Scalable High-Power Battery Emulator for Power Hardware-in-the-Loop Applications

Bar Halivni, *Student Member*, *IEEE*, Daniel Beniaminson, *Student Member*, *IEEE*, Lee Maman, Adi Yankovich,
Michael Evzelman, *Member, IEEE* and Mor Mordechai Peretz, *Member*, *IEEE*
The Center for Power Electronics and Mixed-Signal IC, Department of Electrical and Computer Engineering
Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva, 8410501 Israel
barhal@post.bgu.ac.il, benidani@post.bgu.ac.il, evzelman@bgu.ac.il, morp@bgu.ac.il
http://www.ee.bgu.ac.il/~pemic

***Abstract* – This paper introduces a scalable power hardware-in-the-loop (PHiL) battery emulation system. The battery emulator enables the simulation of real battery voltage profiles with full power rating sink and sourcing capabilities using off-the-shelf components. The battery emulator tracks battery voltage, temperature, and current to provide real-time monitoring of the emulated battery's state of charge (SOC) and remaining useful life (RUL). The emulator operates in a continuous battery emulation mode or a cyclic mode for repetitive battery testing. The new battery emulator can replace end-product batteries during system development and is realized in two parts, PC Graphical User Interface (GUI) and battery emulator (Hardware). A battery profile-generating algorithm is introduced to accurately reflect the behavior of an actual battery during emulation. All measured data and battery voltage profiles are transferred via Wi-Fi to enable maximal freedom in system deployment. An experimental prototype has been built and tested to verify the battery emulation operation. The prototype handles a maximum input voltage of 150V and an input current of 60A.**

Keywords – Battery Emulator, Scalable Power, Programable Power Supply.

I. INTRODUCTION

In modern mobile applications, power consumption increases to facilitate technological advancements in the fields of computing power, sensing, and communication [1]-[2]. Portable electronic devices such as IoT sensors, virtual and augmented reality, smartphones, wearable devices, and even larger applications such as biomedical devices and electric vehicles rely on batteries as a portable power supply. Alongside its ability to provide energy on the go, battery accommodation in applications, as mentioned above, introduces significant design and safety challenges due to battery instability in extreme operating conditions. This can be solved by introducing a battery emulator module that replaces the full product battery during the system development stage. The battery emulator dynamically adjusts the emulator output voltage to mimic a real battery voltage curve [3]-[5]. Thus, the entire system development stage can be performed using the emulator for design validation.

As mentioned previously, the battery emulator can be used in a wide range of applications, and each of these applications requires various power handling capabilities [6]-[10]. The battery emulator can address each application's power requirements by utilizing appropriate power rating off-the-shelf power supplies and electronic loads to handle the voltage regulation. Using off-the-shelf components also significantly reduces costs compared to commercial battery emulators [11]-[12]. In low-power applications, commercial battery emulators can be too expensive or have an excessive maximal power rating. In higher power applications, the maximal rated power of a single load\supply may not be sufficient; in this case, multiple power supplies and electronic loads can be connected in parallel. Connecting multiple supplies and electronic loads allow for an increase in the battery emulator's maximal power as needed.

The objective of this study is to introduce a scalable high-power battery emulator for PHiL applications. The emulator can simulate a wide range of battery voltages and provides current sourcing and sinking capabilities to support bi-directional power transmission. The battery emulation is achieved by utilizing programable standard DC power supplies and electronic loads to regulate the emulator output voltage. This enables system scalability by supporting power supplies and electronic loads in a wide range of power ratings. Paralleling of multiple supplies and electronic loads can also be used to father extend the system power ratings. A generalized scalable battery emulator architecture and a simplified block diagram of the emulator controller are shown in Fig. 1.

