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SEMI-EMPIRICAL CYCLING AGING MODELS WITH ENHANCED ACCURACY FOR A NICKEL MANGANESE COBALT CELL

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Batteries have recently garnered significant attention due to their numerous advantages across various applications, particularly in Electric Vehicles (EVs). However, one of the primary challenges limiting broader industry adoption is the aging of batteries over time. In this study, a semi-empirical aging modelling technique was used to predict battery degradation. Experimental data obtained from a 73 Ah NMC (Nickel Manganese Cobalt) cell to formulate three distinct models based on the Arrhenius Law to predict cyclic aging. Batteries underwent testing at two different temperatures and various depths of discharge (DoD) and C-rates up to approximately 800 cycles. Arrhenius' Law, which relates the rate of a chemical reaction to temperature, provided a solid framework for models. Between the three semi-empirical models developed, SEM-3 demonstrated satisfactory predictive accuracy when compared with the empirical data. Upon examining all data sets, SEM-3 exhibited the lowest Root Mean Square Error (RMSE) value of 0.95 in the model predictions, indicating a high degree of accuracy and reliability in its predictions.

Keywords: Electric vehicles; Battery aging; Cyclic aging.

1. INTRODUCTION

Recently, electric vehicle (EV) adoption has accelerated to reduce emissions associated with transportation and to enhance renewable energy use in transportation [1]. Among the various battery types used in EVs, Lithium-ion (Li-ion) batteries are preferred for their high energy density and technological benefits. Battery aging caused by chemical reactions results in decreased performance and lifetime. Environmental conditions and use characteristics (dis/charge) affect aging, which can be divided into calendar and cyclic aging. Methods for predicting Li-ion battery degradation include electrochemical, electrical, and semi-empirical models. Semi-empirical models (SEM), which merge theoretical principles with experimental data, are more versatile and widely applicable [2]. This research examines the capacity reduction of an NMC battery cell and analyses prediction models for cyclic aging, contributing to the literature on battery life prediction in EVs. The models were developed to enhance accuracy and reliability in predicting battery aging, thus contributing valuable insights to the literature on battery lifespan and performance prediction.

2. MATERIALS AND METHODS

The aging is affected by key factors such as time, temperature, depth of discharge (DoD), stage of charge (SoC), and current rate (C-rate). Equation (1) exemplifies the Q_{loss} aging model as a function of time (t), temperature (T), DoD, and C-rate, where the aging factors (T, DoD, C) are segregated from time:

$$Q_{loss}(T, DoD, C, t) = C_A(T, DoD, C) \times f(t). \quad (1)$$

In this study, semi-empirical approaches combining the temperature dependence of the Arrhenius equation with the power law relationship for the number of cycles were used in cyclic aging models [3,4], which is

$$Q_{loss} = A(DoD, C) \times e^{-\frac{E_a(SoC,C)}{RT}} \times n^z, \quad (2)$$

where E_a, R and n are activation energy, gas constant, and number of cycles (*n*), respectively. Table 1 presents a comprehensive overview of the model equations developed in this study.

Model parameters were determined using the Linear Regression and the Genetic Algorithm methods in MATLAB.

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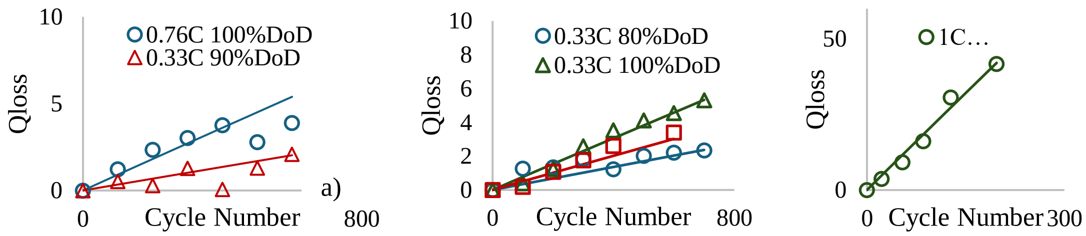
Table 1

Model equations developed in HELIOS cyclic aging models

Model	Equation	Parameters
SEM-1	$a_1 \times \exp\left(\frac{a_2 \times \text{Crate}}{T}\right) \times \exp(a_3 \times DoD + a_4) \times t^{a_5}$	5
SEM-2	$c_1 \times \exp(c_3 \times DoD/T) \times \exp\ (c_3 \times Crate^2) \times n^{c_4}$	4
SEM-3	$c_1 \times \exp(c_3 \times DoD/T) \times \exp\ (c_3 \times Crate^2 + c_4 \times Crate) \times n^{c_5}$	5

3. RESULTS

Assessment of results obtained through the linear regression method shows that SEM-1 exhibited an error value of 18 RMSE, while SEM-2 and SEM-3 demonstrate an error value of 5 and 1.71 RMSE, respectively. Figure 1 shows the experimental data for 40°C and 5°C and the model results of SEM-3, which captures the best fit.



a) b) c)

Fig. 1 – Experimental data and cyclic aging model:a) for 40°C and various DoD-Crate; b) for 5°C and different DoD-Crate; c) for 5°C 1C and 100% DoD.

Similarly, upon evaluating the models derived from the Genetic Algorithm method, SEM-3 once again displayed the most accurate fit with an RMSE of 0.95. The final version of the SEM-3 equation with the optimized parameters is as follows:

$$\boldsymbol{Q_{loss} = 0.003442 \times \exp(11,26341 DoD/T) \times \exp\left(\begin{matrix}14.67921 Crate^2 - \\ 14.562 Crate\end{matrix}\right).n^{0.99}} \qquad (2)$$

4. DISCUSSION AND CONCLUSIONS

A new semi-empirical model incorporating four distinct parameters has been developed, ensuring compatibility with experimental data. The results show that the numerical solution obtained using the Genetic Algorithm yields relatively better RMSE than the analytical solution derived from linear regression. The RMSE of the experimental results at 40°C is 0.64, indicating a high level of accuracy. In contrast, the RMSE for the results at 5°C is 1.15, which is still within acceptable limits. These findings highlight the robustness and sensitivity of the newly developed model under various temperature conditions.

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