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Power hardware-in-loop emulation of a battery for charging systems and grid applications

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Abstract. ***Relevance.*** Batteries are playing an increasingly vital role in power systems due to their utilization in various applications including microgrids, electric vehicles, sustaining geographically isolated communities, and energization of automated devices. Since they are considered as the enabling technology for renewable energy integration, the absence of battery systems from islanded microgrids can result in decreased system reliability and compromised performance due to the intermittency of local sources. Nevertheless, the hazardousness associated with their charging mechanism has led to the urgent continuous development of charging technologies and battery management systems. ***Aim.*** To develop a safe testbed to examine the functionality of newly produced battery charging stations and battery managers without employing actual physical batteries to avoid the hazardous manipulation of batteries and increase flexibility during the design and validation stage. This is accomplished by modeling the electrochemical dynamics of the battery system and integrating the device-under-test to a DC converter, which reacts based on these modeled dynamics. ***Novelty.*** This work adapts one of the most successful Li-ion battery models available in the literature and utilizes it to interact with power electronic devices that exchange power signals. Unlike other work in this field, the design is based on power hardware-in-loop principles and has minimized power consumption characteristics due to its unique configuration. The constructed computer model can be easily reparametrized to describe the dynamics of various battery capacities. ***Methods.*** MATLAB-based simulations of the proposed testbed were conducted for high and low power capacity. A LabView-based program was interfaced with the testbed hardware using a NI-DAQ board to validate the proposed design practically. The testbed hardware components were entirely developed from scratch for experimentation purposes. ***Results.*** The proposed testbed successfully imitated the dynamics of the battery, while the practical results concurred the simulated ones.

Keywords: battery emulation, battery system, renewable energy, power hardware-in-loop, battery chargers

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Программно-аппаратная эмуляция аккумуляторной батареи для систем зарядки и энергосистем

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Аннотация. ***Актуальность.*** Аккумуляторные батареи играют все более важную роль в энергосистемах из-за их использования в различных приложениях, включая микросети, электромобили, электроснабжение географически изолированных районов и питание автоматизированных устройств. Поскольку они считаются технологией, обеспечивающей интеграцию возобновляемых источников энергии, отсутствие аккумуляторных систем в изолированных микросетях может привести к снижению их надежности и производительности из-за прерывистого характера генерирования энергии. Особенности, характерные для функционирования аккумуляторных батарей, приводят к необходимости развития технологий и контроля систем заряда батарей. ***Цель:*** разработка испытательного стенда для контроля зарядных станций и устройств управления ими без использования реальных аккумуляторных батарей, позволяющего повысить безопасность и гибкость этапов проектирования и контроля зарядных станций. Поставленная цель достигается путем компьютерного моделирования динамики электрохимических процессов аккумуляторной батареи и интеграции тестируемого устройства с преобразователем постоянного тока, управляемого этой моделью. ***Новизна.*** В работе применительно к задаче адаптируется одна из самых известных моделей литий-ионных аккумуляторов для управления взаимодействием силовых электронных устройств, которые обмениваются энергией. В отличие от других работ в этой области, конструкция основана на принципах аппаратного обеспечения силовой части и имеет минимальные показатели энергопотребления благодаря своей уникальной конфигурации. Предложенная компьютерная модель параметрируется для описания процесса заряда-разряда аккумуляторов различной емкости. ***Методы:*** компьютерное моделирование и экспериментальная проверка предлагаемых решений. Разработана MATLAB-модель испытательного стенда повышенной мощности. Модель аккумуляторной батареи и системы управления малого энергопотребления в среде LabView с платой NI-DAQ использована для экспериментального подтверждения предлагаемых решений. Для построения экспериментального испытательного стенда разработаны специальные аппаратные компоненты, включая контроллеры. ***Результаты.*** Предложенный испытательный стенд успешно имитировал процесс заряда батареи, при этом практические результаты совпали с расчётными результатами, полученными при моделировании.

Ключевые слова: эмулятор, аккумуляторная система, возобновляемые источники энергии, программно-аппаратный комплекс, зарядные устройства

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Introduction

Energy storage devices are gradually becoming the key element in the modernized power system, especially with the high penetration of renewable distributed generators RDGs. This is a direct consequence of the increased consumer demand and environmental concerns that encouraged the adoption of storage devices as a solution with reduced environmental impact. Recently, storage devices have been extensively utilized in grid applications including frequency and voltage regulation, providing ancillary services like demand peak shaving, balancing renewable energy generation and consumption, and proportionately increasing the reliability of the distribution grid [1]. It has been alleged that the integration of storage devices in conjunction with renewable energy generators, like photovoltaic solar cells, can improve the impact of greenhouse gases by 36–68% for each 1.5 kW of installed capacity [2]. Battery systems, particularly lithium-ion batteries, are considered as the leading candidate for such applications due to their high-energy density, stable performance, long life cycle, and high power capacity [3, 4]. These battery-on-grid applications was boosted by the considerable advancements in microgrids and the rising popularity of renewable-based generation, which can sustain partitions of the electricity grid. Large countries, like the Russian Federation, with numerous communities sprawling across its massive land area can undoubtedly benefit from such configuration to support the local demand of critical and isolated loads during emergencies and grid faults. The proper implementation of battery systems is not confined to on-grid applications, but includes the voguish application in the electric transportation sector which is gaining a lot of attention globally due to the flourishing electric vehicles EVs demand and global regulations [5]. The adoption of EVs has attracted massive investments in the development of charging infrastructure to satisfy the demand and handle the problem of driving anxiety. Although these applications, exemplified in Fig. 1, advertise the importance of battery storage devices and their vast implementations, battery systems suffer from safety challenges due to their thermal, physical, and electrical characteristics [4, 6–8]. Lithium metal is a flammable solvent with exothermal activities and thermal runaway [6]. Thermal, electrical, and aging factors are some of the drivers of lithium-ion batteries hazardous operation, which can lead to high temperatures and combustion. Electrical factors, on the other hand, are caused by the mismanagement of charging and discharging [4]. For this reason, state-of-the-art battery management systems are required to be developed to induce safety and reliability in operation of such systems [8]. Furthermore, hardware and software safety systems and regulations that address concerns such as degradation, cyberattacks, and energy mismatch are imperative for efficient battery utilization [6, 7]. New charging station topologies are also continuously evolving to satisfy the changing operational requirements for each specific application. Nevertheless, these synthesized hardware and software technologies cannot be tested on real-physical batteries due to the potential safety issues previously mentioned. It is, therefore, prime essential to manifest a testing platform that can imitate the power behavior of batteries while interacting with these deployed technologies in the design and verification phase. Ergo, the academic literature is enriched with articles on battery emulation based on various designs.

