreek[7], simply provide basic charging stations without any network features. The simple charging stations could be the platforms for developers to implement their own network services for smart charging purpose. In [8][9][10][11], several charging algorithms and results are presented. However, none of them discuss how to achieve multiplexing control.

Currently, a round-robin algorithm is used to schedule charging in the multiplex charging system WINSmartEV™. In order for EV charge multiplexing to become more appealing to users, fairness in the allocation of charge time should be maximized. In this paper, charge time fairness is defined and an algorithm to maximize this fairness is proposed which will be described in the following sections.

II. EXISTING WINSMARTEV™ SYSTEM

This section introduces the WINSmartEV™ smart-charging infrastructure, the existing network architecture as well as the design of the WINSmartEV™ smart charging station. Fig. 1 shows a WINSmartEV™ four-channel SmartPlug station in a UCLA parking garage, and Fig. 2 shows the outlook of a 4-channel SmartPlug station.

Fig. 1. Installation of a 4-channel SmartPlug station

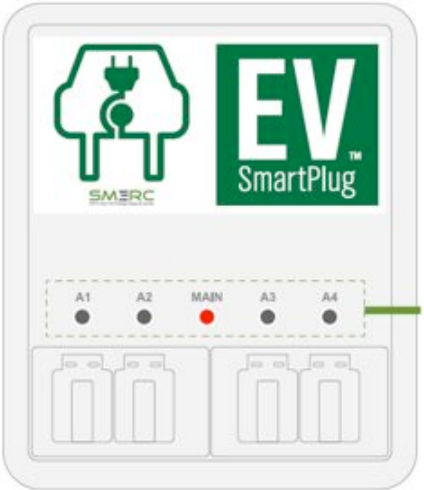

Fig. 2. Outlook of a 4-channel SmartPlug station

Currently, an authorized user is able to check available charging stations, start or stop EV charging, check the charging status, view monthly charging records, and manage user account via a mobile device. A screen shot of the mobile app used is shown in Fig. 3.

Fig. 3. Screen shots of User Control Center

The network architecture of the WINSmartEV™ smart-charging infrastructure is illustrated in Fig. 4.

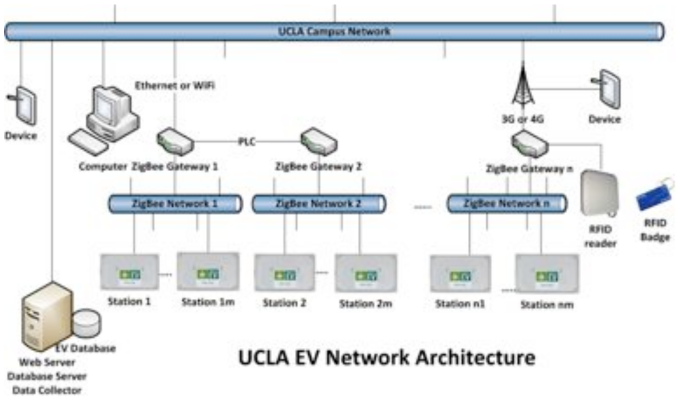

Fig. 4. WINSmartEV™ Infrastructure

By running charging or scheduling algorithms, a SmartPlug station in Fig. 2 can share the power a single 120V power source with four EVs. A standard 15amp 120v outlet can only handle 12amps continuously. A 120v trickle charge for and EV is always 12A; therefore, the station can only turn on 1 channel and charge 1 EV at a time. Because of this constraint, the charging algorithm is the central component of the charging operation. Currently, the station runs round-robin charging algorithm for multiple EVs. The details of round-robin charging algorithm will be discussed below and later it will be compared to the fair charging algorithm being introduced in section III.

A server-based aggregate charging control system controls all charging stations through multiple protocol gateways with 3G connection. 3G communication is necessary due to its applicability anywhere a cellular signal exists, especially where wired or WiFi communication is unavailable. The aggregate charging control system is employed to monitor and control charging activities. There are four major software components in the system including: Database, Station Controller and Data Collector, System Monitoring and Control Center, and User Control Center as shown in Fig. 5. The details of the components are depicted in the following sub-sections.

