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Practical state of health estimation of power batteries based on Delphi method and grey relational grade analysis

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HIGHLIGHTS

- A novel multi-factor consideration for quantitative SOH estimation.
- A hybrid Delphi method and grey relational grade analysis to estimate SOH using six influential factors.
- Employed a panel of experts for weighting in the multi-factor consideration.
- Comparison with conventional SOH estimates based on capacity or power capability.
- Accuracy and sensitivity analyses were performed for validation.

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ABSTRACT

The state of health (SOH) estimation is very critical to battery management system to ensure the safety and reliability of EV battery operation. Here, we used a unique hybrid approach to enable complex SOH estimations. The approach hybridizes the Delphi method known for its simplicity and effectiveness in applying weighting factors for complicated decision-making and the grey relational grade analysis (GRGA) for multi-factor optimization. Six critical factors were used in the consideration for SOH estimation: peak power at 30% state-of-charge (SOC), capacity, the voltage drop at 30% SOC with a C/3 pulse, the temperature rises at the end of discharge and charge at 1C; respectively, and the open circuit voltage at the end of charge after 1-h rest. The weighting of these factors for SOH estimation was scored by the 'experts' in the Delphi method, indicating the influencing power of each factor on SOH. The parameters for these factors expressing the battery state variations are optimized by GRGA. Eight battery cells were used to illustrate the principle and methodology to estimate the SOH by this hybrid approach, and the results were compared with those based on capacity and power capability. The contrast among different SOH estimations is discussed.

1. Introduction

In the past few decades, environmental impacts from the petroleum-based transportation and the fluctuating oil prices have led to renewed interests in electric and hybrid vehicles (xEVs). With rapid development of xEVs, power batteries have become increasingly critical to the powertrain. The state-of-health (SOH) of a battery is a measure of its health condition relative to a pristine state as an indicator of the age and condition of the battery in its life cycle. Although many ways to identify this indicator have been discussed in the literature [1–12], a tangible methodology to estimate SOH remains lacking, especially regarding its applicability in practical use in battery management systems (BMS), since during the lifetime of a battery, its health condition tends to deteriorate due to inevitable, irreversible physicochemical changes in the battery, taking place continuously with usage and aging until the eventual fate the battery is no longer usable in such an application.

The battery performance is typically measured by instruments and expressed in parameters such as voltage, impedance, capacity

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etc. If the SOH is used as an indicator to express the ability of a battery in performing certain functions, an accurate account of such aspect should keep in line with the assessment from these parameters. Battery SOH estimation plays an important role in battery management and application. An accurate SOH estimation can facilitate the design of a battery system as well as the safety and reliability of its operation, including the selection of the most suitable battery, determination of the operating conditions, and planning of the maintenance and replacement schedules. However, it is known that charge–discharge cycles degrade battery performance often via the change of chemical compositions and rate capabilities in the battery. This is why battery life is limited by its performance as a function of cycle number, often called cycle life [13–16].

To date, the definition of SOH remains elusive. Compared to progress in the state-of-charge (SOC) estimation, the methodology for inline SOH monitoring lacks a clear description in the literature. A more accepted convention for a battery's SOH is the ratio of the maximum usable capacity of a battery at any point in life to its rated capacity. The maximum usable capacity is difficult to measure inline during practical applications. Conventionally, it is approximated by estimates using DC resistance (DCR), AC impedance, or open circuit voltage (OCV) as the parameters in various techniques, including curve fittings, filtering using Kalman filters, particle filters, or projections by support vector machines, Gaussian distribution and probability density methods. For those interested in powertrain control, the value of SOH can also be estimated by the power functions with parameters determined from the AC impedance spectroscopy [17–21]. However, as the battery deteriorates, the performance of its power capability, the temperature rise due to heat generation in polarization, and other characteristics such as self-discharge could be changed, and the changes among these characteristics are interrelated. These complicated factors in changing battery performance characteristics should be reflected in the SOH [22,23]. Therefore, using the capacity-based estimation alone to describe SOH may be lopsided. For powertrain control and management, such a simple convention does not reflect the full capability of a power battery in meeting the traction requirements in a vehicle operation. To resolve this issue and concern, here we proposed an interesting approach, using a hybrid methodology that comprises two unique 'decision-making' techniques, grey relational grade analysis (GRGA) and Delphi method (DM), which is often used in dealing with complicated engineering systems that involve 'difficult-to-quantify' parameters to determine criteria for decision making. We applied this hybrid approach to estimate the SOH for eight commercial cells upon aging and compared the results with those assessed by conventions using capacity or power capability as the basis for defining SOH. The contrast among these different assessments is discussed.