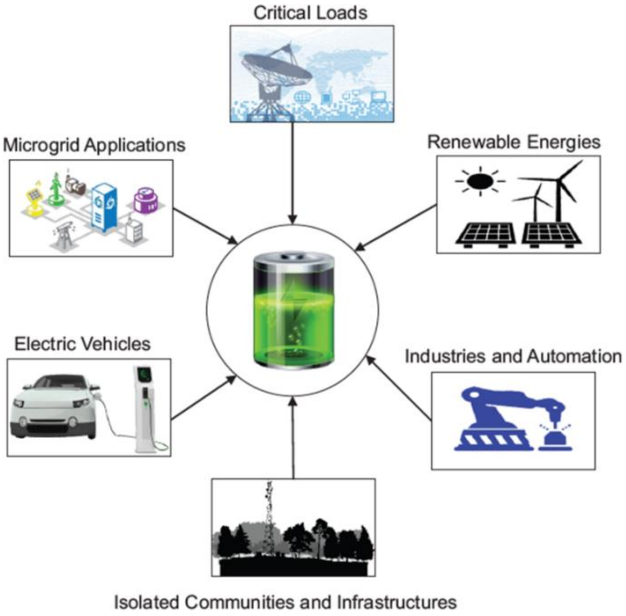


Fig. 1. *Applications of battery systems*
Рис. 1. *Применение аккумуляторных систем энергоснабжения*

The majority of contributions in this field are concentrated on constructing a battery simulator based on hardware-in-loop technologies to test designed battery management systems (BMSs). These systems are ordinarily in constantly developing, since they are obligated to manage thermal and cellular behavior of the battery pack. This direction is similar to our current work in terms of the utilization of generic battery models to test modern designs that typically interact with batteries in real-time. The architecture of such testbeds consists of a battery model, battery simulator deployed on a DSP processor, and power component to establish the communication between the BMS under test and the simulation testbench. However, no power signals are exchanged during these tests and the employed battery models usually focus on analyzing a cell thermal behavior and thermal dynamics. The research in [9] utilized HIL technology to test the cell-to-cell performance of the emulated battery system for BMS applications. The testbench consisted of the battery model in real-time on a dSPACE GmbH battery emulator as an equivalent circuit model for battery cells. The testbench also consists of a switch box, thermal sensors, and a battery charger modeled as an electric vehicle charger. Specialized battery emulators were reviewed and applied to test some commercially available BMS controllers [10]. These emulators are expensive and devised to test certain low-voltage functionalities of battery cells which makes them unsuitable for power tests. Other research implemented the XPC technology, which consists of two PCs, working in real-time, to emulate the battery behavior in managing both the power and temperature of the battery pack [11]. However, only models of the battery and controllers were tested without assessing the capabilities of the power components. A cell-in-loop technology was employed to test the response of a live cell installed in an environmental container [12]. This method is equally effective only when the BMSs and thermal reaction of battery cells are the center of interest. Another application of battery emulators is to test the battery behavior when integrated and interacting with the power grid and power components. A DC/DC converter was used to emulate a decentralized battery management system [13]. The device under test DUT, in this case, was the DC/DC converter while programmable loads, communication devices, and local controllers were used to emulate the simulation scenario. A converter-based battery emulation was introduced in [14] to simulate the battery-on-grid functionality. The testbed used active, reactive, and inertial controllers to investigate the effect of the battery system on a microgrid. The interaction between the regenerative load and battery system in a microgrid scenario was studied in [15], using the HIL testbench. Renewable energy sources were also emulated in the test to establish their effectiveness in charging the battery module.

There is a small portion of the reviewed research articles addressed the implementation of a converter-based battery emulator. These types of testbeds imply the power characteristics of the battery system are to be examined. An interleaved DC/DC boost converter was utilized to emulate the discharge behavior of lithium-ion batteries for testing certain battery-operated applications [16]. A stable power supply was used to energize the converter while a thevenin-based battery model was used with voltage and current controllers to manipulate the converter output and achieve battery emulation. The design, however, can only test the discharge characteristics of the battery. Another research proposed a parametric battery emulator, using a comprehensive set of power converters [17]. The primary objective of the experimental setup is to evaluate the interaction of the battery system with the electric vehicle motoring system based on specific driving patterns. Consequently, the power converters that compose the testbench are controlled to imitate the behavior of both batteries and drive systems in both discharge and charge “regenerative” modes of operation. For emulating the charging and discharging behavior of the battery system, a two-converter testbench was proposed to accomplish more accurate control over the bidirectionally exchanged power [18]. A z-type converter with a single switch was controlled to emulate the battery voltage using a battery model and voltage controller. Power hardware-in-loop (PHiL) technology was used collectively with an RTDS specialized system hardware, which includes a lithium-ion physical model, to evaluate the impact of battery-on-grid operation and related issues [19]. Rapid and stiff frequency rate of change in response to RDGs integration into the electricity grid was studied and mitigated using a battery system in an emulation environment [20]. The authors, however, employed a physical battery model which is arguably a hazardous experimentation provided that extensive safety measures had to be taken.

