Applied Energy 137 (2015) 899–912

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Influence of the vehicle-to-grid strategy on the aging behavior of lithium battery electric vehicles

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HIGHLIGHTS

- A study of a V2G strategy considering the state of health of EVs as fundamental parameter is proposed.
- A Simulation environment with 100 electric vehicle models for two different lithium-ion battery chemistries is implemented.
- Real aging and electrical characteristic data are used to parameterize the battery models.
- Simulation of 1 year for 4 different scenarios for two different ambient temperatures are carried out and compared.

ARTICLE INFO

Article history:
Received 27 February 2014
Received in revised form 9 May 2014
Accepted 28 June 2014
Available online 16 July 2014

Keywords:
Aging model
Electric vehicles
Vehicle-to-grid
Lithium-ion batteries

ABSTRACT

The main goal of this paper is to study the effect of a vehicle-to-grid (V2G) strategy on the lifetime of two different lithium-ion batteries. The work investigates how the aging effect on the electric vehicles' (EV) battery packs due to the additional V2G use can be reduced: it is assumed that the grid is able to identify the cars within the fleet for which the ulterior aging effects caused by V2G usage are restrained in respect of the others. The chosen EVs have to contain enough energy to satisfy the grid requests in terms of power regulation. In order to analyze the possible effects on the EVs due to the mentioned strategy, a V2G simulation environment has been implemented. The system consists of 100 EVs and a grid management strategy subsystem. Each EV is represented by a battery electrical model based on electrical impedance spectroscopy (EIS) data and an aging prediction model parameterized through accelerated aging tests. In order to reproduce real scenario conditions, both the electrical battery model and the aging prediction model have been parameterized for two different cells, a $LiFePO_4$-cathode based and an NMC-cathode based lithium-ion cell. In particular, the accelerated aging tests have been carried out for more than one year, both for calendar and cycling operation, involving around 45 cells for each of the two technologies. The grid subsystem is represented by an algorithm which is able to consider information in terms of aging and type of battery installed in the EV. This subsystem helps to make decisions related to the optimal additional use of each car for a V2G operation. In order to show the applicability and feasibility in terms of battery pack lifetime of the considered V2G management strategy, different scenarios for a period of one year have been simulated. These scenarios consider two different locations with two significantly distinct ambient temperatures, in which the starting conditions of each car in terms of aging state have been selected randomly. The implemented system can be used as a perfect tool to test different grid strategies, taking the aging of the EVs as well as the request in terms of grid power regulation at the same time into account. Furthermore, the entire strategy has been tested including in the system two assembled battery packs, with two li-ion battery chemistries as mentioned earlier. The individual battery management system (BMS) for each technology has been developed in terms of hardware and software requirements. Moreover, the information exchange in terms of aging data between grid and BMS for the V2G strategy has been implemented and tested on a real-time simulation unit.

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http://dx.doi.org/10.1016/j.apenergy.2014.06.063
0306-2619/

1. Introduction

Nowadays electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEV) are considered as one of the possible ways to limit the environment pollution problem. Their integration in the future grid architecture has most likely to take place through the so called vehicle-to-grid (V2G) system [1,2]. Studies and analysis in Germany [3] show that more than 80% of the daily trips of German passengers are placed between 60 and 70 km, while Hartmann and Özdemir [4] have stated that the daily availability of passenger cars that can be plugged into the grid is higher than 89%. Hence, it can be supposed that in the near future EVs could be connected to the grid for an average time of 20–22 h per day. Different applications and V2G scenarios are discussed in Refs. [5–8]. Talebizadeh et al. [6] have studied the influence of 50,000 EVs to the cost of the unit commitment problem, while in [7,8] the attention was focused again on the operation principle of the grid strategy and how the charging strategy can be shifted for an optimal and economical use of the energy in the vehicles. A main point that often is neglected or not sufficiently considered in the literature is the ulterior aging effects caused in the EV and PHEV battery packs due to the additional cycling operation. In this sense, valuable information can be found in Refs. [9–12]. Bashash et al. [10] have considered the effect on the grid that the V2G strategy can have, if the charging process is scheduled in order to limit the battery aging. Similar studies were done by Lunz et al. [11], investigating different scenario and showing the economic saving for the customers. Guenther et al. [12] have delivered a huge contribution in this direction: they have studied the consequence of the participation in grid services on the EV battery lifetime considering different scenarios for a time range of 10 years. The simulation investigates different scenarios; however, it is carried out only for one vehicle. Moreover, it takes into account that the battery will be subjected to the same condition for the entire time window in terms of grid services, even though the variation of the ambient temperature during the year is considered.

