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Test bench and model research of hybrid energy storage

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Abstract

This paper focuses on research into and simulations of an energy storage system with high efficiency (or high durability), consisting of an electrochemical battery, which was connected to a ultracapacitor by voltage converters. An active connection between the battery and the ultracapacitor leads to good load distribution during charging and discharging. By adjusting the DC/DC converter system to a predefined exemplary load cycle, the ultracapacitor assumes high momentary current demand, while the remaining range of power demand is covered by the electrochemical battery. This way the ultracapacitor is used as an efficient energy source, reducing high current consumption from the battery, thus limiting energy losses in the battery and increasing its durability. This paper presents test bench research regarding the static and dynamic states of battery and ultracapacitor work. It contains a discussion on the theoretical and analytical relations underpinning and informing the development of the battery and ultracapacitor models. The paper shows the characteristics of voltage, current, and heat generation on the battery and ultracapacitor selected on the basis of the adopted cycle of power demand. The hybrid energy storage system proposed in this work is particularly suited for use in the zero-emissions building sector, associated with renewable energy sources and other distributed generation devices, and for their stable, durable and efficient operation.

Keywords: $LiFePO_4$ battery; ultracapacitor; energy; hybrid energy storage; simulation model

1. Introduction

In the context of the 2020 climate and energy package [1] the member states of the European Union are required to meet certain obligations, for example, increasing the presence of Renewable Energy Sources (RES) on the energy market to nearly 20% of overall energy usage [1–3] and increasing the share of biofuels in transportation by 10% (for Poland, the required percentage is 15.3%), increase in energy efficiency (by 20%) and decrease of greenhouse gas emissions (e.g. CO_2) to the atmosphere (by at least 20% compared to 1990 emissions). The European Union climate and energy policies for 2030 and 2050 are currently being worked on [4]. In the 2030 perspective [4] new goals are set, including: improvement in energy effectiveness by 27%, increase of RES share to 27% of energy used in the EU and decrease of greenhouse gasses emissions by nearly 40%. The highlighted goals will have a great impact on the development of technology, particularly distributed energy generation devices [5–16], which will have an impact on the competiveness of the Polish economy. One of the crucial elements in improving energy efficiency is advancement in energy storage technology. Various methods of energy storage appear in scientific literature and in industry [17–21] based on the type of energy stored, e.g.: in reversible 2^{nd} type cells (electro-chemical) [22–36], flywheels (mechanical), ultracapacitors (electrical) [37–69], magnetic superconductive coils (electrical) [19–21], pumped storage systems (mechanical) or in underground rock cavities (mechanical) [17, 18], where stored air can be re-used for powering machines, or in heat storage (heat energy) [19–21]. Energy storage technologies were described in detail in works [17–21]. In future, simultaneous to the liberalization of the energy market and prosumer support [70] a rise in interest in electric vehicles will be seen [22, 23, 34, 47, 50, 60, 62, 64, 71, 72], which will make a contribution as an integral part of distributed energy generation devices [71, 72]. Polish law is currently in need of reform as there are no regulations governing the mass introduction of such vehicles on the market. Restrictions on mass introduction arise from vehicle construction issues and external factors. Featuring among the barriers to progress are the limited generation and transmission capabilities of

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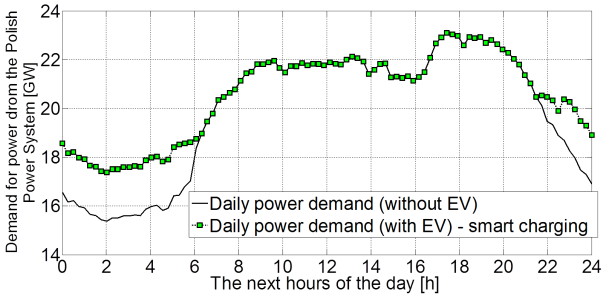


Figure 1: Impact of “smart charging” on power demand from the Polish Power System (KSE)—based on KSE data [73]—charging 1 million electric vehicles

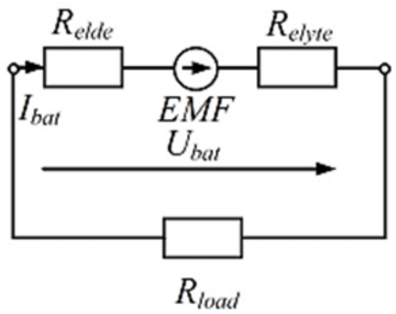


Figure 2: Physical model of an electrochemical battery [22, 24]

the Polish energy industry [73]. Increased peak power use, caused by ungoverned charging of electric vehicles may lead to the overloading of power plants and the power network and cause outages. These assumptions are supported by simulations done for Los Angeles [72].

Fig. 1 presents the results of charging 1 million electric vehicles utilizing night energy valley in “smart charging” mode.

For this reason, governed charging of electrochemical energy storage in electric vehicles is crucial [22, 23, 34, 47, 50, 60, 62, 64, 71, 72]. It is worth pointing out the rationality of charging with energy from renewable energy sources and co-generation systems [5–16], particularly from distributed sources powering the charging stations. Another obstacle to the spread of electric powered vehicles is the lack of infrastructure for fast charging and the resulting restrictions on the range of travel for electric vehicles, especially on the open highway. This is a major inconvenience and a psychological barrier for potential customers.

Another problem to overcome is storage of energy, which has a direct impact on: (i) the possibility of managing the load on the grid, and (ii) the choice of charging system structure. Currently, the high price of electric vehicles is largely caused by the high cost of batteries and long term operating cost in light of their expected lifetime. The answer to battery prices will be to increase demand, which can only occur in favorable political and commercial conditions. In the 2020 time horizon, the International Energy Agency (IEA) [74, 75] predicts that the price for a 1 kWh battery should be less than \$150 (currently \$268). For batteries with capacity of about 24 kWh (typical for electric vehicle batteries, e.g. Nissan Leaf [76]), the price will be approximately \$3600. It is known that electro-chemical energy storage systems have limited power density [19–21] but greater energy density than ultracapacitors [20, 21]. This means that electro-chemical batteries cannot accept very high, instantaneous current loads. In many technical locations [57], such as households, vehicles [22, 23, 34, 47, 50, 60, 62, 64, 71, 72] and work machines, high instantaneous power demands occur. From this point of view, ultracapacitors are a better solution, characterized by very high power density while having low energy density [58].

Hybrid energy storage (electrochemical battery-ultracapacitors) is an intermediate solution, combining the advantages of a battery and an ultracapacitor, with a DC/DC 2-way converter for power distribution between the battery and ultracapacitor [40, 56].

The following work presents: model-supported research of a $LiFePO_4$ battery and electrolytic ultracapacitor in a set load cycle (static as well as dynamic) for consecutive cycles of charge/discharge numbering several dozen and several hundred.

The structure of the following work is as follows: in section 2 the analytical basis for hybrid energy storage, including electrochemical battery and ultracapacitor, is presented. In section 3 the research stand is described. Section 4 shows the results of research conducted on the stand. In section 5 simulation results are presented and compared with the results obtained from the research stand. Section 6 contains a summary of analysis of the results presented in the work.