This research proposes a PHiL-based testbed for battery charging operation. Although the proposed testbed concurs with the reviewed literature in principal objectives and mechanisms, the design building blocks and utilized equipment are deployed to increase efficiency, flexibility, and reduce losses of the testbed. A converter-based battery emulator was employed to imitate the power dynamics of the lithium-ion battery module. A half-bridge topology was utilized for that purpose, which is typically characterized by its simplicity and reduced switching losses. The emulator circuit shares the same power terminals as the charging station DC bus, which implies the exchanged energy between the emulator and charger is in balance. This induced stability and increased safety of emulation as the absorbed energy by the battery emulator fed back to the charging station. The battery dynamics was developed based on the Shepherd model, which accepts the battery current as input and produces the emulated battery voltage as an output. Voltage and current controllers are employed to regulate the emulation converter such that the resulting behavior resembles real battery operation. The ultimate objective of the proposed testbed is to emulate the battery power interactions when connected to the charging station in a manner that enables researchers and designers to safely test their software and hardware products before operational deployment. MATLAB simulations were conducted to verify the design requirements and expected results. While LABVIEW software along with specialized hardware, completely designed and assembled in our laboratory, was used to validate the testbed practically.

Battery model

Many battery models have been reviewed and introduced in the literature. Depending on the targeted applications, these models largely contrast in the addressed parameters and variables. However, this work is more implicated in a battery model that can formulate and emulate the relationship between the battery voltage and current based on the input power. These models must exploit the V-I characteristics of the battery pack while projecting the internal battery parameters on its power behavior. The model utilized in MATLAB/Simulink software, called the Shepherd model, is considered a sufficient, efficient, and accurate description of the battery states during charging and discharging modes. This model was sufficiently developed based on the combined work of different research papers to emulate power, thermal, and aging variations [21–23]. For lithium-ion batteries operating in the discharge mode the input battery current is greater than zero and the discharge characteristics adhere to the following equation:

$$f(\int i, i^*) = E_0 - K\frac{Q}{Q-\int i}i^* - K\frac{Q}{Q-\int i}\int i + A\exp^{-B\int i}.$$

While, when the battery current is reversed, the battery operates in the changing mode and the characteristic equation becomes:

$$f(\int i, i^*) = E_0 - K\frac{Q}{\int i + 0.1Q}i^* - K\frac{Q}{Q-\int i}\int i + A\exp^{-B\int i}.$$

Considering the battery internal resistance, the battery voltage equation can be written as:

$$V_{battery} = f(\int i, i^*) - R_{\text{int}} \cdot i.$$

In these equations E_0 is the constant battery voltage, K is the polarization constant in V/Ah, Q is the battery capacity in Ah, $\int i$ is the integration of the battery current to represent the extended capacity in Ah, i^* is the filtered battery current, A is the amplitude of the exponential region in V, B is the exponential capacity in Ah^{-1}, R_{int} is the battery internal resistance in ohm, i is the unfiltered battery current. By proper selection of battery voltage and capacity, these parameters are adjusted for battery scaling purposes.

The developed model acquires the battery current as input and manifests the battery voltage as output. As illustrated in the model, the battery voltage contains nonlinear dynamics that vary with the supplied current, the battery internal parameters, and the current capacity. Therefore, scaling the battery system by recalibrating the battery internal parameters significantly influences the battery dynamics. Although the adopted MATLAB model accounts for the aging and thermal characteristics of the battery, they are omitted from this work, since they are not relevant to the essential target of the charger testbed.

Proposed testbed design

As previously established, the adopted fundamental concept of this work is to emulate the V-I dynamics of the battery system while interacting with the charging station. The synthesized emulator should behave explicitly like a real battery imitating power interactions based on the selected battery parameters. The proposed battery power simulator contains the following parts:

- bidirectional DC/DC converter to emulate the battery voltage;
- battery model operating on a processor or computer to estimate the actual battery voltage;
- charging station, consisting of the active rectifier and DC/DC charging converter;
- control systems of the charging station and the emulator circuit.

The block diagram of the charging station, connected to the battery emulator, is demonstrated in Fig. 2. The objective of the single-phase rectifier is to stabilize the DC voltage across the DC line capacitor and supply the DC/DC charger with the required current. A half-bridge DC/DC converter was employed to implement the DC charger with the target of adequately providing the charging current through the output filter. This is considered as the simplest charging station which employs uncomplicated battery manager. More complicated charging station architectures are provided in [24].

The battery emulator circuit is illustrated in Fig. 3. As it is seen in the figure, the buck-boost DC/DC converter is utilized to emulate the battery characteristics by emulating the battery voltage on the input terminals. The essential idea here is to manage the voltage and current on the DC line between the device under test DUT “Battery Charging Station” and the DC/DC converter. This can be achieved by supplying voltage in the opposite direction to the charger voltage to emulate battery voltage response. The DC/DC converter will ensure voltage balance by constantly changing the operation mode from buck to boost and vice versa. The following equations represent the battery emulator function:

$$V_{battery} = V_{charger} - V_{emulator},$$
$$I_{battery} = i = -I_{charger}.$$

It is imperative that the battery current is in the opposite direction to the charger current because one is considered an energy generator while the other is assumed as an energy consumer. As it was previously mentioned, the battery model receives the measured battery current and produces the battery voltage, which will be considered as a reference for the outer loop control system of the DC/DC converter. It should be emphasized that both the battery charger and the emulator circuit are supplied from the same DC line, which implies that the excess exchanged energy is fed back to the DC line where the voltage level is maintained by the rectifier control system. Capacitor and inductor filter parameters in Fig. 2, 3 are designed based on the maximum allowable voltage and current ripples respectively.

