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Electric Vehicle Battery Tester

Streszczenie. *W artykule zaprezentowano strukturę zaprojektowanego i wykonanego urządzenia do testowania akumulatorów w pojazdach z napędem elektrycznym. Celem budowy urządzenia była możliwość określenia stanu żywotności poszczególnych akumulatorów wchodzących w skład pakietu wykorzystywanego do zasilania elektrycznego układu napędowego. W pracy przedstawiono możliwości i funkcje urządzenia skonstruowanego w oparciu o mikrokontroler ATMEL ATmega 32. Weryfikację pracy urządzenia zrealizowano w oparciu o testy przeprowadzone na pakiecie akumulatorów LiFePO4 pojazdu elektrycznego Fiat Panda EV. Wyniki testów przedstawiono w końcowej części artykułu.*

Abstract*. The paper presents the structure of the designed and built prototype of a device for testing the batteries in electric vehicles. The design goal was to estimate the health of individual cells of the battery pack powering the electric powertrain. The article presents the capabilities and functions of the device built with ATMEL ATmega32 microcontroller. The testing of the device operation was carried out on a battery pack of the Fiat Panda EV car. The test results are presented in the final part of the paper.* ***(Urządzenie do testowania akumulatorów w pojazdach z napędem elektrycznym)***

Słowa kluczowe: pojazdy elektryczne, tester akumulatorów, akumulatory trakcyjne, akumulatory litowe.
Keywords: electric vehicles, battery tester, rechargeable batteries, lithium batteries.

Introduction

Properties of electric motors used in powertrains are the cause that they displace conventional engines, and find more and more users in the automotive field. Simultaneously, the progress in creating new motor technologies with motors of greater efficiency, power converters and batteries cause general improvement in electric vehicle performance. The trend of falling specific power consumption, with concurrent growing capacity of batteries causing greater vehicle range, can be observed. The market sees emergence of new battery types and battery technologies, such as GRABAT lithium-polymer batteries [1], which specific energy about 1000Wh/kg or [2] Li-S type with specific energy of 500Wh/kg [3], while the specific energy of batteries available so far is 35Wh/kg for Lead-Acid batteries, 50Wh/kg for Ni-Cd, 80Wh/kg for Ni-MH, 100Wh/kg for $LiFePO_4$, 120Wh/kg for Na/NiCl2 molten salt batteries, 150 Wh/kg for Li-PO and 180Wh/kg for Li-ION. The representatives of GRABAT ENERGY assure, that a vehicle equipped with their battery technology could achieve a range of 800km on a single charge that would take at most 10 minutes [4].

In parallel to progress in technology, the regulations also evolve, posing new requirements for electric vehicle component devices. The obligatory standards for conventional and electric vehicles are set by the World Forum for the Harmonization of Vehicles, operating the United Nations Economic Commission for Europe (UN ECE) and covered by UN ECE Regulation No. 100 (also referred to as R100) [5]. The specific regulations regarding the Rechargeable Energy Storage Systems are stated in the chapter 6 of the regulation, which will enter into force in July 2016. Nevertheless the used battery type and regulations, the electric vehicle cost construction calculation indicate that the most valuable component of an electric vehicle is the battery pack. Accordingly, the estimation of battery health is an important part of electric vehicle maintenance, both new and used. Proper diagnostics of a battery pack allows to pick and replace only the damaged cells, and not the entire pack.

The parameters which describe the traction properties of electric batteries are usually: the battery chemistry, nominal cell and battery voltage in Volts [V], battery capacity in Ampere-hours [Ah], battery mass in kilograms [kg]. Additional parameters, describing the state of the battery are: the State of Charge (SOC) expressed as a percentage of charge stored by battery in the range of 0-100%, the Depth of Discharge (DOD), being a reciprocal of SOC and describing the percentage of charge given out by the battery in the range 100-0% and the State of Health (SOH) parameter, which describes the wear factor of the battery with 100% being the new battery and 0% the totally worn battery. The SOH parameter of a given battery depends on many factors, such as: end of charge and end of discharge voltage levels, magnitude of charge and discharge current, the climate in which the battery operates (mainly ambient temperature) and the number of charge-discharge cycles. For instance, the Lead-Acid batteries are capable of about 400 cycles, Li-PO batteries about 250 cycles, Ni-Cd and Li-S about 500, $Na/NiCl_2$ about 1000, Li-ION about 2500, Ni-MH about 3000, $LiFePO_4$ about 7500 and finally, the new lithium-titanate LTO batteries (Li4Ti5O12) are capable of about 15000 cycles. The health of battery is commonly evaluated by an on-board device known as Battery Management System (BMS). These systems estimate the battery SOH basing on: counting the number of cycles, measuring the self-discharge of battery, measuring the voltage in various operational conditions (idle, loaded, changing temperature), keeping track of the charge dispensed and collected, measuring the time of discharge and measuring the battery's internal resistance. An alternative solution, allowing quick estimation of given battery SOH can be a portable or stationary device, connected for the time of the test to the battery pack [6-15]. This paper presents such a device, the Electric Vehicle Battery Tester (EVBT), which allows evaluation of battery's SOH basing on a measurement of its internal resistance and temperature, by using an expert system.