2. Methodology

Fig. 1 shows a flowchart to illustrate the hybrid approach, combining GRGA and DM to derive useful parameters for the estimation of SOH in commercial Li-ion battery cells. The approach takes the advantages of GRGA + DM, both are practical techniques in dealing with complicated systems, of which the information is either lacking or fuzzy, thus inhibiting a clear understanding of the system and an effective development of the control strategy to manage it. Since SOH is a fuzzy state function for a battery system,

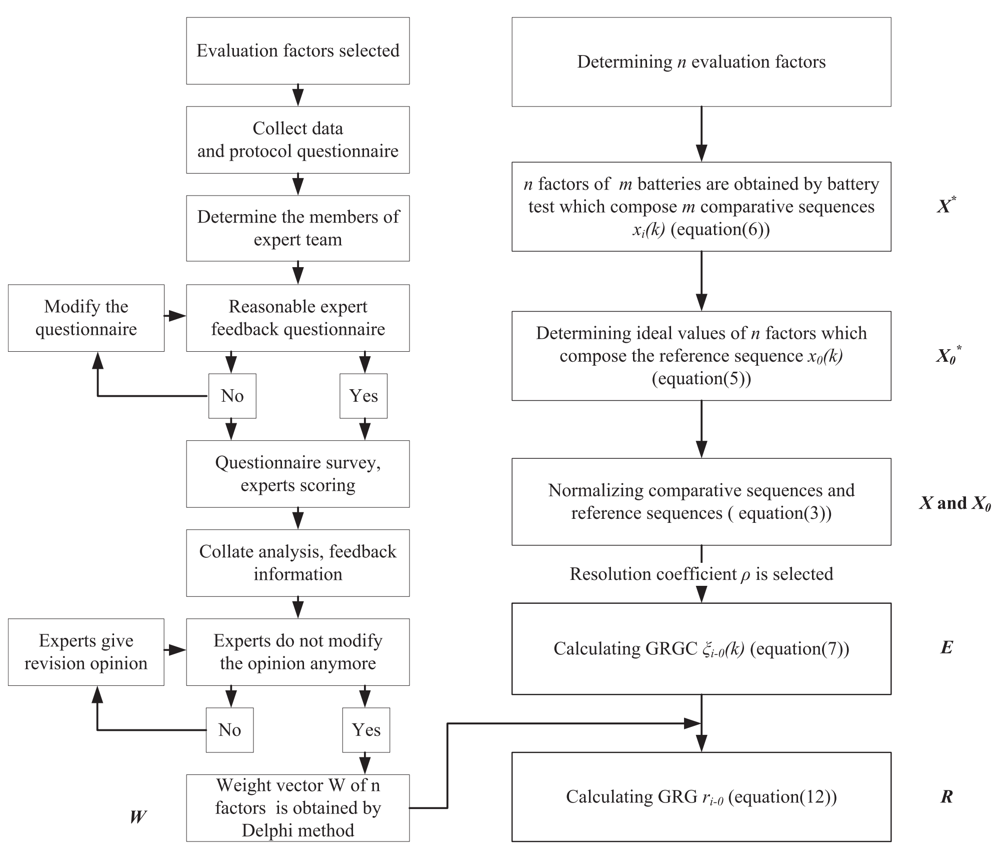

Fig. 1. A schematic illustrating the flowchart of the hybrid approach using the grey relation grade analysis (GRGA) and the Delphi method (DM) for the state-of-health (SOH) estimation of a battery.