Battery Voltage and Current Profile Monitoring System

Sistema de monitoreo de perfiles de voltaje y corriente de una batería

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Abstract

The increasing use of electrochemical batteries in energy storage and electric mobility applications has created a growing demand for reliable experimental tools to characterize their discharge behavior. However, high-precision commercial testing systems are often associated with elevated costs and proprietary architectures, limiting their accessibility in academic and research laboratories with constrained resources. This work presents the development of a low-cost experimental system for the acquisition and analysis of battery discharge curves, employing a DC/DC buck converter (ZK-6522C) as a controlled load, an INA219 sensor for real-time voltage and current measurements, and a MATLAB-based platform responsible for converter control through the Modbus protocol and synchronized acquisition of electrical variables. The experimental results successfully reproduce the characteristic discharge behavior commonly reported in the literature, including the initial voltage drop, the stable voltage plateau region, and the pronounced voltage decline observed near the end of the discharge cycle, thereby validating the system's capability to establish controlled and reproducible discharge conditions. The main contribution of this work is the development of a modular, flexible, and cost-effective platform that serves as an alternative to commercial testing equipment, with potential applications in both power electronics and energy storage research, as well as in the practical education and training of engineering students.

Keywords: Battery monitoring; discharge profiles; Real-Time Monitoring; current measurement.

Introduction

Energy storage has become one of the key technological pillars of the global energy transition, particularly in response to the increasing penetration of variable renewable energy sources such as photovoltaic solar and wind power. The intermittent nature of these resources requires energy storage systems capable of balancing mismatches between power generation and demand, ensuring power quality, and maintaining the stability of electrical grids (Asmelash & Gorini, 2021). In this context, electrochemical batteries, particularly lithium-ion and lead-acid technologies, have emerged as the most widely adopted energy storage solutions due to their technological maturity, high energy density, and scalability. These technologies are extensively used in stationary grid applications, electric mobility, and portable energy systems (Li *et al*., 2023; Sahoo & Timmann, 2023). Numerous studies agree that the development of efficient, safe, and cost-effective energy storage technologies remains a major research priority because of their decisive role in the decarbonization of energy systems and the achievement of sustainability goals (Asmelash & Gorini, 2021; Sahoo & Timmann, 2023).

In parallel, the experimental characterization of batteries through discharge curves constitutes a fundamental tool for evaluating their actual performance, since it enables the observation of voltage, current, and delivered capacity variations as a function of time and applied discharge rate. These curves provide the basis for estimating critical parameters such as effective capacity, internal resistance, and state of charge (SOC), which is an essential variable for the safe management of any battery system (Movassagh *et al*., 2021; Oloyede *et al*., 2024; Zhao *et al*., 2024). Methods such as Coulomb counting rely directly on accurate current and time measurements throughout the discharge process, and their accuracy is affected by cumulative errors that can only be quantified through controlled and repeatable testing procedures (Movassagh *et al*., 2021). More recent approaches, such as sliding-mode observers, also require reliable experimental discharge data for validation purposes (Behnamgol *et al*., 2024). Likewise, the validation of equivalent electrical models and SOC estimation algorithms, whether based on conventional techniques or machine-learning approaches, requires

experimental datasets obtained under well-defined and reproducible discharge conditions (Csomós *et al*., 2017; Zhao *et al*., 2024; Zhu *et al*., 2023).

To establish such conditions in a controlled manner, DC/DC converters play a central role as the interface between the battery under test and the electrical load. The operating and control principles of these switched-mode topologies, including their capability to regulate current or power independently of source voltage variations, have been extensively documented in the classical power electronics literature (Erickson, 2001; Mohan *et al*., 2003). Unlike a fixed resistor or a simple electronic load, a switched-mode converter enables the implementation of constant, variable, or stepwise current and power profiles, which is essential for obtaining comparable discharge curves across different experimental tests (Hidalgo-León *et al*., 2020; Villegas Ceballos *et al*., 2020). Several studies have employed boost, buck-boost, and interleaved converter topologies to accurately regulate charge and discharge currents while minimizing current ripple in the battery cell, thereby preserving its integrity and improving measurement quality (Hidalgo-León *et al*., 2020; Villegas Ceballos *et al*., 2020). This programmable control capability transforms the DC/DC converter into an enabling technology for battery testing and experimental instrumentation, extending well beyond its conventional energy conversion function.