Fig. 4 exhibits the DC charger control system. The outer control loop receives the measured battery voltage and compares it to the set reference voltage. The generated error is regulated using a PI controller, which formulates the current reference signal. Current limitation is integrated with the voltage controller, which represent the maximum and minimum allowable current, I_{Max} and I_{Min} respectively. A second PI controller is then utilized as a current controller and produces the charger control signal. This signal is limited to the range of 0–0.95, which represents the controller saturation levels shown in Fig. 4. The control signal is then translated to PWM signals to control the switching patterns of the DC/DC charger shown in Fig. 2.

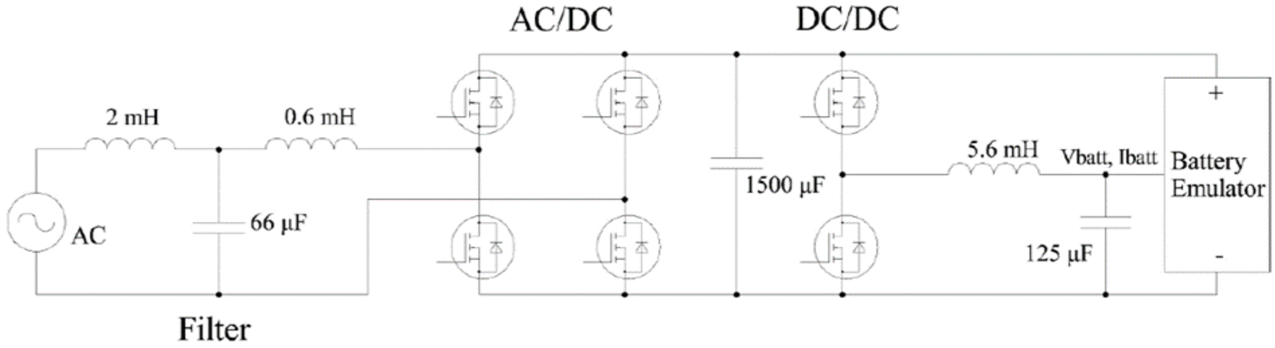


Fig. 2. *Charging station connected to battery emulator terminals*
Рис. 2. *Схема подключения зарядной станции к эмулятору аккумуляторной батареи*

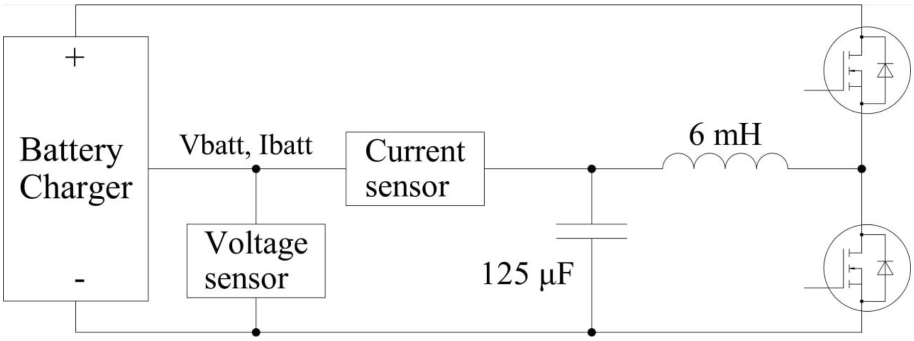


Fig. 3. *Battery emulator circuit connected to charging station terminals*
Рис. 3. *Схема подключения эмулятора аккумулятора к зарядной станции*

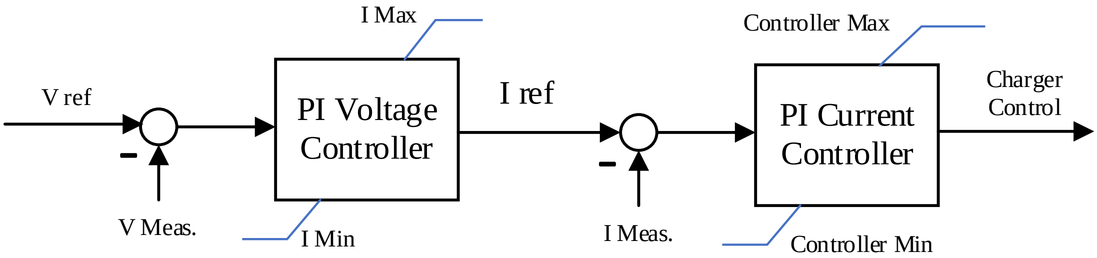


Fig. 4. *DC charger control loops*
Рис. 4. *Структура системы управления зарядной станцией*

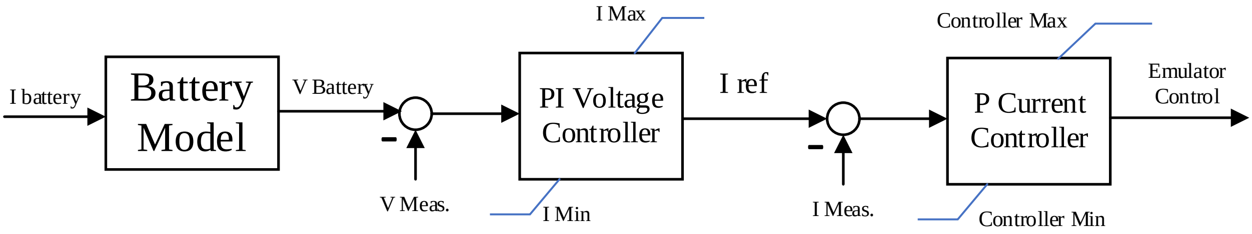


Fig. 5. *Battery emulator control loops*
Рис. 5. *Структура системы управления эмулятором аккумуляторной батареи*

