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Towards a Battery Characterization Methodology for Performance Evaluation of Micro-Grid Systems

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Abstract—Stand-alone micro-grid (MG) systems have been widely studied and installed especially in remote and rural regions. These systems are composed of renewable energy sources (RES) and storage devices. The main component in these systems is the storage device (e.g., batteries), which is used in order to store extra-produced energy during the day for eventual usage at night. However, battery's characterization according to their operating conditions is required to better identify its parameters and study their performance and behavior within MG systems. This paper introduces an instrumentation platform for battery characterization and modeling using recent sensing/actuating equipment. The platform was first deployed for gathering important battery's parameters, which are then used for building a simplified battery model. This model is then integrated into the MG system for evaluation and validation. Simulation results compared to experimental results show the accuracy of the developed battery model.

Keywords—Micro-grid system, RES, Battery, modeling and performance evaluation.

I. INTRODUCTION

The intermittent nature of RES (e.g., solar energy) has motivated the usefulness of storage devices integration and deployment into MG systems. The main aim is to store the extra-produced energy for possible usage when there is no production. Batteries are the most used storage devices in MG systems due to their benefits (e.g., fast response, modularity, and good energy efficiency) [1]. However, their modeling and performance evaluation in MG systems is required in order to evaluate them using both experiments and simulations. Numerous models have been developed and reported in literature (e.g., electrochemical models, electrical-circuit models). Their aim is to estimate and predict their performance and behavior [2, 3]. For instance, electrochemical models, despite their accuracy, are too much complex to represent battery's dynamics for the purpose of state of charge (SoC) estimation. In fact, the complex battery electrochemistry and temperature dependency makes it difficult to obtain the model's parameters. However, electrical-circuit models (e.g., the first order RC model, the second order RC model) are commonly used for batteries' behavior estimation. These models are composed of a voltage source, resistors and capacitors, which can simulate its dynamic behavior. They become more and more accurate

when the model's order increases (i.e., RC networks). Several variants of these models have been reported to estimate as much as possible the battery's behavior. For example, authors in [4, 5] described the electrochemical behavior of a battery taking into consideration many parameters, such as the terminal voltage, the open circuit voltage (OCV), the internal resistance, and the discharging/charging current. A modified version of this model has been developed in [6, 7] by including the OCV as a function of the SoC.

In this work, we focused mainly on Tremblay's model for battery characterization and evaluation using both virtual and real testing. This work is a part of the work we are undertaking under MIGRID project [8], which aims to develop techniques and tools for sizing, modeling, simulation, and experimentation of a smart MG system. This system is mainly composed of photovoltaic (PV) panels, wind turbines and batteries, which are deployed for developing scenarios and services for energy efficiency in buildings [9, 10, 11]. Among the project's purpose is the development of approach for dimensioning RES-based power generation systems, and storage devices [9, 10, 12]. In this paper, we aim to use Tremblay's model for accurate evaluation of batteries already deployed in our EEELab testbed. An instrumentation platform was first developed for battery characterization and modeling using recent sensing/actuating equipment. Important properties are gathered and processed to extract the dynamic model's parameters. This model is then integrated into our MG for both simulations and experimentations. Preliminary results show the accuracy of the introduced battery characterization methodology and the usefulness of the instrumentation platform.

The remainder of this paper is described as follows. In Section 2, an overview of recent work developed for battery characterization and modeling is presented. A mathematical model of a Lead-acid battery is described in Section 3. Section 4 presents the proposed methodology for battery characterization and parameters identification together with its experimental validation. Section 5 presents an application of the battery modeling and its integration in a full MG scenario together with its performance evaluation and validation using both simulations and experimentations. Finally, conclusions and perspectives of the developed model and characterization methodology are given in Section 6.

II. RELATED WORK

Battery modeling or especially the dynamic behaviour of the battery is a very complex procedure and requires a lot of knowledge of the different electrical and electromechanical phenomenon that happens during its charging/discharging processes. The aim is to develop an accurate model, which could be integrated in a simulation tool to study and evaluate its dynamic behaviour [21]. This will help validating experimental results with those obtained from simulations using similar testing conditions. In fact, by relying on an accurate model, the actual battery can be tested using simulations considering different operating environments and scenarios, thus avoiding time consuming laboratory testing.

