Simulations and Experimental Investigations of an Impulse System for Battery Charging in Electric Bike

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Abstract The paper presents simulation results of a push–pull converter allowing energy recovery back to two Sealed Lead-Acid 7 Ah, 12 V serially connected batteries. The converter is powered by three phases of induced voltage from a BLDC motor mounted in the front wheel hub of an electric bike. In a steady state, computed current and voltage waveforms were verified experimentally in the measurement stand on the basis of registered waveforms.

Keywords BLDCM · Generator · Battery charging · Electric bike · Control system

1 Introduction

Utilization of electric bicycles as means of personal transportation, especially in cities, is of great importance from the point of view of ecology and health benefits [1–5]. Replacing internal combustion powered vehicles by classic or electric bikes utilizing maintenance-free batteries reduces greenhouse gas emissions.

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Electrically powered vehicles can, for example, be topped-up when there is an oversupply in the power grid. At the same time, electric bikes can be considered a form of distributed energy storage [6–8].

Most imported electric bikes in Poland lack advanced control system able to efficiently charge the batteries during generative operation of the electric motor [2]. Such systems in electric bicycles could be used in a variety of situations such as riding through the terrain with varying levels of elevation, during braking or pushing the bike while dismounted.

This article describes an attempt by the authors to develop a control system for a P_N = 125 W and 24 V brushless direct current motor (BLDCM) placed in the electric bike's front wheel hub. During generative operation of the BLDC motor, the control system allows to charge a set of two serially connected HV7, 12 V and 7 Ah Seal Lead-Acid (SLA) batteries. The article also presents a simulation study in MATLAB-Simulink and experimental investigations of the BLDC motor performed on a measurement stand.

2 Simulation Model

The most important part, both during charging and discharging, of the BLDCM control system analyzed in this paper are batteries. Batteries' parameters during charging and discharging change nonlinearly. The most important parameters used to model batteries are the effective internal resistance (influenced by electrolyte and electrode type) and voltage. A method of modeling the battery's behavior during operation is quite complex, as it requires to determine a number of coefficients [9–12]. Battery manufacturers provide only the most basic parameters such as: voltage, capacity, or start-up current. Internal resistance or supply voltage characteristics as a function of current and charge are omitted.

Creation of an appropriate simulation model of a BLDC motor during generative operation makes it possible to determine the optimal value of the charging current, instantaneous current, and voltage waveforms and power losses in the individual components of the system consisting of the BLDC motor, rectifier, push–pull converter, and the battery pack. Therefore, in this article, the model of the battery's behavior in MATLAB-Simulink utilizing SimPowerSystem toolbox, during BLDCM's generative operation, is presented. SimPowerSystem toolbox provides multiple battery models such as (for 2010b version): Lead-Acid, Lithium-Ion, Nickel-Cadmium, and Nickel-Metal-Hydride. Figure 1 shows a system schematic which allows one to simulate the process of battery charging from a voltage source —BLDC motor during generative operation.

In order to carry out simulation tests of the charging process in the system as in Fig. 1, it is necessary to know the source voltage and internal resistance of the tested batteries. The article assumes that the battery is 90% charged and it is modeled by defining a nonlinear internal resistance and the nonlinear voltage source, which depend only on the value of current. Figure 2 shows the

