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A Systematic State of Charge based V2G Charging Framework for Frequency Response

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Abstract: As the demand fluctuations are very high, attaining equilibria of power in a grid is a challenging task due to the fluctuations in frequency. Hence, a novel scheme has been proposed which responds to frequency change in the grid using plug-in electric vehicles (PEVs) owing to their high performance battery characteristics and longer plug-in time. In this paper, a systematic framework for vehicle-to-grid (V2G) control has been proposed to limit the charging/discharging of battery with respect to the end user convenience for participating in the frequency response within a range of battery state of charge (SoC) limit.

Keywords: Battery state-of-charge, vehicle-to-grid, frequency control, plug-in electric vehicle.

1. INTRODUCTION

In recent years, many changes are taking place in distribution level because of fast developing distributed generations (DG) and energy storage system (ESS) owing to the environmental and energy security concerns. Large-scale integration of DGs and ESS will create a significant impact in power system. With the increasing generation in distribution level, it is required to have an auxiliary controller at the distribution level along with conventional controllers in power system to enhance system stability. Meanwhile, Plug-in electric vehicles (PEVs), for green transportation obtained great attention. PEVs are considered as the key factor in the new electric power framework due to their ability to curb carbon emissions and to reduce transportation costs.

The utilization of PEVs has been encouraged for its influence in many areas such as frequency regulation in Han et al. (2010), peak shaving in Luo et al. (2013) and spinning reserves in Dallinger et al. (2011). It acts as an efficient complementary high capacity storage device in the grid owing to the high performance battery characteristics and longer plug-in time. At the same time, it serves as a mobile storage device and a controllable load. These services provided by the PEVs have been primarily focused on an economic point of view with respect to the electricity market as discussed in Kempton et al. (2008). Research has also been done regarding the economic feasibility involved with frequency response by PEVs. However, a stringent analysis needs to be done for frequency response considering the SoC constraints of the PEVs for future usage owing to the utilities' economic convenience. The prime objective of plugging EVs into the grid is basically charging the vehicles for future transportation usage. However, EVs discharge for severe frequency dips in the grid without any correspondence to the battery state of charge (SoC) which needs to be maintained for future usage. Additionally, the surplus power in the grid accompanied by an increase in frequency also need to be checked when a particular EV is fully charged since the battery lifetime is being degraded due to over/undercharging as explained in Roscher et al. (2011). Factors such as optimal charging rate, explained in Chen and Cheng (2013), for a battery has also been taken into account to enhance the battery performance of the EVs by incorporating a limit over the rate of charge (RoC). The over/undercharging can be compromised if the end user is benefiting economically by participating solely for frequency regulation. Keeping these factors in mind, a trickling charging method has been proposed in this paper in accordance with the regulatory services and enhancing battery lifetime simultaneously.

This paper is organized as follows. Section II of this paper illustrates on the system topology. Section III of this paper demonstrates the V2G charging framework to participate in frequency response. Various scenarios have been accounted to validate the performance of the scheme through simulation result and elaborated in Section IV. Finally, the paper is concluded in Section V.

2. SYSTEM ARCHITECTURE

The system considered in this paper is shown in Fig. 1. The plug-in stations are accompanied by a bidirectional DC/DC converter in the DC microgrid to regulate the DC link voltage. The DC/DC converter acts as an aggregator which manages the regulation capability and charging/discharging of the EV batteries. Both AC and DC sides are connected through an inverter to maintain the power balance between both sides. The filter as well as grid impedance has been accounted in R_g and L_g in the AC side. The system parameters considered has been depicted in Table 1.

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2.1 Inverter control

To maintain the power balance between both sides, a decoupled inverter control strategy as discussed in Milosevic et al. (2006) has been adopted in this paper. The DC voltage is regulated by the outer control loop whereas the inflow/outflow of power into the grid is governed by the inner control loop. All the control actions have been performed at a switching frequency of 4860 Hz. Hence, the effective time constant of both the control loops have been set accordingly to incorporate faster action under sudden disturbances.