2. Analytical background of hybrid energy storage

In the following subsection the analytical dependencies related to models of a battery and an ultracapacitor are presented. Also presented is the typical parallel connection of the two energy storages, with assumptions for simulation and technical implementation.

2.1. Battery model dependences

This subsection contains a description of an electrochemical battery. A physical diagram of said battery is presented in Fig. 2.

Based on the analysis of Fig. 2, the internal resistance R_{int} of the battery can be calculated as:

$$R_{int}(i_{bat},T,Q) = R_{elde}(T,Q) + R_{elyte} + bEMF(i_{bat},T,Q)I_{bat}^{-1} \quad (1)$$

where: R_{elde}, R_{eleyte}—electrodes and electrolyte resistance, respectively, $bEMF(i_{bat},T,Q)I_n^{-1}$—ratio which defines the relative change of the electromotive force of the polarization during the flow of the nominal current I_n versus EMF for the nominal capacity of Q_n. In this paper the experimental data has been employed to determine R_{int}:

$$R_{int} = (U_m - U_{m+1})/(I_{m+1} - I_m) \quad (2)$$

where: $U_m > U_{m+1}$ and $I_{m+1} > I_m$.
The family of U_m, U_{m+1} characteristics was determined during the experimental research described in [22–25, 28, 29]. Once R_{int} was determined, transforming the following equation (2), it became possible to calculate the EMF, for charging (+) and discharging (–) respectively:

$$EMF = U_{term} \mp i_{bat}\,((U_m - U_{m+1})/(I_{m+1} - I_m)) \tag{3}$$

The internal resistance of the battery R_{int} was determined using the iteration-approximation method [23] and subsequently it was used in the simulation model in order to account for the change of the battery's resistance depending on the change of its SOC. The properties of the electrochemical battery were defined using Peukert's equation, described in detail in [23].

The following relation was used for the purpose of mathematical modeling of a battery's effective capacity:

$$Q_{Bat}(i_{bat}, t, T) = c_T(T)\eta(i_{bat}, T)Q_n \pm \int_0^t i_{bat}(t)dt \tag{4}$$

Knowing that the battery's state of charge is equal to the ratio of its effective capacity to nominal capacity, one can write:

$$SOC = Q_{Bat}Q_n^{-1} = w_T(T)\eta(i_{bat}, T)Q_n^{-1}Q_n - Q_n^{-1}\int_0^t i_{bat}(t)dt = \overbrace{w_{\ T}(T)\eta(i_{bat}, T)|_{\substack{i_{bat} \cong I_n \\ T \cong Tn}}}^{\cong 1} - Q_n^{-1}\int_0^t i_{bat}(t)dt = 1 - Q_n^{-1}\int_0^t i_{bat}(t)dt \tag{5}$$

The EMF electromotive force, which depends on the SOC, can be expressed in the following form:

$$\begin{gathered} EMF(SOC) = EMF_{\min} + \Delta U_{term} \cdot SOC = \\ EMF_{\min} + (EMF_{\max} - EMF_{\min}) \cdot \left(1 - Q_n^{-1}\int_0^t i_{bat}(t)dt\right) \end{gathered} \tag{6}$$

The values of EMF_{min} and EMF_{max} were determined on the basis of experiments [22–25, 28, 29].

2.2. Ultracapacitor and hybrid energy storage model description

In the following subsection the physical model of the ultracapacitor is presented (Fig. 3).

2.3. Model of the hybrid system

Numerous deliberations about ultracapacitors can be found in the scientific literature [50], in many articles a number of simplifications are made, e.g. the inductance in the system is omitted, also omitted are capacitance and resistance of the electrodes, the resistance resulting from self-discharge is equal to ∞– these were the simplifications assumed in [22].

In the following subsection the full description of an electrochemical battery-ultracapacitor hybrid energy storage unit and topology (Fig. 4) is presented, with an analytical description and no simplifications made. Fig. 4a) presents the physical model of the hybrid energy storage system: the battery-ultracapacitor. There is a passive connection topology of battery and ultracapacitor and they are connected to the DC bus directly. This topology is the simplest and cheapest, beating active hybrid energy storage solutions. The advantages of this topology are: reduction of internal losses and effective damping of the transient current under impulse load conditions.

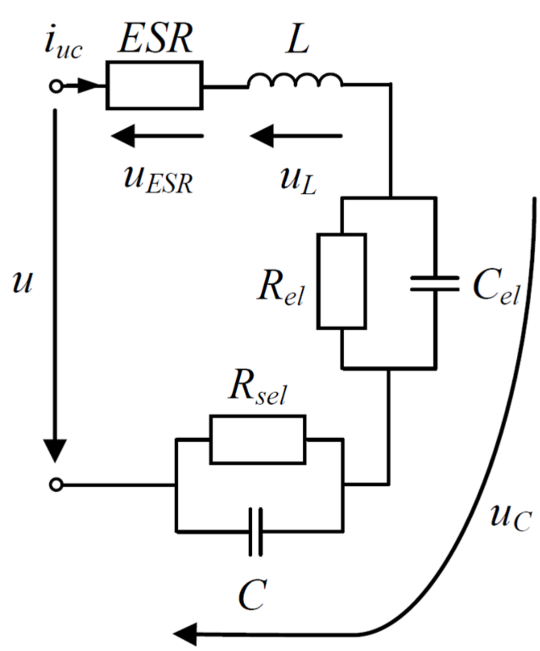


Figure 3: Physical model of the ultracapacitor, where: u_c—ultracapacitor voltage, i_{uc}—the current of ultracapacitor, L—inductance, ESR—the equivalent series resistance

Fig. 4b) shows parallel active hybrid energy topology, where two bidirectional DC/DC converters have been employed. In this case the hybrid energy storage can operate across a wider range of State of Charge and the volumetric efficiency can be improved. There are well known topologies for grid scaled hybrid energy storage application [77].

In Fig. 4c) the cascaded active hybrid energy storage topology with two DC/DC bidirectional converters is illustrated. The battery is isolated by the DC/DC bidirectional converter, the current is controlled to provide smooth power exchange with the battery [77]. This avoids rapid (high current value fluctuation) charge/discharge processes of the battery arising from the intermittency of distributed generation devices, especially renewable energy sources and external load (eg. household power demand). Moreover, the bidirectional DC/DC converter isolates the ultracapacitor from the DC bus. The voltage is controlled to regulate the DC bus voltage when absorbing high frequency power exchanges [77].
Based on analysis of Figures 3 and 4a) and considering the 1^{st} Kirchhoff Law, it can be written that:

$$i = i_{bat} + i_{uc} \Rightarrow i_{bat} = i - i_{uc} \tag{7}$$

The change of voltage consecutively for the battery and ultracapacitor can be written as a set of equations:

$$\begin{cases} u = EMF - i_{bat}R_{int} \\ u = u_c - L\frac{di_{uc}}{dt} - i_{uc}ESR \end{cases} \tag{8}$$