The emulator controller handles system state variables control and data gathering. The controller governs the output voltage regulation according to a recorded battery profile by changing the appropriate device output voltage via serial communication. The battery profile and system telemetry

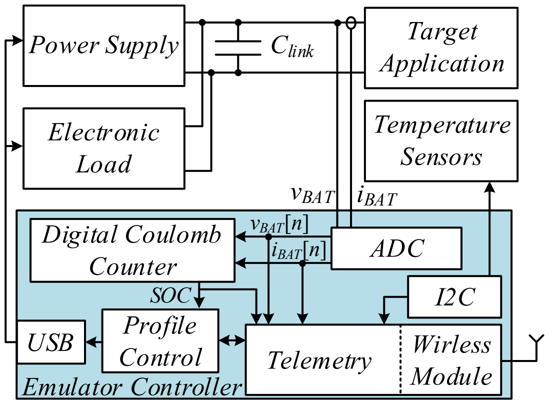

Fig. 1. Scalable battery emulator architecture and a simplified block diagram of the emulator controller.

information are transmitted wirelessly to maximize system flexibility. A further objective of this study is to incorporate additional aspects of the battery emulation to provide an accurate simulation of battery behavior, such as thermal and state-of-health (SOH) changes to the executed battery profile.

The rest of the paper is organized as follows; Section II describes the battery emulator architecture. Section III presents the voltage profile generation and test control algorithm. Experimental verification is provided in section IV. Section V concludes the paper.

II. BATTERY EMULATOR ARCHITECTURE

The architecture of the battery emulator introduced in this work can be divided into two disciplines, a power management network and an emulator controller (Fig. 1). Traditional DC power supplies are commonly used to source power to the load, thus having excellent current sourcing capabilities. On the other hand, DC supplies current sinking capabilities are inadequate during high current operation and rely on high output capacitance to compensate for this limitation. In charging emulation mode, the battery emulator is required to sink the entire load current, which can reach several amps. To overcome this issue, the battery emulator power management network comprises a standard DC power supply and an electronic load to form a highly accurate bi-directional DC power supply that can regulate the emulator output voltage v_{BAT} under any operating conditions. The power supply and the electronic load operate in a complementary manner during the sourcing and charging emulation modes, respectively. The bi-directional DC power supply is connected to a DC link capacitor C_{link} to smooth the transition between the supply and the electronic load and mitigate minor transients of the load connected to the battery emulator terminals.

The battery emulator controller regulates the output terminal voltage by operating the power supply and the electronic load in a constant voltage mode. In constant voltage mode, the emulator output voltage is kept constant within the power limit of the load and the supply. To determine the emulator operation mode for charging or discharging, the controller utilizes the output current measurement to determine the direction of the battery current and turns on the appropriate device for the selected operating mode. Using a serial communication interface such as USB as shown in Fig. 1, allows the controller to change the selected device's constant voltage parameter to accurately present the desired battery voltage in real time. The controller's voltage reading of v_{BAT} is used to provide a real-time feedback on the output voltage presented by the bi-directional supply.

The instantaneous emulator output voltage level (v_{BAT}) is determined by tracking a desired voltage profile, as shown in Fig. 2. The voltage profile describes the relation between the v_{BAT} and the battery state-of-charge (SOC), which represents the percentage of the remaining battery capacity $Q_{re}/Q_{max}[\%]$ where Q_{re} is the remaining battery charge and Q_{max} is the maximal battery charge. The emulator voltage profile is set by the user and can be adjusted to fit a desired test scenario. In infinite battery mode, the voltage remains constant for the entire emulation procedure, while in variable voltage mode, v_{BAT} changes over time to mimic real battery chemistry such as Li-ion, lead-acid, etc. The emulator voltage profile can be dynamically adapted during operation to account for changes in temperature and battery SOH.

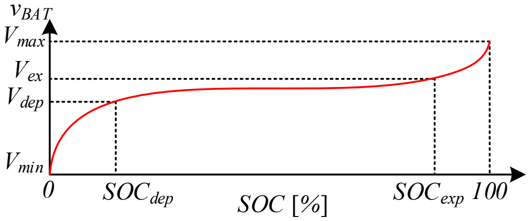

Fig. 2. Li-ion voltage profile as a function of the battery SOC.