In a similar manner, the battery voltage in the DC line is compared to the modeled battery voltage, and the resulting error signal is regulated by the voltage controller. The output of the PI controller is assumed to be the reference current for the DC/DC emulator converter and is compared to the measured battery current to generate a current error signal. A proportional P controller is then employed to control the internal current and produce the reference signal to the PWM generator. The current controller also acts to limit the exchanged current between the DC line and the buck-boost converter, which will protect the DUT from driving high currents or returning circulating current. The employed P controller is also used to calibrate the system when the battery model is changed, or the tested charger is varied. This particularity is very important, since the proposed testbed is adaptable and should work with all tested charging stations and for all battery models. The block diagram of the battery emulator control system is demonstrated in Fig. 5.

Simulation results

In this section, the proposed testbed is constructed in a MATLAB environment to evaluate design parameters and tune the controller blocks. The emulator converter circuit and the charging station are designed in SIMULINK with standard electrical library tools while the battery voltage and capacity were specified based on commercial heavy-duty CTS-Lifepo4 battery modules used in truck applications. The battery model parameters, exhibited in Table 1, were extracted from the exponential discharge curve of the battery. This curve can be obtained from parametrization of generic battery block in MATLAB and plotting the battery characteristics. These parameters significantly vary when the battery rating is changed due to the high nonlinearity of the discharge characteristic curve. Control loops for both the charging station and battery emulator were equally developed jointly in the same environment while a battery model was developed from scratch based on the previously illustrated lithium-ion battery dynamics. The motivation for such an action is to allow a more flexible battery model design and adapt the developed function in various environments for practical implementation.

Table 1. *System parameters (high power)*

Таблица 1. *Параметры системы (высокая мощность)*

Module Модуль	Parameter Параметр	Value Величина	Units Ед. измерения
Battery charger Зарядное устройство	Total power Полная мощность	≈10	kW/кВ
	Output current Выходной ток	19	A/A
	Output voltage Выходное напряжение	540	V/B
Battery Model Модель аккумулятора	E_0	542.179	V/B
	K	0.0397	V(Ah)$^{-1}$/ B(А·ч)$^{-1}$
	Q	100	Ah/А·ч
	A	44.507	V/B
	B	0.6106	Ah^{-1}/А·ч$^{-1}$
	Battery time constant Постоянная времени батареи	1	sec/c
	Initial state of charge Исходное состояние заряда	50	%
	R_{int}	0.053	Ω

Fig. 6 shows the battery charging response assuming that the charger set voltage is relatively higher than the battery-rated voltage. The charging curve is increasing gradually while the battery voltage and modeled voltage are temporarily stabilized to 496 V, which corresponds to the rated battery voltage at the specified state of charge (SoC). The battery voltage represents the voltage of the emulator circuit, while the modeled battery voltage represents the voltage estimated by the numerical model. The fluctuations experienced in the emulated battery voltage are due to the electronic devices employed attempting to imitate the battery behavior. These fluctuations, however, were attenuated when the emulator dynamics converged to the modeled battery dynamics. This behavior is common in PHiL testbeds where a short period is required for the emulation device to perform its task. The battery current attained at 19 A, while the negative sign indicates the direction of the current from the charging station to the battery pack. Although this test verified the effectiveness of the proposed testbed, the accomplishment of the experiential setup is challenging because of the chosen battery parameters and rated power of the charging station. As a consequence, the battery parameters are scaled down by selecting lower voltage and battery capacity. The new parameters are exhibited in Table 2.

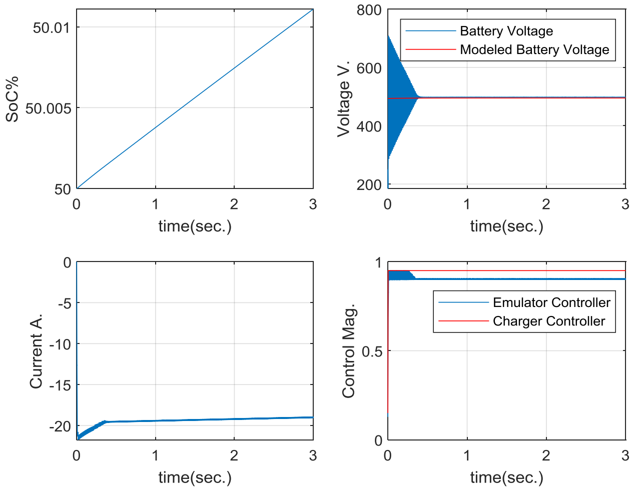


Fig. 6. *Simulation of battery emulator (high power)*

Рис. 6. *Моделирование процесса заряда на эмуляторе аккумуляторной батареи большой мощности*

Table 2. *System parameters (low power)*

Таблица 2. *Параметры системы (низкая мощность)*

Module Модуль	Parameter Параметр	Value Величина	Units Ед. измерения
Battery charger Зарядное устройство	Total power Полная мощность	15.375	kW/кВ
	Output current Выходной ток	3.75	A/A
	Output voltage Выходное напряжение	4	V/B
Battery model Модель аккумулятора	E_0	4.1748	V/B
	K	0.0057	V(Ah)$^{-1}$/ B(А·ч)$^{-1}$
	Q	5.06	Ah/А·ч
	A	0.32331	V/B
	B	12.067	Ah^{-1}/А·ч$^{-1}$
	Battery time constant Постоянная времени батареи	1	sec/c
	Initial state of charge Исходное состояние заряда	50	%
	R_{int}	0.007608	Ω

Once again, the simulation is conducted based on the new parametrization, and the results are compiled in Fig. 7. In the figure, the SoC rate of change is steeper than the previously obtained results, which corresponds to the lower battery capacity. The modeled and simulated battery voltages are concurring with each other, which inferring that both charger and emulator controllers are properly functioning. The dynamic fluctuation in the battery voltage was also observed for less than a second then the emulated voltage coincided with modeled voltage. Battery current is maintained at 3.75 A, while the control signals are retained at a lower level, which also corresponds to the reduced battery rating. Finally, it is immensely important to mention that during the previous tests, the proposed emulator results were evaluated against the results obtained by MATLAB generic battery model. It was discovered that the errors between the estimated battery behavior for both modules were bounded and insignificant. Their errors fluctuated around zero with an RMS value of less than 1. This implies that the developed model and the corresponding testbed are accurately operating with comparable results to the frequently used SIMULINK battery emulation block.

