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Impact of User Drive Style on EV Energy Storage System Aging

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ABSTRACT

In the last decades, the transition to zero-emission automotive transportation has accelerated thanks to the technological advancement of Electric Vehicles (EVs). In particular, the great performance improvements of their Energy Storage Systems (ESSs) in energy and power density have declared this automotive transportation the most promising among the competitors. However, EVs are still being studied by the research community in order to overcome several challenges which limit the large diffusion of this technology on the global market. The aim of this paper is to analyse the relationship between user drive style and battery pack's aging which reduces ESS capacity over the operative time. The analysis is carried out in MatLab/Simulink environment on real urban driving cycles using an experimentally validated ageing-electro-thermal model of a LiNMC cell. The evaluations have been obtained by monitoring the BP State of Health (SoH) under different user's drive styles and operative conditions. The paper's results provide useful information for the ESS manufacturers and designers in order to improve the achievable EVs' road range.

Keywords: Sustainable Mobility, Electric Vehicles, Battery Pack Aging, Lithium Cell Modelling.

1. INTRODUCTION

The increasing concern about pollutant emission in the automotive transportation sector has moved the vehicle customers' attention towards zero-emission vehicles. In this context, electric vehicles (EVs) are one of the most promising no-pollutant vehicle technologies. In particular, the popularity of EVs is mainly due to the high-performance improvement of Lithium-ion battery cells (LiBs), which compose the vehicle's Energy Storage System (ESS). According to [1], the specific power and energy density values reached by lithium cell technology have reduced drivers' range anxiety during vehicle operations. However, lithium cells must overcome several issues which limit the large spread of these vehicles in the automotive transportation market, such as the aging mechanism of LiBs. Indeed, this phenomenon has a negative influence on battery cell performances reducing the capability of storing and providing electrical energy during its useful life [2]. The estimation of the LiBs aging mechanism has been largely studied in literature and several experimental evidence have related the battery cell degradation mainly to operative factors such as the current rate, depth of discharge (DoD) and the cut-off voltage [3],[4],[5].

In literature, the mentioned factors have been studied individually, although they combine themselves in relation to customers' driving habits [6]. Different user's drive styles have a direct impact on battery cells aging mechanism and ESS remaining useful life influencing both the cycling and calendar aging contributions. In this context, this paper investigates the impact of different user drive styles on EV battery pack aging. Starting from an experimentally validated electro-thermal model of a typical lithium cell used in the automotive field, a validated aging model has been implemented in order to achieve BP aging evaluations. Furthermore, a dataset of real EV driving cycles has been categorized on the base of disparate operative factors in order to obtain different user drive styles. In the end, simulation activities have been carried out in order to study the correlation between the considered factors and BP SoH degradation during its useful life.

2. CASE STUDY

In this study, the relationship between users' drive habits and BP aging have been investigated taking into account a dataset of real EV road journey reported in [7]. The road trips have been performed by the commercial EV BMW i3 with ESS capacity and voltage of 42,5 kWh

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and 352 V respectively. Each road journey has different characteristics in terms of speed profile, road slope, mileage etc, which have been used in order to extrapolate different user drive styles. In particular, four parameters have been used for trip classification and each one has been divided on different levels. Firstly, the dataset has been divided in terms of power request by the user during the operation. This parameter has been classified into light and aggressive values according to the EV average speed, acceleration and road slope of the specific trip. Secondly, the level of reached DoD before the user starts the charging operation. This parameter has been classified into three levels which are 40%, 60% and 80% respectively. The third parameter is the type of charging operation used by the user. This parameter has been divided into standard and fast-charging operations. The last parameter is the ambient temperature at which the EV operates. This parameter is indirectly linked to user drive habit and the three chosen values are low, medium and high temperature which correspond to 283, 298 and 313 K respectively.

All the parameters' variations have been combined in order to obtain different user drive habits that have been tested in a simulation environment. In particular, the used methodology starts from the determination of the user drive style to study. Successively, simulation activities based on the road trip to test have been performed. The numerical activities are carried out using an electro-thermal and aging BP scaled model. In this regard, the electro-thermal model is used to obtain operative parameters such as average BP temperature, discharged/charged capacity and current rate values during operation and simulation time. The obtained results have been used as input for aging model which predicts the BP State of Health estimating its degradation during the working cycle. If this value is below the lower limit value, the simulation stops. On the other hand, the numerical activity restarts until the SoH limit is reached. In this study, the lower limit of SoH is fixed at 80%, considering this value at which the EV is unable to guarantee a reliable road range to the user during the operation. In the next section, the modelling and experimental activities on the single battery cell are presented.