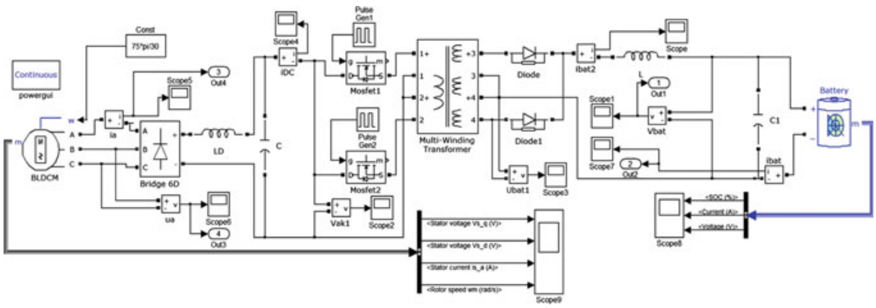

Fig. 1 Schematic of a system used for simulation of a battery charging process

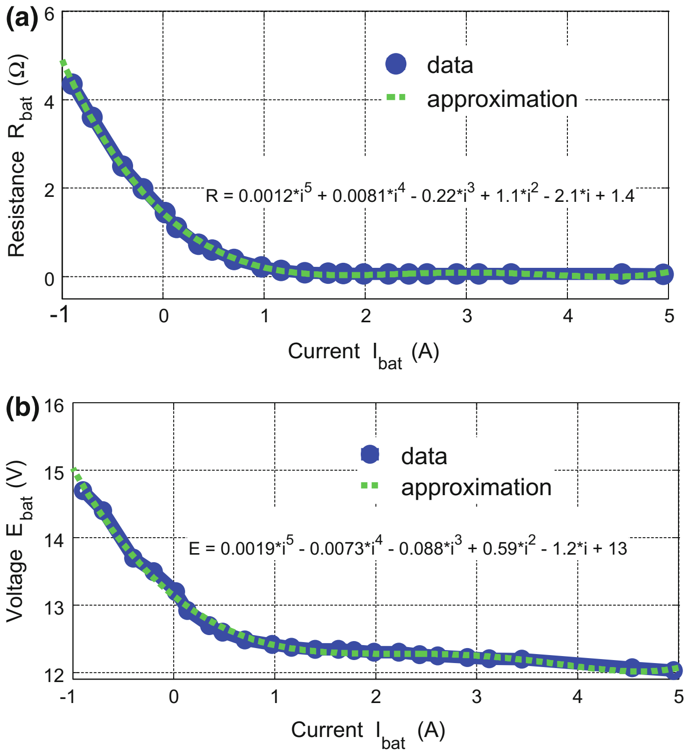

Fig. 2 **a** internal resistance and **b** source voltage characteristics of the 7 Ah, 12 V battery as a function of load current

characteristics of changes in the internal resistance of a Sealed Lead-Acid 7 Ah, 12 V (90% charged battery).

The characteristics shown in Fig. 2 were obtained experimentally by performing a very short load current measurements using a differential method. The study was

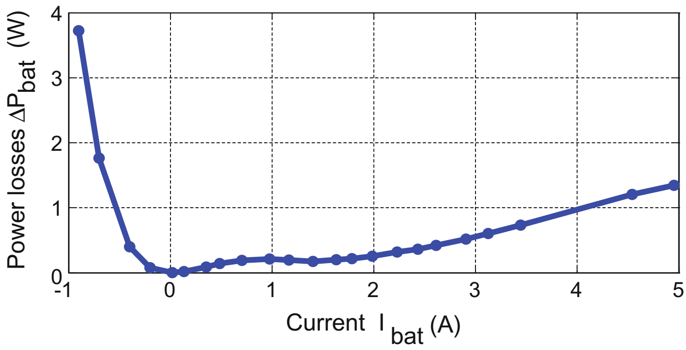

Fig. 3 Power losses ΔP_{bat} of a single battery

performed for small current increments around the base currents shown in Fig. 2 (data points). After each voltage and current measurement, the battery was disconnected for a time needed for the source voltage E_{bat} to return to the initial state E_{bat0}.

A similar procedure was used for determination of the characteristics during battery charging. Positive current in Fig. 2 indicates that the BLDC motor is being supplied from the battery, while negative current indicates the charging process. From the characteristics presented in Fig. 2, it is possible to determine power losses ΔP_{bat}, which occur during the battery charging process (negative current) or while the motor is being supplied (positive current).

From the power loss characteristics in Fig. 3,it follows that during the battery charging process, as a result of an increase in its internal resistance, applying current greater than 0.1 Q (where Q is the battery's capacity—7 Ah) results in greater power losses than for the same current when motoring.

3 Simulation Results

Figures 4 and 5 show waveforms of i_{bat} charging current, u_{bat} battery voltage as well as u_a phase voltage and i_a phase current of the BLDCM, while charging two batteries in a set, calculated from the model shown in Fig. 2.

The generative operation model of the BLDC motor consisting of a push–pull converter and battery set makes it possible to determine instantaneous values of voltage and current waveforms.