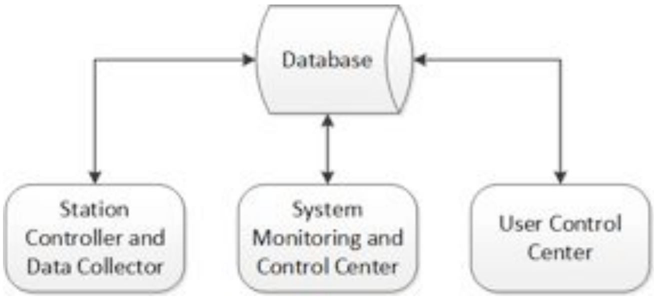

Fig. 5. Four major components in Smart Charging Infrastructure

A. Database

The database stores all the information of gateways, stations, charging algorithms, EV users, parking lots, and cities. The charging status, user charging records and other management information are also recorded in the database.

B. Station Controller and Data Collector

The Station Controller and Data Collector sends commands to the charging station to control charging while gathering and accumulating power information. The station controller automatically controls the stations based on the selected charging algorithms such as real-time algorithms or scheduling algorithms. Round-robin and FCFS (First-come, first-served) are the examples of real-time algorithms. Scheduling algorithms can be developed either by time, energy price, or energy amount. The station controller has the flexibility and extensibility for the administrator to update the charging algorithm. While the station controller controls the stations, the data collector periodically collects the status of each station. Fig. 6 shows the round-robin charging algorithm implemented in WINSmartEV™ system.

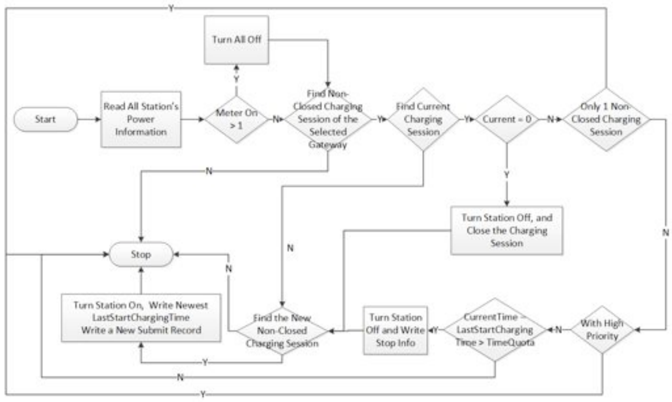

Fig. 6. Round-robin Charging Algorithm

The server's operation flows include enable charging and disable charging. In each routine, two processes need to be done including read meter on/off status and read meter's power information. The return values of read meter's power information are voltage, current, and active power. In the enable charging routine, the server sends out the command to turn on the relay of the meter. After that, the server will wait for $T_{waiting}$ seconds and send out the read power information command. For the disable charging routine, the server will turn off the relay of the meter. The server will then wait for $T_{waiting}$ seconds and send out the read power information command to make sure there is no current drawn on the channel.

C. System Monitoring and Control Center

The System Monitoring and Control Center is designed with multiple purposes as shown in Fig. 7. The charging stations can be manually controlled and monitored by the system administrator. In addition, the administrator is able to setup and manage the parameters of the charging stations including the IP address, selection of charging algorithm, power source, etc. The administrator can also edit, manage the user account. The reports of the power usage and charging records are generated from the Monitoring and Control Center.

Fig. 7. Screen shot of Monitoring and Control Center

D. User Control Center

The user control center, as shown in Fig. 3, allows the authorized user to check available charging stations in selected parking lot and city, start or stop charging, check the charging status, view monthly charging records, and manage the user account via mobile a device. Currently the EV user is capable of managing his EV charging via mobile phone. The EV user needs to sign in via internet to establish connection to the server.