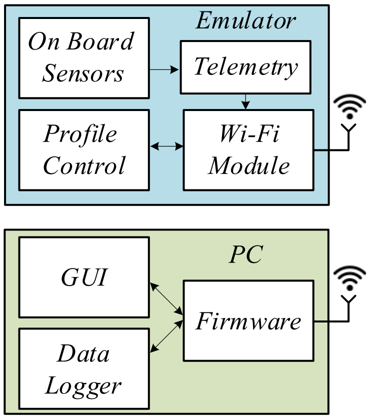

Fig. 3. Simplified block diagram of the wireless connection and data flow between the battery emulator to the PC.

The battery profile shown in Fig. 2 demonstrates a typical Li-ion battery voltage profile. For a discharge cycle, the battery starts at a fully charged state (SOC = 100%), and the voltage is V_{max}. As the battery is discharged, the voltage decreases exponentially until it reaches V_{ex} at a battery capacity of SOC_{exp}. From SOC_{exp} to SOC_{dep} the voltage remains relatively constant and decreases to V_{dep}. At the final stage, the voltage exponentially decreases to V_{min} until SOC = 0%. The battery charge cycle is performed similarly in the opposite direction from V_{min} to V_{max}. If the user intends to perform a partial charge/discharge cycle, the initial SOC can be set to 0% and 100%.

The emulator operation is controlled wirelessly via Wi-Fi by a remotely located PC, Fig. 3 shows the simplified block diagram of the wireless connectivity. The onboard sensors at the battery emulator module transfer their results of system variable measurements (v_{BAT}, i_{BAT}, and temperature) to the telemetry block. In addition to the system variables, the telemetry block also tracks the battery SOC and operating mode. The collected data is transmitted to the PC via the Wi-Fi module and processed by the PC firmware. The emulator controller receives the desired output voltage profile wirelessly. This allows maximal flexibility for more complicated tests that require dynamic adaptations of the battery profile during tests. On the PC side, the information received from the onboard emulator sensors is fed to a data logger block and presented to the user by the GUI. The user can set the required test parameters through the GUI, such as battery capacity, current SOC, nominal battery voltage, and voltage profile. For repeated tests, a test repetition count is used to set the charging or discharging cycle count.

III. VOLTAGE PROFILE GENERATION AND TEST CONTROL ALGORITHM

The battery emulator voltage profile shown in the previous section is critical in emulating true battery chemistry. The voltage profile generation and execution procedure are detailed in Fig. 4. The PC firmware generates the profile using user-defined parameters (Fig. 4) fed to the GUI. A model of charging and discharging a battery is calculated and transmitted wirelessly to the emulator controller through these parameters. The voltage profile is generated in every cycle of the battery emulator procedure of repetitive test (REP is greater than 0) procedure and once for a continuous battery test operation.

After the profile generation completion and loading, the battery emulator enters the emulation phase shown in Fig. 4 (red dashed line). During the emulation phase, the emulator controller calculates the battery SOC and Remaining Useful Life (RUL) simultaneously. The spent battery charge (Q_s) computation is carried out by the digital Coulomb Counter by integrating over time the measured instantaneous battery current i_{BAT}. Then, the remaining battery charge Q_{re} and SOC can be calculated. Several prediction methods are commonly used today based on artificial intelligence, filtering, and statistical data to provide the user with an accurate estimation of RUL. In this work, the RUL calculation is based on the constant current discharge estimation. The remaining battery discharge time is calculated by dividing the remaining battery charge Q_{re} by the average drawn current based on the i_{BAT} moving average. Using a relatively simple RUL estimation drastically reduces the computational efforts of the emulator controller.

