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State of health assessment for lithium batteries based on voltage–time relaxation measure

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ABSTRACT

The performance of lithium batteries degrades over time. The degradation rate strongly depends on stress conditions during use and even at rest. Thus, accurate and rapid diagnosis of battery state of health (SOH) is necessary for electric vehicle manufacturers to manage their vehicle fleets and warranties. This paper demonstrates a simple method for assessing SOH related to battery energy capability (SOH_E). The presented method is based on the monitoring of U_{relax} over aging. U_{relax} is the open-circuit voltage of the battery measured after full charging and 30 min of rest. A linear dependence between U_{relax} and remaining capacity is noted. This correlation is demonstrated for three different commercial battery technologies (different chemistries) aged under different calendar and power cycling aging conditions. It was determined that the difference between two U_{relax} voltages measured at two different aging states is proportional to SOH_E decay. The mean error of the linear model is less than 2% for certain cases. This method could also be a highly useful and rapid tool for a complete battery pack diagnosis.

1. Introduction

Currently, energy storage systems represent a real need in daily life. Such systems are present in most electronics,especially in portable gadgets. Several battery technologies have been widely studied and developed, and real efforts are currently oriented to develop more powerful, longer-lived, and more secure batteries [1]. Particularly, lithium batteries are the best solution as energy storage systems in the field of portable electronics. Their success is due principally to their high energy and power density [1].

Lithium batteries also influence our transport mode. In fact, because of the depletion of fossil fuel resources and severe legislation to limit urban pollution, vehicle manufacturers are making a clear transition to electrified vehicles. Green transportation will represent nearly 2% of the total European vehicle fleet by 2020 [2]. In total, 750,000 electric vehicles have been sold worldwide, 250,000 of which are from then Renault–Nissan alliance.

A traction battery pack represents between one-third and one-half of the price of an electric car. Unfortunately, the electric performance of batteries degrades over their lifetime [3]. In fact, battery power and capacity capabilities decrease when the vehicle is used or even at rest.

The main aging processes are related to, but not limited to, solid electrolyte interphase growth, active material loss, and lithium plating [3–5]. These processes consume reversible lithium and increase battery resistance, affecting battery performance [3]. Furthermore, the battery aging rate is sensitive to temperature, state of charge (SOC), depth of discharge, and current magnitude, and several researchers are attempting to model battery performance fade over aging [6–9]. Predicting battery performance decay in advance using models is interesting for the optimization of battery durability, design, and thus electrified vehicle cost.

The performance of a battery pack decays over the lifetime of a vehicle until it no longer meets vehicle requirements. Nevertheless, the determination of criteria defining the end of life of a battery for a certain application is not trivial. Generally, the state of health (SOH) of a battery is related to its capability to store and restitute energy at a certain power, but its definition is not trivial and subject to debate. Obviously, the battery SOH definition depends so on the set of specifications of a specific industrial application. Nevertheless, for vehicle manufacturers, the battery pack is considered to be at EOL (End Of Life) when its capacity decreases by 20% and its resistance increases by 200%.

Several researchers are focusing on SOH assessment over time [10–15]. In fact, SOH diagnosis is interesting because it quickly and

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as precisely establishes as the battery's ability to ensure the requested performance goals. This could save time and effort and lead to greater satisfaction by the final client. Frequently, SOH is defined as a state of health related to energy capability (SOH_E) or/ and to power capability (SOH_P) [15]. Accurately and simply predicting either one is particularly interesting to quantify aging and thus replace worn-out battery packs as needed in cases when vehicle manufacturers, such as Renault, rent vehicle battery pack to the final users [12].

In this work, SOH_E is defined in (1) as the percentage of the remaining battery capacity (RBC) and the initial battery capacity (IBC) at the beginning of life (BOL).

$$SOH_E(\%) = 100\% \times {}^{C_{RBC}}/_{C_{IBC}} \tag{1}$$

C_{RBC} (Ah) and C_{IBC} (Ah) describe the available capacities in ampere hours, when discharging the battery at 1C under room temperature until reaching the minimum voltage from a fully charged state. As defined, the SOH_E range could be between 100% at BOL and 0% at 0 Ah of battery capacity.

2. State of the Art

SOH_E diagnoses can be divided into online and offline techniques. Each technique has its advantages and drawbacks in term of implementation, time duration, and precision. Thus, a good compromise among these advantages and drawbacks is a key for a vehicle manufacturer to select the suitable technique. In this article, simplicity and feasibility were chosen as the criteria of SOH_E technique benchmarks.