3. MODELLING AND EXPERIMENTAL ACTIVITIES

3.1 Modelling

As explained in the previous section, the simulation activity is necessary in order to evaluate the BP SoH degradation due to the considered user drive habits. In this work, the simulation activities have been simplified by scaling the BP power request to a single-cell point of view. The scaling operation has been obtained by studying a pouch battery cell based on Nickel-Manganese-Cobalt lithium technology whose electrical characteristics are 3.7 V and 20 Ah. To achieve the considered BP voltage, the battery cells are arranged in S98P6 electrical configuration.

Concerning the electro-thermal model choice, a lumped parameter model has been chosen in order to obtain a good trade-off between simulation results accuracy and the time cost required in simulation [8]. As matter of fact, lumped parameter models describe the battery cell behavior through the equivalent circuit analogy. The chosen model is composed of Thevenin Equivalent Circuit model (ECM) and a Single State Thermal Lumped model for the electrical and thermal behavior respectively. This multidomain model is implemented in MatLab/Simulink environment and it is characterized by a synergic connection between these two domains. In particular, the electrical part estimates the terminal voltage and heat rate generation due to Joule losses while the thermal part uses the heat generation evaluation to estimate the battery operative temperature, which influences ECM's electrical parameters. In addition, the battery's parameters are influenced also by the battery cell's cycling and calendar aging. The aging contribution is taken into account using a literature-validated model of the studied lithium cell technology [9]. The used model describes the two aging mechanisms in terms of battery cell capacity fading based on a huge experimental campaign that lasted several years. Results have suggested that this mechanism is due to calendar contribution is mainly related to time and ambient temperature, as expressed in Figure 1-a.

$$Q_{cal,\%} = 14786 * \sqrt{t} * e^{\left(-\frac{E_a}{R*T}\right)} \qquad \text{(a)}$$

$$Q_{cyc,\%} = \left[(aT^2 + bT + c) * e^{(dT+e)*I_{rate}}\right] * Ah_{thr} \qquad \text{(b)}$$

Fig. 1. Calendar (a) and Cycling (b) Capacity Fading Equation.

As shown by the above equation, the aging mechanism has been evaluated in percentage and it has an exponential relationship with Temperature (T), activation Energy (Ea) and Universal Gas Constant (R) while it is related to the simulation time (t) by a square relationship. On the other hand, the cycling aging term is related to ESS's parameters such as the battery cell's temperature, current rate value, reached level of State of Charge and charged/discharged capacity during the operation following the equation (Figure 1-b).

3.2 Experimental Activities

The described electro-thermal battery model has been parameterized and validated. The experimental activities have focused on studying the behavior of two different LiNMC cells. The first one had a State of Health (SoH) near 0 %, while the second cell was a brand-new one. The main objective is to characterize the battery cell behavior at both aging statuses in order to obtain a characteristics interpolation in all the SoH range. In particular, two kinds of tests have been carried out. The first one is called Hybrid Pulse Power Characterization test, which has been repeated at different ambient temperatures, while the second test is called Thermal Relaxation test. The experimental work has been performed in Energy Storage Laboratory of the Institute of Science and Technology for Sustainable Energy and Mobility using the test bench described in [10]. In particular, the test bench is composed of a Power Supply, used in combination with a Variable Load, in order to control the current profile provided to the battery cell, and of a Climatic Chamber in order to regulate the ambient temperature in a range of -233 to 450 °K. The battery cell current and voltage have been monitored using Hall Effect sensors while cell temperature has been acquired with a PT-100 sensor.

The parameterization activities have been performed using Parameter Estimation toolbox in Simulink Environment. This toolbox is based on a linear regression algorithm which estimates model parameter values minimizing the difference between experimental and simulation output. Furthermore, the HPPC at 298 °K has been used to validate the model and test its reliability. In particular, the predicted battery cell terminal voltage and temperature trends fit the experimental results with a maximum residual error of ± 0.3 V and ± 0.6 K respectively.

4. RESULTS AND DISCUSSION

The considered daily journey is a home-work trip and comes back of about 100 km. In this context, the BP temperature is reset to ambient one every time the user reaches the destination. This routine is followed till the BP SoC reaches the DoD reference value and the EV is recharged either at the workplace or at home. The simulation activities have started studying the influence of the different ambient temperatures on BP aging fixing the DoD at 40%, the light power request and the standard charging protocol. The chosen combination has revealed that the longest duration of BP is achieved at ambient temperature. In this regard, the BP lasts for 23 years, and this value of BP's useful life is considered as an ideal case and a reference for our evaluations. In Figure 2, all the simulation results are reported using a standard charging operation. As expected, results suggest that the higher ambient temperature has the worst negative impact on BP useful life accelerating the SoH drop of about 45% while the BP life is reduced by only 12% at lower temperatures. Changing the DoD values, the EV useful life decreases for DoD values higher than 40%. In particular, the BP life reduction has a parabolic relationship with the DoD with a maximum of 60% of about 6.3%.

