Optimal Charging of Plug-in Electric Vehicles for a Car Park Infrastructure

Tan Ma, *Student Member, IEEE*, Ahmed Mohamed, *Student Member, IEEE*, Osama Mohammed, *Fellow, IEEE*

***Abstract*-This paper proposes an intelligent workplace parking garage for plug-in hybrid electric vehicles (PHEVs). The system involves the developed smart power charging controller, a 75kW photovoltaic (PV) panel, a DC distribution bus and the AC utility grid. Stochastic models of the power demanded by PHEVs in the parking garage and output power of PV are presented. In order to limit the impact of PHEVs' charging on the utility AC grid, a fuzzy logic power flow controller is designed. Based on their power requirements, PHEVs were classified into five charging priorities with different rates according to the developed controller. The charging rates depend on the predicted PV output power, the power demand by the PHEVs and the price of energy from the utility grid. The developed system can dramatically limit the impacts of PHEVs on the utility grid and reduce the charging cost. The system structure and the developed PHEVs smart charging algorithm are described. Moreover, a comparison between the impacts of the charging process of the PHEVs on the grid with/without the developed smart charging technique is presented and analyzed.**

***Index Terms*-Charging priority levels, fuzzy logic, hybrid DC distribution system, plug-in hybrid electric vehicles, solar energy, impacts limitation.**

I. INTRODUCTION

PLUG-IN hybrid electric vehicles (PHEVs) are gaining popularity due to several reasons; they are convenient, sleek, quiet, and less polluting to the environment. PHEVs have the potential of reducing fossil energy consumption and green- house gas emissions and increasing the penetration of sustainable energy sources such as solar energy and wind energy into our daily life [1]-[3]. Furthermore, most personal vehicles in the US are parked more than 95% of the day and generally follow a daily schedule [4]. Therefore PHEVs can be used as mobile energy storage in the future. More than 75% of drivers in the U.S.A travel less than 45 miles round trip for their daily commute, which is just right for PHEVs. Many of today's PHEVs can go up to 100 miles on a single charge. This is because battery technology continues to advance and hence batteries are becoming smaller while storing more energy. It is forecasted that in North America PHEVs will be on the roads in large numbers in the very near future [5].

However, with the increasing of the number of PHEVs, huge impacts on the utility take place if properly designed smart charging techniques are not utilized. Uncoordinated and random charging activities could greatly stress the distribution system causing several kinds of technical and economic issues, such as suboptimal generation dispatch, huge voltage fluctuations, degraded system efficiency and economy, as well as increasing the likelihood of blackouts because of network overloads. In order to maximize the usage of renewable energy sources and limit the impacts of PHEVs' charging to the utility AC grid, a smart power flow charging algorithm and controller should be designed. Moreover, accurate PV output power and PHEVs power requirement forecasting models should be built. PHEVs need to participate in vehicle-to-grid (V2G) and vehicle-to-vehicle (V2V) power transactions during the charging process; accordingly fully controlled bi-directional AC-DC/DC-AC and DC-DC converter are needed in this system.

In [6], [7], load management solutions for coordinating the charging process of multiple PHEVs in smart grid system based on real-time minimization of total cost of generating the energy plus the associated grid energy losses were proposed and developed. However, they did not consider the inclusion of a renewable energy source in the system, which holds the implementation of these algorithms back since we know that the concept of PHEVs is attached with obtaining the power to charge them from renewable energy. In addition, the control strategy did consider charging priority level, but the level is based on how much the owner of the PEV is willing to pay, not the state of charge (SOC) of the PHEVs' batteries. So the efficiency of V2V and V2G service is low.

In [8], [9], an intelligent method for scheduling the usage of available energy storage capacity from PHEVs is proposed. The batteries on these PHEVs can either provide power to the grid when parked, known as V2G concept or take power from the grid to charge the batteries on the vehicles. However, the detail about the energy dispatch during charging and V2G process is not given. Also the SOCs of the PHEVs' batteries are not considered during the process.

A fully controlled bi-directional AC-DC/DC-AC converter has been designed and implemented in [10]. This converter has the capability of controlling the amount of power flowing between the AC and DC sides of the systems in both directions while operating at unity power factor and within acceptable limits of time harmonic distortion (THD) for the current drawn from the grid. Hence, the amount of power flowing in either direction can be set to a certain pre-set value while the controlled rectifier working as a voltage rectifier maintains the power balance as it is free to supply any power needed in the DC grid. In addition, a controlled DC-DC boost converter and a

The authors are with the Energy Systems Research Laboratory, Department of Electrical and Computer Engineering, Florida International University, Miami, FL 33174 USA (e-mail: mohammed@fiu.edu).

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TABLE I
PARAMETERS FOR PHEVS IN DIFFERENT SIZE

PHEVs model	Percentage	Battery capacity (kWh)	Energy consumption per mile (kWh/mile)
compact sedan	32.5%	10-20	0.2
full-size sedan	37.5%	20-30	0.3
mid-size SUV or pickup	20%	30-40	0.45
full-size SUV or pickup	10%	40-50	0.6

bi-directional DC-DC converter are proposed and tested in [11]-[13].

In this work, a hybrid DC PHEVs workspace parking garage charging system is established and tested. A 318V grid-connected DC power distribution network combined with PV and PHEVs parking garage is designed. Accurate PV and PHEVs power stochastic models based on statistics theory are studied. Meanwhile a fuzzy logic power flow controller is designed.