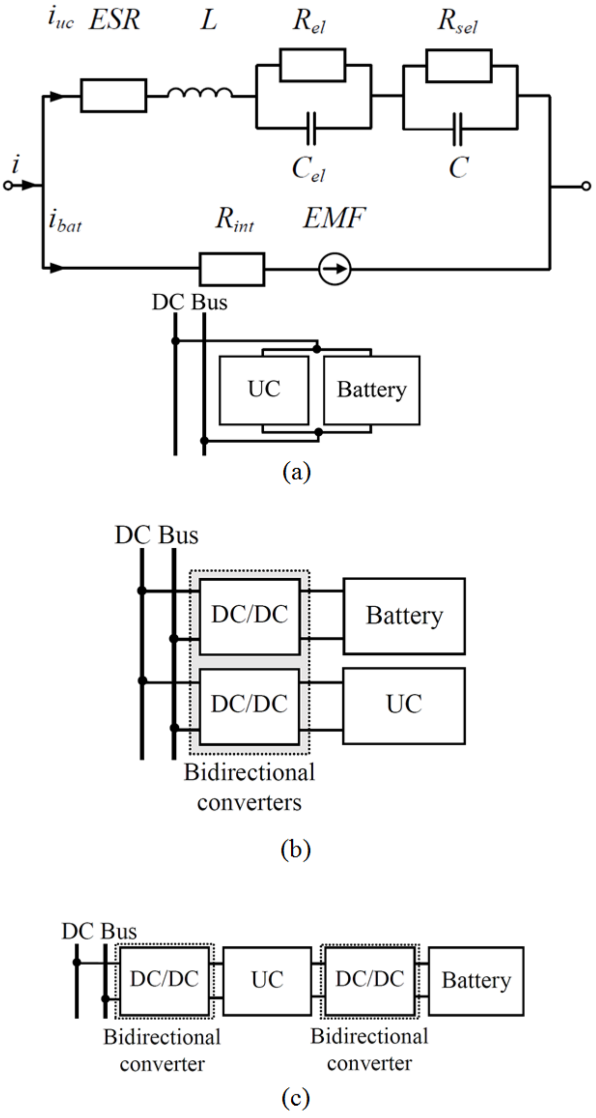


Figure 4: a) Physical model of the hybrid system: battery-ultracapacitor (passive hybrid energy storage topology), b) parallel active hybrid energy storage topology, c) cascaded active hybrid energy storage topology

Placing (7) into (8) results in:

$$u = EMF - (i - i_{uc})\, R_{int} \Rightarrow u - i_{uc}R_{int} = EMF - iR_{int} \tag{9}$$

Knowing that for the ultracapacitor the relation between current i_{uc} and voltage u_c can be written as:

$$i_{uc} = C\frac{u_c}{t} \quad \text{or } i_{uc} = C\frac{du_c}{dt} \tag{10}$$

Solving equation (8) with equation (10) results in:

$$i_{uc} = C\left(\frac{u}{t} + \frac{L}{t}\frac{di_{uc}}{dt} + \frac{i_{uc}}{t}ESR\right) \tag{11}$$

or in differential form:

$$i_{uc} = C\left(\frac{du}{dt} + L\frac{d^2 i_{uc}}{dt^2} + ESR\frac{di_{uc}}{dt}\right) \tag{12}$$

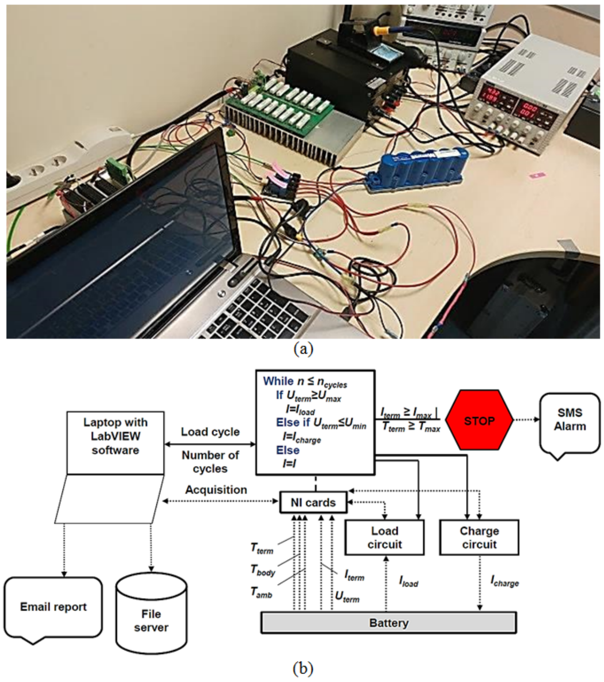


Figure 5: a) Photo of the test stand, b) Schematic diagram of the test stand

Placing dependency (11) into (9) we get:

$$u - \left\{R_{int}C\left(\frac{u}{t} + \frac{L}{t}\frac{di_{uc}}{dt} + \frac{i_{uc}}{t}ESR\right)\right\} = EMF - iR_{int} \tag{13}$$

And similarity in differential form, placing dependency (12) into (9) we get:

$$u - \left\{R_{int}C\left(\frac{du}{dt} + L\frac{d^2 i_{uc}}{dt^2} + ESR\frac{di_{uc}}{dt}\right)\right\} = EMF - iR_{int} \tag{14}$$

Inserting dependency (10) into equation (14), after sorting out the variables, the final dependency can be written:

$$u - R_{int}CESR\frac{di_{uc}}{dt} - R_{int}i_{uc} - R_{int}LC\frac{d^2 i_{uc}}{dt^2} = EMF - iR_{int} \tag{15}$$

Presented dependencies (1)–(15) were used to create the simulation model, as presented in section 5.

3. Test stand description

The measurement chain (Fig. 5a) consists of a PC class computer running the measurement and control application. The PC is connected via a USB to NI Compact DAQ 9174 modular data acquisition chassis with the following modules: NI 9206 analog input +/- 10 V module for voltage measurements, NI 9213 thermocouple module for temperature measurements, NI 9263 analog output +/- 10 V module for controlling the load unit, NI 9401 digital TTL input/output module for relay control of charge and load circuits. Voltage and temperature measurements are handled directly by the NI 9206 and NI 9213 modules. Current is measured by +/- 25 A current to a voltage sensor, connected to NI 9206 module. Measured voltage is converted back to the current value in the measurement application. Ambient temperature and temperatures of the battery connector and battery casing are measured with type K thermocouples.

Control over the measurement chain is provided by NI 9236 and NI 9401 modules. The NI 9401 digital TTL input/output module controls two TTL compatible relays for switching between the charging circuit and load circuit. The load circuit connects the battery to a controllable load power unit. The voltage output of the NI 9263 module sets the amount of current drawn from the battery. Total load power is up to 1 kW, with active cooling. The charging circuit connects the battery to a TTi CPX400DP programmable laboratory power supply, rated for up to 420 W with max. output current of 30 A up to 20 V DC. The power supply output can be controlled by software via TCP/IP (Ethernet)—Fig. 5b).
The experiment was conducted on a 3.3 V, 2.5 Ah $LiFePO_4$ battery and 16.2 V DC ultracapacitor (Maxwell Technologies, 8 cells, each cell voltage equal to 2.7 V, the capacity of the ultracapacitor $C = 58$ F). Similar research on hybrid energy storage (Lead Acid Battery connected with ultracapacitors) to start a combustion engine was conducted and described in detail in[78].

