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MODELLING AND SIMULATION OF REPEATED CHARGING/DISCHARGING CYCLES FOR SELECTED NICKEL-CADMIUM BATTERIES

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Abstract

The main aim of the paper is to present a developed methodology of simulation of the energy efficiency of a selected energy storage unit. The authors focused their actions on batteries that could be the base for an energy storage system possible to apply in a modernized hybrid-shunting locomotive. Three different nickel-cadmium batteries were selected as representatives for the study. Simulation was focused on repeated cycles of charging and discharging the batteries. The simulation model generally consists of three main components: a specified load cycle, a dynamic model of the DC electrical machine and a model of the Ni-Cd battery. The input data for the battery model is based mostly on the parameters provided by the manufacturer data sheets. However, an internal resistance had to be measured for each battery. Conducted simulations provided information about the electromotive force, state of charge, an average efficiency of the battery, as well as the temperature changes during the cycle. The proposed approach to the battery simulation can be also applied for the loading cycles similar to those that occur during the actual operation of the locomotive. The current study is a part of the project focused on modernization of the diesel-electric shunting locomotive to the hybrid one.

Keywords: *Dynamic simulation, charging/discharging cycle, Matlab Simulink*

1. Introduction

In recent times, the significant growth of interest in hybrid vehicles can be observed. Development of such vehicle entails many problems. An appropriate design of the energy storage system is the most notable of these problems. Specificity of work of the energy storage system and the batteries themselves depends largely on the purposes of the vehicle use. Designers have to remember that not every type of battery can be used in hybrid vehicles. Therefore, it is necessary to determine the operating conditions for the batteries. Computer simulations can be one of the method that allows the designers to verify whether the selected battery type can be applied in considered solution [1]. Moreover, the typical batteries usually have a certain operating temperature, which retains their parameters, and an appropriate cooling system has to be designed to ensure the correct battery operation. Presented studies are a part of the project focused on modernization of a classic diesel-electric shunting locomotive. All components above the locomotive frame e.g. diesel engine, generator could be replaced by new components – smaller and more eco-friendly diesel engine, higher-class generator and alternative power sources like batteries. Therefore, it is necessary to simulate batteries intended for a use the in-modernized locomotive in different load conditions.

2. Description of the simulation model

The simulation model depicted in Fig. 1 was developed in Matlab Simulink computer code. It consists of the main components listed below:

1. A specified load cycle (Fig. 2) including a speed increase phase, a constant speed phase and a speed decrease phase; phases are cyclically repeated until the complete discharge of battery; a speed extortion was applied to determine the load cycle.
2. A dynamic model of the DC electric machine that operates with the batteries cyclically charging (generator operation mode) and discharging (motor operation mode) them.
3. A model of the nickel-cadmium battery in three basic configurations with different nominal capacities (220 Ah, 140 Ah and 190 Ah).

Simulation model of the battery was developed because of mathematical relations taken from [2-5]. Electromotive force of a single cell can be written in the following form:

$$E(k) = 0.9 + 0.3k\,, \tag{1}$$

where k is the battery state of charge, (SOC) defined as a ratio of usable capacity to the nominal capacity:

$$k = SOC = Q_u / Q_{nom}\,, \tag{2}$$

Usable capacity can be calculated according to the following relation [2]:

$$Q_u = c_\tau(\tau) \cdot \eta_{acc}(i_b, \tau) \cdot Q_{nom} \pm \int_0^t i_b(t)\,\mathrm{d}t\,, \tag{3}$$

where i_b is charging or discharging current of a battery, depending on the sign before the integral, Q_{nom} is the nominal capacity, $c_\tau(\tau)$ is the temperature rate of change of the nominal capacity, and η_{acc} is the stored energy ratio equal to:

$$\eta_{acc} = \left(\frac{i_b(t)}{I_{nom}}\right)^{-\beta}, \tag{4}$$

where: I_{nom} is nominal current for the battery, and β is the index of the stored energy ratio.