This paper is organized as follows, the system description and problem formulations are given in section II, the stochastic models of the PHEVs parking system and PV are given in section III, the details of the developed real-time fuzzy logical power flow controller is given in section IV, a method to classify PHEVs into five priority levels and how to adjust their charging rates is given in section V, results and discussion are given in section VI and finally, some concluding remarks are provided in section VII.

II. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

Consider a workplace parking garage DC hybrid power system equipped with a PV panel and having certain parking positions. Each workday some vehicles will park in the garage during the working hours. Those vehicles have different sizes, battery capacities and energy consumptions per mile. The specific detail is shown in Table I. Whenever a PHEV is connected to the parking garage, the owner of it will set the departure time, and the system will make a record. Usually at the departure time, the SOC of the batteries is expected to be at least 80%. In order to take the battery protection into consideration, the PHEVs' SOC of the batteries shouldn't go below a certain limitation. After reaching this limitation, instead of using electric energy, PHEVs will consume gas by using the combustion engine.

The schematic diagram of the system under study is shown in Fig.1. As can be seen, the PHEVs with their bi-directional DC-DC chargers and the PV source with its DC-DC regulating interface share a common DC bus. Hence, the charging park acts as a DC micro-grid that has the ability to send or receive power from the main grid. The amount of power transferred between the AC and DC sides is determined according to the decision of the developed energy management algorithm. Fig. 2 shows the response of this converter to a step change in the DC current reference from -4 A to 1 A; this means that the current will reverse its direction instead of sending power from the DC

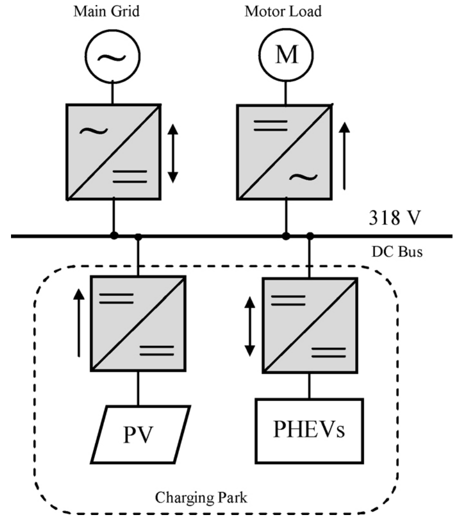

Fig. 1 Schematic diagram of the investigated system

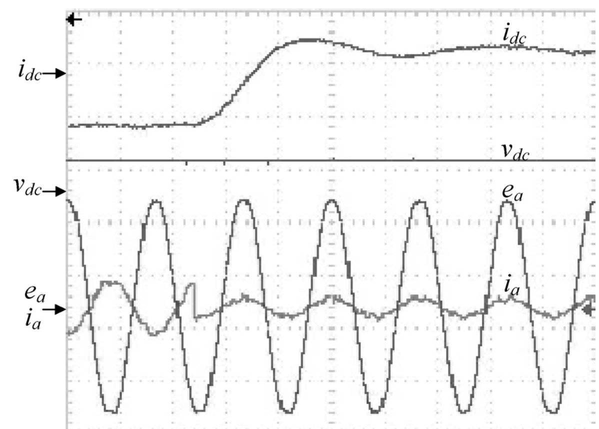

Fig. 2 Bi-directional converter response to a step change in the DC current reference from -4 to 1 A. (a) DC current, i_{dc}(4 A/div, 10 ms); (b) DC voltage, v_{dc}(1000 V/div, 10 ms); (c) AC phase voltage, e_a(30 V/div, 10 ms); (d) AC current, i_a(5 A/div, 10 ms).

micro-grid to the AC side to receiving power. More simulation and experimental results on this converter as well as the controlled rectifier were illustrated in [1]-[2]. In addition, a controlled DC-DC boost converter and a bi-directional DC-DC converter are utilized to interface the PV source and the PHEVs to the DC bus as shown in Fig. 1.

In order to limit the impact of PHEVs' charging to the utility AC grid mean while let the PHEVs participate in the V2V and V2G power transactions, the parking garage should have a smart charging algorithm that can adjust the charging rates for PHEVs under different utility AC energy price (E_{price}) and different power flow estimation (P_{grid}). Since the hourly E_{price} is assumed to be pre-known, the most essential point is to estimate P_{grid} , which is given by (1).

$$P_{grid} = P_{PV} - P_{total} - \hat{P}_{upcoming} \tag{1}$$

where

TABLE II
ARRIVAL AND DEPARTURE TIMES DISTRIBUTION PARAMETERS

	Arrival		Departure	
Parameter	Weekday	Weekend	Weekday	Weekend
$\mu_T[h]$	9	11	18	15
$(\sigma_T)^2[h]$	1.2	1.5	1.2	1.5

- P_{PV} is estimated PV output power for next period T;
- P_{total} is the power needed by the PHEVs that are already parked in the parking garage;
- $\hat{P}_{upcoming}$ is the estimated power requirements by the upcoming PHEVs which will connect to the parking garage in the next period T.

In order to design the smart charging control algorithm, an accurate power requirements forecasting model is needed to estimate P_{grid}.

For the power flow control for next period T, the charging rates for different PHEVs should be adjusted based on E_{price} and P_{grid}. Because the system is highly nonlinear, fuzzy logical controller is a good choice for solving this issue.