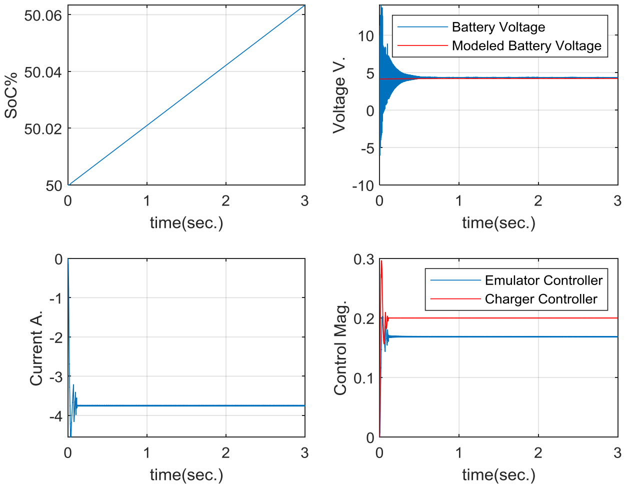


Fig. 7. *Simulation of battery emulator (low power)*
Рис. 7. *Моделирование процесса заряда на эмуляторе аккумуляторной батареи малого энергопотребления*

Practical results

In this part, the testbed design is implemented practically for validation purposes. The formulated models and controllers in the previous section are transferred into the LABVIEW G-language environment to establish a more empirical and experimental-based real-time application. The experimental layout is shown in Fig. 8 where the main hardware components are labeled. A dedicated NI-DAQ PXI-6025e interface card was employed to establish the communication between the LABVIEW environment and the integrated hardware. This DAQ device has an astonishing speed of 200 kS/s for analog input functionality, which qualifies it to read from multiple channels almost simultaneously. Furthermore, it was utilized to deliver the control signals from the computer to the controller module. Although this DAQ device can produce an output voltage signal within the range of ±10 V, the signals were scaled down to accommodate the analog input capabilities of the Amigo Heart controller, which is based on STM microcontroller technology. This controller, which functions as a PWM signal generator, was developed by one of our team members to tackle the practical implementation of industrial control systems. In the design, each controller was employed to generate opposing polarities PWM signals that drive two transistors forming the corresponding converter leg. These power converters are wired to power filters that work contrary to each other to emulate the power characteristics of the battery system. Voltage and current sensors were installed between two power filters, while the sensed signals were wired back to the DAQ device. Scaling and calibration were conducted on both the computer and controller to compensate for the variable operational range of different components. Software filters were also implemented to isolate noise and prevent spiky measurements.

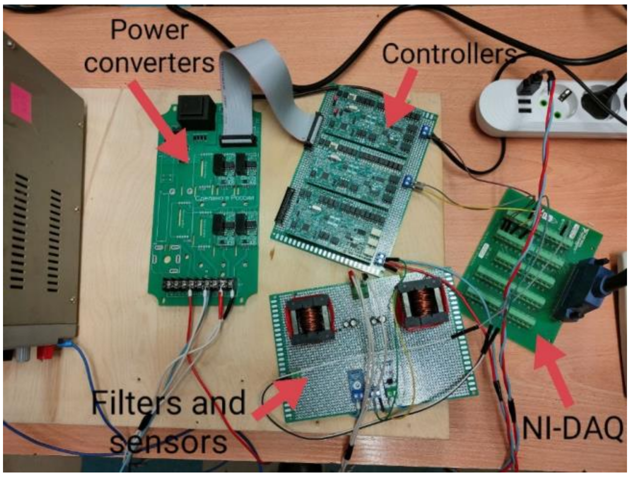


Fig. 8. *Experimental setup of the proposed testbed (low power)*
Рис. 8. *Экспериментальный стенд зарядного устройства с эмулятором аккумуляторной батареи малого энергопотребления*

The front panel of the developed LABVIEW program is exhibited in Fig. 9 [25]. This program double functions as a control and monitoring platform. The battery parameters can be specified within the panel, which means that the battery model can be scaled with simple modification. Sensor and controller calibration can also be performed using this interactive panel. Furthermore, the sensor measurements are demonstrated and registered.

Fig. 10 demonstrates the emulated and real measured voltages. The emulated voltage is generated by the real-time battery dynamics with real current as input to the model. The tracking error between two voltages is minimal, while the small fluctuations are due to sensor noise and controller calibration. These fluctuations could be reduced by employing more accurate voltage and current sensors and upscaled hardware devices. This behavior is attenuated in higher power testbed according to the noise reduction characteristics of utilized sensors.

The measured battery current is illustrated in Fig. 11. The current maintained at 3.75 A level, which is considered as realization of the previously obtained MATLAB results. This current is the maximum allowable current by the currently available power supply unit.