At the end of the emulation phase, the battery emulator enters a data logging mode. The data logging is performed in a case where there was a communication malfunction between the emulator and the GUI during the emulation phase. The data gathered by the emulator controller is saved locally during the operation and transmitted to the PC data logger. In a case where no communication issues are detected during the emulation phase between the PC and the emulator, this stage is skipped. Past the data logging stage, the battery emulation procedure returns to the profile generation sequence in the GUI if additional charging or discharging cycles are required (REP not equal to 0). In the last charge cycle, the battery emulator halts operation and returns to the initial stage, and waits for the initiate test command.

An essential part of high-fidelity simulation of a physical battery is its degradation over time. Battery SOH represents the degradation state of the battery capacitance of the battery after prolonged use (that is, after a certain number of discharge and charge cycles) compared to the performance of the battery in its optimal condition (usually straight after the production phase). The SOH is defined as the ratio between the maximum charge of the battery and the nominal capacity of the battery. Fig. 5 demonstrates the charge and discharge curves of the battery as a function of time for several cases of SOH. As shown in Fig. 5, the change in battery SOH is manifested as a reduction of the battery discharge time (T_d) for lower values of SOH. In a similar manner, the battery charging time shortens as well.

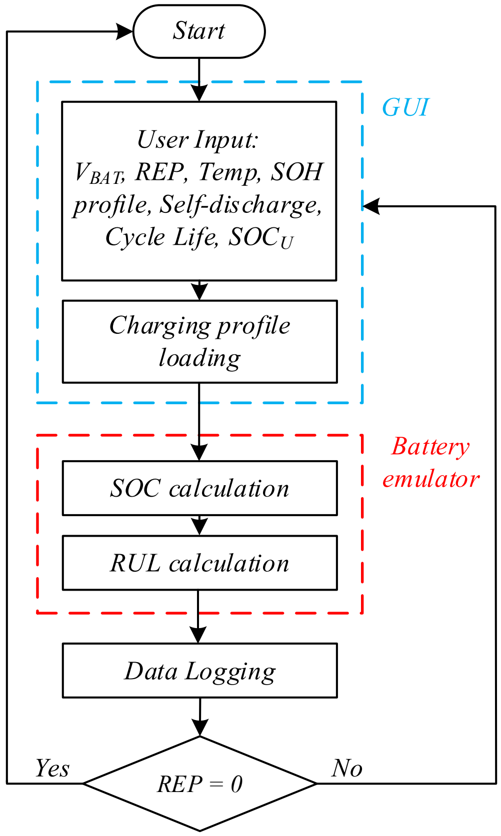

Fig. 4. Battery emulator voltage profile generation and execution flow for continues and repetitive tests.

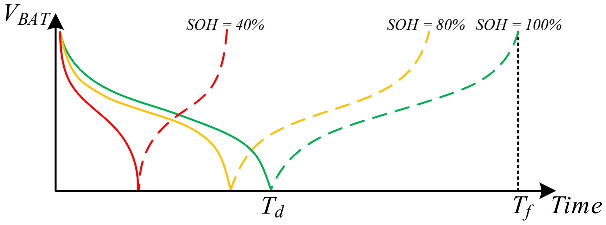

Fig. 5. Battery charge (solid line) and discharge (dashed line) curves at constant load current for given SOH.

Battery temperature is another emulation parameter that represents the effects of environmental temperature change on the battery capacity. Unlike SOH, which indicates the degradation of the battery according to its past use, the temperature of the battery affects its performance in a shorter time frame. While the user can specify an initial temperature for the test in the GUI, which affects the offline generated voltage profile, the emulator onboard sensors measure the emulator temperature in real-time to dynamically adjust the voltage profile during operation. It should be noted that the effect of temperature on the V-T curve illustrated in Fig. 5 is similar to the effect caused by SOH degradation.