Regarding the current state of the art, robust and highly accurate solutions, such as commercial battery testing systems like Arbin platforms and multistage converter-based battery emulators, provide millisecond-level resolution and multi-channel control capabilities (Villegas Ceballos *et al*., 2020). Publicly available datasets containing charge and discharge voltage curves acquired using specialized equipment have also been reported and are valuable for the training and validation of battery models (Voicila *et al*., 2026). Nevertheless, these systems and datasets are typically generated using expensive instrumentation and proprietary architectures, offering limited flexibility for educational purposes or exploratory research in resource-constrained laboratories. Furthermore, a significant portion of the datasets and models available in the literature focus primarily on SOC estimation algorithms rather than on the accessible design of the data acquisition platform responsible for generating such datasets (Csomós *et al*., 2017; Movassagh *et al*., 2021; Oloyede *et al*., 2024; Wang *et al*., 2024; Zhao *et al*., 2024; Zhu *et al*., 2023). This situation highlights a gap in the development of low-cost, modular, and reproducible experimental systems that integrate a DC/DC converter as a controlled load together with instrumentation for electrical variable acquisition, serving both rigorous battery characterization and educational applications.

To address this challenge, the present project proposes the development of an experimental system for obtaining and analyzing battery discharge curves using a DC/DC converter as a controlled loading element. The proposed methodology includes the implementation of the converter, the development of voltage and current sensing instrumentation, and the synchronized acquisition of relevant electrical variables, namely voltage and current, with the objective of constructing the characteristic discharge curves of batteries under different operating conditions. The primary contribution of this work is the development of a flexible, replicable, and cost-effective platform that represents an alternative to commercial solutions, enabling customizable discharge profiles and facilitating subsequent analysis of the acquired data.

Finally, the proposed system aims to provide a valuable tool for both applied research in power electronics and energy storage, as well as for the practical training of students in these fields. By providing an accessible experimental environment, the platform facilitates the study of battery electrical behavior under controlled and reproducible conditions, thereby supporting both scientific research and engineering education.

Methodology

A. System Overview

The proposed methodology for the development of the experimental system is illustrated in Fig. 1. The system consists of four main components: (i) the battery under test, which serves as the object of analysis and from which voltage and current profiles are obtained during the discharge process; (ii) a ZK-6522C DC/DC buck converter, employed as a controlled load to regulate the battery discharge demand, in accordance with the concept of a programmable interface reported for this type of topology (Erickson, 2001; Hidalgo-León *et al*., 2020; Mohan *et al*., 2003; Villegas Ceballos *et al*., 2020); (iii) an Arduino board equipped with an INA219 current and voltage sensor, used as the data acquisition system for real-time measurement of the electrical variables involved in the test; and (iv) a laptop running MATLAB, which functions as both the control unit for the converter and the data acquisition and sampling platform.

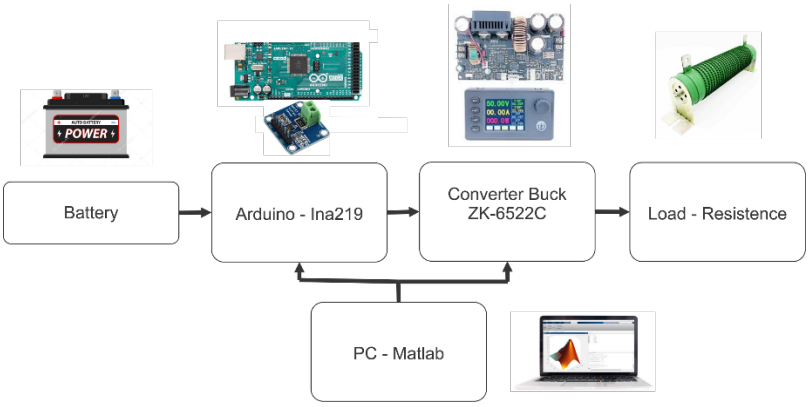


Figure 1. Block diagram of the proposed experimental system.
Source: Author's own work.

B. Discharge Circuit Configuration

The analysis procedure assumes that the battery is initially fully charged, thereby enabling the acquisition of the complete discharge profile down to the cutoff voltage. The battery serves as the energy source supplying the buck converter. An INA219 sensor is installed between the battery and the converter input to continuously measure the current and voltage delivered by the battery throughout the experiment. These measurements are subsequently used to calculate additional parameters, such as instantaneous power and accumulated discharged capacity.

The buck converter is controlled through the Modbus communication protocol using MATLAB, enabling remote configuration of the converter operating point and ensuring repeatable testing conditions across different experiments. This feature addresses a common limitation identified in the literature regarding low-cost experimental battery testing platforms, namely the lack of reproducible and programmable operating conditions. For battery discharge characterization purposes, a constant output voltage demand is established and maintained throughout the test. Under these conditions, the energy extracted from the battery is dissipated through a 1 Ω load resistor connected to the converter output.

C. Data Acquisition and Recording

The Arduino board, together with the INA219 sensor, performs real-time sampling of voltage and current at the connection point between the battery and the converter. The acquired measurements are transmitted to MATLAB, where the synchronized recording of the variables of interest, namely voltage and current, is carried out. This acquisition framework constitutes the basis for the subsequent construction of the battery discharge curves under the predefined testing conditions.