The terminal voltage during the battery charge/discharge can be expressed as follows:

$$U(t,k) = E(k) \pm i_b(t) \cdot R_{int}\,, \tag{5}$$

where R_{int} is internal resistance of a single cell.

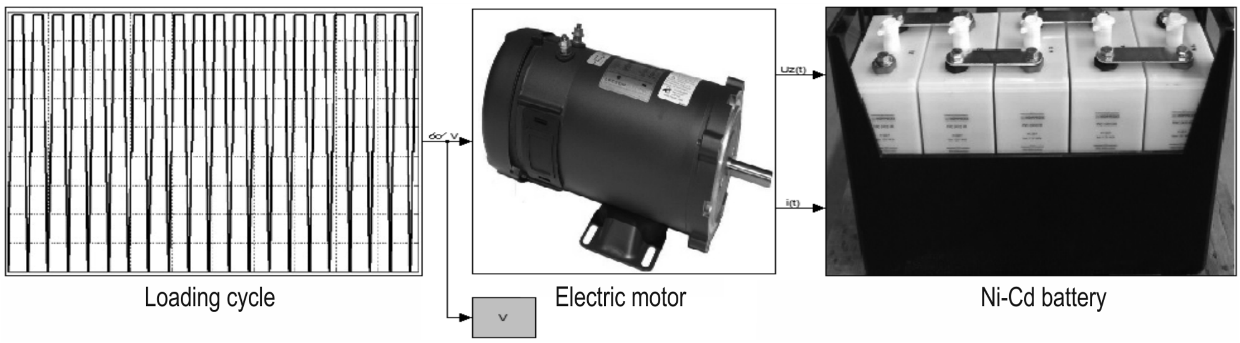

Fig. 1. An ideal scheme of the simulation model developed in Matlab Simulink for a specified loading cycle

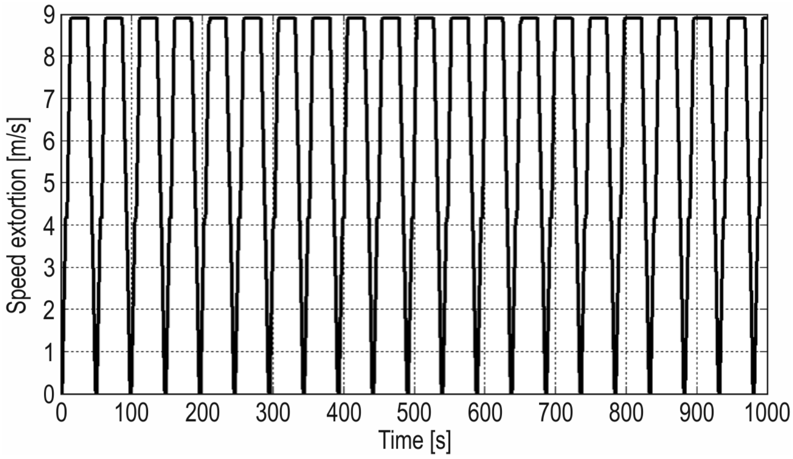

Fig. 2. A specified loading cycle applied as a speed extortion for the simulation

Three different batteries were simulated during the studies. Two of them were manufactured by Hoppecke, whereas the third one – by the Saft company. Since technical parameters provided by data sheets were not adequate, it was necessary to conduct an experimental test of internal resistance. Current and voltage were measured using Fluke 45 Multimeter. The obtained results are provided in Tab. 1. Voltage measurement for KH 220 P and KX 140 P batteries was performed either directly at the battery terminals, but on the connector. Moreover, the measurement was carried out for a packet of 5 cells, whereas for the KH 190 P battery, a single cell was tested. Nominal cell voltage for all three batteries was equal to 1.2 V. Required changes of the temperature in the simulation model (Tab. 1) were taken from the results of an experimental test of the batteries carried out within the framework of the project in order to assess their physical parameters and energy efficiency. Tab. 2 provides the input data for the dynamic model of the DC electrical machine and the powered mass, which is a load for batteries during the cycle.