Several battery models were developed these last decades, and could be categorized into two main categories, electrochemical and ECMs [18, 19, 20, 25, 26]. ECMs have been considered among the most suitable solutions, especially when the battery has to be integrated in high-level system simulations. They provide mainly a suitable accuracy while maintaining in average an acceptable computation complexity. The focus of the work presented in this paper is to establish a model of the battery that we have deployed in our EEELab testbed [8] for integrating them into a MG system for simulations and experimental studies. We have selected ECMs to describe the performance behaviour and to identify these batteries' parameters. In fact, the identification methodologies of parameters of such models have been presented by several research works [25, 26]. For example, in [13, 14], authors computed the parameters of their model from experimental data. OCV tests were established upon successive discharges of the battery by injecting current pulses. The estimation of battery parameters using some adaptive Kalman Filter methods was also developed by authors in [15, 16]. Another method, called impedance spectroscopy, which is a slightly complicated technique, is proposed in [17] in order to identify the parameters of ECMs.

Several variants of these models have been afterwards developed in order to estimate as much as possible the battery's behaviour. For example, Shepherd and Tremblay models [4, 5, 6, 7] described the electrochemical behaviour of a battery taking into account many parameters (e.g., OCV, SoC). An important feature of these models is the simplicity to extract the model parameters, which can be provided using

three points of the manufacturer's discharge curve [6, 7]. However, most of the work to date focused on battery characterization for electric vehicles. In this work, we used the Tremblay's model and we introduced a methodology for characterizing and studying the behaviour of our deployed battery in a MG system. The peculiarity of this battery model is the simplicity of the extraction of the dynamic model's parameters.

Next section reviews the Tremblay's model and its important parameters that could be used for battery instrumentation and characterization. A testbed scenario is set-up for conducting simulations and experimentations using an example of a MG system, which is composed of a PV panel, a battery, and a building's load.

III. AN OVERVIEW OF TREMBLAY MODEL

The Tremblay's model, illustrated in Figure 1, is similar to the Shepherd's model but can represent the battery's behaviour more accurately. This model takes into consideration the OCV as a function of the remaining capacity in the battery, or more precisely the SoC. The term concerning the polarization resistance is slightly modified and the term concerning the polarisation voltage is added to represent the OCV behaviour more accurately (i.e., the non-linearity relationship between the OCV and the SoC) [6]. The Lead-acid battery voltage in both discharge ($i > 0$) and charge ($i < 0$) processes are expressed by eq (1) and eq (2) respectively.

$$V_{batt} = E_0 - Ri - K \frac{Q}{Q-it} (it + i^*) + \exp(t) \quad (1)$$

$$V_{batt} = E_0 - Ri - K \frac{Q}{it-0.1.Q} i^* - K \frac{Q}{Q-it} it + \exp(t) \quad (2)$$

where, V_{batt} is the battery voltage (V), E_0 is the battery constant voltage (V), K is the polarization constant (V/(Ah)) or polarization resistance (Ω), Q is the battery capacity (Ah), i_t is the actual battery charge (Ah), R is the internal resistance (Ω), i is the battery current (A), i^* is the filtered current (A), and $\exp(t)$ is an expression that represents the exponential zone voltage (V). The battery is then modelled using a simple controlled voltage source, which corresponds to the OCV, in series with a constant resistance, as depicted in Figure 1. This model adopts the same characteristics for the charge and the discharge processes. The OCV is then expressed as a function of the battery's SoC.