Since at a certain time, the PHEVs in the parking garage may have different SOCs and different departure time, their average constant power requirements are different. On one hand, some PHEVs may need a huge amount of energy and the departure time is close, then this kind of PHEVs should be classified into the high priority level. On the other hand, some PHEVs' SOC are already high and their departure times are several hours later, then this kind of PHEVs should be classified into the low level. Therefore PHEVs priorities classification should be designed.

The objective of this paper is to design a grid-connected workplace hybrid DC PHEVs charging parking garage system, with fuzzy logic power flow controller and PV. The goal is to limit the impact of PHEVs' charging to the utility AC grid and maximize the utilization of power generated from PV.

III. MODELING THE STOCHASTIC PHEVS PARKING SYSTEM

A. PV Output Power Forecasting Model

In order to manage the energy in the charging park in a real time manner, the power available from the PV source should be predicted and considered. Accuracy of the decision made by an algorithm is affected by the accuracy of the predictive models used to model the uncertainties in the system, i.e. PV power in this case. Hence, we count on real data to forecast the PV output power. The data forecasting process was based on PV data collected over 15 years on an hourly basis for an example PV system in the state of Texas. The output power data was used as the output to be forecasted, whereas the day of the year (1-365) and the hour of the day (1-24) were used as inputs. Different model evaluation indices were used to validate the developed mathematical models. The forecasting model used to predict the PV output in this paper is regenerated from the model derived in [14] using the historical PV data described in the previous subsection.

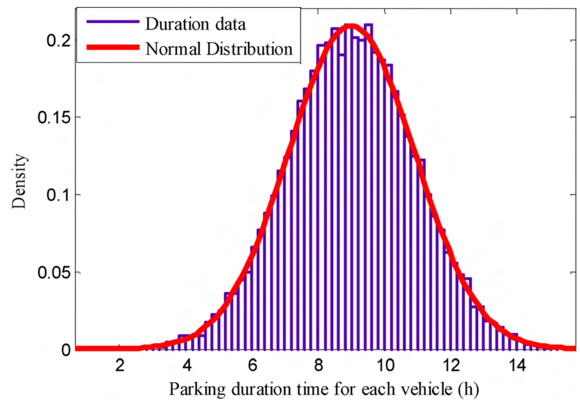

Fig. 3 The PDF of the daily parking duration.

B. PHEVs Power Requirement Forecasting Model

In order to develop an accurate PHEVs parking system model, it is essential to estimate the probability density function (PDF: a function that describes the relative likelihood for this random variable to take on a given value [15]) of the power needed by each PHEV when it is connected to the parking lot $\hat{P}_{PHEV}$. This variable is varying based on the PHEVs models, parking duration times, daily travel distances.

For the purpose of protection, battery should not be over discharged. Because PHEVs can use both electric energy and fossil energy, once the SOC of the battery is below 10%, PHEVs stop using electric energy. Therefore, the electric energy of a PHEV can be used before the next charge is 70% of the total battery capacity. If the energy consumption is more than this value, PHEV will use gas. Therefore, if the total energy consumption for a certain PHEV before next charging is less than 70% of its battery capacity, the energy needed by it for next time of charging is $M \times E_m$. Otherwise, the energy needed by it is 70% of its battery capacity. The constant charging power needed by this PHEV is given as below (2) and (3). In order to find $\hat{P}_{PHEV}$, we need firstly to get distribution of daily travel distance, daily parking duration time.

If total energy consumption is less than 70% of the battery capacity:

$$\hat{P}_{PHEV} = \frac{M_d \times E_m}{D_t - A_t} \tag{2}$$

If total energy consumption is equal or more than 70% of the battery capacity:

$$\hat{P}_{PHEV} = \frac{70\% \times B_c}{D_t - A_t} \tag{3}$$

where

- M_d is the driver's daily travel distance;
- A_t is the PHEV's arrival time;
- D_t is the PHEV's departure time;

- E_m is the PHEV's energy consumption per mile;
- B_c is the PHEV's battery capacity.

In this work, the parking garage is located in some workplace like a company whose office hours are from 9:00am to 18:00 pm. Based on the Central Limit Theorem (the conditions under which the mean of a sufficiently large number of independent random variables, each with finite mean and variance, will be approximately normally distributed [16]), the distribution of the PHEVs arrival and departure time is shown as the Table II. With the PDFs of A_t and D_t, the joint probability density function of $D_t - A_t$ can be founded, which is the daily parking duration time. It's a normally distributed random variable with μ_d and $\sigma_d = 1.92a$. The PDF of the daily parking duration is shown in Fig. 3.

Based on the known driving pattern statistics, the average yearly total miles driven of U.S.A is 12,000 miles with 50% of drivers drive 25 miles per day or less, and 80% of drivers drive 40 miles or less. So a log normal distribution with $\mu_m = 3.37$, $\sigma_m = 0.5$ is selected to approximate the PDF of M_d, which shows that the total yearly driving distance average is 12,018 miles, 48% of the vehicles drive 25 miles or less each day, and 83% of the vehicles drive 45 miles or less each day, which closely approximate the driving performance results from [1]. The distribution function for M_d is given in (4).

$$f_X(x;\mu_m,\sigma_m) = \frac{1}{x\sigma_m\sqrt{2\pi}}\exp\{-\frac{(\ln x-\mu_m)^2}{2\sigma_m^2}\} \quad (4)$$

