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Short Report

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A novel hybrid model to describe hysteresis in Li-Ion batteries of electric vehicles

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Abstract

Considering the environmental aspects, electric vehicles are of very high demand these days. In electric vehicles, battery is the main source of power generation. Lithium (Li)-ion batteries are extensively used in electric vehicles. One of the bottlenecks of Li-ion type batteries is the hysteresis losses that it suffers while charging and discharging. The hysteresis in Li-ion batteries occurs due to the fact that the discharge equilibrium potential is always lower than the charge equilibrium potential for the same state of charge (SoC). In order to accurately measure the SoC, it is essential to accurately predict the hysteresis in the battery. Li-ion batteries show significant asymmetry in the hysteresis loops. In this study we use a relatively new asymmetric hysteresis model, combined with the Bouc-Wen model to fit hysteresis in Li-ion batteries. To validate the hybrid model, we consider some of the published experimental results of battery hysteresis. The hybrid model is computationally simple and it can capture a range of data with all key hysteretic characteristics.

Keywords: Li-ion batteries, state-of-charge, hysteresis, asymmetric loops

1 Introduction

Considering the increasing air pollution due to the vehicular emission, the current automobile industries are putting a significant thrust to shift from internal combustion (IC) engine based vehicles to electric vehicles (EVs). We note that battery is the main component of an electric vehicle for power generation. Among all types of batteries, Lithium (Li)-ion batteries are used most in electric vehicles [1, 2].

One of the primary advantages of Li-ion type batteries is the ease of recharging. Other than that Li-ion batteries offer high energy density, high efficiency and long durability. However, during the charging-discharging cycles, Li-ion batteries suffer hysteresis loss due to the difference in discharge equilibrium potential and the charge equilibrium potential for the same state of charge (SoC) [3–5]. There are several reasons reported, in the literature, that cause hysteresis in Li-ion type batteries, e.g., thermodynamic effects, mechanical stress and microscopic distortions, see e.g., [6, 7].

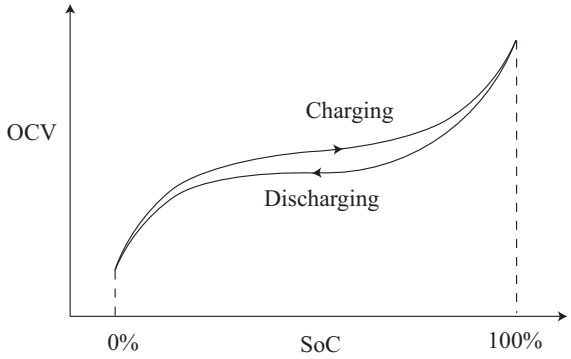


Figure 1: A typical hysteresis loop observed in Li-ion batteries. Here, SoC is the state-of-charge and OCV is the open circuit voltage.

Figure 1 shows a typical charging-discharging hysteresis loop observed in Li-ion type batteries.

Due to complex physio-chemical behaviors, it is difficult to make accurate measurements of state of charge (SoC) of the Li-ion batteries [8–17]. On the contrary, it is very important to develop a good battery management system (BMS) in order to increase the battery life and vehicle safety. The battery management system involves in (a) cell monitoring, (b) cell balancing, (c) power optimization, (d) safety and (e) battery charging optimization. In order to develop an accurate battery management system, it is required to estimate the state-of-charge precisely.

In the literature, several mathematical models have been developed to measure internal state of a battery. The available mathematical models can be divided into three categories, namely, electrochemical, data-driven (using artificial neural network and machine learning) and equivalent circuit models, see [18, 19]. One of the key qualitative features of the Li-ion hysteresis is that the loops are asymmetric in nature. Many of the available models are either too complex, or, they cannot accurately capture all qualitative aspects of battery hysteresis. Recently, Yan *et. al.* [20] developed an asymmetric model to describe hysteresis observed in Li-ion batteries.

With the above motivation, we develop a simple but novel approach to capture Li-ion battery hysteresis. In this study, we use a combination of the Bouc-Wen model [21, 22] with a relatively new asymmetric hysteresis model [23]. Note that the Bouc-Wen model is very popular model for mechanical systems. Also, the asymmetric model of [23] was originally developed from hysteresis in an elastic body with random microcracks [24]. Here, we demonstrate a novel application of a hybrid model to capture hysteresis in Li-ion batteries. For the validation of our model, we use a set of published experimental results.

2 Hybrid hysteresis model

In this section, we will use the Bouc-Wen model [21, 22], combined with a relatively new scalar asymmetric hysteresis model [23], to capture hysteretic behavior observed in Li-ion batteries.

For the sake of completeness, we briefly discuss the Bouc-Wen model and the asymmetric hysteresis model of [23] below.