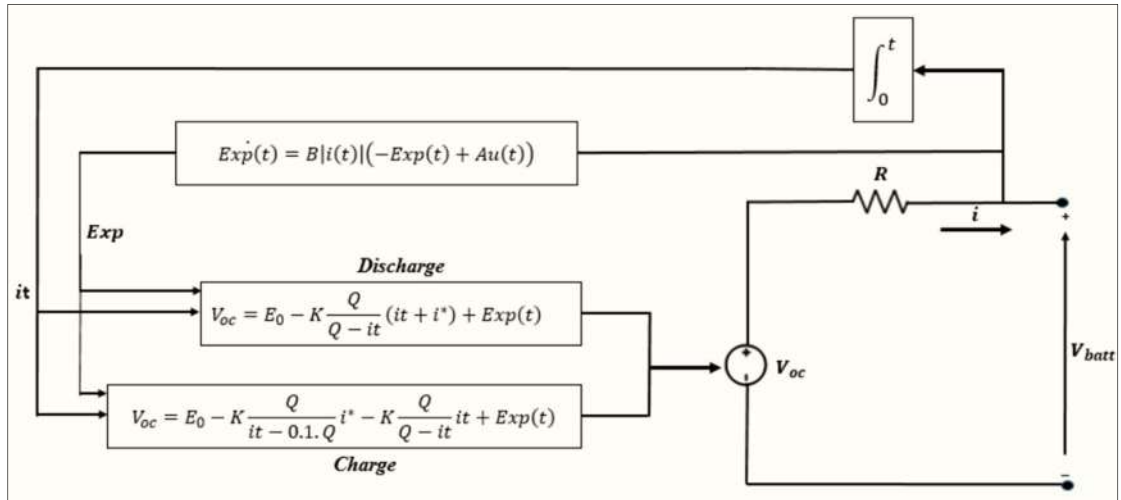


Fig. 1. The battery model

The filtered current i^* , which flows through the polarization resistance, can solve the algebraic loop problem due to the simulation of electrical systems. For the Lead-acid battery, the hysteresis phenomenon between the charge and the discharge is taken into account [6]. This phenomenon, which takes place in the exponential area, can be expressed by a non-linear dynamic system as follows:

$$\dot{\exp}(t) = B|i(t)|(-\exp(t) + Au(t)) \quad (3)$$

where $\exp(t)$ is the exponential zone voltage (V), $i(t)$ is the battery current (A), $u(t)$ represents the charge or discharge mode, A is the exponential zone amplitude (V), and B is the exponential zone time constant inverse (Ah)⁻¹. It's worth noting that the exponential zone voltage depends on its initial value $\exp(t=0)$ and the charge ($u(t) = 1$) or discharge ($u(t) = 0$) mode.

In order to integrate the battery, which we have deployed in our actual MG system, into Matlab/Simulink, the identification of its parameters is first required. Our main aim is to have the model of our battery for both simulations and experimentations. This model could be used to estimate other parameters (e.g., SoC), which is required to develop context-driven approaches for managing and controlling RES production and consumption [11]. Next section is dedicated to the proposed characterization methodology together with the model validation.

IV. CHARACTERIZATION METHODOLOGY AND MODEL VALIDATION

In order to extract battery's parameters, we have deployed a general test-bed as illustrated in Figure 2. It is composed of a 12V (Nominal voltage), 24Ah (Nominal capacity) Lead-acid battery manufactured by the Genesis NP24-12R, and a set of sensors in order to extract the battery's voltage, current and temperature during the discharge and charge cycles and the ambient temperature as well. The sensors are connected to an acquisition board (e.g., Arduino) in order to collect the data, and then send them to a cluster for processing and storage [8, 28, 29]. A web application is also developed in order to

visualize and extract in real time the battery's characteristics [28, 29]. Moreover, the developed platform provides other information about the battery's SoC, which could be calculated using existing methods, such as the coulomb counting method and Kalman Filter [25].

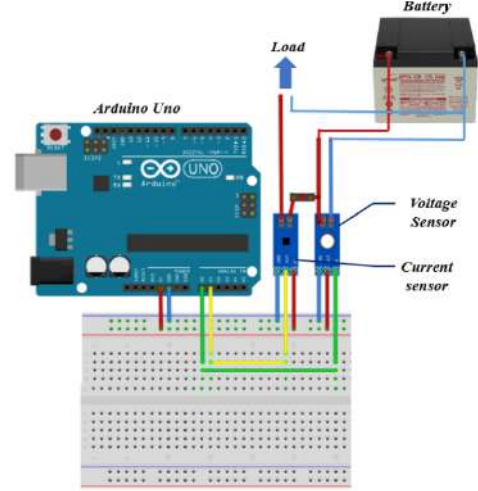


Fig. 2. Battery characterization test-bed

Figure 3 depicts the procedure followed in order to identify the battery parameters and validate the battery model. Several charge/discharge experimentations have been conducted and data are first processed and filtered. From these data, we applied the Least Squares method [22, 23, 24, 27] in order to extract the battery parameters as shown in the Table I. It's worth noting that, same parameters have been extracted for both charging and discharging data. Moreover, in order to validate this process we have used the battery model with identified parameters values and computed the estimated current and voltage.