With the PDF of daily duration time, PDF of daily travel distance, power consumptions of each class of PHEVs, by using the MATLAB statistic distribution fitting toolbox and Monte Carlo simulation with 30000 samples, the PDF of constant power needed by each PHEV when it is connected to the parking lot: $\hat{P}_{PHEV}$ is finally found as an inverse Gaussian distribution with $\mu_p = 1.573$ and $\lambda_p = 3.652$. The distribution function for $\hat{P}_{PHEV}$ is given in (5). The PDF of the M_d, $\hat{P}_{PHEV}$ are shown in Fig. 4 and Fig. 5, respectively.

$$f_X(x,\mu_p,\lambda_p) = \sqrt{\frac{\lambda_p}{2\pi x^3}}\exp\{-\frac{\lambda_p}{2\mu_p^2 x}(x-\mu_p)^2\} \quad (5)$$

After getting the probability distribution function of $\hat{P}_{PHEV}$, the forecasting model of power needed by PHEVs in the parking system is built. Together with the forecasting model of the power generated by renewable energy sources and hourly price of the energy from utility grid, a real-time smart parking system is established. For instance, at a certain time *t*, the SOC of the PHEVs already parked in the parking lot and their power requirements are already know, in order to forecast the power needed by the PHEVs which will arrive during the upcoming period *T*, we can use the following equation.

$$\hat{P}_{upcoming} = \int_t^{t+T} f_{A_t}(x,\mu_{A_t},\sigma_{A_t})dt \times NP \times \hat{p}_{PHEV\_avg} \quad (6)$$

where

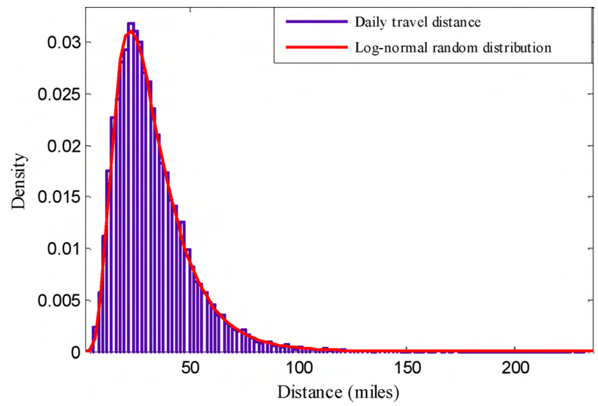

Fig. 4 The PDF of the daily travel distance.

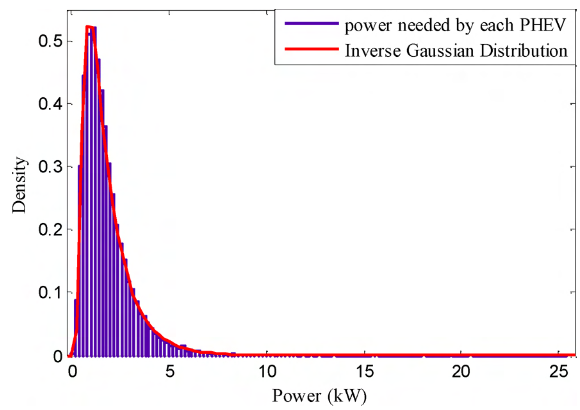

Fig. 5 Power needed by each PHEV when connected to the parking garage.

- NP is the total number of PHEVs that will park in the parking lot this day;
- $f_{A_t}(x,\mu_{A_t},\sigma_{A_t})$ is the PDF of the arriving time A_t;
- $\hat{P}_{PHEV\_avg}$ is the average constant power requirement for all PHEVs when they are connected to the parking lot. $\hat{P}_{PHEV\_avg}$ can be calculated from the PDF of $\hat{P}_{PHEV}$.

IV. Real Time Fuzzy Logical Power Flow Controller

In the previous section, the model of the parking garage is already built and the PDF of the $\hat{P}_{PHEV}$ is already known. Together with the stochastic model of PV and hourly energy price from the AC utility grid, a smart charging algorithm with fuzzy logical power flow controller is designed. The flowchart is shown as Fig. 6.

The charging rates of PHEVs in different priority levels for next period is varying based on the forecasting of the power generated by the PV, the forecasting of the power needed by the upcoming PHEVs, the price of the utility energy grid and the power need by the current PHEVs. Without V2V and V2G service, the power flow for next period between the utility AC grid and the hybrid parking system can be calculated using (1).

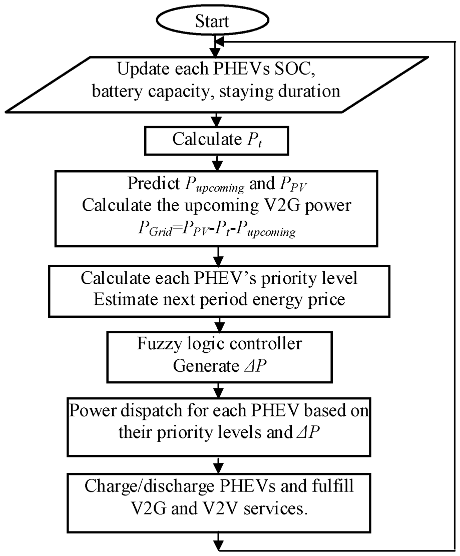

Fig. 6 The flowchart of the developed real time fuzzy logical charging controller.