Figure 2 presents the physical implementation of the experimental system used to validate the battery discharge process. The figure illustrates the arrangement and interconnection of the components described in the methodology, including the battery under test, the ZK-6522C buck converter, the INA219 sensor employed for voltage and current acquisition, the 1 Ω load resistor connected to the converter output, and the laptop running MATLAB, which is responsible for converter control through the Modbus protocol as well as data acquisition and recording. This configuration enabled the controlled reproduction of the predefined discharge conditions and allowed the experimental verification of the integrated operation of all system subsystems prior to the analysis of the obtained results.

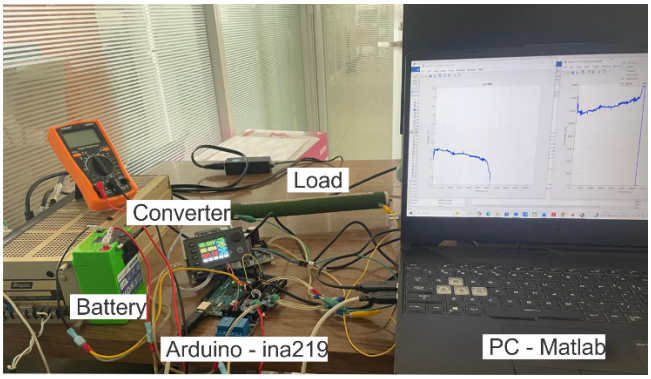


Figure 2. Physical setup used for the discharge test.
Source: Author's own work.

Results

The results obtained from the battery discharge process are presented in Fig. 3. The measured discharge curve exhibits the characteristic behavior consistently reported in the literature for electrochemical batteries (Csomós *et al*., 2017; Movassagh *et al*., 2021; Oloyede *et al*., 2024; Zhao *et al*., 2024; Zhu *et al*., 2023): an initial voltage drop associated with the internal resistance of the cell, followed by a relatively stable discharge region, commonly referred to as the voltage plateau, where the voltage decreases gradually while the stored capacity is delivered to the load. Finally, a sharp voltage decline is observed as the battery approaches a deep-discharge condition, indicating the cutoff point of the experiment.

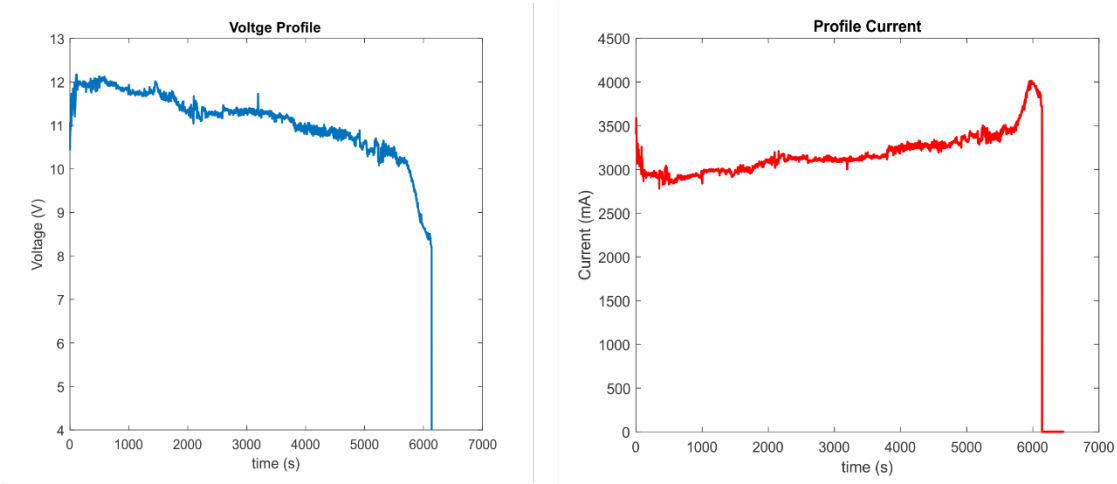


Figure 3. Discharge curve obtained from the experimental system.
Source: Author's own work.

The successful acquisition of this discharge profile using the proposed system confirms the capability of the buck converter, operating under a constant voltage demand and controlled through the Modbus protocol from MATLAB, to establish sustained and reproducible discharge conditions throughout the testing process, as proposed in the methodology. Furthermore, the results validate the combined operation of the INA219 sensor and the data acquisition stage for the synchronized measurement of voltage and current, which are the fundamental variables used to construct the discharge curve shown in Fig. 3.

These preliminary results demonstrate that the developed platform is capable of reproducing the expected electrical behavior of a battery during discharge. Consequently, the proposed system provides a solid foundation for future applications involving the comparative characterization of different loading conditions, discharge rates, and battery technologies. Additionally, the platform offers significant potential as an

educational tool for experimental activities in power electronics and energy storage systems, providing a practical and accessible environment for battery testing and analysis.

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