The flowchart shown in Fig. 6 describes the battery emulator control flow during a battery emulation test. After system initialization, based on user input to the GUI the system is able to work in two modes of operation, continuous and repetitive. In a continuous mode of operation, the system will charge and discharge indefinitely until stopped by the user in a similar manner to a real battery. In contrast, in a repetitive mode of operation, the algorithm will only perform the set number of iterations entered by the user. At the beginning of each iteration, the battery emulator SOC is initialized and the iteration counter (REP) is progressed, this stage is skipped in continuous operation. After the emulator initialization is complete the test begins. During this stage, the battery emulator tracks the battery's current direction. If the current value is positive, the battery is being charged, and the bi-directional power supply operates in sink mode (V_s = 0 and V_{EL} = V_{BAT}). If the battery current is negative, the battery emulator is being discharged by the load, in this scenario the bi-directional power supply operates in a source mode. In either case of battery emulation, the battery emulator's up-to-date SOC is compared with SOC_{max} and SOC_{min} to determine if the charging\discharging cycle is complete. If the cycle is complete, the emulator returns to the continuous mode node. If the cycle isn't complete the algorithm returns to the battery current direction evaluation. In a case where the battery emulator reaches the maximal iteration count, the control algorithm breaks out from the charge\discharge loop and return to system initialization stage

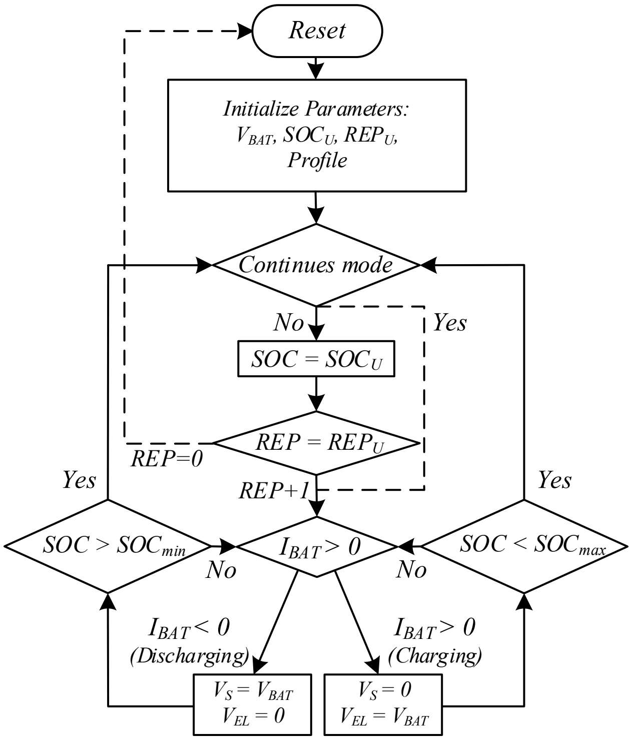

Fig. 6. Simplified flow chart of the battery emulator control flow during a battery emulation test.

IV. EXPERIMENTAL VERIFICATION

The scalable PHiL battery emulation system introduced in this study has been validated using an experimental prototype which has been built and tested. The prototype experimental setup which shown in Fig. 7, is realized with multiple USB terminals and all the required analog front-end peripherals. The battery emulator prototype is rated for maximum input voltage of 150V and input current of 60A, the rest of the converter parameters are shown in Table I. The emulator controller has been implemented on a low-cost ESP32 microcontroller capable of multiprotocol wireless communication to support real-time wireless telemetry.

The battery emulator preliminary results demonstrating battery charging and discharging are shown in Fig. 8 and Fig. 9, respectively. During the charge\discharge cycle, the emulator follows a single-cell Li-Ion based battery voltage profile as discussed in Chapter II. The simulated battery has a capacitance of 83mAh and is being charged and discharged with a constant current source of 1A. This results in a total emulation time of 5 min. The voltage profile is divided into three major sections, the exponential time T_{ex} where the battery voltage correlates to the battery SOC in an exponential manner, T_{const} where the v_{BAT} is almost constant; and $T_{d,}$ which simulates the battery behavior when the battery charge is depleted. The smooth resultant output voltage profile demonstrates the high accuracy of the emulator measurements, the digital battery charge calculations, and power delivery units.