The next period price of the energy E_{price} and the next period forecasting power flow P_{grid} are used as the two inputs of the real time Mamdani-type fuzzy logic power flow controller to determine the charging index δ_p, which will determine the charging rates of PHEVs in different priority levels. The power flow between utility AC grid and DC hybrid system: P_{grid} is described as "negative", "positive small", "positive medium", "positive" and "positive big". Similarly, the energy price E_{price} is described as "very cheap", "cheap", "normal", "expensive", and "very expensive". The method implemented for defuzzificationis centroid based. Within the model, minimum and maximum are used for "AND" and "OR" operators, respectively. The output of the fuzzy controller is the index δ_p which is used for adjusting the charging rates for PHEVs in different priority levels. The parameter δ_P is described as "NB", "N", "Z", "P" and "PB", which stand for negative big, negative, zero, positive and positive big. The Mamdani-type model based fuzzy rules of the fuzzy logical power flow controller is given in Table III. The surface of the fuzzy controller's rules and the membership functions of p_{grid}, E_{price} and δ_p are shown in Fig. 7 and Fig. 8.

TABLE III
FUZZY LOGIC RULES

E_{price} \ P_{grid}	Negative	Positive small	Positive medium	positive	positive big
very cheap	Z	P	PB	PB	PB
cheap	Z	P	P	PB	PB
normal	N	Z	P	P	PB
expensive	N	N	Z	P	P
very expensive	NB	N	Z	P	P

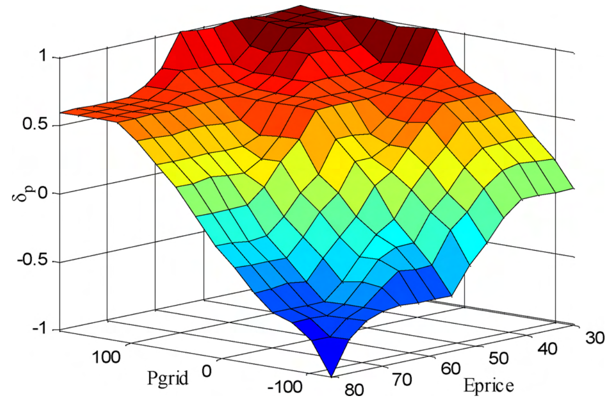

Fig. 7 Surface of the fuzzy logic controller's rules.

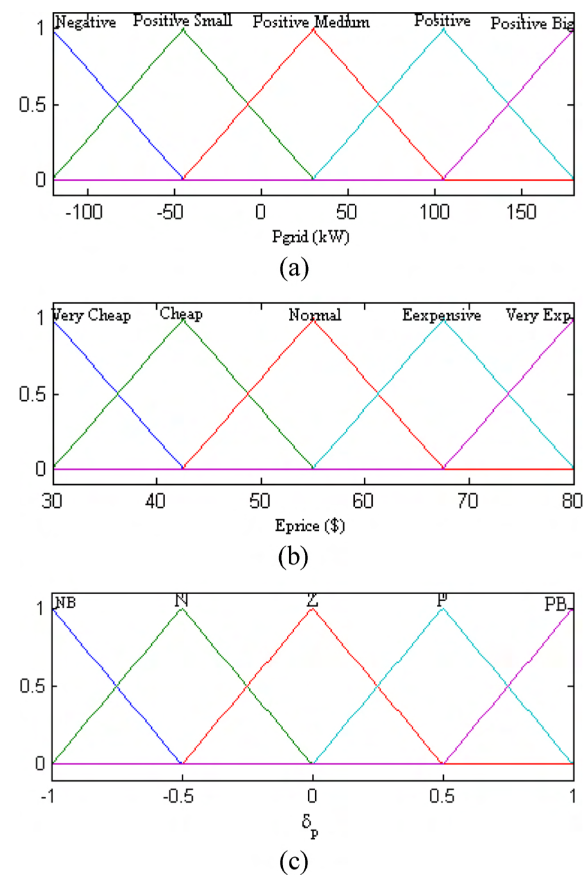

Fig. 8 Membership functions. (a) Power flow; (b) Energy price; (c) Power flow control index.

With the charging index δ_p, which varies from -1.0 to 1.0, the charging rates for PHEVs in different priority levels will be obtained.

V. CLASSIFICATION OF PHEVS INTO FIVE PRIORITY LEVELS

The charging rates of different PHEVs with different SOCs and power requirements should apparently be charged with different charging rates. For example, a PHEV is connected to the parking lot at 9:00am and the departure time is 6:00pm, the SOC of charge is 65%, then the average constant power required by this PHEV is small. At the same time, another PHEV is connected to the parking lot also at 9:00am but will

TABLE IV
CHARGING RATES FOR DIFFERENT CHARGING LEVELS

Priority level	Power requirement	Maximum charging rate	Minimum charging rate
Level 1	$p \geq 15\,kW$	12kW	12kW
Level 2	$10\,kW \leq p < 15\,kW$	12kW	6kW
Level 3	$5\,kW \leq p < 10\,kW$	8kW	0kW
Level 4	$2\,kW \leq p < 5\,kW$	5kW	-5kW
Level 5	$p < 2\,kW$	2kW	-8kW

leave at 10:30am and the SOC is only 10%, then this PHEV's average constant power requirements is larger than the former one, which means the charging situation of this PHEV is more emergent than the former one. So in order to reduce the impact of the PHEVs' charging to the utility AC grid, at a certain time, different PHEVs should be charged at different charging rates. What's more, since the former PHEV will stay in the parking lot more than 8 hours, it can be viewed as energy storage during this period. For instance, at a certain time the energy price is below the daily average price, and PV generates more power than the total PHEVs requirements, then the extra power can be saved in this PHEV as backup energy, by doing this the priority level of this PHEV will keep decreasing. At another time during this period, the price of utility grid energy is high also the power generated by the PV can't meet the total PHEVs power requirement, instead of buying power with high price from the utility grid, the parking system can get the backup extra energy from this PHEV, by doing this the priority of this PHEV will increase. So during the whole day, all PHEVs priorities are varying with their SOCs, by doing this energy can be delivered betweenV2G and V2V.The five charging priorities are shown in Table IV.