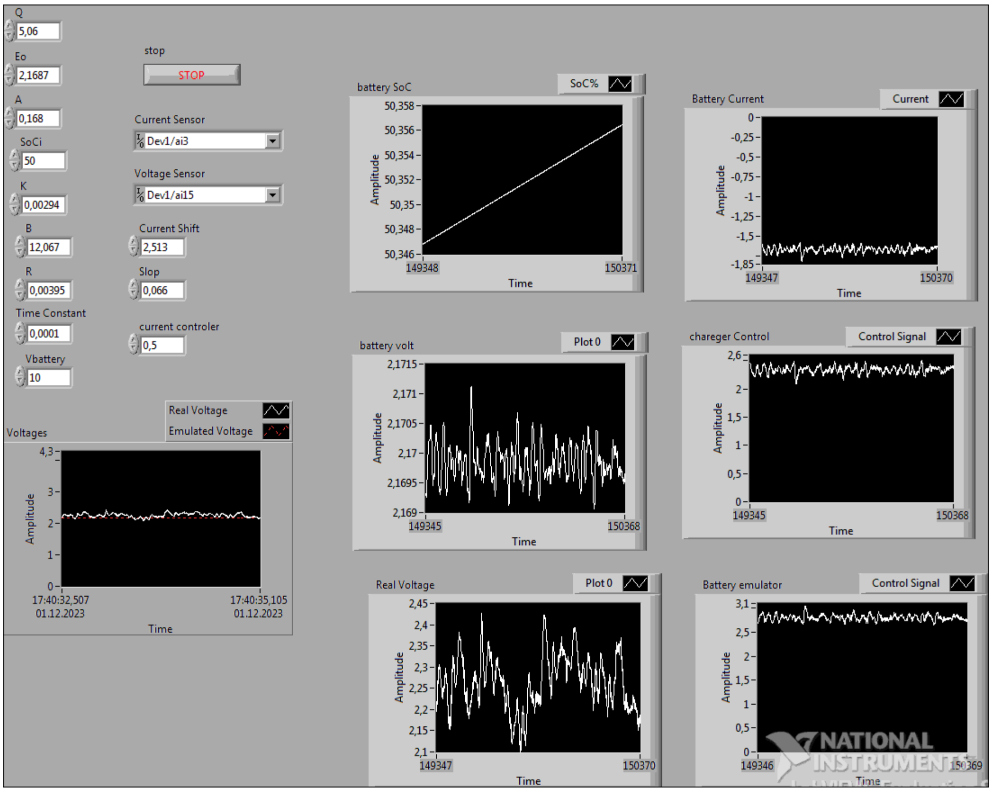

Q 5,06
Eo 2,1687
A 0,168
SoCi 50
K 0,00294
B 12,067
R 0,00395
Time Constant 0,0001
Vbattery 10
Current Sensor Dev1/ai3
Voltage Sensor Dev1/ai15
Current Shift 2,513
Slop 0,066
current controler 0,5

Fig. 9. *Front panel of the LABVIEW control and monitoring center*
Рис. 9. *Лицевая панель центра управления и мониторинга экспериментальным стендом в среде LABVIEW*

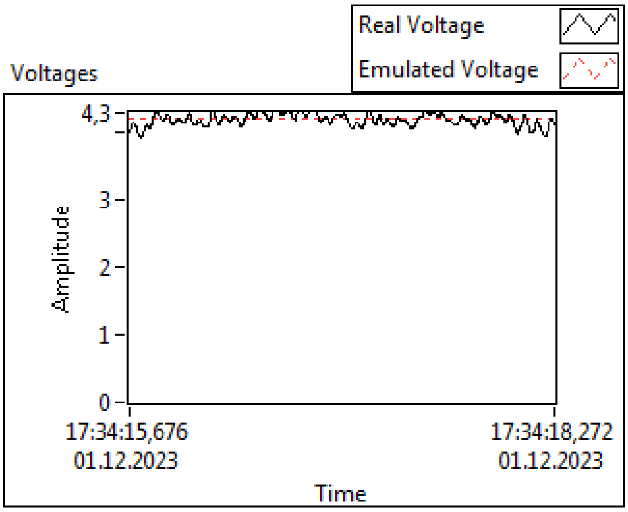


Fig. 10. *Emulated and real battery voltage*
Рис. 10. *Диаграммы эмулируемого и реального напряжения батареи*

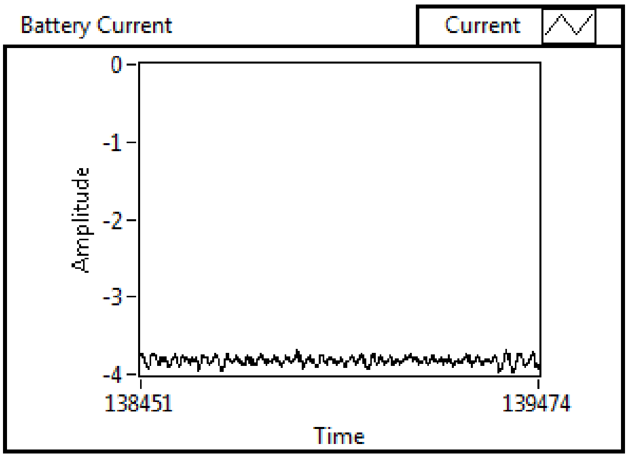
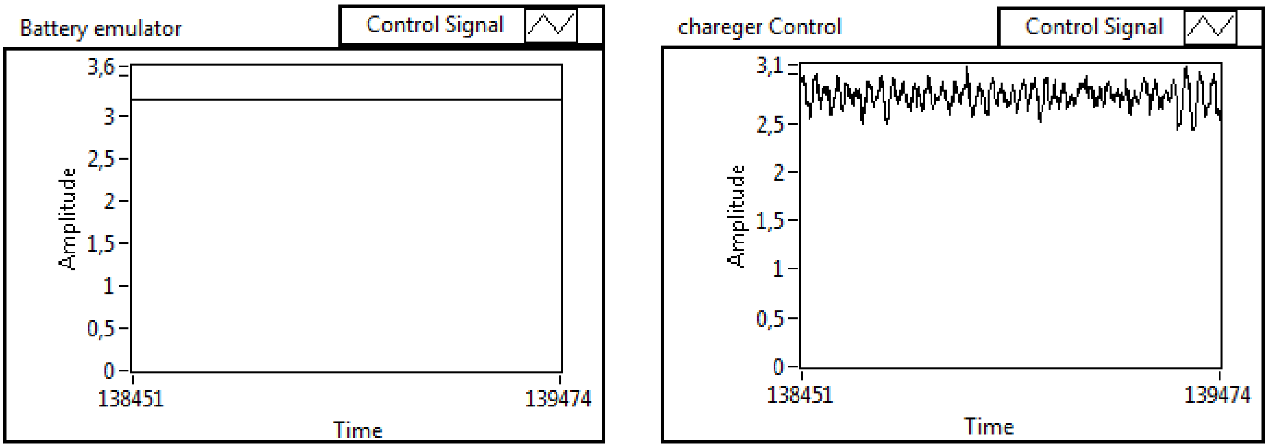