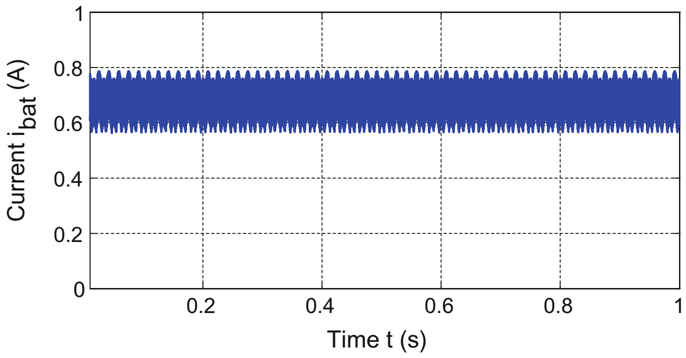

Fig. 4 Waveforms calculated on the basis of the model from Fig. 2 of battery charging current i_{bat}

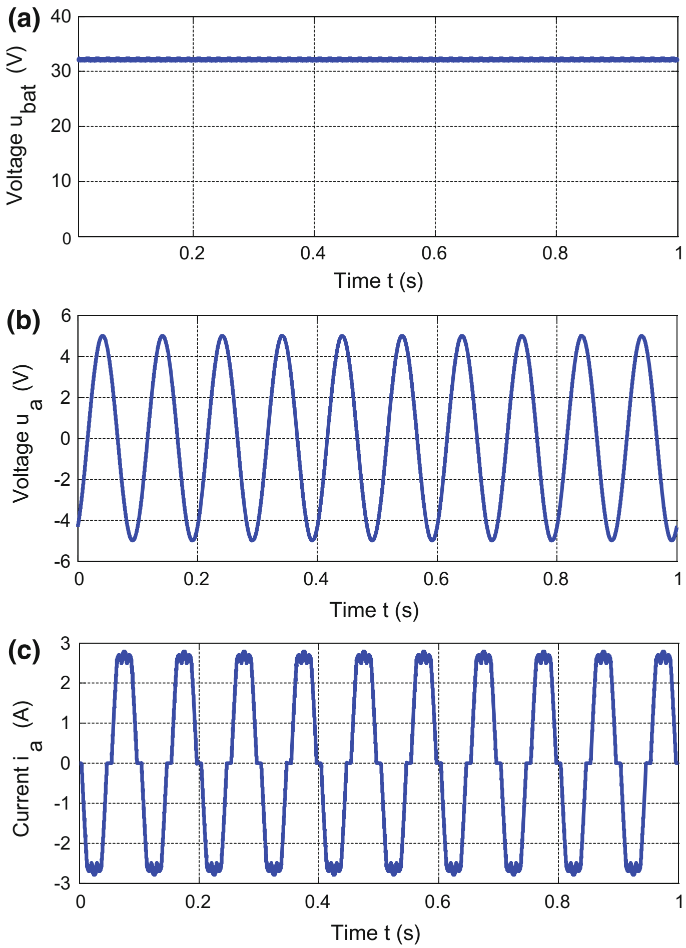

Fig. 5 Waveforms calculated on the basis of the model from Fig. 2 of **a** battery voltage u_{bat}, **b** u_a motor phase voltage and **c** i_a phase current of the BLDC motor

4 Results of Experimental Investigations

Figure 6 presents a simplified schematic of the power and control parts of the impulse circuit used for energy recovery from BLDC motor's phase winding induced voltages.

The converter presented in Fig. 6 operates in push–pull configuration and is used to boost the voltage in order to charge two 7 Ah, 12 V serially connected batteries. The charging process starts when BLDC motor's induced phase voltages reach 1.6 V. The charging current values are regulated by potentiometers and PWM circuit in the range between 0 and 0.7 A and set to reach 0.1 Q value in the finishing part of the charging process. The charging current can be arbitrarily changed depending on the rotational speed of the BLDC which corresponds to induced voltage values. The control part of the impulse circuit was implemented using Silicon SG2525A integrated circuit [13].

Figure 7 presents an overview of examined BLDC motor (operating as a generator) and other important devices incorporated into the measurement stand.