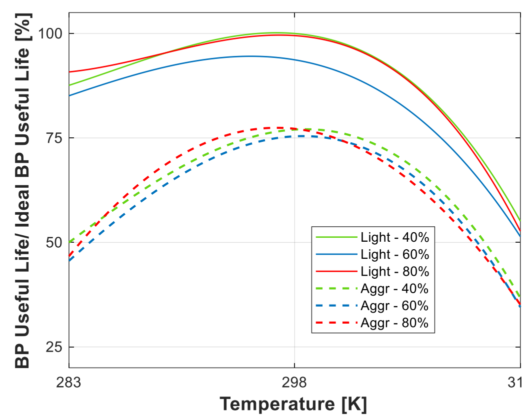

Fig. 2. Simulation Results for all DoD values and for Light and Aggressive (Aggr) Power Request.

This trend is confirmed at higher temperatures with an aging acceleration of about 3,7% and 2,4% for medium and high DoD values respectively. However, at 283K, the BP life improves by about 3,2% for high DoD values. The variation of the power request from light to aggressive increases the BP aging during its lifetime. In particular, results confirm the relation between DoD and BP aging with an average SoH drop of 25%, 55% and 70% for ambient, low and high ambient temperatures.

Further evaluations have been made by repeating all the simulations with fast charge operation as shown in Figure 3. As shown in the figure, for light power request, the SoH degradation presents the same relationship with all the parameters for ambient temperature values of 298 K and 313 K. In this case, the BP useful life decreases only in amplitude and the worst impact is achieved at higher temperatures and medium DoD values, with a reduction of 53.7%. On the other hand, the BP has some benefits at lower temperatures presenting a BP useful life growth as DoD increases due to the higher average

BP temperature which decelerates the BP aging. It should be noted that the combination of the aggressive power request and fast charge changes the SoH degradation trend with the DoD. In particular, as the DoD increases, the BP useful life decreases for higher and standard temperature. At 313 K, the worst case is achieved with a BP useful life reduction of about 75%.

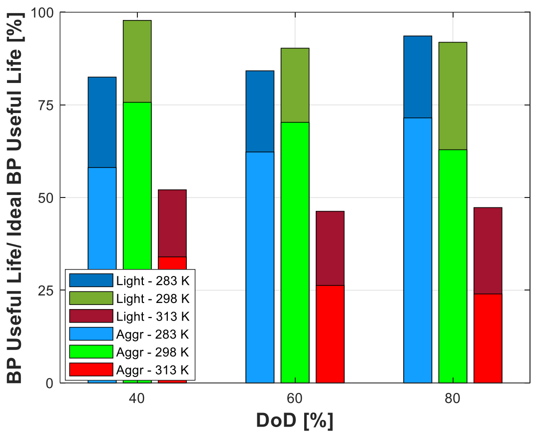

Fig. 3. *Simulation Results for all parameters combinations with fast charge operation.*

To summarize, the performed analysis has quantified how different driver habits could affect the BP aging mechanism. In particular, the combination of an aggressive power request and fast charging may drop the BP's useful life by over 50 %, especially when the ambient temperature is above 298 K. The same combination has a lower impact on SoH degradation at standard temperature while this trend is inverted at lower temperatures thanks to the overheating of the BP during the charging operation. It should be noted that an aggressive power request reduces the effect of DoD on SoH degradation with a standard charging operation. However, the DoD values influence the aging mechanism with fast charging accelerating the aging mechanism as the DoD value grows.

5. CONCLUSION

In this paper, the relationship between different user drive styles and BP SoH degradation has been investigated. Firstly, an electro-thermal lumped parameter model of a 20 Ah LiNMC cell has been developed and validated. Further, a validated aging model based on the considered lithium technology has been chosen from the literature. The two models have been used in a combined way in order to carry out simulation activities from a single-cell point of view considering a commercial car of 43 kWh. Successively, a dataset of real EV trips has been classified and categorised in order to formulate different driver habits to study.

Results have shown that for the user light drive style, standard ambient temperature, low DoD, light power request and slow charging operation present an ideal case in order to preserve BP from the aging mechanism. Among the parameters, the DoD has a minor impact on BP's useful life than the ambient temperature and power request at standard charging operation. However, it influences the SoH degradation during the fast charging increasing the time required by the BP to be charged and, consequently, its average temperature. Concerning the ambient temperature effect, higher temperatures have the worst impact on the BP's SoH degradation achieving the worst-case scenario in combination with fast charging operation and aggressive power request. In addition, the fast-charging operation increases the BP degradation of about 20% promoting the aging mechanism.

Future developments may concern the importance of cooling systems in preserving BP from aging. In particular, several studies may focus on how different cooling strategies may affect the BP's useful life

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