Tab. 1. Internal resistance R_{int} of single cell of considered Ni-Cd batteries

Battery type (Manufacturer)	FNC 2403 HR (Hoppecke)	KFX 140 RP (Hoppecke)	SRX 1900 P (Saft)
Designation / Nominal capacity, Q_{nom} [Ah]	KH 220 P / 220	KX 140 P / 140	KH 190 P / 190
Internal resistance, R_{int} [Ω]	0.0469	0.0466	0.0195
ΔT (for I = 5C), [°C]	12	2	6

Tab. 2. Input data for the dynamic model of the electrical machine and the powered mass

Electrical machine	Nominal current [A]	125
	Winding resistance [Ω]	0.1
	Inductance [H]	0.0055
	Electric constant [V·s/rad]	0.238
	Mechanical constant [N·m/A]	0.238
	Nominal torque [N·m]	60
	Nominal / Maximum speed [rev/min]	3600 / 5200
	Moment of inertia of the rotor [kg·m^2]	0.031
Powered mass	Mass [kg]	50
	Dynamic radius of the wheel [m]	0.26
	Moment of inertia of the wheel [kg·m^2]	0.46
	Efficiency of transmission [%]	97

Summing up, mathematical formulas applied in the simulation model allow analysis of following parameters during the given cycle:

- terminal voltage of the battery U_t,
- state of charge *SOC*,
- charge/discharge current $i(t)$,
- electromotive force $E(SOC)$,
- battery temperature $T_b = f[i(t)]$,
- stored energy ratio η_{acc} (battery efficiency).

3. Results of simulation

Selected results of the simulation are depicted in the form of time histories. In some cases, amplification of the load cycle was applied, e.g. amplification 10× means that the charge/discharge current was increased 10-times. It reduces duration of the simulation and allows observation of higher dynamic of the model.

Changes in electromotive force for all three considered batteries are presented in Fig. 3a. As can be seen in the figure, the decrease in the electromotive force is closely related to the nominal capacity of the battery. The same situation occurs in the case of changes in SOC (State of Charge), see Fig. 3b. Complete discharge occurs after 1040, 870 and 620 seconds for the 220 Ah, 190 Ah and 140 Ah battery, respectively. Practical conclusion is that increasing the cell capacity increases operating time. It provides valuable information while selecting the traction battery for the hybrid vehicle.