The battery charge cycle was set to 3 A and was continued until a maximum voltage of 3.6 V was reached, after which the battery was switched to load circuit. The load cycle chosen for the experiment was a repeating draw of 2 A, 4 A and 6 A, each load being of 5 seconds duration. The load cycle was continued until it achieved a minimum voltage of 1.8 V (for dynamic cycle) or 2 V (static cycle with 2.6 A, 4.3 A, 5.8 A and 7 A constant current load, respectively).

4. Research results

The following section presents the static and dynamic load cycle research results for electrochemical $LiFePO_4$ battery and MAXWELL BMOD0058 E016 B02 ultracapacitor.

4.1. $LiFePO_4$ battery research in static and dynamic cycle

In the following subsection the research conducted on $LiFePO_4$ battery was presented. The battery had the following parameters: $U = 3.3$ V, $Q = 2.5$ Ah. Static and dynamic load tests were conducted.

In Fig. 6a research results for static cycle are presented. Based on an analysis it was concluded that as the load increased (increase of discharge current) so did the temperature of the battery terminals and casing: For discharge current of 7 A the temperature does not exceed 45°C on the terminals and 32°C on the battery case (heat emission is proportional to Ri^2 factor). To estimate the processes related to heat emission in detail, the thermal resistance model is applied, as described in detail in [35, 79–83]. The cycle-to-cycle efficiency of the battery decreases as the discharge and charge current increases. Greater losses occur related to active and concentration polarity changes. The decrease in usable battery capacity (decrease in active area of the electrodes) is accelerated if the battery is operated in boundary conditions (charging and discharging with currents above 5°C, for example: 1 C—one hour discharge current, eg. for nominal capacity equal 20 Ah, 1 C equal 20 A, 5 C equal 100 A for this value of the battery capacity).

In Fig. 6b research results are presented for $LiFePO_4$for the dynamic discharge cycle. The battery was charged with 3 A current up to the voltage of 3.6 V, then it was discharged by a periodic current load of 3 A–6 A–9 A (each value of current lasted for 5 seconds). The battery was discharged until $U_{termmin} = 1.8$ V voltage was reached.

Based on an analysis of Fig. 6b it was concluded that $LiFePO_4$ batteries perform well in dynamic load conditions (discharging with 3.6°C current did not cause the battery parameters to exceed permissible values, i.e. the temperature of the battery case did not exceed 34°C, the temperature on the battery terminals did not exceed 53°C).

4.2. Ultracapacitor research in static and dynamic cycle

The following subsection presents the research conducted on the MAXWELL BMOD0058 E016 B02 ultracapacitor. The ultracapacitor had the following parameters: $U = 16.2$ V DC (8 cells, each cell voltage equal to 2.7 V). Static and dynamic load tests were conducted.

Based on an analysis of Fig. 7a it was concluded that the ultracapacitor operates at high efficiency when charged and discharged with 18 A currents (time of a charge/discharge cycle equal to the consecutive cycle). Furthermore, the ultracapacitor operates at high efficiency even under dynamic load (charging with 12 A current, discharge with 6 A–12 A–18 A currents, each value lasting 5 seconds) (Fig. 7b). The temperature on the terminals did not exceed 35°C and the operation of the ultracapacitor was stable.

5. Simulation model based on experimental research of hybrid energy storage system

5.1. Experimental research versus simulation model verification

The following subsection presents: Research and simulation results for given load cycle for the MAXWELL BMOD0058 E016 B02 ultracapacitor (analysis for single cell with nominal voltage 2.7 V, Fig. 8a and $LiFEPO_4$ battery, with parameters: $Q = 2.5$ Ah, nominal voltage 3.3 V (Fig. 8b). For both ultracapacitor and the battery the relative error did not exceed 0.1%, which can be considered as satisfactory.

After performing the identification of the model, the simulation for $LiFePO_4$ battery-ultracapacitor hybrid energy storage was performed as per subsection 5.2.

5.2. Simulation results of hybrid energy storage

The following subsection presents the simulation results for parallel configuration of $LiFePO_4$ battery and the MAXWELL BMOD0058 E016 B02 ultracapacitor (analysis for single cell, nominal voltage 2.7 V).

In Fig. 9a the values of current distribution for battery, capacitor and a hybrid system of the two are presented. Fig. 9b

