HYSTIMATOR: EIS-based method to physically model hysteresis of LFP battery

G. Thenaisie, C. Brivio, A. Hutter

Withing The HYSTIMATOR project, CSEM addressed the hysteresis phenomenon in lithium iron phosphate (LFP) battery cells by using low-frequency Electrochemical Impedance Spectroscopy (EIS) and Distribution of Relaxation Times (DRT) analysis. It integrates hysteresis characteristics into a physics-based Equivalent Circuit Model and significantly reduces Root Mean Square Error (RMSE) during real-world laboratory testing. This approach holds promise for enhancing State of Charge (SoC) estimation in LFP battery cells, especially in embedded Battery Management Systems (BMS).

In recent years, due to the shift towards cleaner energy policies, a cumulative annual growth rate of 15-20% has been observed for the adoption of battery electric vehicles (BEVs) and Battery Energy Storage Systems (BESSs) [1]. Lithium iron phosphate batteries (LFP), which are both cost-effective and inherently safer compared to other NMC or NCA-based battery technologies, have become increasingly popular. Major players in the industry, such as Tesla and BYD, are placing their bets on LFP batteries for the foreseeable future.

Estimating the State of Charge (SoC) in LFP batteries is still a challenge due to two main factors: (i) LFP batteries have a flat OCV (Open Circuit Voltage) relationship, making it difficult to gauge SoC based on voltage alone; (ii) LFP chemistry exhibits strong hysteresis between charging and discharging conditions, further complicating accurate SoC calculations.

The HYSTIMATOR project, funded by SFOE (Swiss Federal Office of Energy) under project number SI502441-0[2], tackled this challenge. It built upon CSEM's battery modeling and state estimation expertise, extending it to the realm of LFP chemistry.

Previous studies in non-equilibrium thermodynamics have shown that within LFP batteries, the process of ions intercalation is governed by three distinct dynamics: lattice reconfiguration, ion diffusion, and bulk diffusion. Consequently, this research proposes that hysteresis in LFP batteries is not an inherent characteristic but rather a slower relaxation process when compared to other battery chemistries.

We used EIS at very low frequency deconvoluted by Distribution of Relaxation Times (DRT), which magnifies the information provided by EIS by highlighting the main dynamic phenomena[3], to measure the hysteresis phenomenon and model it.

The testing campaign has been performed at the CSEM BIH, on several 90 Ah LFP cells, both fresh and aged, under controlled condition. Specifically, EIS were measured from 1 kHz down to 10 μHz by using potentiostats/galvanostats.

In addition to the typical DRT peaks associated with interfacial dynamics and charge transfer processes at high/medium frequencies, we identified three more peaks at specific relaxation times, confirming the three-stage intercalation process described in literature. Leveraging these EIS/DRT insights, we propose a physics-based Equivalent Circuit Model (ECM) that represents the seven key phenomena with seven RC elements (see Figure 1), coupled with an OCV derived via a standard symmetric GITT protocol.

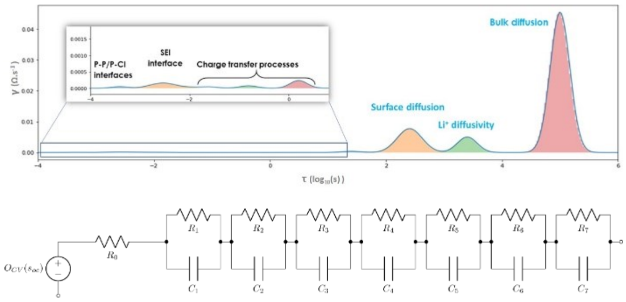

Figure 1: DRT of the studied 90Ah LFP cell and associated ECM model.

The proposed ECM has been validated against an existing model from literature, without hysteresis compensation. Two different power profiles have been employed: (i) a dynamic profile (DYN) to assess behavior with fast and replicating square current profiles (5-minute steps, see Figure 2), and (ii) a GITT discharge/charge profile to assess during full charge-discharge cycle with intermittent currents. The assessment of the model's accuracy involved the use of the Root Mean Square Error (RMSE) indicator, which measures the consistency between the estimated terminal voltage and the actual terminal voltage.

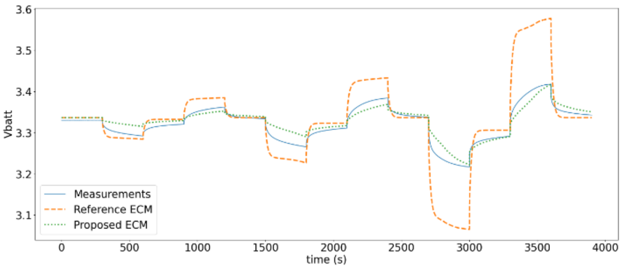

Figure 2: Models' performance comparison at SoC=50% for DYN test.

The results for fresh cells confirm that the proposed ECM outperforms the reference model by a factor of two to four, depending on the simulated profile. As the cells age, both models experience increased errors, but the rate of error increase is approximately two times lower in the proposed model compared to the reference model. This resilience in performance with aged cells validates the potential of the proposed ECM for use in a Kalman filter or other filtering framework to enhance state estimation accuracy for LFP cells.

This research contributes to the advancement of battery modeling techniques and lays the foundation for more precise State of Charge (SoC) estimation methods in LFP-based battery applications.

1 Future Market Insights (2021), "Battery Management System Market - Europe Industry Analysis 2016 – 2020 and Opportunity Assessment 2021– 2031

2 https://www.aramis.admin.ch/Texte/?ProjectID=50922

3 P. Iurilli, C. Brivio, R. E. Carrillo, and V. Wood, "Eis2mod: A drt-based modeling framework for li-ion cells," IEEE Transactions on Industry Applications, vol. 58, no. 2, pp. 1429–1439, 2022