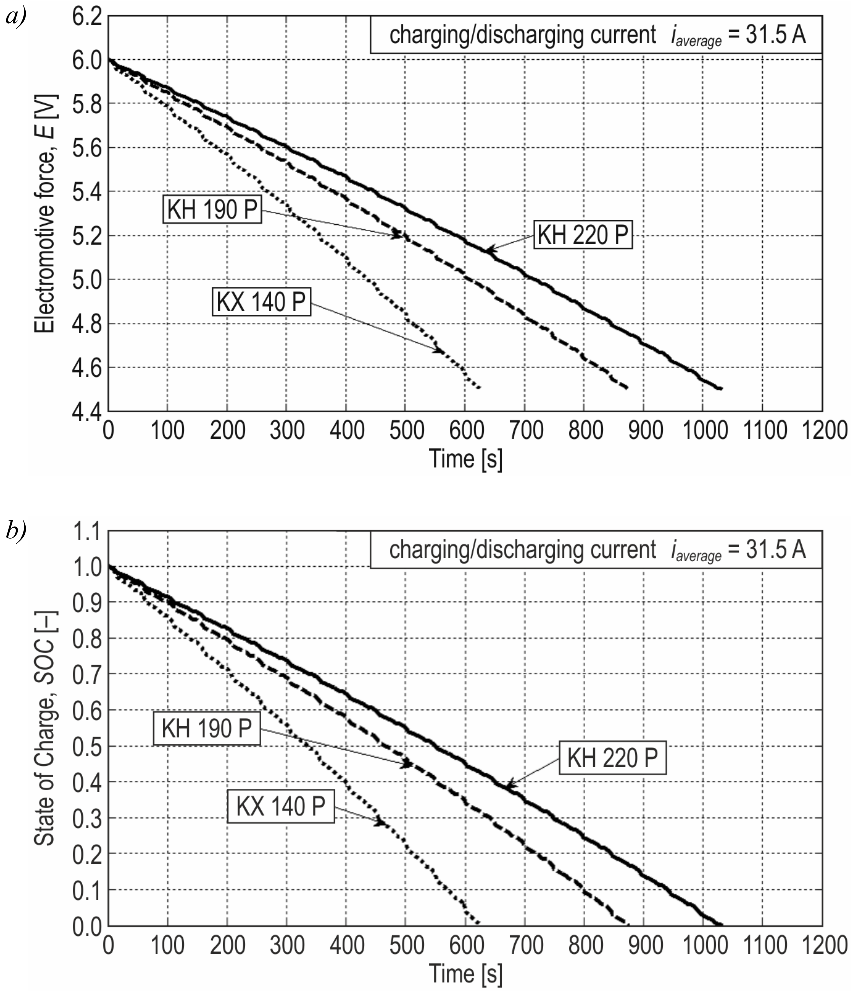

Fig. 3. Time history of the electromotive force (a) and the state of charge (b) for all considered batteries

Figure 4 shows changes in the stored energy ratio for the KH 220 P, KX 140 P and KH 190 P battery. This parameter can be also considered as battery efficiency. It should be noticed, that the efficiency exceeds 1 in some moments of the loading cycle. It is caused by the imperfection in mathematical formulas used in calculation. Moreover, negative values of the efficiency are related to the change in the direction of power flow in the system. Average efficiency for all batteries ranged from 0.50 to 0.65. Obtained battery efficiency is similar to the values found in the literature [3].