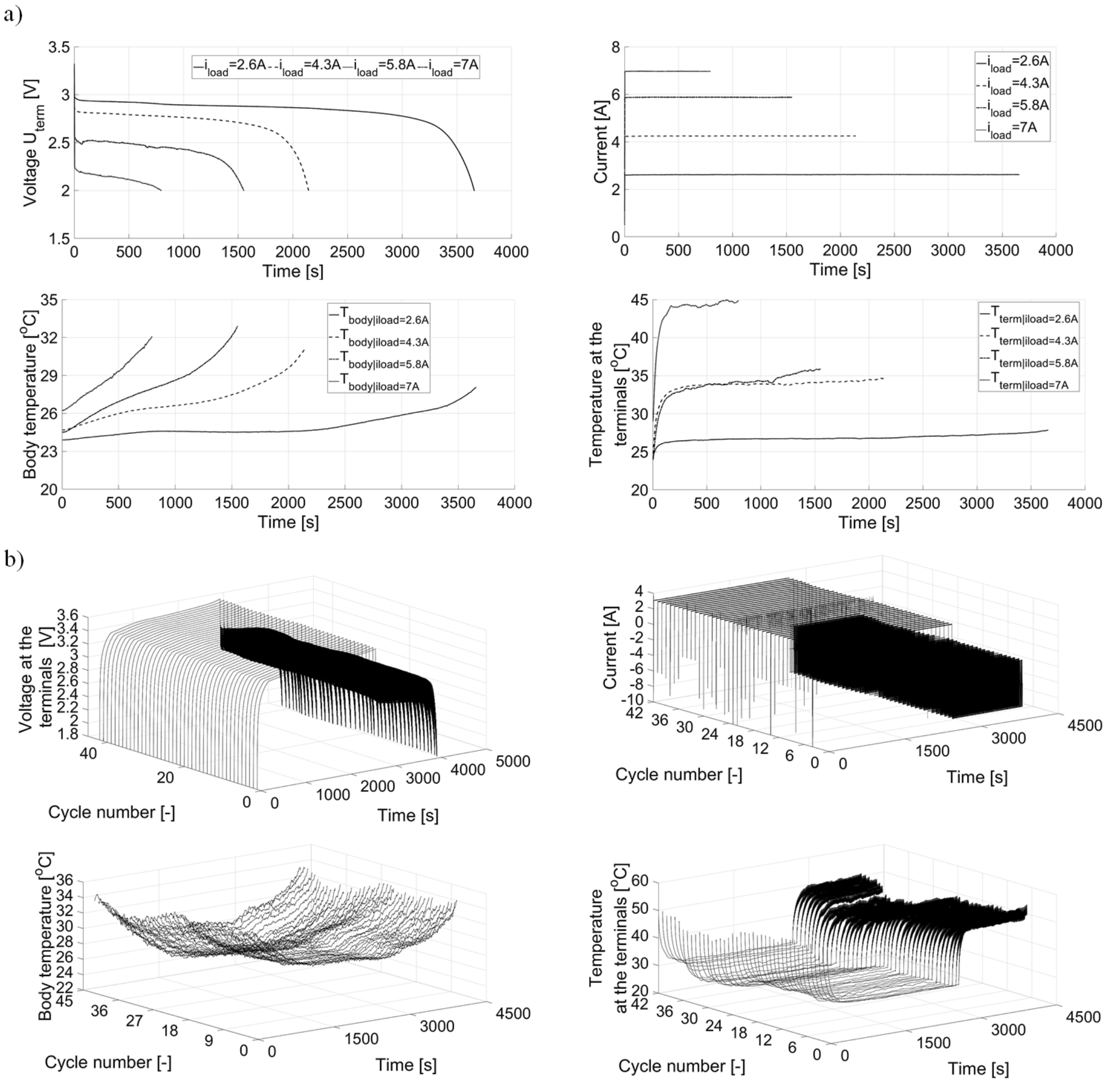


Figure 6: Graphs of LiFePO$_4$ battery in: a) static cycle, b) dynamic cycle

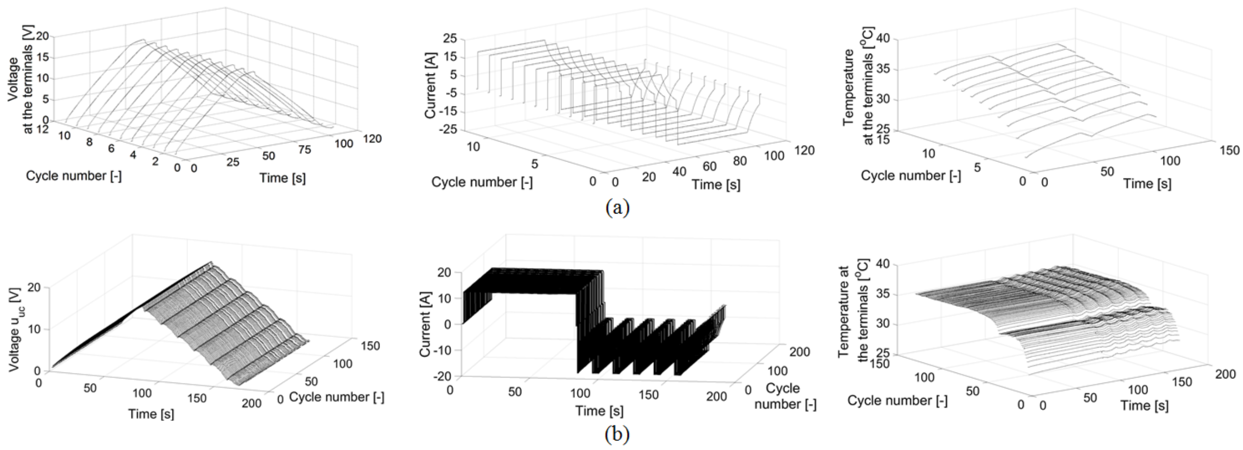


Figure 7: Graphs of the ultracapacitor in: a) static cycle—20 A constant current charging/discharging, b) dynamic cycle—12 A constant current charging, 6 A–12 A–18 A discharging (5 sec intervals) for voltage, current and temperature at the terminals, respectively

presents the voltage change in the hybrid system after connecting the battery and ultracapacitor in parallel, resulting in equalization of voltage. It is worth mentioning that, in parallel configuration, the temporary current loads are handled by the ultracapacitor (Fig. 9a) while the battery is discharged with lesser current, not exceeding 4 C.

6. Summary and Conclusion

This paper presents research on $LiFePO_4$ battery and ultracapacitor performance under static and dynamic load. Analytical descriptions of both energy storage systems are presented and they were used to create a simulation model of a hybrid energy storage system consisting of a $LiFePO_4$ battery and an ultracapacitor. The models of the battery and ultracapacitor were identified. By comparing the simulation results with test stand research it was concluded that relative error between the simulation and test bench results did not exceed 0.1%, which can be considered satisfactory. Moreover, the presented model is useful for identifying off-line selected ultracapacitor parameters in the time and frequency domain [84], especially in electric vehicle and microgrid applications.

Based on the research conducted it was concluded that the main advantages of a hybrid energy storage system in the case of mobile application include: Limitation of current, smoothing out of voltage changes, high density of energy (battery effect) as well as high density of power (ultracapacitor effect).The main disadvantages of the system in mobile applications include: Higher cost of the system, greater weight (important for electric vehicle applications) and the need for constant monitoring of voltage by a BMS system.

For stationary applications, the main advantages are: The possibility of using the energy storage system to start up large cogeneration systems based on gas engines (especially at temporary events, where cogeneration systems are moved from place to place), microturbines, flexible cooperation with wind turbines and other renewable energy sources. Hybrid energy storage systems can be especially beneficial in zero-emission architecture projects and offgrid installation (due to the daily energy requirement cycles in households, especially prosumers equipped with microinstallations). The disadvantages are similar to mobile applications, with the exception of weight, which is usually less important in systems of this type.

It is worth highlighting that a hybrid energy storage system has a longer expected lifetime. In the case of an ultracapacitor: above one million charge/discharge cycles; in the case of a $LiFePO_4$ battery: 5 to 10,000 cycles.

The authors of the article are currently developing new computational methods for hybrid energy storage systems utilizing fractional order derivatives, which are particularly important in describing processes where diffusion occurs and dominates.

Moreover, as a result of their research the authors conclude that models currently employed, i.e. using recursive neural networks [36], should be refined and include changes of lifespan of hybrid energy storages during simulation. This approach offers new insight in terms of making precise predictions of expected lifetime and long time operation of hybrid energy storage systems, as well as when estimating the profitability of investment projects based on hybrid energy storage systems.

References

[1] Directive 2009/28/EC of the council of 23 april 2009, on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

[2] Directive 2012/27/EU of the European Parliment and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.

[3] A. Chmielewski, R. Gumiński, J. Mączak, S. Radkowski, P. Szulim, Aspects of balanced development of res and distributed microcogeneration use in poland: Case study of a μchp with stirling engine, Renewable and Sustainable Energy Reviews 60 (2016) 930–952.

[4] CO EUR 13 CONCL 5 (2030 CLIMATE AND EERGY POLICY FRAMEWORK), Brussels (24 October 2014).

[5] L. Szablowski, J. Milewski, J. Kuta, K. Badyda, Control strategy of a natural gas fuelled piston engine working in distributed generation system, Rynek Energii (3) (2011) 33–40.

[6] A. Chmielewski, R. Gumiński, J. Mączak, Selected properties of the dynamic model of the piston-crankshaft assembly in stirling engine combined with the thermodynamic submodel, International Journal of Structural Stability and Dynamics (2017) 1740009.

[7] J. Milewski, Ł. Szabłowski, J. Kuta, Control strategy for an internal combustion engine fuelled by natural gas operating in distributed generation, Energy Procedia 14 (2012) 1478–1483.

[8] A. Chmielewski, R. Gumiński, T. Mydłowski, A. Małecki, K. Bogdziński, Research on HONDA NHX 110 fueled with biogas, CNG and E85, in: 2nd International Conference on the Sustainable Energy and Environment Development - SEED'17 IOP Conference Series: Energy and Enviromental Studies, 2017, in print.