The measurement stand (Fig. 7) consists of the following:

- BLDC motor rated at 125 W, $U_N = 24$ V, $n_N = 120$ rpm, mounted in the electric bike's front wheel hub;

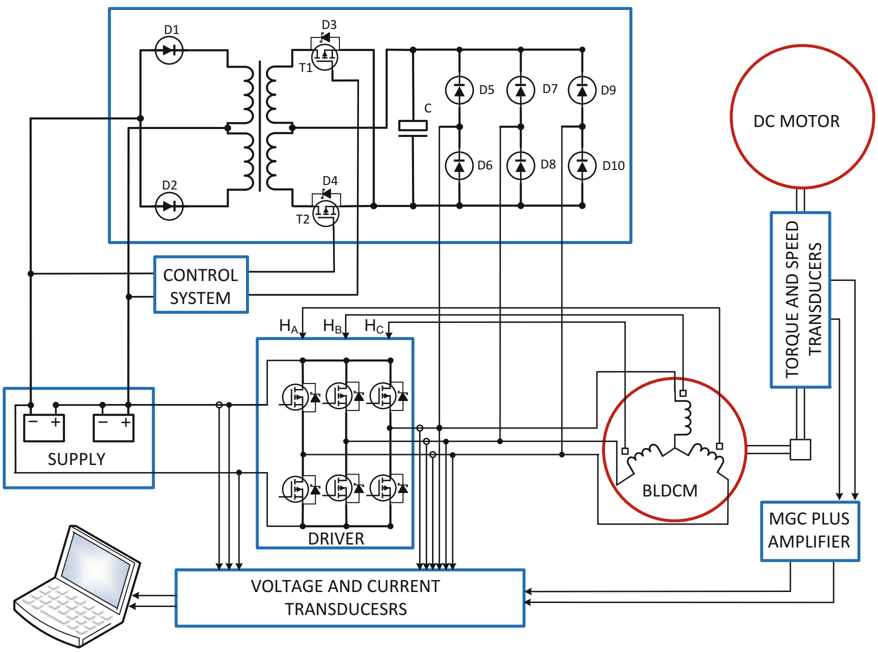

Fig. 6 Simplified schematic of the power and control parts of the impulse circuit used for energy recovery

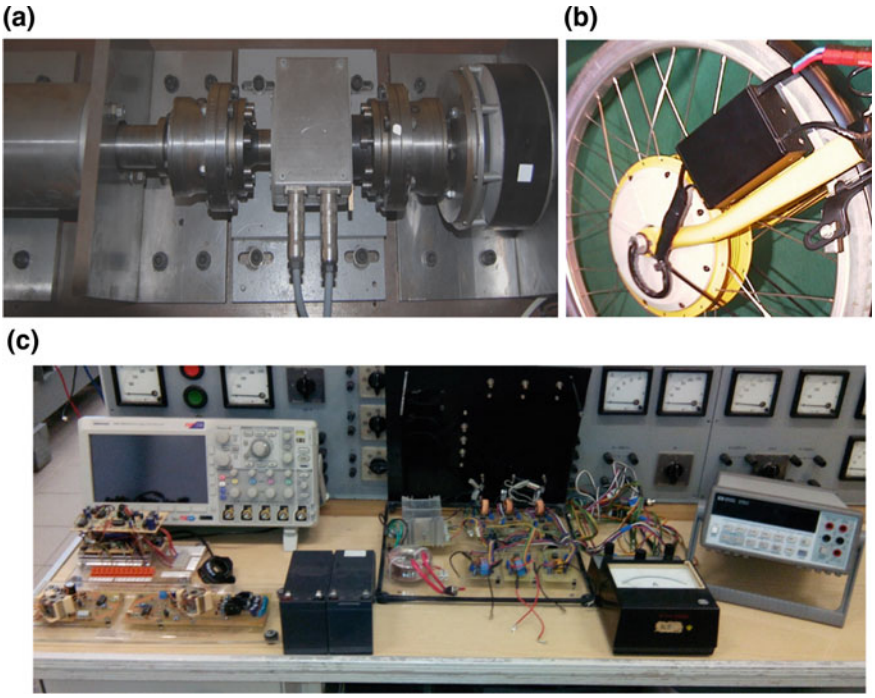

Fig. 7 An overview of **a** examined BLDC motor operating as a generator, **b** BLDC motor mounted in the front wheel hub, **c** the most important tools utilized in the measurement stand