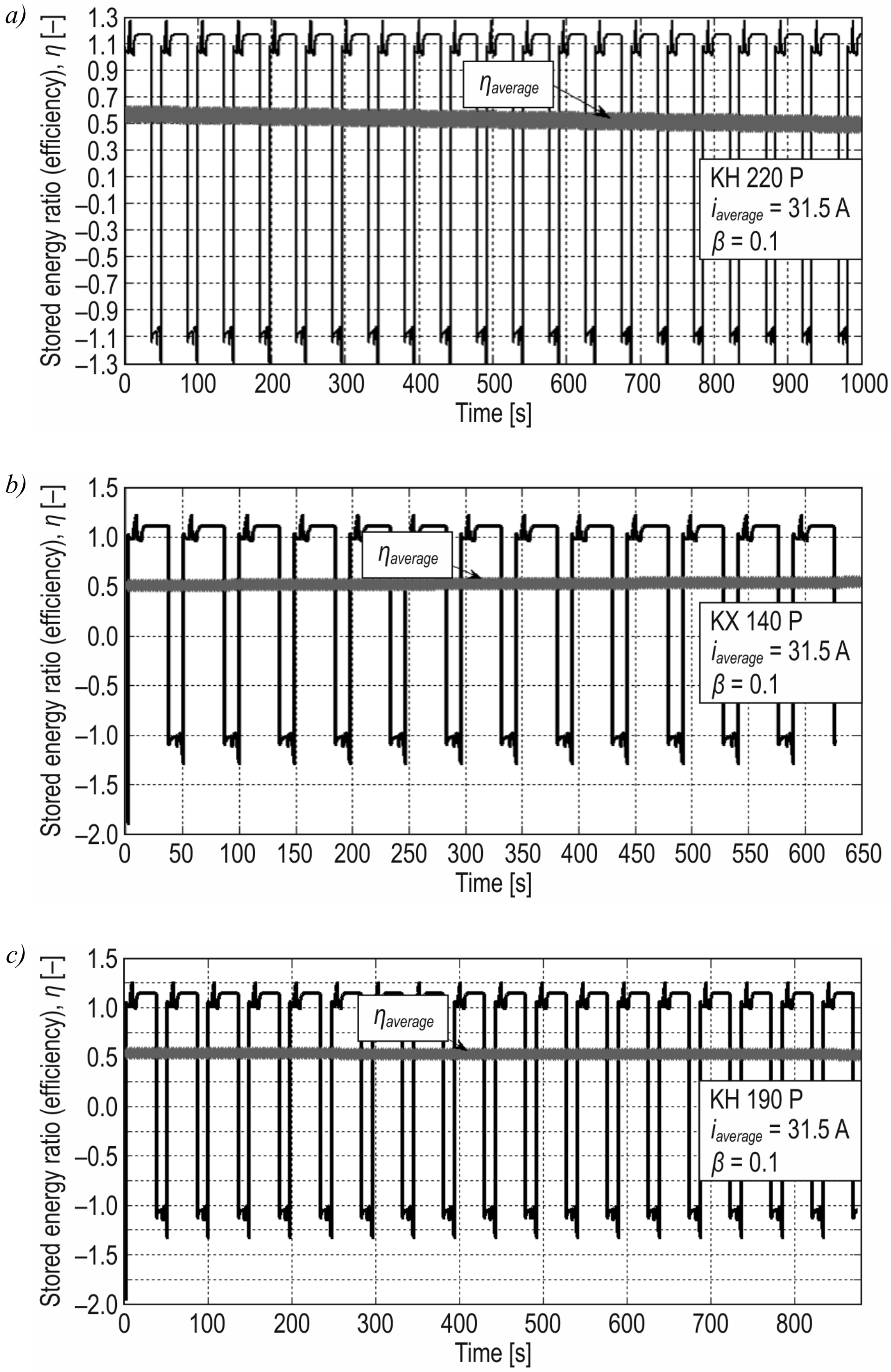

Fig. 4. Changes in the storage energy ratio for the batteries under consideration: a) KH 220 P, b) KX 140 P, c) KH 190 P; 10× amplification of the loading cycle was applied

Changes in charging and discharging current are presented in Fig. 5. It can be observed that waveforms differ from each other only in simulation time. It informs about the operating time of the battery to its total discharge and it results from the usable capacity of the battery.