III. Proposed Fair Charging Algorithm

The user's charge ratio τ can be defined as the ratio of the charge time T_{Charge} and the stay time T_{Stay} in (1)

$$\tau \equiv T_{Charge} / T_{Stay} \quad (1)$$

For a completely fair charging system, the charge ratio τ of each user should be the same. For a fair enough charging system, τ of each user should be close enough. The round-robin charging algorithm seems fair at the first glance. However, from 4 of 16 users' charging records, the distributions of τ are not evenly distributed as shown in Fig. 8.

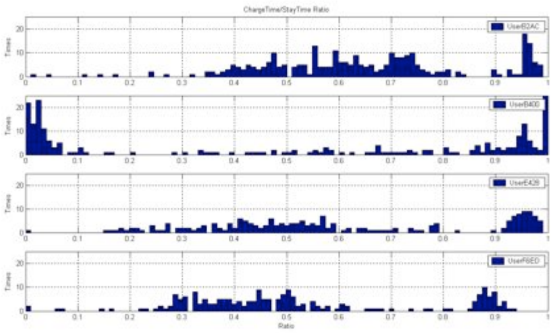

Fig. 8. Charge Ratio Distributions of 4 users.

The four users' mean and standard deviation of the charge ratio, $\mu(\tau)$ and $\sigma(\tau)$, are summarized in Table 1.

TABLE I. MEAN AND STANDARD DEVIATION OF CHARGE RATIO

UserID	Records	$\mu(\tau)$	$\sigma(\tau)$
B2AC	292	0.65	0.19
B400	227	0.53	0.45
E428	202	0.60	0.25
F6ED	208	0.52	0.23

From the statistic view point, $\mu(\tau)$ and $\sigma(\tau)$ can be used to describe more users' distributions. Fig. 9 shows the distribution of 16 users' charge ratio by $\mu(\tau)$ and $\sigma(\tau)$.

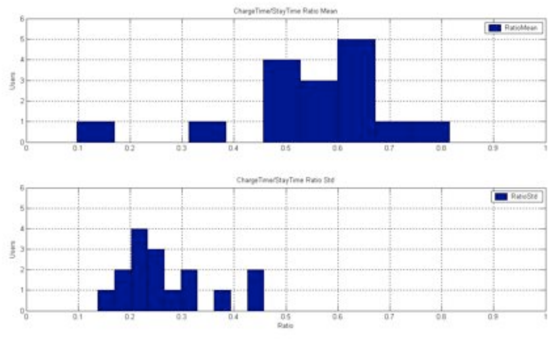

Fig. 9. ChargeTime Ratio Distributions of 16 users

Again, the distributions of $\mu(\tau)$ and $\sigma(\tau)$ can be described by four parameters: $\mu[\mu(\tau)]$, $\sigma[\mu(\tau)]$, $\mu[\sigma(\tau)]$, and $\mu[\sigma(\tau)]$ which are summarized in Table II.

TABLE II. MEAN AND STANDARD DEVIATION OF $\mu(\tau)$ AND $\sigma(\tau)$

Parameter	$\mu[\mu(\tau)]$	$\sigma[\mu(\tau)]$	$\mu[\sigma(\tau)]$	$\sigma[\sigma(\tau)]$
Value	0.56	0.16	0.27	0.09

When a system is fair, every user's $\mu(\tau)$ should be close to $\mu[\mu(\tau)]$. Therefore, both $\sigma[\mu(\tau)]$ and $\mu[\sigma(\tau)]$ must approach 0 as the system approaches complete fairness for each user. Here we define the fairness index α in (2)

$$\alpha \equiv 1 - \{\sigma[\mu(\tau)] + \mu[\sigma(\tau)]\}/2 \tag{2}$$

Only when both $\sigma[\mu(\tau)]$ and $\mu[\sigma(\tau)]$ approach 0, does the fairness index α approach 1. This is used to indicate the fairness of the system. The parameter $\sigma[\sigma(\tau)]$ can be viewed as the convergence of the system. When the system is fair, $\sigma[\sigma(\tau)]$ will converge to 0.

