Fast Power Charging Strategy for EV/PHEV in Parking Campus with Deployment of Renewable Energy

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***Abstract*—Electric Vehicles (EV) and Plug-in Hybrid Electric Vehicles (PHEV) are being considered as aspirant competitors of traditional fuel engine vehicles and more attractive goods to consumers in recent years. The current power grid is being challenged by the increasing power demand from ordinary power supply and extract demand of developing power charging stations for EV/PHEV. The architecture and efficient operation of fast power charging stations is becoming a popular research topic both in academia and industry. In this paper, we introduce a candidate EV/PHEV fast power charging station mechanism, based on the combined power resource of current electrical grid and local renewable energy. As the proposed relevant component, the local renewable energy can become the positive power supplement for reducing the integral demand of charging stations to power grid and slowing down the consumption of non-renewable natural energy. A quantitative stochastic scheme is established for analyzing the performance of the outlined system via employing arguments from queueing theory and economics, after clean energy is deployed. The results figures show that the integral power demand can be reduced by arranging our mechanism and the win-win benefits can be shared by utilities and power consumers.**

I. Introduction

In order to reduce the usage of nonrenewable energy resources, foreign oil dependence, and the Green House Gas (GHG) emissions, Electric Vehicles (EV) and Plug-in Hybrid Electric Vehicles (PHEV) have gained popularity in the western world [1]–[4]. This trend is also supported by the improvements in the battery storage technology [1] and incentives offered by the governments to reduce the cost of ownership. For instance, according to [1], more than $250,000$ EV/PHEVs were sold in the first three years of their introduction. It is further projected that 50% of the new car sales will be composed of EVs and PHEVs by year 2050. On the other hand, to achieve the projected market portion charging stations have to be deployed to extent the all-electric driving range.

As the main power supply bases of EV/PHEVs, the design and the operation of the EV/PHEV charging stations are considered as one of the most important research topics in smart grid. Not just as public power charging stations for ground transportation, but such smart grid infrastructures can also be deployed in parking lots, university campuses, and at any other related public places to accommodate the EV demand during daytime. These stations will ubiquitously solve the charge depleting issues of users living in densely populated areas and provide complimentary charging service to customers with garage charging options.

Academia and industry have already established a conductive charging system architecture for electric vehicles as the standards for charging system and details can be found in its updated version [5], [6]. In order to compete against gas-powered counterparts, fast charging technology is highly desired by the EV owners. Fast charging technology also enables utilities to make extra profit by serving customers. On the other hand, the power grid is not designed to serve "energy-hungry" vehicles, and concurrent charging of large amount of EVs will strain the power grid beyond its operation capacity [7]–[10]. To that end, several fast charging station technologies have already been introduced via the exploration in academia and industry [11]–[14].

There has been a growing body of literature on the fast public charging station architecture based on DC charging mode. In [7] Bayram et al. proposed a fast charging station architecture along with an energy storage device, which is employed as an additional power supply to minimize the peak demand fluctuations and protect distribution grid components from failures. From power engineering perspective, Bai et al. [11] proposed an electric vehicle charging station model for the fast DC charging of multiple electric vehicles. An energy storage system connected to the DC bus is employed for solving the sizing problem via using Monte Carlo simulations. The DC bus is established as the bridge to enable energy sharing between chargers. Vasiladiotis et al. [12] focused on a power converter architecture, which includes integrated stationary Battery Energy Storage Systems (BESS) as the power buffers at each converter level for reducing negative influence of the charging station on the distribution grid during AC/DC conversion stage.