The Bouc-Wen hysteresis model is given by

$$\dot{f}_1(t) = \dot{x}(t)\left\{A - \left[\beta\,\mathrm{sgn}(\dot{x}(t)f_1(t)) + \gamma\right]|f_1(t)|^n\right\}, \tag{1}$$

where $x(t)$ is the given input and $f_1(t)$ is the corresponding output of the system. Here, $A > 0$, $\beta > 0$, $\gamma \in [-\beta, \beta]$ and $n > 0$ are the model parameters. Figure 2(a) shows a typical response of the Bouc-Wen model.

The scalar asymmetric hysteresis model of [23] is given by

$$\dot{\theta}(t) = \frac{\kappa}{|x(t)| + \epsilon}\left\{A_1 + \theta_a\,\mathrm{sgn}(\dot{x}(t)) + \beta_o\,\mathrm{sgn}(x(t)\dot{x}(t)) - \theta(t)\right\}\cdot|\dot{x}(t)|, \tag{2}$$

where $\theta(t)$ is an internal variable, and $x(t)$ is the input given to the system. Here, κ, A_1, θ_a, and β_o are model parameters, while $0 < \epsilon \ll 1$ is a regularization parameter to take care of the singularity at $x = 0$.

The hysteretic output is given by

$$f_2(t) = \theta(t)|x(t)|^\alpha\,\mathrm{sgn}(x(t)). \tag{3}$$

Here, α is a positive parameter. Figure 2(b) shows a typical response of the asymmetric hysteresis model. Note that the hysteresis loop is asymmetric and pinched at the origin.

Now, we combine the asymmetric hysteresis model, given by Eqs. (2) and (3) with the Bouc-Wen model to generate a special type of response as shown in Figure 2(c). In the response, we add the hysteretic outputs of the two models.

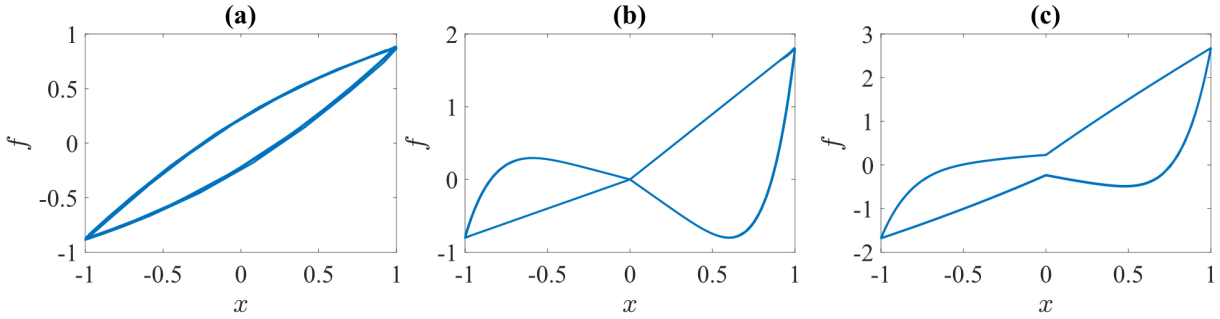


Figure 2: (a) A typical response of the Bouc-Wen model. Parameters used: $A = 1$, $\beta = 0.5$, $\gamma = 0.1$ and $n = 1$. (b) A typical response of the hysteresis model of [23]. Parameters used: $\kappa = 5$, $\theta_a = 0.5$, $\beta_0 = 1.2$ and $\epsilon = 10^{-6}$. Here, $f(t) = \theta(t)z(t)$. (c) A typical response of the hysteresis model combined with both the Bouc-Wen model and the hysteresis model given by Eqs. (2) and (3). Here the output force $f(t)$ is the sum of hysteretic output of two models. The input $x(t) = \sin 2\pi t$ is used for all three cases.

3 Results and Discussion

For demonstration of the hybrid model discussed in Section 2, we take a set of four experimental results from previous studies, namely, case (a) [25], case (b) [20], case (c) [15], and case (d) [16]. These results correspond to the hysteretic effects observed during the charging and discharging cycles of Li-ion batteries.

We use a nonlinear least squares method to generate numerical fits to the experimental data. Note that our hybrid model has a set of nine fitted parameters. We used the inbuilt function `fminsearch` of MATLAB to minimize the error in least squares sense, see [24].

Figure 3 shows the results of fitting of the four cases (a) [25], (b) [20], (c) [15], and (d) [16]. The fitted parameters are reported in Table 1. We use the same set of parameter values for all cases, to establish the robustness of the model. The maximum percentage errors in fitting are reported in Table 1. Maximum percentage error

$$e_{\max} = \frac{\max(f_{exp} - f_{num})}{(f_{exp})_{\max}} \times 100\%.$$

Note that the hybrid model is able to fit all experimental data reasonably accurately.