A. Fair Charging Algorithm

In the fair charging algorithm, if the second user's charging session overlaps the first user's session, the sever will predict second user's ChargeTime $T_{Charge}(2)$, change the first user's ChargeTime $T_{Charge}(1)$, calculate and backup the first user's remain charge time LeftChargeTime $T_{Left}(1)$. After finishing parameters calculations, the server will stop first user's session and start the second user's charging session. Before the first user leaves, after finishing certain portion of the second user's session, the charging station will switch back to finish the first user's session before the first user leaves. Fig. 10 shows the concept of the fair charging algorithm.

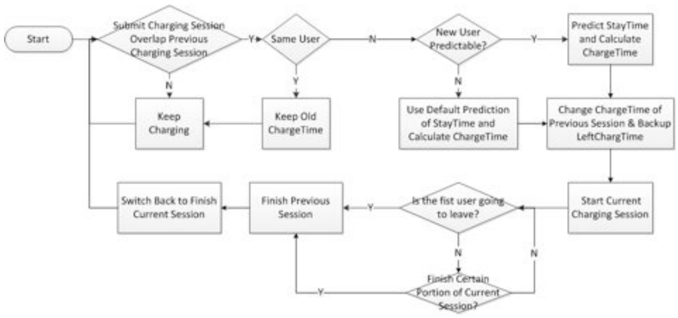

Fig. 10. Flow Chart of Fair Charging Algorithm

If a third user submits a charging request during the second user's session, the software will treat the third user as the overlap user of the second user. The charging station will calculate and backup the LeftChargeTime $T_{Left}(2)$ and stop the second user's session. The third user's session will start after the calculation of ChargeTime $T_{Charge}(3)$. A fourth user will be treated as the overlap user of the third user, and so on.

B. User's Stay Hour Prediction

The Fair Charging Algorithm counts heavily on the accuracy of the prediction of user's stay hour. From the charging records, we found 3 types of people described in the following:

1) Type 1: The distribution of T_{Stay} is independent of the Check-in time $T_{CheckIn}$. In this case, $u(T_{Stay})$ should be larger than $\sigma(T_{Stay})$, and the correlation $\gamma[T_{CheckIn}, T_{Stay}]$ should be close to 0. Fig. 11 shows a sample of type 1 predictable person with $u(T_{Stay}) = 0.11, \sigma(T_{Stay}) = 0.03$, and $\gamma[T_{CheckIn}, T_{Stay}] = 0.067$

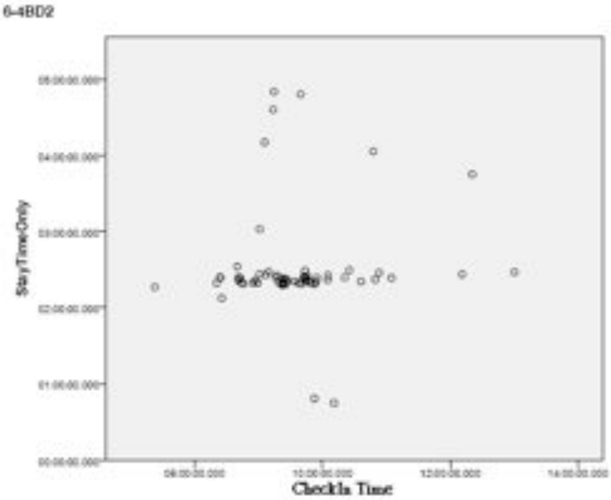

Fig. 11. Sample of Type 1 Predictable Person

2) Type 2: T_{Stay} depends on $T_{CheckIn}$. In this case, the correlation $\gamma\left[T_{CheckIn}, T_{Stay}\right]$ should be a negative value. A simple linear regression function is used to predict T_{Stay} according to the user's charging records. Fig. 12 shows a sample of type 2 predictable person with the correlation $\gamma\left[T_{CheckIn}, T_{Stay}\right] = -0.5984$