For the purpose of surveying the impacts on distribution transformer loading and system bus voltage profiles of the test distribution grid, Yunus et al. [13] provided a stochastic fast charging model in literature. As the necessary measures for

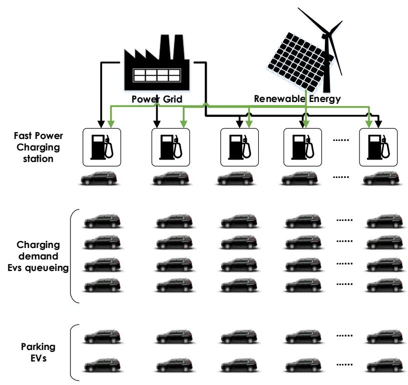

Fig. 1. EV/PHEV Parking Campus with Upgraded Fast Power Charging Station

handling the charging level problem at the charging station, local energy storage and Static Var Compensator (SVC) are required to be deployed at the fast power charging stations. Considering about the reduction of the EV's power charging time and the stress on the grid for avoiding peak power, Song et al. [14] proposed a power charging station architecture with an energy storage system sustains ultra capacitor as the core strain on the system, because of its durability, high power density, and likely further improvements in energy density. Renewable energy resources are recognized as a promising resource for power supply. Deploying distributed generation on fast power charging stations will further reduce the stress on the grid, minimize electricity transmission congestion, and support demand response resources, which will be realized by supporting the stochastic traffic of demand EV/PHEV in random area and save consumer's ordinary and excess charging cost via dynamic pricing policy [15]. In this paper, our main contribution are listed as follows:

1) We define an available and reasonable mechanism for the parking campus with candidate fast power charging station, based on ordinary power grid and more effective supplement from renewable energy.
2) By using a quantitative stochastic scheme, we establish a control model for the power charging queueing in proposed parking campus.
3) Economics interests are introduced into the scheme and equally considered between utilities and power consumers.

The remainder of the paper is organized as follow. In Section II, we describe the considered scenario of parking campus with candidate fast power charging station. In Section III, we explain the proposed mechanism of the charging queueing control system. The system performance evaluation is introduced in Section IV. Finally, conclusions are drawn in Section V.

II. Considered Scenario of Parking Campus with Updated Fast Power Charging Station

A. *Proposed Parking Campus*

Public fast power charging station is recognized as an effective solution for promoting the durability of EV/PHEV during the consumer's daily traffic activities. However, as profiled in the introduction, the additional power demand introduced by the massive penetration of EV/PHEVs will be hardly supported by the current power grid. In this section, we provide a definition of the considered charging station scenario which accommodates large-scale EV/PHEVs demand.

We propose this parking campus located in industrial park or university campus where the customer demand is highly stochastic and thus unpredictable. The goal of the station is to supply wide-range of consumers a certain level of quality of service, by employing a local power charging system based on local renewable energy system (strong power dynamos (wind and solar)) which also includes local energy storage infrastructures as depicted in Figure1. During parking time, each EV/PHEV can choose fast power charging service or not, which depends on the consumer's private willing, the current power status of its automotive battery, and parking duration.

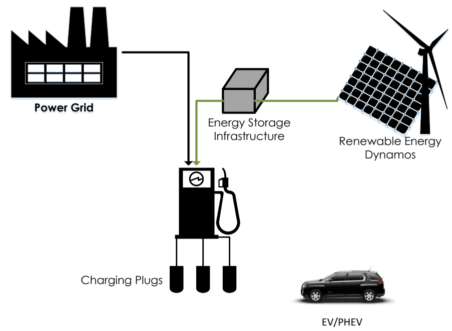

Fig. 2. Architecture of Upgraded Fast Power Charging Station

B. *Updated Fast Power Charging Station*

In this proposed parking campus, the global power demand from grid is dynamic. In order to reduce the probability of overload in local distribution power network and offset electricity transmission congestion, [7] employed local energy storage item on fast power charging station. The local device can be charged by power grid when the charging station is idle. Compared with the fast power charging station scheme proposed in [7], the updated charging station integrates local renewable energy as the additional power support resources. The core insight is the parking EV/PHEVs power demand can be satisfied either by constant power supported by utilities or with the local energy storage devices charged by local renewable energy resources, even directly get charging service from the local renewable energy resources. The architecture of upgraded fast power charging station is presented in Figure 2. Depending on the above characterization, we proposed a strategy based on the following points:

1) Charging station draws a constant power from the grid and the local renewable energy resources.
2) To fulfill stochastic and temporary power charging demand, we employ a local renewable energy system includes local energy storage device and local renewable energy dynamos (wind and solar).