Fig. 11. *Battery current*
Рис. 11. *Диаграмма тока заряда аккумуляторной батареи*



a/а b/б

Fig. 12. *Emulator (a) and charger (b) control signals*
Рис. 12. *Диаграммы сигналов управления эмулятором (а) и зарядным устройством (б)*

Fig. 12 compares the generated control signals by the charging station and the battery emulator controllers. It can be observed that the emulator controller saturated at the maximum achievable control signal output 3.2 V, which represents the maximum analog input of the microcontroller system. The charger controller, however, fluctuates below the 3.1 V level. The proximity between two signals is crucial to accomplish power balance and battery emulation. The SoC of the emulated battery is shown in Fig. 13 with a gradually increasing value. This indicates that the battery is charging, and the direction of energy is from the charging station toward the emulated battery. The battery emulator can be made to test the discharge functionality. However, it is a less critical test, since the most hazardous battery behavior occurs in charging. Furthermore, the discharge process requires a load emulation, which is out of the scope of this research.

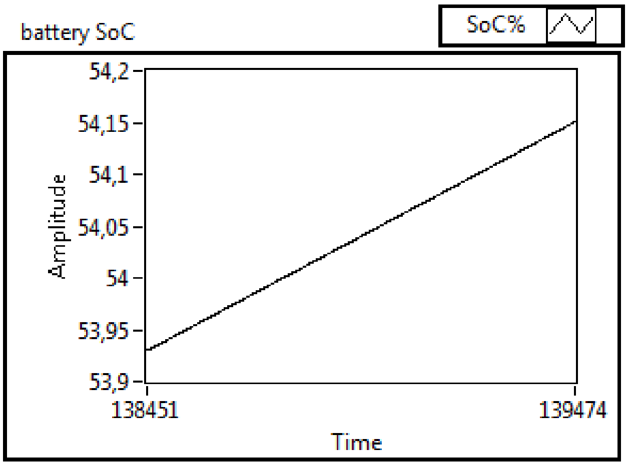


Fig. 13. *Battery state of charge*
Рис. 13. *Диаграмма уровня заряда аккумуляторной батареи*

According to the exhibited performance and by comparing the MATLAB simulations with the obtained practical results, the proposed testbed effectively accomplished the desired design targets. The testbed can emulate a battery system with any capacity and functionality and can only be limited by the utilized hardware capabilities. Conclusively, the proposed testbed offers a more flexible battery emulation variant and satisfactory performance, with a substantially cheaper price tag than the commercially available counterparts.

The obtained results of the operational testbed indicated the possibility of utilizing the proposed design for testing real battery charging stations with the compliance with the international standers of electrical system installation parameters and test methods IEC 62933-2-1:2017 and IEC 62933-1:2018 for ESS. The tested system capacity was in compliance with the systematic performance testing procedures described in the standers under nominal voltage and current. Round-trip testing and other parametric tests like charge-discharge effectiveness were not carried out, since the discharge procedure lays outside the scope of this research. Furthermore, it should be mentioned that the designed testing power hardware devices obeyed the UL 1741 (2010) international standers for axillary enabling power devices.

Conclusion

The presence of batteries in power systems has become vitally important due to their regulative and energy-balancing functionates. Applications of battery systems range from automated devices and industries to grid-supporting and renewables integration. Industries and research facilities are increasingly engaging in the development of battery-related technologies to enable faster charging and safer utilization. Nevertheless, batteries pose significant hazards because of their exothermal reactions and electrical mismanagement. This is detrimental to the battery industry and researchers involved in this scientific sphere since they constantly devise modern charging stations and battery managers to accommodate the soaring demand of various applications. This work proposed a battery emulation testbed to allow safer and more flexible experimentation of newly created technologies during the design and validation stages. The testbed emulates the V-I characteristics of lithium-ion batteries by using battery model dynamics and power converter. This converter is regulated to interact with the charging station resembling the behavior of a physical battery. MATLAB simulations were conducted to verify the design parameters and set a reference of anticipated performance. Then, the proposed testbed was implemented practically using the LABVIEW environment and synthesized power components. The practical results coincide with the simulated results, and the testbed accomplished the required performance. The designed testbed is quite competitive in terms of price and flexibility to other commercially available solutions. Future goals are to utilize the testbed flexibility and reconfigurability to emulate more complicated functionalities and control systems that involve the interaction of battery systems with different loads and grid scenarios. Furthermore, the battery model could be developed in the VHDL environment and deployed on an FPGA device to reduce the bulky size of the computer and associated interface devices. This modification will also eliminate the need for foreign licensed software.

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