Furthermore, the analysis and studies always neglect the differences in the vehicle battery packs, in terms of cell chemistry and actual aging state. The aim of this work is to simulate a V2G system with numerousness EVs, and to investigate the consequences on battery aging when the availability of each car to take part in the grid regulation depends on (i) the actual aging state, (ii) the battery chemistry and (iii) the cost of the grid service participations in terms of battery lifetime. A model to predict aging variation of the battery for different load profiles will be introduced. The battery model and the aging prediction model will be presented. Both are parameterized and validated with real data for two different lithium-ion cells and used to simulate 100 EVs. Moreover, the interaction procedure between each vehicle and the grid will be clarified. At the end, simulation results are presented considering different scenarios and countries. The result discussion shows which effects a V2G strategy has, when each of the available EVs is used if the battery aging variation is limited (i.e. cheaper) in respect of the inconvenient ones. The work is structured as follows: in Section 2 the V2G simulation environment is depicted, each component is introduced and the interaction between EVs and the grid is explained; in Section 3 the simulation scenarios are introduced and the results are critically discussed, considering which additional system improvements can be done to obtain a better future integration of the EVs into the grid system; the work is closed with the conclusion in Section 4.

2. Model setup

In Fig. 1 the general idea of the studied system is illustrated. The main components are the grid and the EVs as energy storage systems. The following exchange of information between the two actors takes place in form of:

- Power, which the grid needs to satisfy the momentary requirements.
- The value of the battery state-of-health (SOH) variation that each power profile requested from the grid will cause in the battery pack.

In order to consider a high variability of the different participants (i.e. EVs), it is fundamental to take into account that the batteries in the different vehicles can contain different cell chemistries. Moreover, if the single vehicle is compared with others, the actual battery SOH is different, as each battery has had its own history, and thus it has aged during its lifetime in a different way. These two factors play an important role especially in terms of grid decisions, as the initial battery investment cost depends on the single battery type (chemistry and manufacturer), as well as on the speed of the aging process which depends also on the actual battery SOH.

It is important at this point, for a better further understanding, to describe how the grid and the cars have to communicate in a V2G scenario. The communication mechanism is depicted in Fig. 2, and takes place in 4 steps:

1. The grid collects all the information from the available cars, i.e. the cars that are connected to the net and not in the charging process in a defined moment. This information can for example consist of the actual battery state-of-charge (SOC) and SOH. In this moment the grid has also the knowledge of the power requests in the near future.
2. The grid can propose and send to each available car information in form of package with N different load profiles, fulfilling the following condition:

$$\sum_{i=1}^{m} P_{n,m} = P_{req} \quad n = 1, 2 \ldots N \tag{1}$$

   where m is the number of cars, N is the total number of the sent usage profiles, and P_{req} is the power requested from the grid in the moment in which the communication takes place (from the grid side, the value of the power can be positive or negative, in case of battery discharge or charge respectively).
3. For each of the N usage profiles proposed, the EV battery management system (BMS) has to predict the possible SOH variation that every profile would generate on the battery pack. In order to accomplish this task, the BMS has to be equipped with aging prediction models able to prognosticate the battery lifetime depending on the future short term conditions, in terms of environment (ambient temperature) and operation (battery current rate).
4. The grid receives the whole information from each EV and calculates which is the best combination of load profiles that can be used to:
   a. Satisfy the grid requirement in terms of power;
   b. Limit as much as possible the SOH variation of the entire available EVs.

The question which may arise is what the next near future means, and how often the communication process should take place. A possible solution considers the definition of a time window as fundamental element of the system; for example, the window can have duration of one hour. Inside each window, the communication process between EVs and grid described above (point 1–4 in this