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

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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

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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

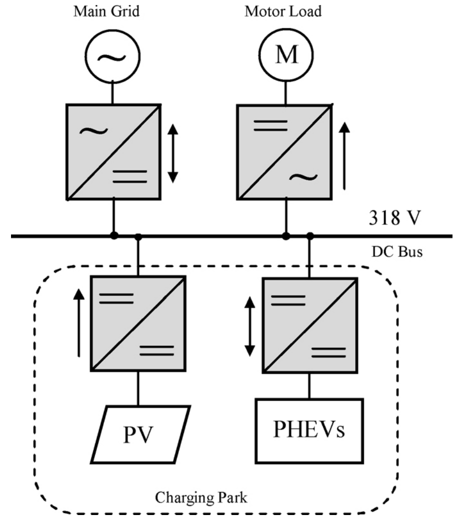

Fig. 1 Schematic diagram of the investigated system

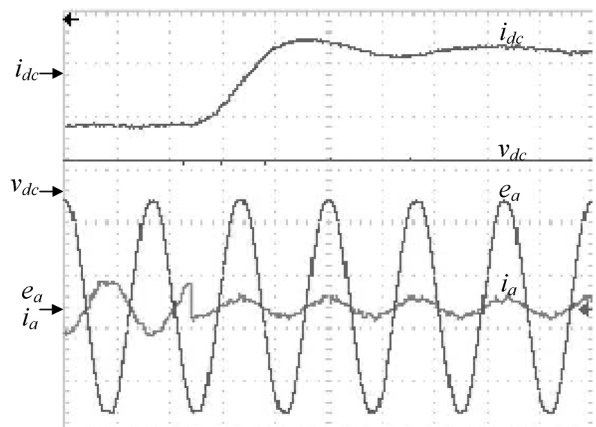

Fig. 2 Bi-directional converter response to a step change in the DC current reference from -4 to 1 A. (a) DC current, i_{dc}(4 A/div, 10 ms); (b) DC voltage, v_{dc}(1000 V/div, 10 ms); (c) AC phase voltage, e_a(30 V/div, 10 ms); (d) AC current, i_a(5 A/div, 10 ms).

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).

$$P_{grid} = P_{PV} - P_{total} - \hat{P}_{upcoming} \qquad (1)$$

where