[9] J. Milewski, M. Wołowicz, Ł. Szabłowski, J. Kuta, Control strategy for a solid oxide fuel cell fueled by natural gas operating in distributed generation, Energy Procedia 29 (2012) 676–682.

[10] A. Chmielewski, R. Gumiński, T. Mydłowski, A. Małecki, K. Bogdziński, Research study of HONDA NHX 110 powered by an alternative fuel, in: 2nd International Conference on the Sustainable Energy and Environment Development - SEED'17 IOP Conference Series: Energy and Enviromental Studies, 2017, in print.

[11] Z. Chłopek, J. Biedrzycki, J. Lasocki, P. Wojcik, Assessment of the impact of dynamic states of an internal combustion engine on its operational properties, Eksploatacja i Niezawodność - Maintenance and Reliability 17 (1) (2015) 35–41.

[12] A. Chmielewski, R. Gumiński, J. Mączak, Selected properties of the adiabatic model of the stirling engine combined with the model of the piston-crankshaft system, in: Methods and Models in Automation and Robotics (MMAR), 2016 21st International Conference on, IEEE, 2016, pp. 543–548.

[13] A. Matuszewska, M. Owczuk, A. Zamojska-Jaroszewicz, J. Jakubiak-Lasocka, J. Lasocki, P. Orliński, Evaluation of the biological methane potential of various feedstock for the production of biogas to supply agricultural tractors, Energy Conversion and Management 125 (2016) 309–319.

[14] A. Chmielewski, S. Gontarz, R. Gumiński, J. Mączak, P. Szulim, Research study of the micro cogeneration system with automatic loading unit, in: Challenges in Automation, Robotics and Measurement Techniques, Springer, 2016, pp. 375–386.

[15] J. Lasocki, K. Kołodziejczyk, A. Matuszewska, Laboratory-scale investigation of biogas treatment by removal of hydrogen sulfide and carbon dioxide., Polish Journal of Environmental Studies 24 (3) (2015) 1427–1434.

[16] A. Chmielewski, S. Gontarz, R. Gumiński, J. Mączak, P. Szulim, Research on a micro cogeneration system with an automatic load-applying entity, in: Challenges in Automation, Robotics and Measurement Techniques, Springer, 2016, pp. 387–395.

[17] P. Krawczyk, Ł. Szabłowski, S. Karellas, E. Kakaras, K. Badyda, Comparative thermodynamic analysis of compressed air and liquid air energy storage systems, Energy 142 (2018) 46–54.

[18] L. Szablowski, P. Krawczyk, K. Badyda, S. Karellas, E. Kakaras, W. Bujalski, Energy and exergy analysis of adiabatic compressed air energy storage system, Energy 138 (2017) 12–18.

[19] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding, Progress in electrical energy storage system: A critical review, Progress in Natural Science 19 (3) (2009) 291–312.

[20] X. Luo, J. Wang, M. Dooner, J. Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, Applied Energy 137 (2015) 511–536.

[21] A. Chmielewski, K. Lubikowski, S. Radkowski, Energy storage technologies: review, Zeszyty Naukowe Instytutu Pojazdów - Proceedings of the Institute Of Vehicles 102 (2) (2015) 13–21.

[22] A. Szumanowski, C. Yuhua, P. Piórkowski, Method of battery adjustment for hybrid drive by modeling and simulation, in: Vehicle Power and Propulsion, 2005 IEEE Conference, IEEE, 2005, pp. 681–687.

[23] A. Szumanowski, Y. Chang, Battery management system based on battery nonlinear dynamics modeling, IEEE transactions on vehicular technology 57 (3) (2008) 1425–1432.

[24] A. Chmielewski, J. Mączak, P. Szulim, Experimental research and simulation model of electrochemical energy stores, in: International Conference Automation, Vol. 550 of Advances in Intelligent Systems and Computing, Springer, 2017, pp. 236–246.

[25] A. Chmielewski, J. Mączak, P. Szulim, Experimental research of electrochemical energy storage, in: International Conference Automation, Vol. 550 of Advances in Intelligent Systems and Computing, Springer, 2017, pp. 227–235.

[26] A. Czerwiński, Akumulatory, baterie, ogniwa, WKŁ, 2012.

[27] A. Chmielewski, S. Radkowski, Modelowanie procesu ładowania akumulatora elektrochemicznego pracującego w układzie kogeneracyjnym, Zeszyty Naukowe Instytutu Pojazdów 2 (98) (2014) 83–89.

[28] A. Chmielewski, P. Szulim, S. Gontarz, Modelowo-wsparte badania elektrochemicznych magazynów energii, Rynek Energii 126 (5) (2016) 37–45.

[29] A. Chmielewski, S. Gontarz, R. Gumiński, J. Mączak, P. Szulim, Badania elektrochemicznych magazynów energii [Research on electrochemicalenergy stores], Przegląd Elektrotechniczny 92 (10) (2016) 231–234.

[30] A. Chmielewski, P. Szurgott, Modelling and simulation of repeated charging/discharging cycles for selected nickel-cadmium batteries, Journal of KONES 22 (1) (2015) 55–62.

[31] A. Ostadi, M. Kazerani, A comparative analysis of optimal sizing of battery-only, ultracapacitor-only, and battery–ultracapacitor hybrid energy storage systems for a city bus, IEEE Transactions on Vehicular Technology 64 (10) (2015) 4449–4460.

[32] A. Chmielewski, K. Bogdziński, P. Szulim, T. Mydłowski, Test stand for operational research of energy storage: description and preliminary research, Zeszyty Naukowe Instytutu PojazdówIn print.

[33] A. H. Fathima, K. Palanisamy, Optimization in microgrids with hybrid energy systems–a review, Renewable and Sustainable Energy Reviews 45 (2015) 431–446.

[34] A. Chmielewski, P. Szulim, M. Gregorczyk, R. Gumiński, T. Mydłowski, J. Mączak, Model of an electric vehicle powered by a pv cell—a case study, in: Methods and Models in Automation and Robotics (MMAR), 2017 22nd International Conference on, IEEE, 2017, pp. 1009–1014.

[35] A. Chmielewski, R. Gumiński, K. Bogdziński, P. Szulim, J. Mączak, Model based research on electrochemical battery connected with 3 diodes model of pv module - selected properties, in: Proceedings of 14th INTERNATIONAL CONFERENCE Dynamical Systems Theory and Applications, Łódź, Poland, 2017, in Print.

[36] A. Chmielewski, J. Możaryn, R. Gumiński, P. Szulim, K. Bogdziński, Experimental evaluation of mathematical and artificial neural network modeling of energy storage system, in: Proceedings of 14th INTERNATIONAL CONFERENCE Dynamical Systems Theory and Applications, Łódź, Poland, 2017, in Print.

[37] R. Zheng, R. Cai, M. Li, An on-line active energy flow split strategy for battery-ultracapacitor energized pmsm driving system, in: Industrial Electronics Society, IECON 2016-42nd Annual Conference of the IEEE, IEEE, 2016, pp. 2694–2701.

[38] M. Ruba, S. Ciornei, H. Hedesiu, C. Martis, Complete fpga based real-time motor drive simulator with bidirectional battery and ultracapacitor power supply, in: Advanced Topics in Electrical Engineering (ATEE), 2017 10th International Symposium on, IEEE, 2017, pp. 186–191.