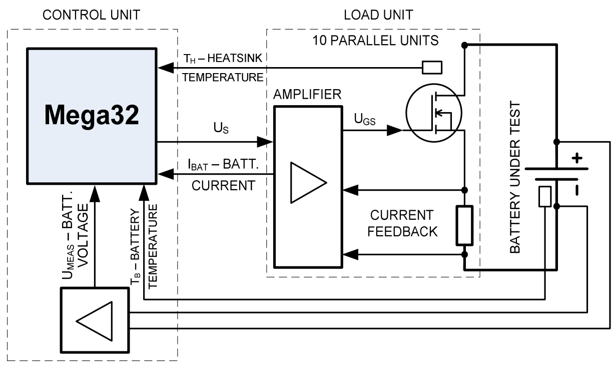
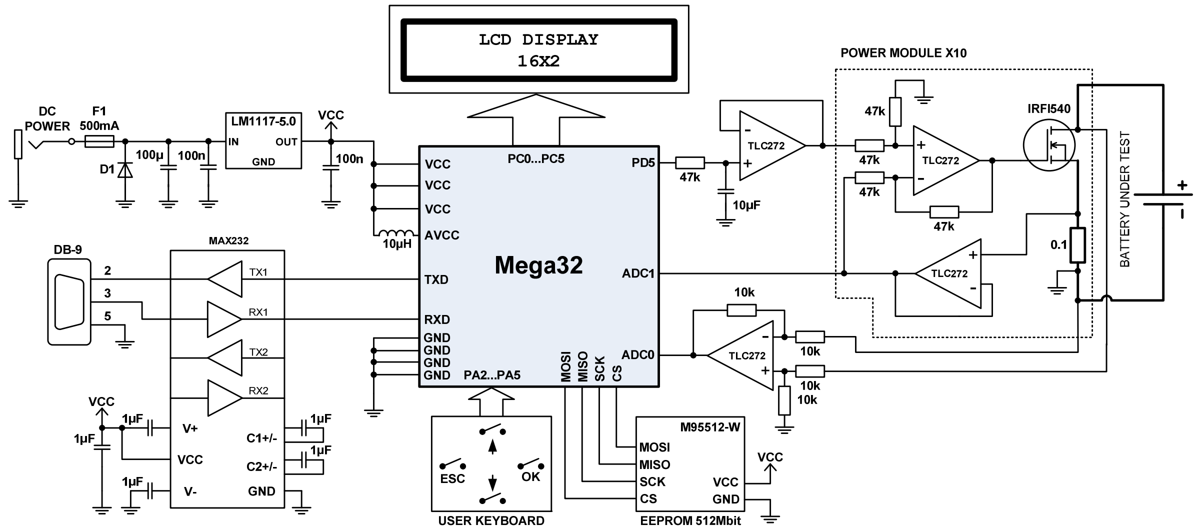


Fig.1. EVBT structure



Rys.2. Electric Vehicle Battery Tester schematic diagram

EVBT structure

The EVBT device consists of two functional blocks: a control unit and a load unit. The control unit has been deployed in an ergonomic handpad shaped enclosure, it contains the digital system of the device, together with a microcontroller, an LCD display, and user keyboard. Power connector, RS-232 DB9 and load unit connectors are also present. The RS-232 connector allows serial connection to a PC, allowing easy archiving of collected data, and is compatible with RS-232 to USB converters.

The EVBT control unit is built around the ATMEL AVR ATmega32 microcontroller. The microcontroller is powered by an external 9V, stabilized power supply, via an LM1117-5.0 voltage regulator supplying 5V power. The 9V input is also used to directly power the load unit. An alphanumeric LCD display with 4 rows and 16 columns of characters is compatible with HD44780 standard. The D4-D7 control pins are connected to PC.0 through PC.3 microcontroller ports, RS pin to PD.6 port, E pin to PD.7 port. The load unit consists of aluminum heatsink on which there are 10 separate, parallelly connected and controlled load modules, which load the connected battery. In order to test the battery, the load modules are connected to it by a pair of 50mm2 cross-section copper stranded test wires. Larger than required cross section causes less variation of cable resistance due to ohmic heating. A single load module consists of a power resistor with a resistance of 0.1Ω (with tolerance of 5%) used to measure the current, a IRFI540 insulated body type MOSFET transistor and a voltage controlled, single supply differential amplifier used to control the current flowing through the MOSFET. The amplifier's non-inverting input receives the voltage U_S which controls the transistor current by changing the gate-source voltage, and thus - the power dissipation of the resistor and transistor. In order to achieve more uniform current spread across all 10 load modules, the power resistors were resistance matched from a larger batch.