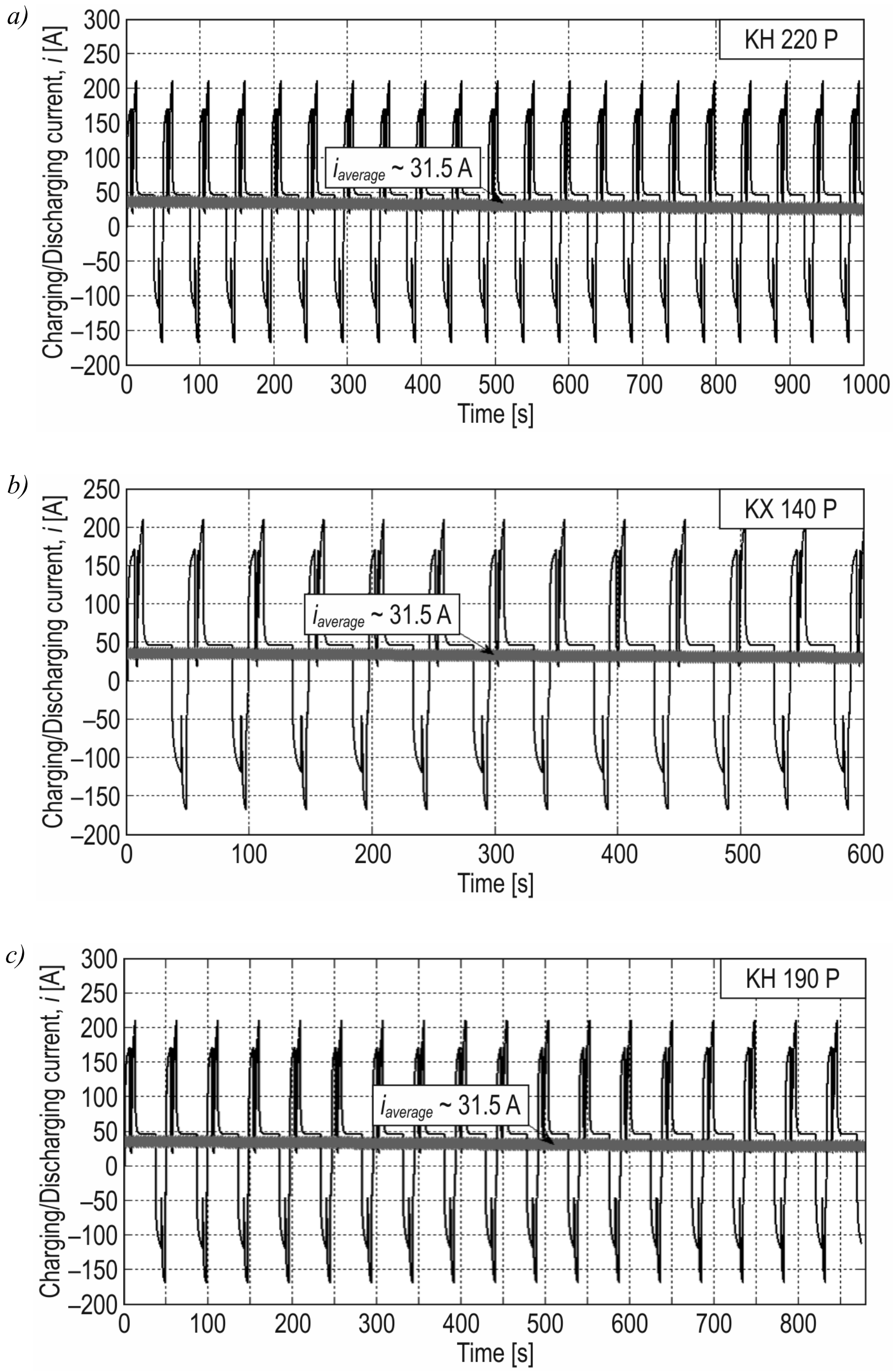

Fig. 5. Changes in charging/discharging current for the batteries under consideration: KH 220 P (a), KX 140 P (b), KH 190 P (c); 10× amplification of the loading cycle was applied

Changes in the terminal voltage are depicted in Fig. 6. The voltage oscillations are lower for the KH 190 P battery than for two others probably due to few-times lower internal resistance. Therefore, it can be concluded that internal resistance of the cell is a decisive parameter for voltage oscillation. Higher internal resistance of the cell increases the voltage oscillations in the loading cycle.

4. Summary and conclusions

Results of the carried simulation allow formulate practical regularity concerning the battery capacity. Increasing the capacity affects on the loading/operating time (charging/discharging