3) When the fast power charging station is idle, all available power from local generated renewable energy dynamos can be used to charge the local energy storage device. Also, the power consumption in energy storage infrastructures during power charging service stage, can be patched by the local generated renewable energy in real-time.
4) Depending on the generation efficiency of local renewable energy dynamos, the charging capacity of fast charging stations in parking campus can be elevated via continuable local renewable energy supplying.

III. Control Model for Power Charging Queueing

A. Queueing Model for the Fast Charging Station

Our explored stochastic model for the fast charging station has some similarities to an Erlang-B blocking system, but still has significant differences. As we employed local renewable energy dynamos in proposed parking campus, the power support based on renewable energy resources can be recognized as long-term sustainable supply. So the efficiency of the additional power supply on charging station will depend on service level of the local renewable energy dynamos. Once the generation level of renewable energy dynamos can be maintained on high level with delightful Quality-of-Service, more parking EV/PHEVs can be charged via additional power supply based on renewable energy. Then the global service level of fast charging station can be upgraded or fall down to the basic service when the efficiency of renewable energy dynamos is influenced by negative factors. This status is proposed as "Service Jumped". We assume that arrivals of EV/PHEVs can be patterned as a Poisson process. We select the term block customers for those customers who require charging service but could not be served immediately. In this study, we premeditate two types of blocking and the status of "Service Jumped":

1) Type 1: Classical Erlang-B blocking appears when all charging plugs are in use, the consumers do not wait and leave. This type of blocking depends on number of servers (charging plugs) in the system [16].
2) Type 2: This blocking happens when there is not enough power or energy in the system to satisfy consumer charging demand. So the consumers will wait in the parking campus.
3) Status of "Service Jumped": The service level of fast power charging station in proposed parking campus can be improved to higher level to serve large-scale charging demand consumers, and also be pulled back to lower level cause longer blocking queueing. It occurs when the efficiency of local renewable energy dynamos is changed by less predictable natural conditions.

We mainly focus on type-2 blocking situations and the status of "Service Jumped" in subsequent chapters.

B. Stochastic Control Model

Electrical vehicles arrive to the proposed parking campus according to a Poisson process of rate λ. We assume that the number of EV/PHEVs can be accommodated by the power grid in this parking campus is N. If additional vehicles require charging service, those can be charged by the local energy storage infrastructures at any point in time. We assume quantifiable charging levels of the local energy storage devices in number of vehicles that can be charged. The capacity of the local storage device is defined as K. Then we can provide that if fully charged it can present service to K EV/PHEVs simultaneously, under the quantization assumption. We further assume that the service times of the EV/PHEVs are exponentially distributed with rate μ. We select ν as the service rate for describing the charging time of the local energy storage device. As mentioned previously, a vehicle can be charged from the grid as long as the number of EV/PHEVs does not exceed N. Additional vehicles can be charged from the local energy storage infrastructures, provided that the storage power level can satisfy the additional requirement, otherwise they will be blocked. Also, as we analyzed above, "Service Jumped" can appear and sustain the fast charging station serve more EV/PHEVs in the parking campus when the local renewable energy dynamos are keeping high generation rate. The"jumped" level is defined as β. The capacity of the"Service Jumped" is Q.