[39] T. Azib, C. Larouci, A. Chaibet, M. Boukhnifer, Online energy management strategy of a hybrid fuel cell/battery/ultracapacitor vehicular power system, IEEJ Transactions on Electrical and Electronic Engineering 9 (5) (2014) 548–554.

[40] A. Mirzaei, A. Jusoh, Z. Salam, E. Adib, H. Farzanehfard, Analysis and design of a high efficiency bidirectional dc–dc converter for battery and ultracapacitor applications, Simulation Modelling Practice and Theory 19 (7) (2011) 1651–1667.

[41] A. Kuperman, I. Aharon, A. Kara, S. Malki, A frequency domain approach to analyzing passive battery–ultracapacitor hybrids supplying periodic pulsed current loads, Energy conversion and management 52 (12) (2011) 3433–3438.

[42] H. Marzougui, M. Amari, A. Kadri, F. Bacha, J. Ghouili, Energy management of fuel cell/battery/ultracapacitor in electrical hybrid vehicle, International Journal of Hydrogen Energy 42 (13) (2017) 8857–8869.

[43] W. Henson, Optimal battery/ultracapacitor storage combination, Journal of Power Sources 179 (1) (2008) 417–423.

[44] B. Hredzak, V. G. Agelidis, G. Demetriades, Application of explicit model predictive control to a hybrid battery-ultracapacitor power source, Journal of Power Sources 277 (2015) 84–94.

[45] P. Zhang, A. Mills, J. Zambreno, P. H. Jones, The design and integration of a software configurable and parallelized coprocessor architecture for lqr control, Journal of Parallel and Distributed Computing 106 (2017) 121–131.

[46] A. Kuperman, I. Aharon, Battery–ultracapacitor hybrids for pulsed current loads: A review, Renewable and Sustainable Energy Reviews 15 (2) (2011) 981–992.

[47] T. D. Atmaja, et al., Energy storage system using battery and ultracapacitor on mobile charging station for electric vehicle, Energy Procedia 68 (2015) 429–437.

[48] H. Zhou, T. Bhattacharya, D. Tran, T. S. T. Siew, A. M. Khambadkone, Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications, IEEE transactions on power electronics 26 (3) (2011) 923–930.

[49] M. M. Patankar, R. G. Wandhare, V. Agarwal, A high performance power supply for an electric vehicle with solar pv, battery and ultracapacitor support for extended range and enhanced dynamic response, in: Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th, IEEE, 2014, pp. 3568–3573.

[50] A. Szumanowski, P. Piorkowski, Y. Chang, Batteries and ultracapacitors set in hybrid propulsion system, in: Power Engineering, Energy and Electrical Drives, 2007. POWERENG 2007. International Conference on, IEEE, 2007, pp. 122–127.

[51] G. Mandic, A. Nasiri, Modeling and simulation of a wind turbine system with ultracapacitors for short-term power smoothing, in: Industrial Electronics (ISIE), 2010 IEEE International Symposium on, IEEE, 2010, pp. 2431–2436.

[52] E. Manla, G. Mandic, A. Nasiri, Development of an electrical model for lithium-ion ultracapacitors, IEEE Journal of Emerging and Selected Topics in Power Electronics 3 (2) (2015) 395–404.

[53] M. Michalczuk, L. M. Grzesiak, B. Ufnalski, Experimental parameter identification of battery-ultracapacitor energy storage system, in: Industrial Electronics (ISIE), 2015 IEEE 24th International Symposium on, IEEE, 2015, pp. 1260–1265.

[54] X. del Toro García, C. de la Cruz, P. Roncero-Sánchez, A. Parreño, A small-scale hybrid energy storage system for modeling and control validation purposes, in: Industrial Electronics Society, IECON 2015-41st Annual Conference of the IEEE, IEEE, 2015, pp. 003702–003707.

[55] N. Jayalakshmi, D. Gaonkar, V. Kumar, R. Karthik, Battery-ultracapacitor storage devices to mitigate power fluctuations for grid connected pv system, in: India Conference (INDICON), 2015 Annual IEEE, IEEE, 2015, pp. 1–6.

[56] D. Pavković, M. Cipek, M. Hrgetić, M. Mance, Dc bus feed-forward/feedback control for evs with battery/ultracapacitor energy storage system, in: Smart Technologies, IEEE EUROCON 2017-17th International Conference on, IEEE, 2017, pp. 318–323.

[57] P. Piórkowski, Zastosowanie superkondensatorów do rozruchu silników spalinowych w trudnych warunkach [Application of supercapacitors to start combustion engines in tough conditions], Logistyka (3) (2015) 3918–3927, in Polish.

[58] P. Piórkowski, The influence of ultracapacitors on the stability of primary source's operation, Przegląd Mechaniczny (4) (2013) 38–42.

[59] A. Khaligh, Z. Li, Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art, IEEE transactions on Vehicular Technology 59 (6) (2010) 2806–2814.

[60] A. Chu, P. Braatz, Comparison of commercial supercapacitors and high-power lithium-ion batteries for power-assist applications in hybrid electric vehicles: I. initial characterization, Journal of power sources 112 (1) (2002) 236–246.

[61] A. Burke, Cost-effective combinations of ultracapacitors and batteries for vehicle application, in: Proceeding AABC 2002, Las Vegas, 2002.

[62] T. Bartley, Ultracapacitors and batteries for energy storage in heavy-duty hybrid-electric vehicles, in: presented at the 22nd Int. Battery Seminar Exh., Fort Lauderdale, FL, 2005.

[63] R. M. Schupbach, J. C. Balda, The role of ultracapacitors in an energy storage unit for vehicle power management, in: Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th, Vol. 5, IEEE, 2003, pp. 3236–3240.

[64] J. Van Mierlo, P. Van den Bossche, G. Maggetto, Models of energy sources for ev and hev: fuel cells, batteries, ultracapacitors, flywheels and engine-generators, Journal of power sources 128 (1) (2004) 76–89.

[65] A. Kuperman, I. Aharon, A. Kara, S. Malki, A frequency domain approach to analyzing passive battery–ultracapacitor hybrids supplying periodic pulsed current loads, Energy conversion and management 52 (12) (2011) 3433–3438.

[66] N. M. Ismail, M. K. Mishra, Control and operation of unified power quality conditioner with battery-ultracapacitor energy storage system, in: Power Electronics, Drives and Energy Systems (PEDES), 2014 IEEE International Conference on, IEEE, 2014, pp. 1–6.

[67] F. Guo, Y. Ye, R. Sharma, A modular multilevel converter based battery-ultracapacitor hybrid energy storage system for photovoltaic applications, in: Power Systems Conference (PSC), 2015 Clemson University, IEEE, 2015, pp. 1–6.

[68] F. Guo, R. Sharma, A modular multilevel converter with half-bridge submodules for hybrid energy storage systems integrating battery and ultracapacitor, in: Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE, IEEE, 2015, pp. 3025–3030.

[69] R. Gu, P. Malysz, A. Emadi, A novel battery/ultracapacitor hybrid energy storage system analysis based on physics-based lithium-ion battery modeling, in: Transportation Electrification Conference and Expo (ITEC), 2015 IEEE, IEEE, 2015, pp. 1–6.