TABLE I. IDENTIFIED BATTERY PARAMETERS

	$E_0(V)$	$R(\Omega)$	$K(\Omega \text{ OR } V/Ah)$	$A(V)$	$B(Ah^{-1})$
PARAMETERS	13.32	0.54306	0.0531	$1.557 \cdot 10^{-5}$	1.7233

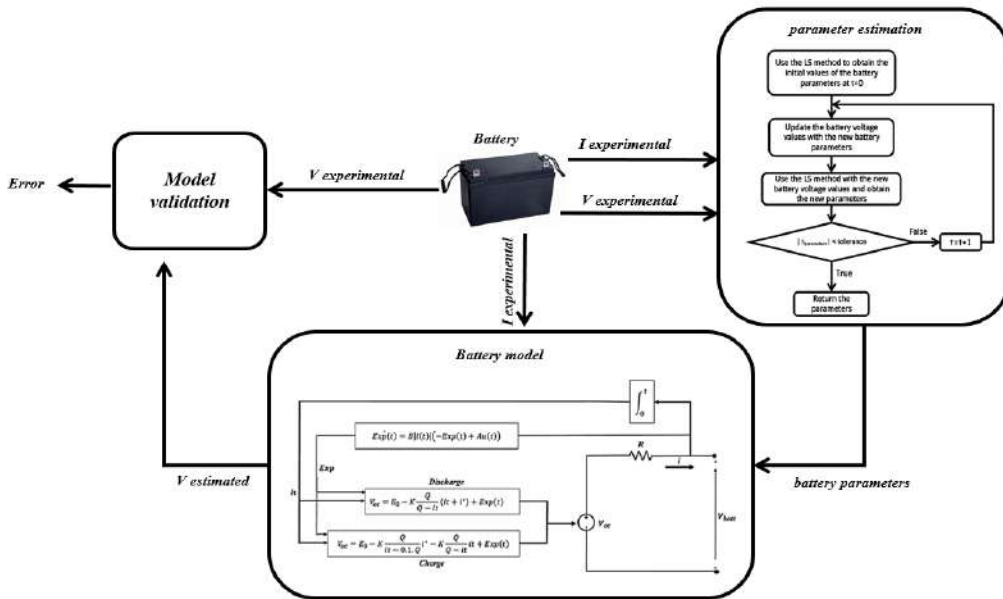
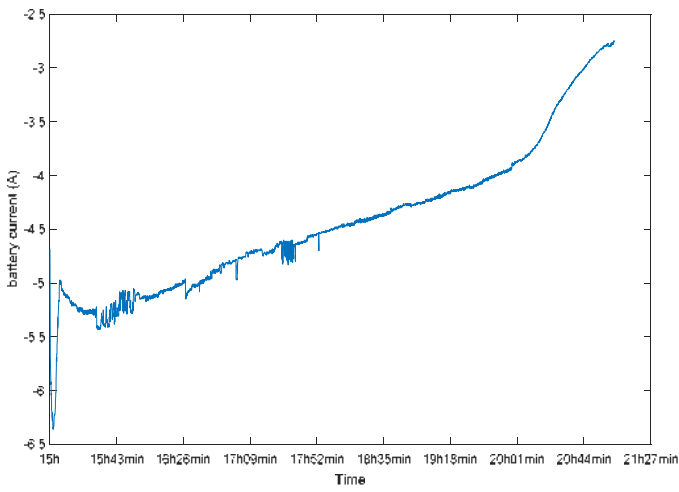
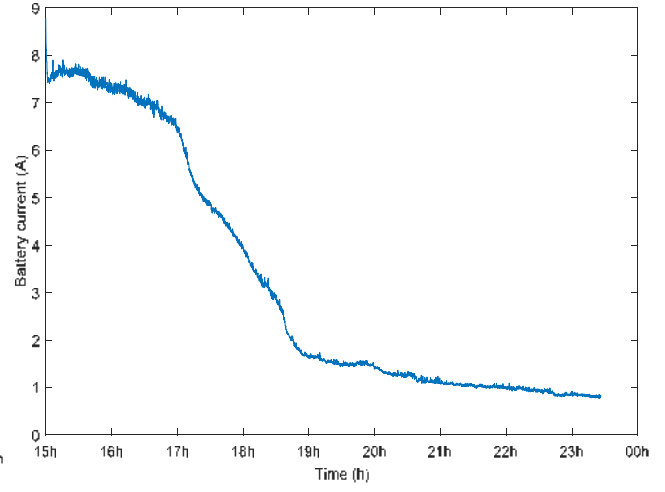