The dynamics of proposed stochastic assumptions and operational regime of the charging station, are captured by a continuous time birth-death Markov chain with finite three-dimensional state space shown in Figure 3. First dimension of the state space corresponds to the number of EV/PHEVs can be charged by the fast power charging station, as well as the second dimension to the charge level of the local energy storage device. The third dimension of the state space provide the renewable energy supply level for current charging status on fast charging station, which depends on the status of "Service Jumped". Specifically, we assume (i, j, β) denote a generic state, with $0 \leqslant i \leqslant N{+}j$ and $0 \leqslant j \leqslant K$. For instance, the (0, 0, 0) status corresponds to a setting where there are no EV/PHEVs being serviced, the local energy storage item is empty, and no additional power supply from local renewable energy dynamos; similarly, all the status (i, 0, 0), $0 \leqslant i \leqslant K$ to a setting where i vehicles are being charged, but the local energy storage device is still empty and no additional power supply from local dynamos. In order to avoid painting the figure too complex, we just select the row maintains (0, 0) to (N, 0), and another row maintains (0, K) to ($N{+}K$, K) from two-dimensional state space to represent the "Service Jumped" status. In the updated level β, the charging time of the local energy storage device is still ν. At the same time, the service times of the EV/PHEVs are still exponentially distributed with rate μ, like in the two-dimensional state space. The Markov chain states ($N{+}j$, j, β), $0 \leqslant j \leqslant K$ represents the blocking ones, where the current charging queueing on station rejects new arrivals.

The birth and death rates are profiled in Figure 3. The death rates are proportional to the number of vehicles being served and similarly for the birth rates, since we should consider about the arrivals of new vehicles and charging the local

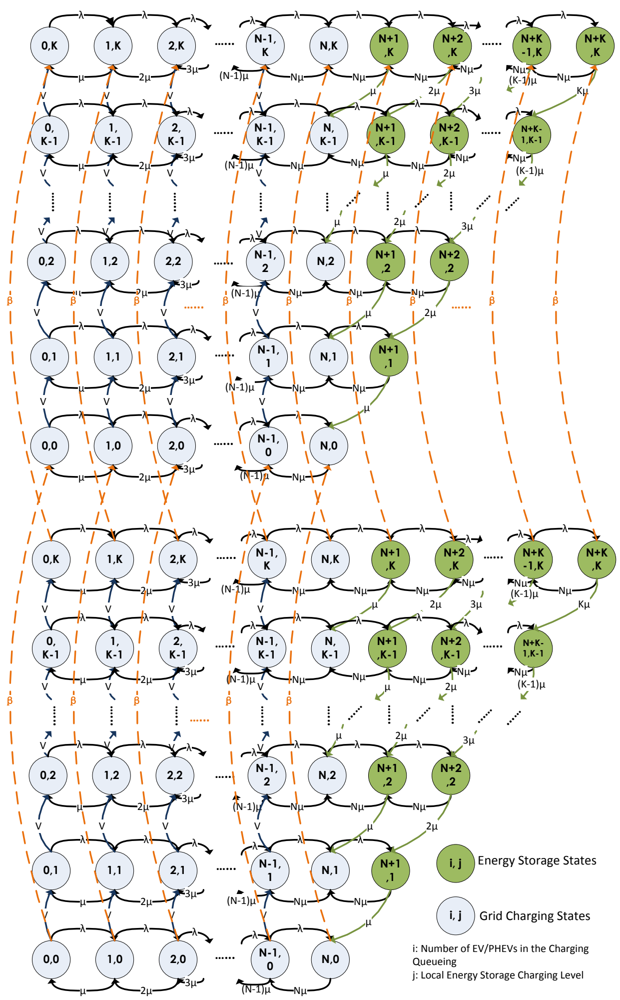

Fig. 3. Continuous Time Markov Chain

energy storage infrastructure. Also the "Service Jumped" level is also being considered as one of important parameters in our mechanism. The total number of status in the Markov chain is :

$$\Theta = \sum_{1}^{Q} \beta \cdot [(N+1) \cdot (K+1) + \sum_{1}^{K} i] \quad (1)$$