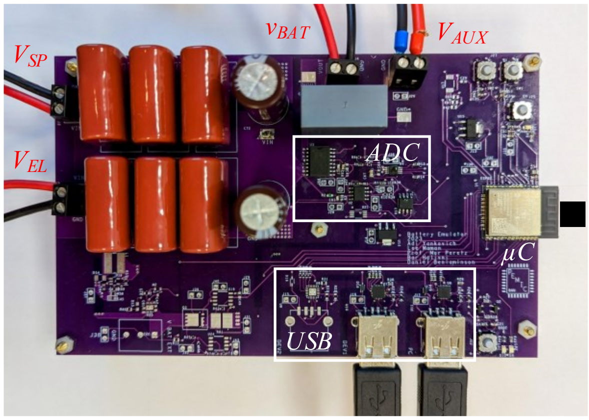

Fig. 7. 150V/60A battery emulator experimental prototype.

TABLE I – EXPERIMENTAL PROTOTYPE PARAMETERS

Parameter	***Value/Type***
Input voltage V_{in}	0-150V
Input current I_{in}	0-60A
Link capacitance C_{Link}	50µF
Controller	ESP32-S3
ADC resolution	12 Bit
Current measurement resolution	40 mA/Bit
Voltage measurement resolution	40 mV/Bit

Fig. 10 shows the battery emulator continues operation mode. Prior to the charging phase, the battery voltage is static at the battery profile minimal voltage of 3V. Once a current start to flow into the emulator as shown by I_{BAT} the battery voltage rises according to the calculated real-time SOC and programed profile. The charging cycle is executed with a CC-CV charging battery charger and is complete when the battery voltage reaches the maximal value of 12V. Since the emulator operates at continues mode, the battery voltage remains constant at the steady-state period marked as T_s, since no current is drawn or injected to the emulator. The steady-state period ends as a load is connected to the emulator asynchronously to the controller operation and the discharge phase begins, discharging the emulator in constant current.

Fig. 11 and Fig. 12 demonstrate the battery emulator receptive mode operation. The battery emulator is being charged and discharged respectively using a constant current source and load. At the end of each charge\discharge cycle, the battery emulator SOC is set back to its original value, setting the appropriate battery voltage and the following cycle is initiated immediately. The discontinues step in SOC occurs until the requested cycle count is reached, in this simulation 3 cycles are executed.

V. CONCLUSION

A battery emulator for power hardware-in-the-loop applications has been introduced and demonstrated using a 150V/60A experimental prototype. The introduced battery emulator is capable of processing a full rating current sink and sourcing, only limited by the used of-the-shelf components. The battery emulator tracks battery voltage, temperature, and current to provide real-time monitoring of the emulated battery's state of charge (SOC) and remaining useful life (RUL). The emulator supports two emulation modes, a continuous battery emulation mode or a cyclic mode for repetitive battery testing. A battery profile-generating algorithm is introduced to precisely replicate the behavior of an actual battery during emulation. The battery voltage profile loading and real-time telemetry between the battery emulator and the GUI have been carried over wireless communication.