Fig. 3. Block diagram of the battery's characterization methodology and validation model

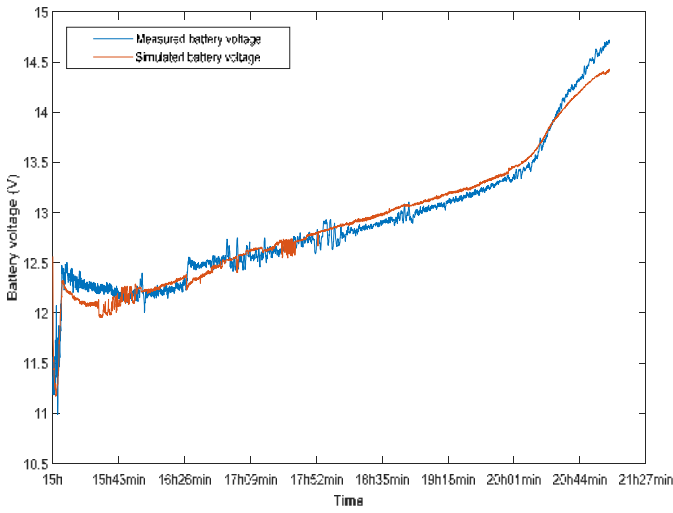


(a)

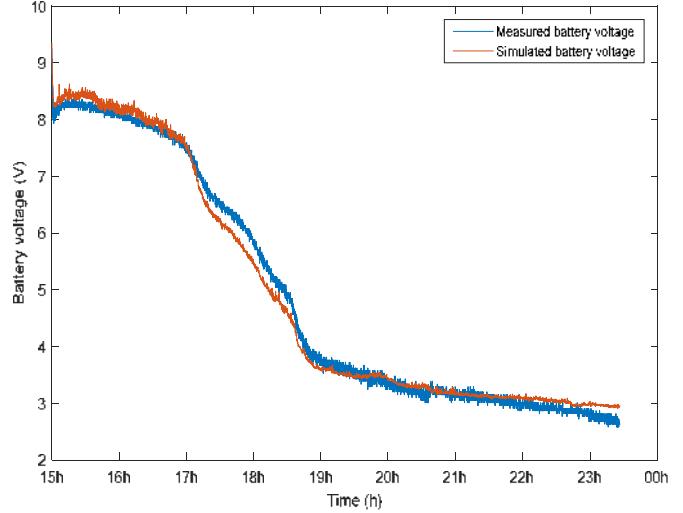


(b)

Fig. 4. The current values in both modes, a) charging and b) discharging

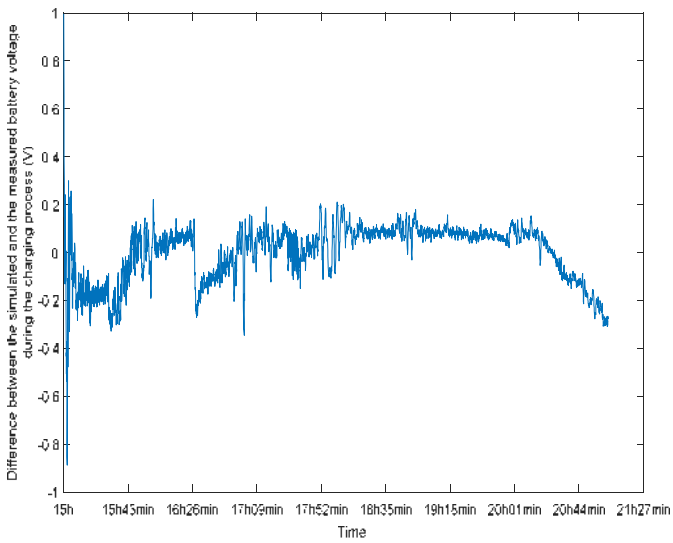


(a)