IV. System Performance Evaluation

A. Evaluating with Deployment of Local Renewable Energy Resources

The model is based on the following principles: the parking campus operator obtains revenue from each charged EV/PHEV. At the same time, all the parking EV/PHEV should pay for duration in the parking campus. Let C_g and C_r be the revenue obtained per EV/PHEV when charged from the grid and the local energy storage device. We assume that i_s represents the service status, and s is the number of EV/PHEV under this state. Further, let C_P denotes the parking cost per EV/PHEV. Finally, we assume that the local renewable energy dynamos and storage device have a fixed installation cost C_0. In order to denote the stationary probability for generic status, we select δ_s as the parameter in the following equation. Then the profit equation per each EV/PHEV in the proposed parking campus can be composed as follow:

$$P = \sum C_g \cdot i_s \cdot \delta_s + \sum C_r \cdot i_s \cdot \delta_s + C_P - C_0 \quad (2)$$

B. Parking Campus with Fast Charging Station Profit Model

By using some simple financial principles, relates pricing parameters and existing parameters in parking campus system, we present a profit model for parking campus and also acceptable results for consumers. In global level of the power support for the proposed parking campus, the following principle should be considered, which power demand from grid in parking campus plus the additional local renewable energy supply should less than current power grid supply in parking campus. So we define several parameters as follow:

TABLE I
CHARGING SPEED IN DC FAST CHARGE STATION [17]

Charging Power	Compact EV	SUV/Sedan	Heavy Truck
50 kW	15 min	22 min	46 min
75 kW	11 min	15 min	32 min
100 kW	8 min	12 min	22 min
125 kW	6.5 min	9 min	19 min
150 kW	5 min	8 min	16 min

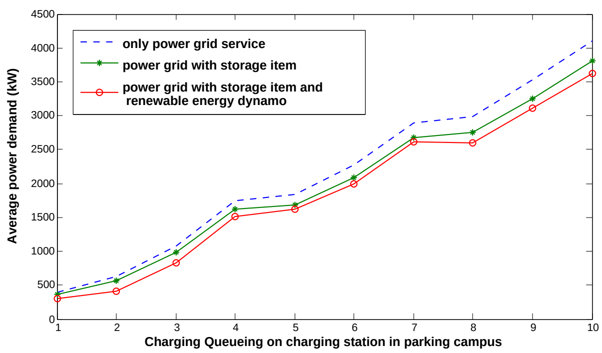

Fig. 4. Global level power supply under different mechanism in parking campus

1) the value of power demand per EV/PHEV in parking campus P_n^D;
2) power charging duration in parking campus t;
3) power resource price p includes two kinds of prices, p_r is the price of renewable energy; p_g is the price from power grid.

So the consumer's payment can be calculated by using the following equation:

$$Sum = \int_0^{t'} (p_g \cdot P_n^D)\mathrm{d}t + \int_0^{t''} (p_r \cdot P_n^D)\mathrm{d}t \quad (3)$$

$$t' + t'' \leqslant t \quad (4)$$

$$p_r \leqslant p_g. \quad (5)$$

From Table I we explore the popular dynamic EV/PHEV power charging times that are decided by the charging power on fast charging station. Through employing the parameters we discussed previously and the ones from Table I, we get Figure 4 to depict the compared result. As we can recognize from Figure 4, if the power gird become only power supply resource, the global level power demand would be raised via the rising of charging queueing on station in the proposed parking campus. Even the middle curve shows that the power consumption can be partly satisfied with local energy storage infrastructure, but the improvement is not so gratifying. Furthermore, the local energy storage infrastructure also need to be charged via using the power from grid, when the system is idle. Obviously, the mechanism based on local storage item and renewable energy dynamo sustain the optimal solution among other two representative schemes.

V. CONCLUSIONS

In this paper, we proposed an EV/PHEVs parking campus with upgraded fast power charging stations supplied by local renewable energy resources. A quantitative stochastic model for analyzing the introduced mechanism is explored by using queueing theory and financial considerations. The focus in our paper is the addition of local renewable energy system includes renewable energy dynamos and local energy storage infrastructure on fast charging station in the proposed parking campus. The renewable energy resources are employed as additional power supply to reduce the probability of peak load in local distribution grid network and satisfy immediate charging demand, especially when the capacity of power grid is not idle and unavailable. The insights included in our mechanism are provided via analysis and evaluation results, which would become crucial in this early stage of designing the smart grid and parking campus with fast power charging station of the future. More complex, flexible and consumer behavior based control system for proposed parking campus will be explored as future work.