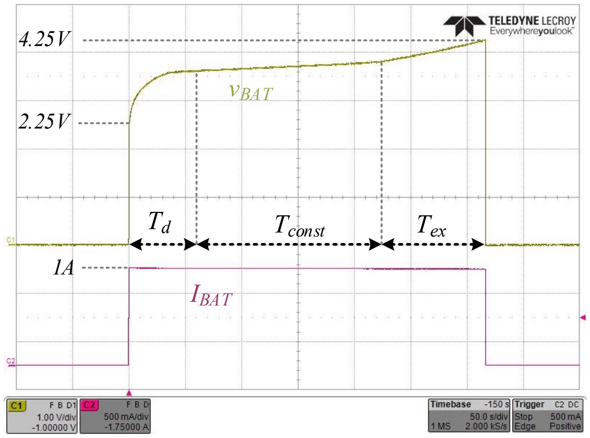

Fig. 8. Single Li-Ion cell simulation of an 83mAh battery charged with 1A constant current charging.

ACKNOWLEDGMENTS

This research was supported by the ISRAEL SCIENCE FOUNDATION grant number 2186/19.

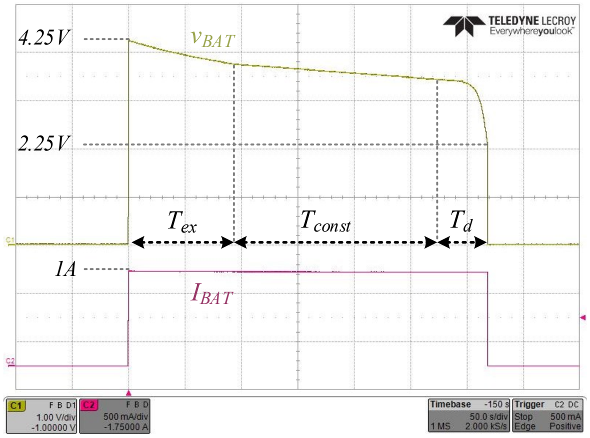

Fig. 9. Single Li-Ion cell 1A constant current discharge simulation of an 83mAh battery.

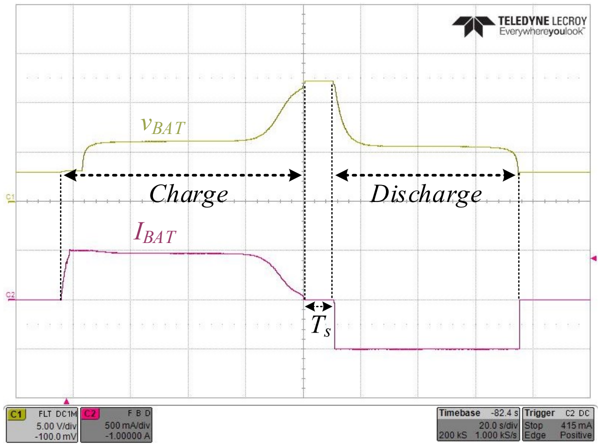

Fig. 10. Battery emulator continuse operation demonstration with CC-CV charging profile and constant current discharge phase.

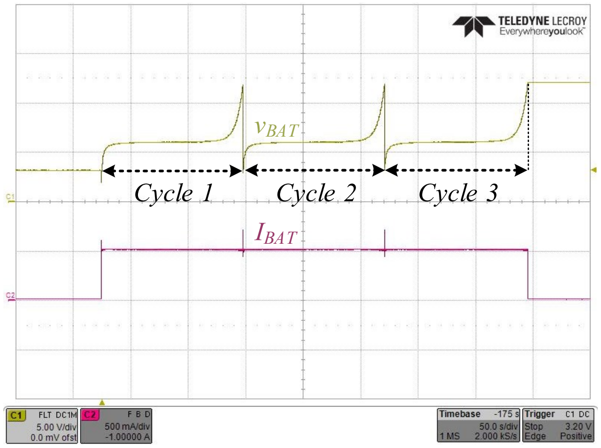

Fig. 11. Repeteive mode battery charging using a 0.5A cosntat current source demonstrating 3 rapid charging cycels between 3V and 12V Li-Ion profle.