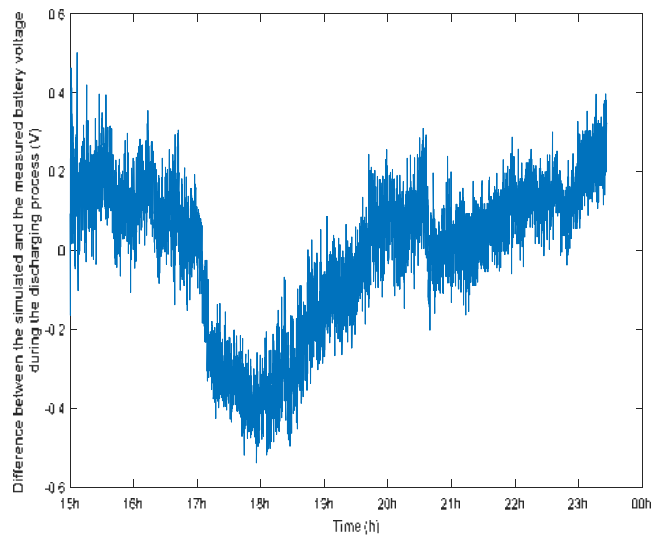


(b)

Fig. 5. The simulation and experimental voltage values in both modes, a) charging and b) discharging



(a)



(b)

Fig. 6. The error values (the difference between the simulation and experimental voltage values), a) charging and b) discharging mode

Figure 4 depicts the current for both charging and discharging modes during the experiments. The voltage values during charging and discharging modes from both simulations and experiments are illustrated in Figure 5. As shown in this figure, the experimental and the estimated curves have approximately similar behaviour. Figure 6 depicts the residuals, which are the difference between the estimated and measured battery voltage, for both charging and discharging modes. We observe that the errors are around the threshold (i.e., the maximum error must be lower than 5% [21]). This could be caused by the fact that the battery model doesn't take into consideration the temperature effect on the battery properties, the measurement noises and the lack of stability of the sensors used in the experiments or likely by the misunderstanding of electrochemical scale process.

V. APPLICATION ON MG SYSTEM

The battery model is integrated in Matlab/Simulink in order to use it for simulating our deployed MG system. The architecture of this system integrates a small PV-battery system as depicted in Figure 7 [10]. It is mainly composed of a PV panel with 265 Watts as a peak power, a battery of 25 Ah, and a ventilation system, including two ventilators operating at 24 Watts and 12V with a PWM control [30]. As stated above, the platform prototype is also deployed in order to extract the power in each branch of the system.

The purpose of this installation is to show the behavior of the system and also the accuracy of the battery model. We have conducted several experiments and simulations and results of 24 hours are depicted in Figure 8. We observe in

Figure 8 that during the day, the ventilation system is supplied by the PV panel while the battery is charged by the extra PV production. However, the grid supplied the electricity to the load during the night instead of the battery, especially after 5AM when the battery's SoC is less than a given threshold (e.g., 40% in this experiment) [10]. Moreover, Figure 8 shows the accuracy of the battery model. It shows that the voltage values obtained from both simulation and experiments are slightly similar and evolve with same trends.