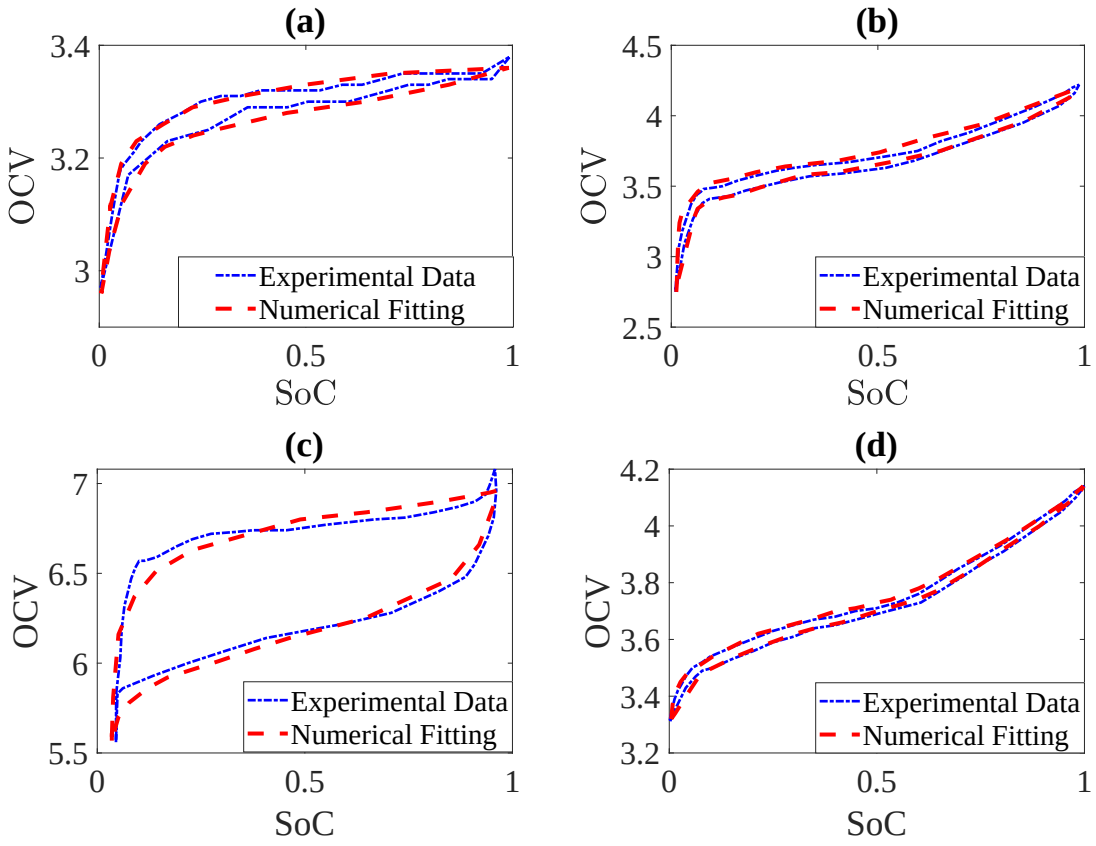


Figure 3: The results of fitting obtained from the hybrid hysteresis model.

Table 1: The parameters used to obtain the numerical fits of Figure 3.

Cases	A	β	γ	n	κ	A_1	θ_a	β_o	α	$e_{\max}(\%)$
(a)	1.007	1.813	0.5265	1	2.5412	1.1304	0.7277	2.3423	1.5678	2.7
(b)	1.007	1.813	0.5265	1	2.5412	1.1304	0.7277	2.3423	1.5678	1.2
(c)	1.007	1.813	0.5265	1	2.5412	1.1304	0.7277	2.3423	1.5678	3.9
(d)	1.007	1.813	0.5265	1	2.5412	1.1304	0.7277	2.3423	1.5678	0.9

4 Conclusion

In this study, we developed a hybrid hysteresis model with combination of the Bouc-Wen model [21, 22] and an asymmetric model developed in [23]. The model has been effectively used to capture hysteretic behavior observed in Li-ion battery charging-discharging cycles. The proposed framework was validated by fitting experimental data using a nonlinear least squares based optimization, demonstrating a significant match between the simulated and observed hysteresis loops.

We note that the hysteresis observed in Li-ion batteries show complex nonlinear behavior due to complex physio-chemical behaviors of the batteries. The hysteresis loops show significant asymmetries, which are difficult to capture using simple mathematical models. In the existing literature, several mathematical models are available to describe hysteretic behaviors in Li-ion batteries. However, most of the models are either too complex, or, they cannot capture all key qualitative behaviors of hysteresis. With this motivation, we developed a novel approach, which is computationally simple and can capture key qualitative behaviors of Li-ion battery hysteresis. In future, we will improve our approach in order to capture Li-ion battery hysteresis including minor loops due to partial charging-discharging cycles.

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