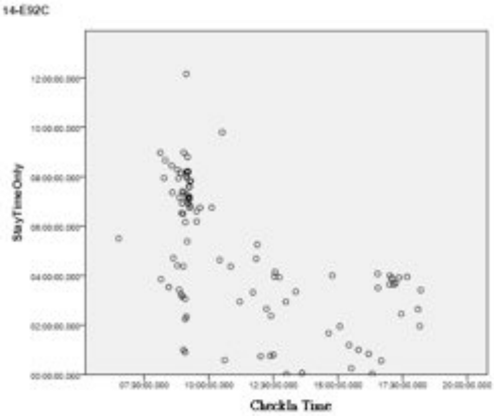

Fig. 12. Sample of Type 2 Predictable Person

3) Type 3: Unpredictable. For those who do not belong to type 1 ro type 2, we use the average stay time of all users to predict T_{Stay}. Fig. 13 shows a sample of type 3 unpredictable person with $u(T_{Stay}) = 5.98$, $\sigma(T_{Stay}) = 13.38$, and $\gamma\left[T_{CheckIn}, T_{Stay}\right] = 0.0398$

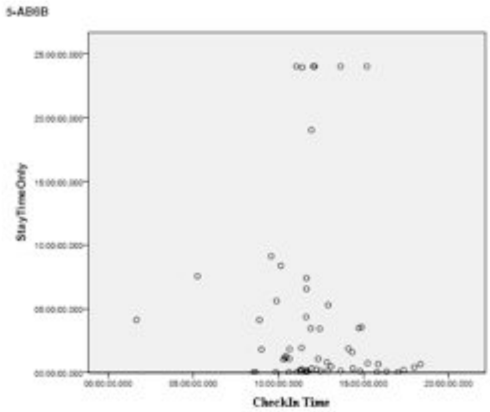

Fig. 13. Sample of Type 3 Unpredictable Person

IV. Experiments and Results

Experimental results of User's Stay Hour Prediction and Fair Charging Algorithm are presented in the following subsections.

A. *User's Stay Hour Prediction*

In order to show to the accuracy of prediction, we define the error rate of prediction $\varepsilon(T_{\Pr edict})$ in (3)

$$\varepsilon\left(T_{\Pr edict}\right) \equiv \frac{\sqrt{\left(T_{Stay} - T_{\Pr edict}\right)^2}}{Max\left(T_{Stay}, T_{\Pr edict}\right)} \quad (3)$$

According to the prediction rule introduced in section III, the users' T_{stay} prediction error rate distribution is shown in Fig. 14. Note that the first and the second charts represent $\mu\left[\varepsilon(T_{\Pr edict})\right]$ and $\sigma\left[\varepsilon(T_{\Pr edict})\right]$ for predictable people while the third and the forth represent $\mu\left[\varepsilon(T_{\Pr edict})\right]$ and $\sigma\left[\varepsilon(T_{\Pr edict})\right]$ for unpredictable people.

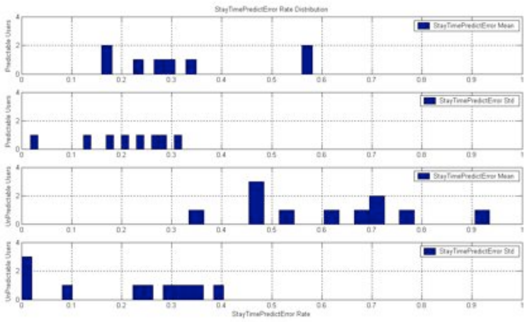

Fig. 14. Prediction Error Rate Distribution

The data shows that the predictable people have better behavior in both $\mu\left[\varepsilon(T_{\Pr edict})\right]$ and $\sigma\left[\varepsilon(T_{\Pr edict})\right]$.