PHEVs' charging priority levels are just dependent on their power requirements. Also because of bi-directional power flow, PHEVs can be charged and discharged, so their charging priority levels are varying with time. PHEVs in levels1, 2 and 3 can only be charged. Those PHEVs either need a lot of energy (such as SOC is only 10% when connected to the parking station) or will leave in a short time but still have not met the owners charging requirement (such as SOC is only 65% but will leave in half an hour). PHEVs in level 4 and 5 can be discharged to fulfill the V2G and V2V service, those PHEVs will continue staying in the parking lot for a longer time, at the same time their SOCs are already high enough. But as the time passes, the PHEVs in low level may jump to higher levels and vice versa. With the charging index δ_p, the charging rates of PHEVs in levels 1-5 are given in (7)-(11).

$$p_{charging\_rate} = 12, \quad (7)$$

$$p_{charging\_rate} = 9 + 3 \times \delta_p, \quad (8)$$

$$p_{charging\_rate} = 4 + 4 \times \delta_p, \quad (9)$$

$$p_{charging\_rate} = 0 + 5 \times \delta_p, \quad (10)$$

$$p_{charging\_rate} = -3 + 5 \times \delta_p. \quad (11)$$

VI. RESULTS AND DISCUSSION

In this part, a 318V DC workplace parking garage hybrid power system equipped with a 75kW photovoltaic (PV) panel has 350 parking positions, and each workday around 300 vehicles will park in the garage during the work hour from 9AM to 6PM. In the 300 vehicles, around 60% of them are PHEVs. The battery capacities, energy consumptions per mile of PHEVs in different sizes are given in Table I. The parking garage will upgrade all the information every 6 minutes, and generate new charging index δ_p to adjust the charging rates for the PHEVs parking in it. All the PHEVs are assumed be only charged at this workplace parking garage, and the state of charge (SOC) of the batteries are expected to be over 80% at their departure times. The PHEVs' SOC of the batteries shouldn't go below 10%.

Two experiments are done both in MATLAB simulation and hardware test. The first one is the power flow between the utility grid and the DC hybrid PHEVs parking garage without real-time charging optimal control and the second one contains real-time fuzzy logic charging optimal control. Both experiments are under same conditions: same number and types of PHEVs, same departure and arrive times, same hourly energy price and same power generated by the PV.

The simulation of the power flow during the daytime and the PHEVs' SOCs at departure time for parking garage without optimal charging method is shown in Figs.9 and 10. Whenever

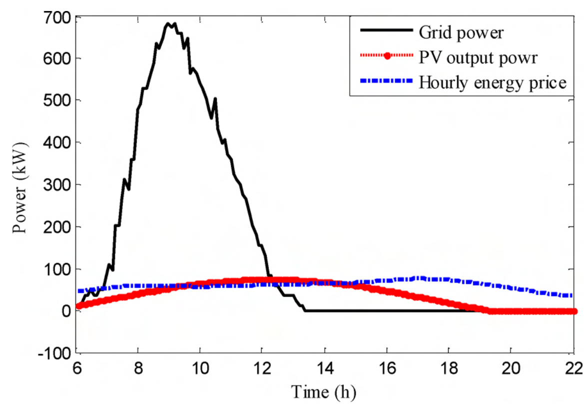

Fig. 9 Hourly power flow from AC grid without optimal controller.

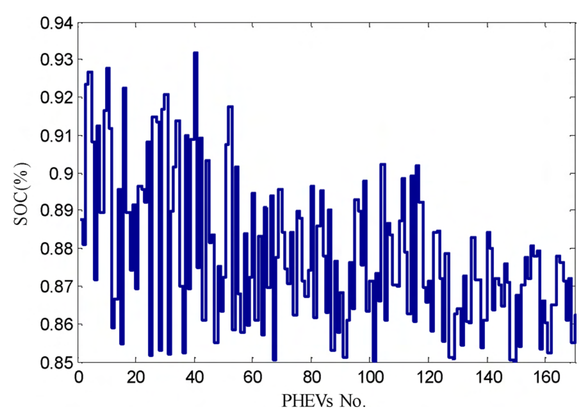

Fig. 10 PHEVs' SOCs at their departure time without optimal controller.