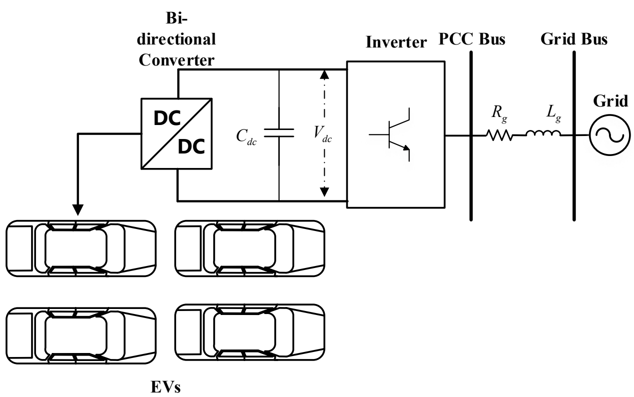

Fig. 1. System Architecture

2.2 Optimal charging characteristics

The optimal charging characteristics has been well-defined in Fig. 2 following the power inflow/outflow from the battery. As explained in Roscher et al. (2011), the battery lifetime is enhanced if it is being charged at a limited rate which also implies that the charging gets slower. In case of EVs, the slow charging can be undermined considering its standstill duration and battery performance of the end user. Hence, a current limit has been used in the DC/DC converter during power exchange. The control objective of charging of PEVs which depends on the frequency variation including SoC limits is the primary emphasis in this paper.

In Fig. 2, P_{max} is denoted by the maximum power absorbed from or injected into the battery owing to the optimal charging characteristics for longer battery life. This has been accounted with effect to change in frequency. As it can be seen from the figure, the RoC increases with the increase in frequency whereas decreases with the decrease in frequency. It has been shown in Fig. 2 to denote the change in RoC with change in frequency from f_1 to f_2. Corresponding to $\pm P_{max}$, change in frequency can also be attributed to f_{min} and f_{max} respectively, described in detail in Section III.

Table 1. System parameters

Parameters	Values
DC link voltage (V_{dc})	510 V
DC link capacitence (C_{dc})	2 mF
R_g, L_g	0.3 Ω, 2 mH
Grid voltage	320 V
Grid frequency	60 Hz

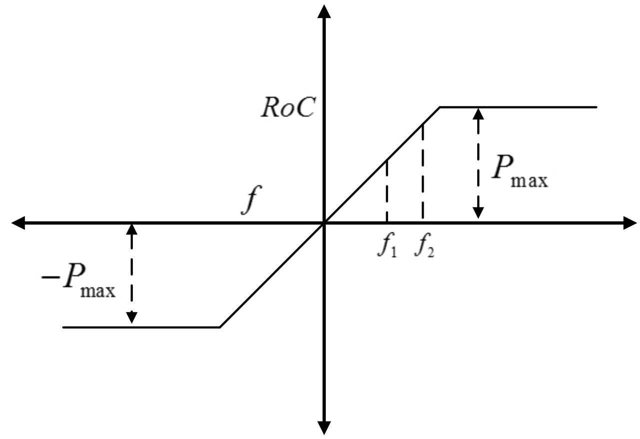

Fig. 2. Proposed V2G control

2.3 Charging mode

This paper is based on level 2 EV chargers. Many fast charging level 3 chargers have been analyzed in the literature (See Dost et al. (2014)). One of the fastest evolving level 3 chargers is CHAdeMO (charge de move) charger which has been designed for high capacity applications requires a communication system to link itself with the battery management system. Wireless inductive charging is also being recently adopted in many countries which takes place by magnetic resonance explained in Lukic and Pantic (2013).

3. V2G CONTROL STRATEGY

The charging/discharging of the EVs is governed by the frequency response in the grid. Usually, the power mismatch is balanced by controllable output power plants such as gas turbine power plants. However, the ability of PEVs in terms of regulatory services has not yet been realized in the literature. Hence, a V2G control scheme has been proposed in this paper which looks after the SoC constraints for future usage of EVs. Also, the factors responsible for deteriorating battery life has been prioritized which has been monitored by a charge seizing control scheme.

3.1 V2G Control

This control scheme has been implemented in the bidirectional DC/DC converter used alongwith the battery in EVs. Since level 2 charging philosophy has been adopted in this paper, utilization of DC/DC converter is crucially recommended since the battery parameters may vary for different EVs.

In Fig. 3, RoC-SoC characteristics for nominal frequency has been plotted to emphasize the optimal charging characteristics of a battery. As it can be seen from the figure, RoC can attain a maximum optimal charging value within a set of $[SoC_{low}, SoC_{high}]$ whereas owing to the enhancement of battery lifetime, it starts decreasing beyond the set. SoC_{low} and SoC_{high} are the SoC setpoints where RoC starts decreasing exponentially whereas SoC_{min} and SoC_{max} are the EV battery operating setpoints. The exponential decrease in RoC has been achieved by using a