B. *Fair Charging Algorithm*

In the simulation, we use the same Check-In Time in the charging records as the input of the fair charging algorithm. After redistributing the power, the mean and the standard deviation of the ChargeTimeRatio τ are calculated in Table III.

TABLE III. Comparison between $\tau_{RoundRobin}$ and τ_{Fair}

Charging Algorithm	$\mu[\tau]$	$\sigma[\tau]$
RoundRobin	0.6014	0.5561
Fair	0.7281	0.2329

From the simulation results, the increase of $\mu[\tau]$ and the decrease of $\sigma[\tau]$ mean that the users more evenly get more energy from the charging station. To see how the system treats each user, the ChargeTimeRatio τ of each user are separately accumulated. The distribution of $\mu[\tau]$ and $\sigma[\tau]$ of each user is shown in Fig. 15.

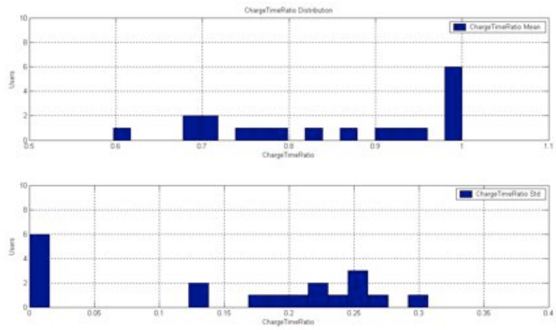

Fig. 15. New ChargeTime Ratio Distribution

The parameters of Fairness and Convergence are summarized in Table IV.

TABLE IV. FAIRNESS COMPARISON

Index	**Parameter**	**Charging Algorithm**	
		Round-Robin	*Fair*
Charge Ratio Average	$\mu[\mu(\tau)]$	0.5770	0.8492
Fairness Condiction 1	$\sigma[\mu(\tau)]$	0.2345	0.1374
Fairness Condiction 2	$\mu[\sigma(\tau)]$	0.2649	0.1509
Convergence	$\sigma[\sigma(\tau)]$	0.4018	0.1138
Fairness	α	0.7503	0.8558

The results show that the Fair Charging Algorithm is fairer to the users compared with the round-robin algorithm.

V. DISCUSSION

With this definition of charge time allocation fairness and an algorithm to maximize it, the user appeal of multiplexing can be enhanced. If the time to switch charging between EVs is close to zero, then the optimization algorithm can be executed so that fairness is being maximized at all times by continuously switching the charging to the EV that will maximize fairness. However, given hardware and network constraints, the period of time to switch charging from one EV to the next can be as high as 5 minutes. If exact stay time of the EVs is known, then fairness maximization can be obtained while only switching charging once, the minimum number of times required. However, if EVs stay time is unknown, then fewer switching may often leave the charge time alocation for each EV vary lopsided and unfair. In real world applications, the switching time is significant and the stay times are predictions with more or less certainty. Given these constraints, the optimal of the fairness algorithm execution would take into account both charge switching time and the confidence of the stay time's prediction in order to find the best time between switching.

VI. CONCLUSION

WINSmartEV™ not only provides an energy efficient, economical, and user friendly smart technology for charging EVs, but also enhances the stability and reliability of the local power system by managing EV charging. WINSmartEV™ not only provides an energy efficient, economical, and user friendly smart technology for charging EVs, but also enhances the stability and reliability of the local power system by managing EV charging. This system also provides the capability of multiplexing in order to more efficiently allocate scarce grind and circuit resources to the maximum number of users. In order to enhance user acceptance of multiplexing, a definition of charge time allocation fairness is defined and an algorithm is proposed to maximize this fairness. With the fair smart charging scheduling algorithm implemented on the server, our infrastructure would serve as one of the key components in the nation wide smart grid application to provide more economical, energy efficient EV charge system.

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