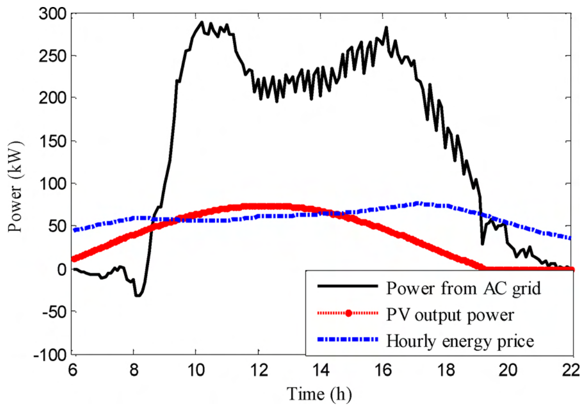

Fig. 11 Hourly power flow from AC grid with optimal controller

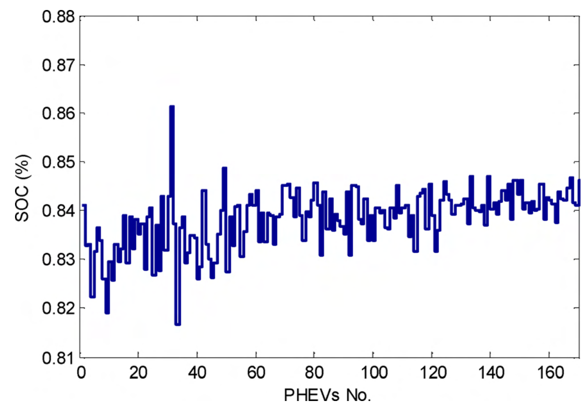

Fig. 12 PHEVs' SOCs at their departure time with optimal controller.

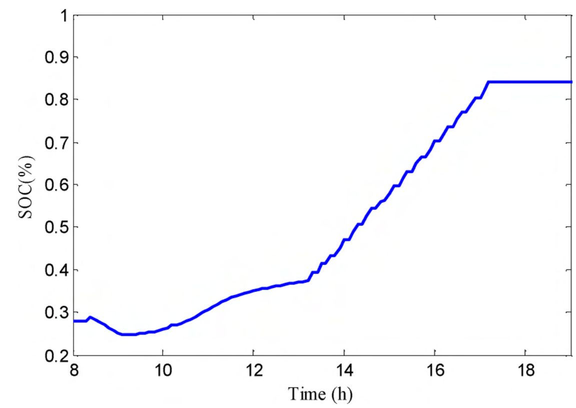

Fig. 13 Variation of PHEV's SOC during the charging process.

a PHEV is connected to the parking garage, it will be charged with a constant charging rate: 10kW, it will not stop charging until the SOC of its battery reach 80%. From the simulation it is clear the peak happens around 9AM, because most of the PHEVs arrive around this time every day. The peak is near 700kW, and the power flow above 300kW lasts from 7:30AM to 11:20 AM, more than three and half hours. After 13:30 PM, the charging stops, because all the PHEVs that are parking in the garage at that time already meet the charging requirement. After 13:30PM, because no more new PHEVs connect to the parking garage, there is no power flow between the utility AC grid and the parking garage. But at that time, the PV's output power is still high, while the energy price at that time is cheap. It's not a good time to sell power to the AC grid, but the parking garage without optimal charging control doesn't have any other options but selling power. From Fig. 10 it is clear all the PHEVs SOCs are above 80% at their departure times, this make sense because all of them are charged with the same high enough charging rates.

The simulation of the power flow during the daytime and the departure PHEVs' SOC for parking garage with optimal fuzzy logic charging controller is shown in Figs 11 and 12. From Fig.11 it is clear that the peak of the power flow from AC utility grid to the smart parking garage is limited below 300kW, and the power flow which is above 250kW only lasts from 9:30AM to 11:20AM and partly in the afternoon around 16:00PM, all together no more than two and half hours.

What's more, when the energy price goes high, the power flow from the AC side will decrease apparently, which happens around 17:00PM. Also when the PV output power is above a certain amount, power flow from AC grid to the smart charging garage will decrease because more PHEVs will be charged by the power generated by the PV. From Fig. 10 we can see all the PHEVs' SOCs are above 80% at their departure times, which also meets the charging requirements.

Fig. 13 shows the variation of a randomly chosen PHEVs' SOC during the charging process with optimal fuzzy logic charging controller. This PHEV is connected to the parking garage at 8:18AM, and the departure time is 17:12PM. When this PHEV is connected to the parking garage, the SOC is around 28%, and the PHEV's owner enters the departure time 17:30 PM. So the charging system can calculate the real time average power requirement for this PHEV. At the very beginning from 8:00AM to 10:00AM, because the duration time is long, this PHEV's average power requirement is low, and it is classified in to level 4 or level 5. And at that time the energy price is high, so instead of buying power from AC grid, the parking garage use the energy stored in this PHEVs to charge PHEVs in the higher level. That's why the SOC of this PHEV is decreasing during this period. From 10:00AM to 13:30PM, during this period the AC grid energy price is low, so more power are bought from AC side. And because δ_p is positive, this PHEV's charging rate is positive. However, because the duration time is still long, the priority level is still low, so the charging rate is small. After 14:00 PM, because the departure time is near, the priority level is high, and the charging rate is higher than before. This charging rate is kept until 17:12PM, when the SOC is already above 80% and the departure time is very near. So this PHEV doesn't participate in V2G or V2V power transactions anymore and the SOC is constant for the rest of the time.