- DC motor driving the BLDC motor via a torque measuring shaft made by Hottinger Baldwin Mestechnik;
- Six transducers set used for instantaneous value measurement of voltages and currents, utilizing A3515LUA Hall-effect sensor described in [14, 15];
- Digital mixed signal oscilloscope MSO 3014;
- Two SLA gel batteries KOBE HV7 12 V, 7 Ah;
- BLDC motor control system (with utilization of PICAXE microcontroller) and push–pull converter used for energy recovery (with utilization of SG3525 Pulse Width Modulator Control Circuit [13]).

The registered waveforms (with utilization of the voltage and current transducers set) of the charging current i_{bat} and u_{bat} battery voltage are shown in Fig. 8. The phase voltage u_a and i_a phase current of the BLDC motor during the charging process are presented in Fig. 9. The last one second of the registered waveforms (Figs. 8 and 9) correspond to the simulation tests presented in Fig. 4.

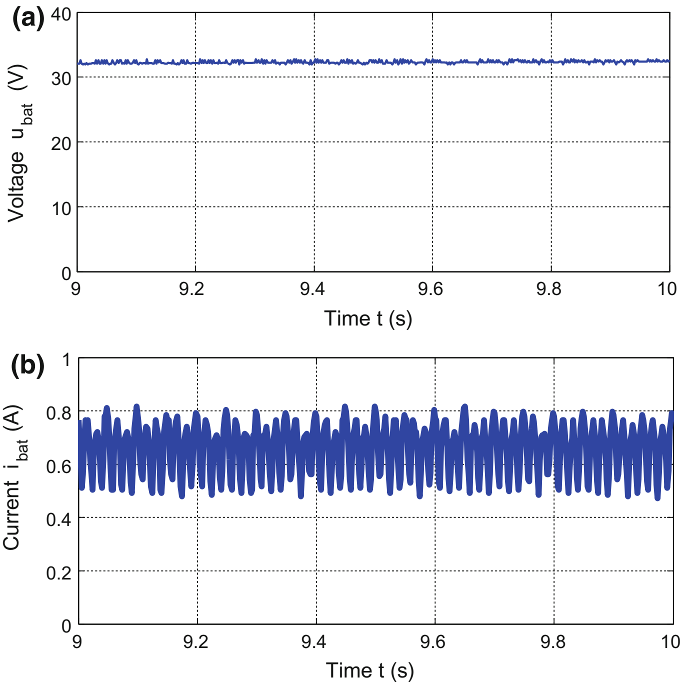

Fig. 8 Registered waveforms of **a** battery charging current i_{bat}, **b** battery voltage u_{bat}

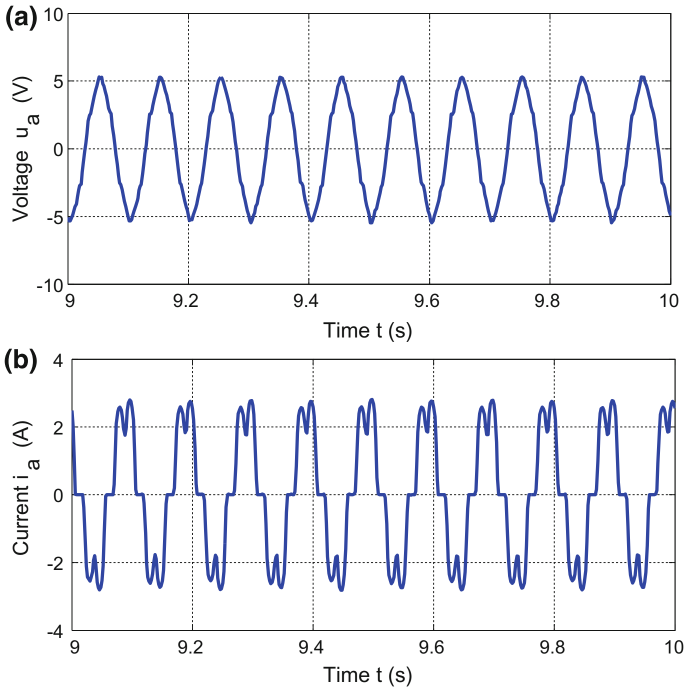

Fig. 9 Registered waveforms of BLDC motor's **a** phase voltage, **b** phase current