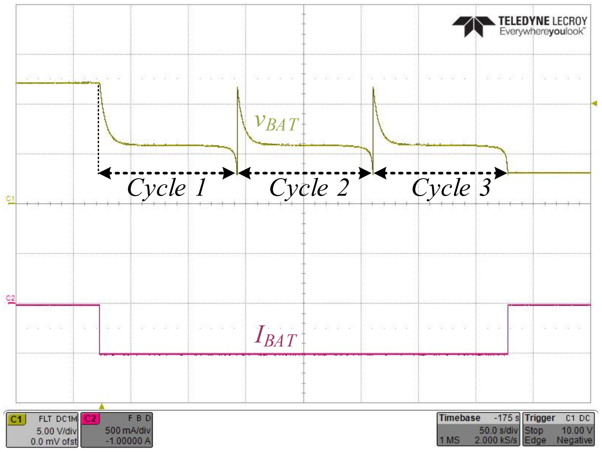

Fig. 12. Repeteive mode battery discharging using a cosntat current 0.5A load.

REFERENCES

[1] Y. -W. Kwon, E. Tilevich, "Reducing the Energy Consumption of Mobile Applications Behind the Scenes," *IEEE International Conference on Software Maintenance*, pp. 170-179, 2013.

[2] P. K. D. Pramanik *et al.*, "Power Consumption Analysis, Measurement, Management, and Issues: A State-of-the-Art Review of Smartphone Battery and Energy Usage," *IEEE Access*, vol. 7, pp. 182113-182172, 2019.

[3] F. Bin, P. Fuming, "A Simple Estimation Method for State of Health of Li-ion Battery with Charging Curve," *IEEE 3rd International Conference on Civil Aviation Safety and Information Technology (ICCASIT)*, pp. 1054-1060, 2021.

[4] Y. Song, M. Park, M. Seo, S. W. Kim, "Improved SOC estimation of lithium-ion batteries with novel SOC-OCV curve estimation method using equivalent circuit model," *4th International Conference on Smart and Sustainable Technologies (SpliTech)*, pp. 1-6, 2019.

[5] N. Daniil, D. Drury, "Investigation and validation of methods to implement a two-quadrant battery emulator for power Hardware-in-the-Loop Simulation," *Annual Conference of the IEEE Industrial Electronics Society*, pp. 2070-2075, 2016.

[6] S. Thale, R. Wandhare, V. Agarwal, "A novel low cost portable integrated solar PV, fuel cell and battery emulator with fast tracking algorithm," *IEEE Photovoltaic Specialist Conference*, pp. 3138-3143, 2014.

[7] A. Collet, J. -C. Crébier, A. Chureau, "Multi-cell battery emulator for advanced battery management system benchmarking," *IEEE International Symposium on Industrial Electronics*, pp. 1093-1099, 2011.

[8] . v. Klitzing, U. Schäfer, "A Highly Dynamic 600 V / 300 A Battery Emulator for Testing of Automotive Electric Drive Trains," *European Conference on Power Electronics and Applications*, 2021.

[9] D. Li *et al.*, "A Converter-Based Battery Energy Storage System Emulator for the Controller Testing of a Microgrid with Dynamic Boundaries and Multiple Source Locations," *IEEE Energy Conversion Congress and Exposition*, pp. 1-8, 2022.

[10] O. Shekoofa, N. Pouryaie, K. Sohrabzadeh. M. Rezvani, "Improving the EGSE of power subsystem by design and development of a battery emulator for space applications," *International Conference on Recent Advances in Space Technologies*, pp. 761-766, 2009.

[11] T. Mesbahi, N. Rizoug, P. Bartholomeus, P. Le Moigne, "Li-Ion Battery Emulator for Electric Vehicle Applications," *IEEE Vehicle Power and Propulsion Conference (VPPC)*, pp. 1-8, 2013.

[12] L. Buccolini, S. Orcioni, S. Longhi, M. Conti, "Cell Battery Emulator for Hardware-in-the-Loop BMS Test," *IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, pp. 1-5, 2018.