In the literature, several approaches have been demonstrated for RBC and corresponding SOH_E monitoring and could be divided to five groups [15].

The first four groups are based on battery voltage change versus energy throughput (Ah stored or restored from the battery). In fact, charging or discharging a certain amount of ampere-hours under the same current induces a higher voltage change for a battery that has a lower capacity and higher resistance (aged battery) than the same battery that has a higher capacity and lower resistance (at BOL or at a better SOH). Likewise, the OCV variation after a certain amount of energy throughput is sensitive to RBC and could be useful for battery capacity monitoring.

The difference between the first four group of methods consists of how battery voltage change or battery OCV is measured or predicted. The fifth group is considered more as an electrochemical approach.

For the first group, the battery capacity determination is based on the state of charge pre-established relation SOC = f(OCV). Measuring OCV change versus ampere-hour throughput is useful for RBC determination that could be retrieved using basic equations [16]. The drawback of this technique is that the SOC = f(OCV) relation is relatively subject to changes through aging [17]. In addition, this operation is possible only between two distinct SOCs and by measuring their corresponding OCV after a relatively long rest time. The occurrence of these circumstances for an accurate capacity determination is uncommon in real driving situations because of random power solicitation without sufficient battery rest time.

For the next three groups, the measurement of the RBC is based on the estimation of OCV, SOC, or the battery voltage change under current through models, algorithms, and various methods [15]. Many techniques have been investigated and sometimes combined, including electrical models, Kalman filters, and artificial intelligence such as neural networks and/or fuzzy logic [14,18–20]. Unfortunately, most of these techniques suffer from high computational time and resources and training step shortage, and the parameters must be adaptable and updated to minimize computational divergence. Moreover, these techniques are generally difficult to implement in battery management systems (BMS).

The fifth group uses a different approach based on the incremental capacity analysis (ICA) and/or the differential voltage analysis (DVA) in relation to battery capacity [21–23]. The ICA picks shifting, and its magnitude change over aging is the key to RBC monitoring. Unfortunately, the online usefulness of this method is disputable because of the non-constant current profiles in real vehicle driving situations. To avoid this issue, ICA could be used under battery charging. Nevertheless, the charging current should be as low as possible to accurately detect voltage plateaus and corresponding picks. Likewise, this technique is unsuitable for fast charging.

The complexity of these models and the random driving style have compelled researchers to investigate battery capacity monitoring during charging, which is under more predictable conditions but could also be unpredictable under intelligent charging mode if it is linked to smart grid strategies [12,13,24].

In previous works, Eddahech et al. investigated the constant current (CC) and constant voltage (CV) charging modes over aging to identify battery SOH_E [11,12]. Through aging, they demonstrated a decrease and an increase in charging time for CC and CV phases, respectively, using several technologies. The CV charging phase was particularly interesting for SOH_E determination. In fact, current profiles under CV charging decrease more slowly over aging. By using a parameter identification tool and analyzing current profiles at the CV charging phase, SOH_E could be retrieved through a pre-established linear correlation between identified parameters and battery SOH_E. Considering that the occurrence of CV charging just before full charging is not rare, this method is a very promising solution and could be embedded in a battery management system and/or a charger environment. The real challenge of Eddahech et al's method is the need for an accurate current measurement system and a computing tool for parameter identification.

In this study, the aging of the eCH-OCV, measured 30 minutes after full charge (U_{relax}), was particularly correlated to RBC with different aging conditions and battery chemistries. U_{relax} was compared for a given battery but at two different aging states. Likely, the U_{relax} voltage difference between two distinct aging states is proportional to SOH_E decay.

3. Experimental

In this work, three different battery technologies were aged under different aging conditions. The battery characteristics and test conditions are summarized in Table 1.

Before aging, all batteries were cycled between voltage limits for a minimum of 6 times to identify suspicious elements. Each time, the battery was fully charged using the corresponding protocol (Table 1) and discharged under 1C current at 25 °C, until reaching its minimum voltage limit under the current. For all aging tests, 3 battery elements were tested to ensure reproducibility

For calendar aging, battery elements were charged under the corresponding CCCV charging protocol detailed in Table 1 and then set to the target SOC by discharging at 1C for a certain time = 1 h × (100-SOC)/100 at 25 °C. The batteries were then stored in climatic chambers at the corresponding aging temperature and SOC.

Capacity checkups were performed approximately every two months, and the checkup time was sometimes shortened or extended for extreme aging conditions. The battery capacity was measured at 25 °C (after 6 h of temperature stabilization) and after full charge by discharging the battery element at 1C until reaching