REFERENCES

[1] D. of Energy, "Ev everywhere road to successs," U.S. DoE, Tech. Rep., 2014.

[2] E. Commission, "Competitiveness of the eu automotive industry in electric vehicles," European Commission, Tech. Rep., 2012.

[3] D. of Energy, "Ev everywhere blueprint," U.S. DoE, Tech. Rep., 2013.

[4] J. Järvinen, F. Orton, and T. Nelson, "Electric vehicles in australia's national electricity market: Energy market and policy implications," *The Electricity Journal*, vol. 25, no. 2, pp. 63–87, 2012.

[5] S. Std, "J1772,," *Sae electric vehicle conductive charge coupler, Nov*, 2001.

[6] P. Ponticel, "Sae standard on ev charging connector approved," *Development*, vol. 2011, pp. 10–17, 2010.

[7] I. S. Bayram, G. Michailidis, M. Devetsikiotis, S. Bhattacharya, A. Chakrabortty, and F. Granelli, "Local energy storage sizing in plug-in hybrid electric vehicle charging stations under blocking probability constraints," in *Smart Grid Communications (SmartGridComm), 2011 IEEE International Conference on*. IEEE, 2011, pp. 78–83.

[8] I. S. Bayram, "A three-layered system level modeling approach to electric transportation." Ph.D. dissertation, 2013.

[9] I. Bayram, G. Michailidis, M. Devetsikiotis, and F. Granelli, "Electric power allocation in a network of fast charging stations," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 7, pp. 1235–1246, July 2013.

[10] I. S. Bayram, G. Michailidis, and M. Devetsikiotis, "Unsplittable load balancing in a network of charging stations under qos guarantees," *IEEE Transactions on Smart Grid (to appear)*.

[11] S. Bai, D. Yu, and S. Lukic, "Optimum design of an ev/phev charging station with dc bus and storage system," in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*. IEEE, 2010, pp. 1178–1184.

[12] M. Vasiladiotis, A. Rufer, and A. Béguin, "Modular converter architecture for medium voltage ultra fast ev charging stations: Global system considerations," in *Electric Vehicle Conference (IEVC), 2012 IEEE International*. IEEE, 2012, pp. 1–7.

[13] K. Yunus, H. Z. De La Parra, and M. Reza, "Distribution grid impact of plug-in electric vehicles charging at fast charging stations using stochastic charging model," in *Power Electronics and Applications (EPE 2011), Proceedings of the 2011-14th European Conference on*. IEEE, 2011, pp. 1–11.

[14] J. Song, A. Toliyat, D. Turtle, and A. Kwasinski, "A rapid charging station with an ultracapacitor energy storage system for plug-in electrical vehicles," in *Electrical Machines and Systems (ICEMS), 2010 International Conference on*. IEEE, 2010, pp. 2003–2007.

[15] M. Liserre, T. Sauter, and J. Y. Hung, "Future energy systems: Integrating renewable energy sources into the smart power grid through industrial electronics," *Industrial Electronics Magazine, IEEE*, vol. 4, no. 1, pp. 18–37, 2010.

[16] G. Bolch, S. Greiner, H. de Meer, and K. S. Trivedi, *Queueing networks and Markov chains: modeling and performance evaluation with computer science applications*. John Wiley & Sons, 2006.

[17] I. S. Bayram, G. Michailidis, M. Devetsikiotis, F. Granelli, and S. Bhattacharya, "Smart vehicles in the smart grid: Challenges, trends, and application to the design of charging stations," in *Control and Optimization Methods for Electric Smart Grids*. Springer, 2012, pp. 133–145.