[70] A. Chmielewski, S. Radkowski, Prosumer on the energy market: case study, Zeszyty Naukowe Instytutu Pojazdów-Proceedings of the Institute of Vehicles 102 (2015) 23–29.

[71] J. García-Villalobos, I. Zamora, J. San Martín, F. Asensio, V. Aperribay, Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches, Renewable and Sustainable Energy Reviews 38 (2014) 717–731.

[72] J. D. Kim, M. Rahimi, Future energy loads for a large-scale adoption of electric vehicles in the city of los angeles: Impacts on greenhouse gas (ghg) emissions, Energy Policy 73 (2014) 620–630.

[73] Polskie Sieci Elektroenergetyczne, accessed 26.02.2017.
URL `http://www.pse.pl/index.php?dzid=14&did=2477`

[74] International Energy Agency, accessed 15.10.2017.
URL `https://www.iea.org/`

[75] Ministerstwo Energii - Plan Rozwoju Elektromobilności w Polsce, accessed 08.10.2017.
URL `http://bip.me.gov.pl/node/26453`

[76] Nissan Leaf, in Polish.
URL `https://www.nissan.pl/pojazdy/nowe-pojazdy/leaf/wydajno%C5%9B%C4%87-akumulator.html`

[77] W. Jing, C. H. Lai, S. H. W. Wong, M. L. D. Wong, Battery-supercapacitor hybrid energy storage system in standalone dc microgrids: a review, IET Renewable Power Generation 11 (4) (2016) 461–469.

[78] E. Jankowska, K. Kopciuch, M. Błażejczak, W. Majchrzycki, P. Piórkowski, Badanie połączenia akumulatora ołowiowego z superkondensatorem jako układu hybrydowego do rozruchu silnika spalinowego [study on combination of lead acid bettery with supercapacitors into a hybrid system to start combustion engine], Komel Maszyny Elektryczne - Zeszyty Problemowe 114 (2) (2017) 107–114, in Polish.

[79] Y. Lai, S. Du, L. Ai, L. Ai, Y. Cheng, Y. Tang, M. Jia, Insight into heat generation of lithium ion batteries based on the electrochemical-thermal model at high discharge rates, International Journal of Hydrogen Energy 40 (38) (2015) 13039–13049.

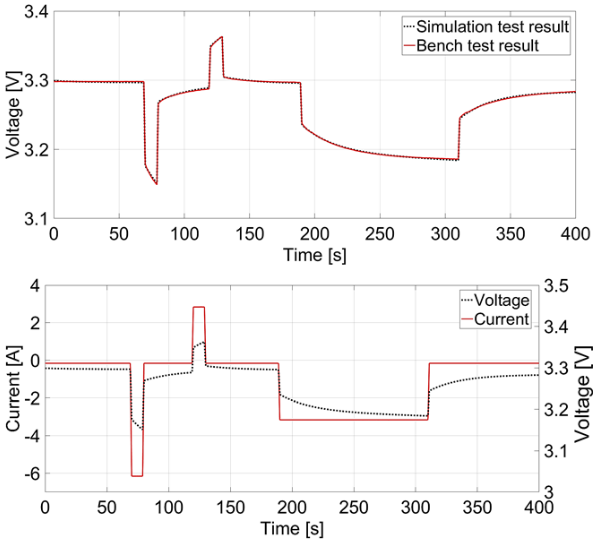
[80] J. Li, Y. Cheng, M. Jia, Y. Tang, Y. Lin, Z. Zhang, Y. Liu, An electrochemical–thermal model based on dynamic responses for lithium iron phosphate battery, Journal of Power Sources 255 (2014) 130–143.

[81] Y. Saito, M. Shikano, H. Kobayashi, Heat generation behavior during charging and discharging of lithium-ion batteries after long-time storage, Journal of Power Sources 244 (2013) 294–299.

[82] Q. Wang, Q. Sun, P. Ping, X. Zhao, J. Sun, Z. Lin, Heat transfer in the dynamic cycling of lithium–titanate batteries, International Journal of Heat and Mass Transfer 93 (2016) 896–905.

[83] L. Saw, Y. Ye, A. Tay, Electro-thermal characterization of lithium iron phosphate cell with equivalent circuit modeling, Energy Conversion and Management 87 (2014) 367–377.

[84] A. Chmielewski, P. Piórkowski, R. Gumiński, K. Bogdziński, J. Możaryn, Model-based research on ultracapacitors, in: Advances in Intelligent Systems and Computing, International Conference Automation, 22nd Conference on Automation – Innovations and Future Perspectives, Springer, 2018, in Print.



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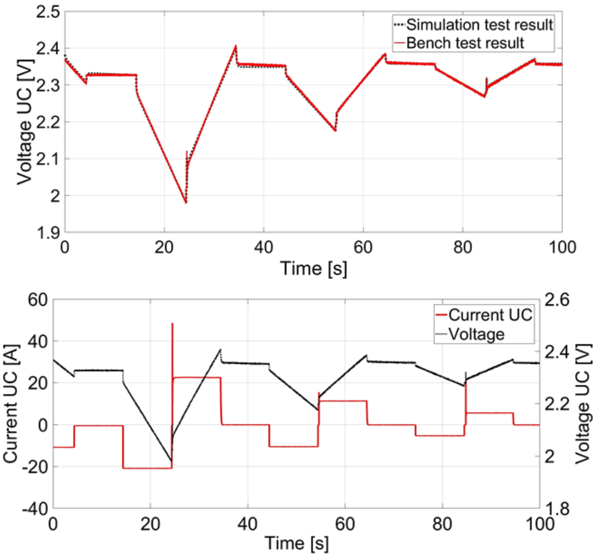
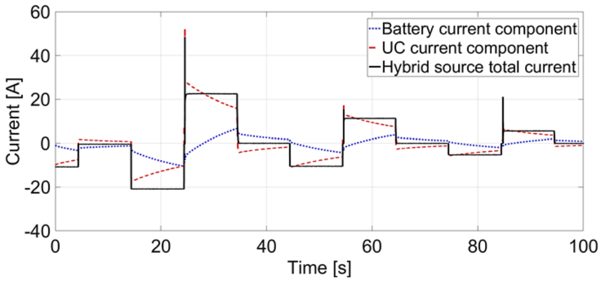
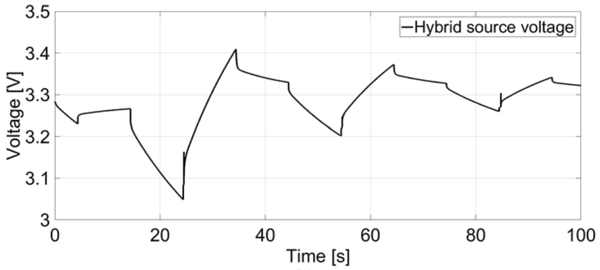


(b)

Figure 8: Comparison simulation test result and bench test result for: a) LiFePO$_4$ battery, b) ultracapacitor MAXWELL BMOD0058 E016 B02 in specific load current cycle



(a)



(b)

Figure 9: Simulation results for hybrid energy storage: ultracapacitor-LiFePO4 battery for: a) current, b) voltage, respectively