Fig. 14 shows the comparison of the voltage variation on the AC bus corresponding to the PHEVs' charging process with/without optimal fuzzy logic charging controller. It is clear during for the charging without optimal charging controller, the voltage on the AC bus will drop to around 0.75P.U of the rated voltage. Also, the voltage below 0.9P.U lasts more than three hours. With the optimal charging controller, the voltage of the

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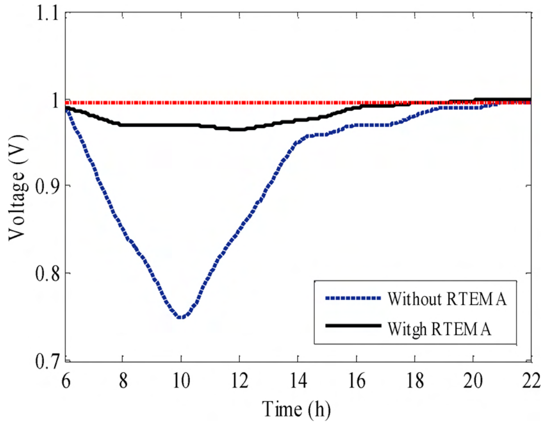

Fig. 14 The voltage on the AC bus corresponding to the PHEVs charging process with/without optimal fuzzy logic charging controller.

AC bus during the whole charging process is above 0.95P.U.

VII. CONCLUSION

This paper presented a model for a grid-connected workplace hybrid DC PHEVs charging car parking infrastructure involving renewable sources and utility grid connectivity. To forecast next period power flow, accurate PHEVs and PV power stochastic models were developed. The fuzzy logic power flow controller was designed to control the real-time power flow. A new power dispatch method based on PHEVs priority levels and a real-time PHEVs charging algorithm was developed. Furthermore, bi-directional DC-DC and AC-DC converters were designed to let the PHEVs participate in the V2V and V2G services. The simulation results show that the optimal power flow control algorithm can maximize the utilization of PV output power for charging of PHEVs and simultaneously decrease the impacts on the grid greatly. At the same time, the PHEVs' SOCs at their departure time are all above the charging requirement. The system presented in this paper benefits both the AC utility grid and PHEVs' owners.

REFERENCES

[1] J. Voelcker, "How Green Is My Plug-In?" Spectrum, *IEEE*, vol.46, no.3, pp.42-58, March 2009.
[2] "Technology roadmap: Electric and plug-in hybrid electric vehicles (EV/PHEV)," International Energy Agency (IEA), 2011.
[3] A.Y. Saber, G.K. Venayagamoorthy, "Plug-in Vehicles and Renewable Energy Sources for Cost and Emission Reductions," *IEEE* Transactions on Industrial Electronics, vol.58, no.4, pp.1229-1238, April 2011.
[4] J. Tomicand W. Kempton, "Using fleets of electric drive vehicles for grid support," J. Power Sources, vol. 168, no. 2, pp. 459-468, Jun. 2007.
[5] S.G. Wirasingha, N. Schofield, A. Emadi, "Plug-in hybrid electric vehicle developments in the US: Trends, barriers, and economic feasibility," Vehicle Power and Propulsion Conference, 2008. VPPC '08. *IEEE*, vol., no. pp.1-8, 3-5 Sept. 2008.
[6] S. Deilami, A.S. Masoum, P.S. Moses and M.A.S. Masoum, "Real-Time Coordination of Plug-In Electric Vehicle Charging in Smart Grids to Minimize Power Losses and Improve Voltage Profile," *IEEE* Transactions on Smart Grid, vol. 2, no. 3, pp. 456-467, September 2011.
[7] A.S. Masoum, S. Deilami, P.S. Moses, M.A.S. Masoum and A. Abu-Siada, "Smart load management of plug-in electric vehicles in distribution and residential networks with charging stations for peak shaving and loss minimisation considering voltage regulation," Generation, Transmission & Distribution, *IET*, vol.5, no.8, pp. 877-888, August 2011.
[8] P. Mitra, G.K. Venayagamoorthy and K.A. Corzine, "Smartpark as a Virtual STATCOM," *IEEE* Transactions on Smart Grid, vol. 2, no. 3, pp. 445-455, September 2011.
[9] C. Hutson, G.K. Venayagamoorthy and K.A. Corzine, "Intelligent Scheduling of Hybrid and Electric Vehicle Storage Capacity in a Parking Lot for Profit Maximization in Grid Power Transactions," Energy 2030 Conference 2008. *IEEE*, pp. 1-8, Nov. 2008.
[10] A. Mohamed, M. Elshaer and O. Mohammed, "Bi-Directional AC-DC/DC-AC converter for Power Sharing of Hybrid AC/DC Systems ," in Proc. of *IEEE* PES General Meeting 2011, Detroit, Michigan, USA.
[11] M. Elshaer, A. Mohamed and O. Mohammed, "Integration of Sustainable Energy Sources into DC Zonal Electric Distribution Systems," in Proc. of *IEEE* PES General Meeting 2011, Detroit, Michigan, USA.
[12] A. Mohamed, M. Elshaer, O. Mohammed, "High-Quality Integration of Fuel Cells Energy into Electric Grids," in Proc. Of 4th International Symposium on Resilient Control Systems, ISRCS 2011, Boise, Idaho, USA, Aug. 9-11, 2011.
[13] A. Mohamed and O. Mohammed, "Smart Optimal Control of DC-DC Boost Converter in PV Systems," in Proc. of the Transmission and Distribution Conference and Exposition: Latin America (T&D-LA), 2010 *IEEE*/PES, pp. 403-410, Sao Paulo, Brazil, Nov. 2010.
[14] P. Bacher, H. Madsen and H. Nielsen, "Online short-term power forecasting" Solar Energy, vol. 83, issue 10, pp. 1772-1783, Oct. 2009.
[15] E. Weisstein, "Making Math World," Mathematical Journal 10, 2007.
[16] L. Cam, Lucien, "The central limit theorem around 1935," Statistical Science, pp. 78-91, 1986.