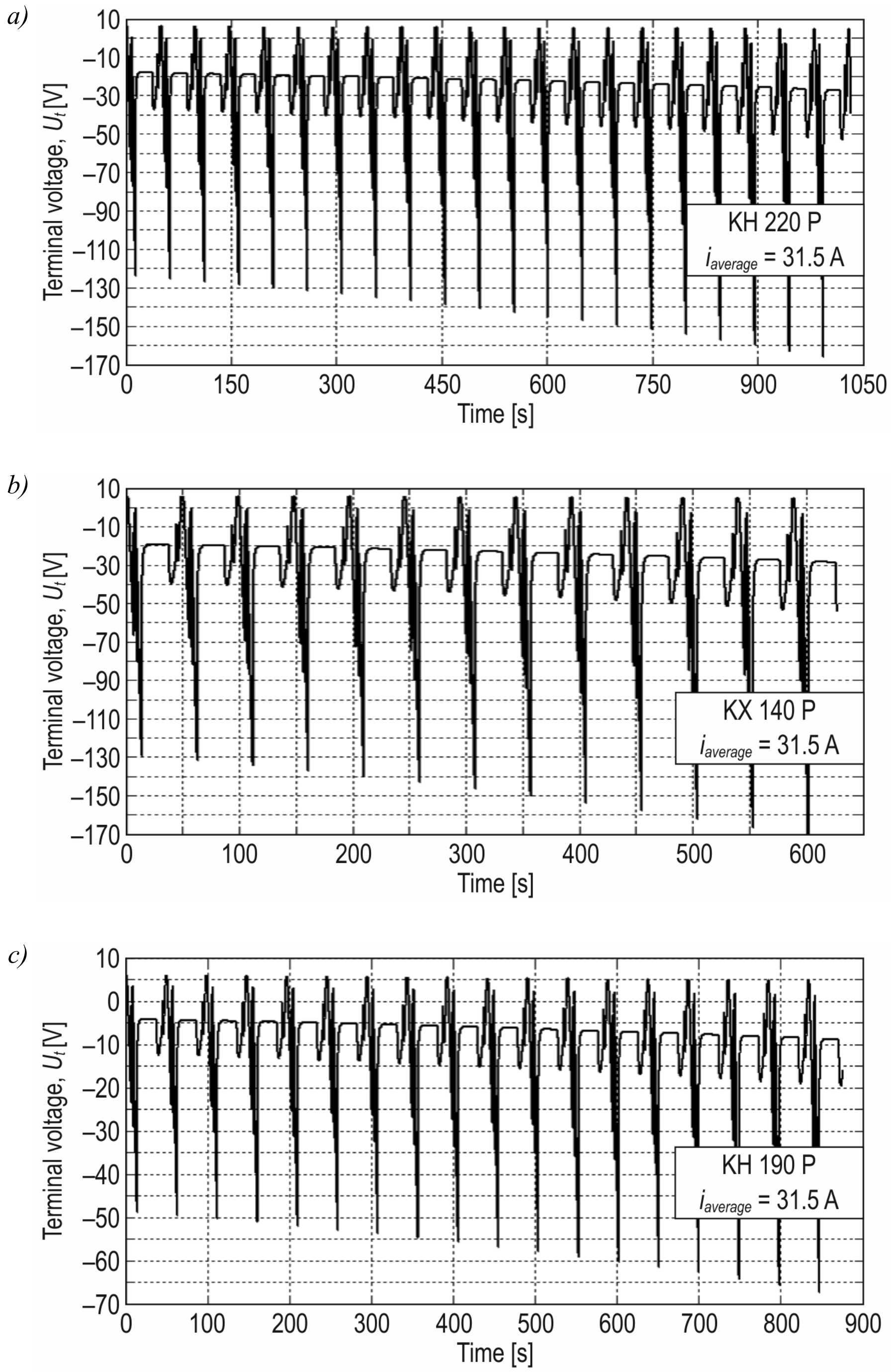

Fig. 6. Changes in terminal voltage for batteries under consideration: KH 220 P (a), KX 140 P (b), KH 190 P (c); 10× amplification of the loading cycle was applied

current at a specified voltage of the battery). With regard to the hybrid powertrains, increasing the capacity increases the time by which the battery can operate as a supportive or secondary redundant power source.

Higher values of the charging/discharging current cause an increase in the operating temperature of the battery – results are not presented in the paper. Determination of a mutual relation between current and temperature gives ~~a~~ practical information that can be used for selection of the Battery Management System (BMS). Such systems usually are based on the monitoring of several parameters including the growth of the temperature gradient, values of charging/discharging current, and the battery voltage. Hence, the following ranges of the battery operation, reported in [4-12], can be specified for different states of charge (*SOC*):

– *SOC* < 0.2 – particularly adverse operation of the battery (its lifetime is reduced). The BMS usually limits discharging and informs the user about the low battery.
– 0.2 < SOC < 0.8 – linear operating range of the battery (lifetime is prolonged). Efficiency of the battery is the highest in this range.
– 0.8 > *SOC* > 1.0 – BMS usually limits the charge current and the cell balancing begins. Close to the *SOC* = 1 the charging time increases significantly.

Conducted simulations provided information about the electromotive force, a state of charge, average efficiency of the battery, charging/discharging current. The proposed approach to the battery simulation is planned to be applied for the loading cycles similar to those that occur during the actual operation of the locomotive.

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