5 Conclusion

The paper presents a simple model of the impulse system for battery charging in electric bike powered by a BLDC motor during the generative operation. The model employs the calculation of internal resistance and source voltage characteristics obtained experimentally by performing a very short load current measurements using a differential method. The presented system makes it possible to conduct simulations of instantaneous values of voltages and currents during Sealed Lead-Acid battery charging. During the generative operation the direction of power transfer changes. The power produced by the BLDC motor constitutes an input power.

Results from the presented simulation model correlate favorably with experimental investigation.

Future research focus could shift to include a system for fully regenerative braking, different battery technologies such as Li-ion or even fuel cell technology [16].

References

1. Thiyagarajan, V., Sekar, V.: Controlling of brushless dc motors in electric bicycles using electronic based circuit with 8-bit microcontroller. Int. J. Eng. Sci. Emerg. Technol. (IJESET) **4**(1), 26–34 (2012)
2. Nadolski, R., Ludwinek, K., Staszak, J., Jaskiewicz, M.: Utilization of BLDC motor in electrical vehicles. Electr. Rev. **4**, 180–186 (2012)
3. Zahedi, A.: Electric vehicle as distributed energy storage resource for future smart grid. In: 22nd Australasian Universities Power Engineering Conference (AUPEC), pp. 1–4, September 2012
4. Spagnol, P., et al.: A full hybrid electric bike: how to increase human efficiency. In: Proceedings of IEEE American Control Conference, pp. 2761–2766, June 2012
5. Corno, M., Berretta, D., Spagnol, P., Savaresi, S.M.: Design, control, and validation of a charge-sustaining parallel hybrid bicycle. IEEE Trans. Control. Syst. Technol. **24**(3), 817–829 (2016)
6. Muetze, A., Tan, Y.C.: Electric bicycles—a performance evaluation. IEEE Ind. Appl. Mag. **13**(4), 12–21 (2007)
7. Heydt, G.T.: The next generation of power distribution systems. IEEE Trans. Smart Grid **1**(3), 225–235 (2010)
8. Taylor, J., Maitra, A., Alexander, M., Brooks, D., Duvall, M.: Evaluation of the impact of plug-in electric vehicle loading in distribution system operations. In: Proceedings of IEEE Power and Energy Society General Meeting, pp. 1–6, July 2009
9. Barsali, S., Ceraolo, M.: Dynamical models of lead–acid batteries: implementation issues. IEEE Trans. Energy Convers. **17**(1), 16–23 (2002)
10. Schweighofer, B., Raab, K.M., Brasseur, G.: Modeling of high power automotive batteries by the use of an automated test system. IEEE Trans. Instrum. Meas. **52**(4), 1087–1091 (2003)
11. Tian, S., Hong, M., Ouyang, M.: An experimental study and nonlinear modeling of discharge I-V behavior of valve-regulated lead-acid batteries. IEEE Trans. Energy Convers. **24**(2), 452–458 (2009)

12. Ceraolo, M.: New dynamical models of lead–acid batteries. IEEE Trans. Power Syst. **15**(4), 1184–1190 (2000)
13. SG3525 Pulse Width Modulator Control Circuit. Datasheet, January 2005, Rev. 5
14. Ludwinek, K.: Measurement of momentary currents by Hall linear sensor. Prz. Elektroteh. **10**, 182–187 (2009)
15. Ludwinek, K.: Practical application of a linear Hall-effect sensor in contactless measuring of current temporary values. Int. Rev. Electr. Eng. **8**(5), 1631–1640 (2013)
16. Chang, Y.T., Chen, P.C., Liu, Y.C., Chang, S.B.: The development of the PEM fuel cell power system for the electric bike. In: 9th World Congress on Intelligent Control and Automation (WCICA), pp. 1041–1046, June 2011