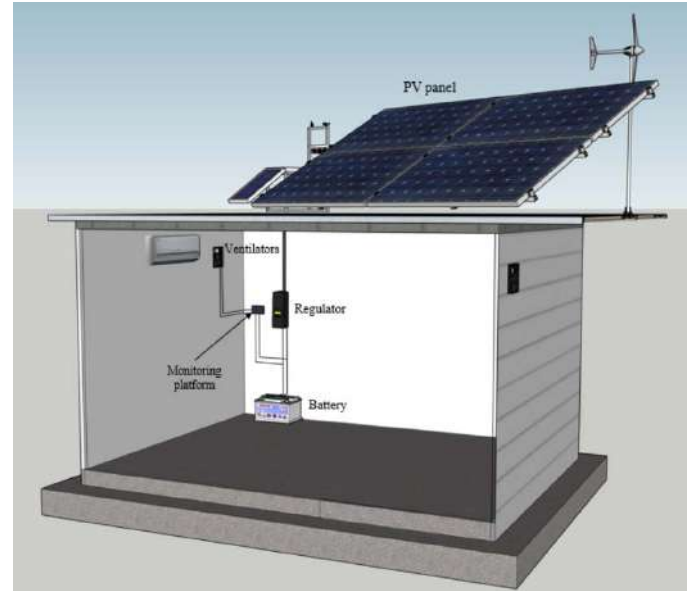


Fig. 7. The MG system deployed in the EEELab testbed

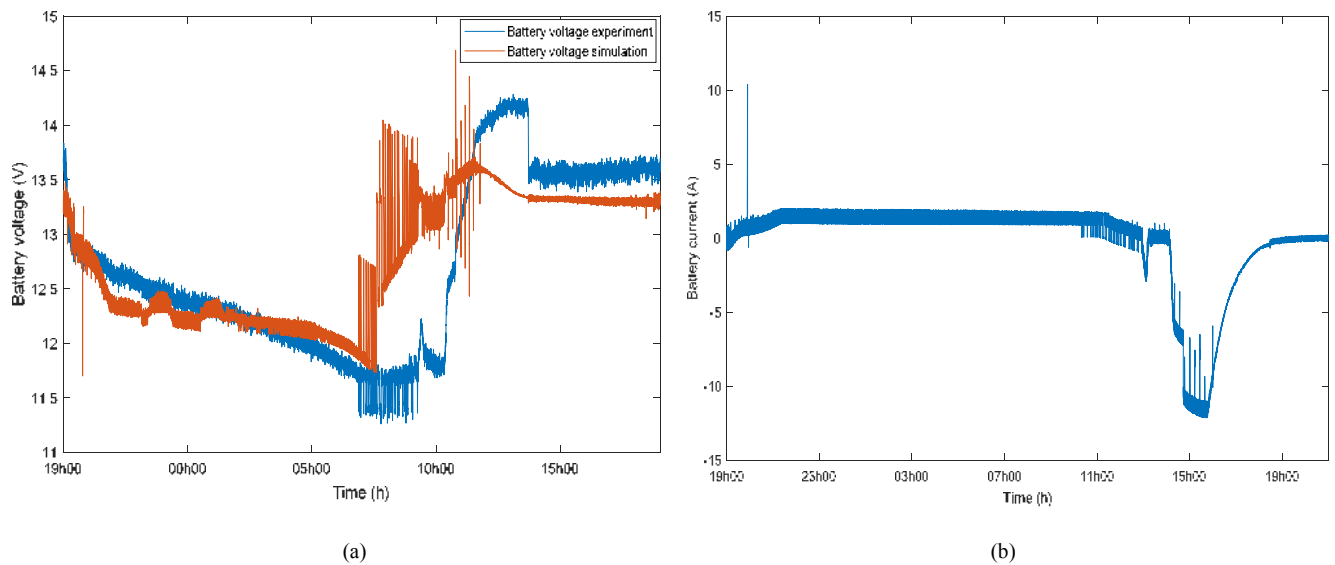


Fig. 8. a) The simulation and experimental battery voltage, b) the battery current

VI. CONCLUSIONS AND PERSPECTIVES

In this work, we have tackled battery's characterization and modeling issue to better identify its parameters and study its performance and behavior within MG systems. An instrumentation platform was first deployed using recent sensing/actuating equipment for gathering important battery's parameters. These parameters were then used for building a simplified battery model. We mainly get inspired from Tremblay's model and used the Least-squares method in order

to identify the battery's parameters. The model is accurately representing the battery behaviour in both charge and discharge modes. Finally, obtained model was integrated into both virtual (using Matlab/Simulink) and real MG system for testing and evaluation. Simulations and experimental results show the efficiency and the accuracy of this model for estimating the battery voltage. However, we can observe that the simulated and experimental results does not coincide nicely due to the fact that the battery model doesn't take into

consideration the temperature effect on the battery properties. Therefore, our ongoing work focuses on the study of the temperature effect on the battery and the improvement of the battery model. It's worth noting that including additional sensors to have more contextual data, such as battery temperature and ambient temperature, requires a sophisticated battery instrumentation platform, which is under investigation. More experiments will be conducted and new results will be presented to calibrate and enhance the model. The enhanced model will be used for estimating the SoC values, which could be integrated for developing context-driven approaches [11] for controlling and managing RES, batteries, when connected to the electric grid.

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