An additional amplifier measures the voltage on the power resistor and creates a feedback signal delivered to the inverting input of the differential amplifier which stabilizes the current flowing through the transistor. One of the feedback signals is also passed to the ADC1 input of the microcontroller and is used to determine the current flowing through the battery. The dependence of load current of one load module is a function of U_S voltage and can be expressed by the following equation:

(1) $$I_{BAT} = k \cdot U_S - p, \quad for \quad U_S > 1{,}54\ [V]$$

where:
k, p - scaling coefficients, respectively:

$$k = 11{,}023\ \left[\frac{A}{V}\right],\ p = 17{,}02\ [A]$$

The maximum current of one load module is 20A, with 10 modules together, the whole load unit can draw up to 200A of current from the tested battery. The differential amplifier in each load module works in a closed current feedback loop, and drives the MOSFET into the linear part of its characteristic so the current can satisfy the (1) dependency. In case of a full 200A load, about 1/3 of the power is dissipated in the MOSFET transistors and 2/3 in the power resistors. The voltage on the tested battery is measured by sampling the voltage on the output of a measurement differential amplifier, which inputs are connected to the test wires, from the load unit side. Compensation of the voltage drop on the test cables is performed digitally, by adding the measured voltage U_{MEAS} to the value of calculated voltage drop using known values of battery current I_{BAT} and cable resistance R_{CABLE}. Cable resistance was calibrated during EVBT manufacture and is permanently loaded into the microcontroller's memory.

(2) $$U_{BAT} = U_{MEAS} + I_{BAT} \cdot R_{CABLE}$$

The EVBT has a safeguard against testing batteries with too great a voltage (e.g. 12V lead-acid batteries). In case of measuring more than 4.5V on the battery connectors, the possibility of loading the battery will be locked-out, and the user will be informed of this fact by an appropriate message displayed on the LCD.

The EVBT has two digital temperature sensors, in the form of DS18B20 sensors, with 0.1°C resolution. One of the sensors is permanently attached to the load unit's heatsink and measures its temperature T_H, the other is connected to the control unit by a flexible cable and is used to measure the temperature of the tested battery T_B.

The goal of the heatsink sensor is to protect the load modules from being damaged by too high temperature, caused by excessive, sustained power dissipation. When the sensor registers temperature in excess of 75°C, the control unit will disable the loading of the battery and display an appropriate message on the display. The operation of load unit can be reestablished after the heatsink cools down to below 70°C.

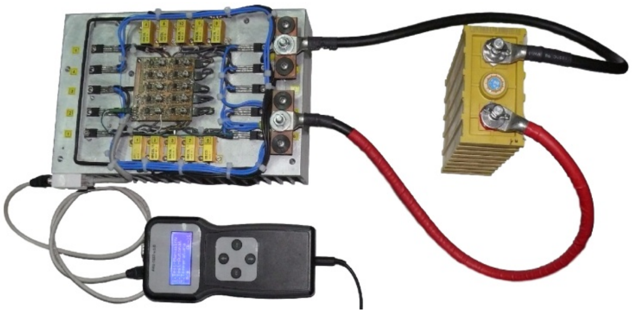


Fig.3. Electric Vehicle Battery Tester during SOH determination of a LiFePO4 battery

The EVBT can be operated by a four button user keyboard, located on the handpad containing the control unit. Pressing the ESC key leaves the currently selected function and returns to the parent function, with the topmost level being the main menu. The main menu is operated by UP, DOWN and OK buttons. The devices offers the choice of five main functions: entering the parameters of tested battery, automatic test, manual test with selection of load current and loading time, battery capacity test and measurement without loading. After selection of one of five functions, by pressing the UP and DOWN buttons, and acknowledging the choice with OK button, the user is allowed to select the functions parameters (wherein some functions do not have any parameters to be set, e.g. the automatic test function). Further steps of the function, or entered parameter values are always confirmed with the OK button.

Fig.4. View of load unit of the EVBT

The first function allows to enter into the EVBT tester the parameters of connected battery - its type and capacity in Ampere-hours. The user can select from 7 battery types: Li-Ion, Li-PO, LiFePO4, Ni-Cd, Ni-MH and Lead-Acid 2V. The range of possible capacities is 1-999Ah. Entering these parameters is a necessary step in order to correctly perform the measurement. The tester stores in its non-volatile EEPROM memory the parameters of most recently tested battery, allowing quick testing of same batteries in succession. The used EEPROM memory, with 512Mbits of capacity and connected to the microcontroller with the SPI bus is also used to store the database used by the testing algorithm and the testing results. Up to 1000 test results are stored, the test number is displayed after the test finishes.

The automatic test function measures the internal resistance of the connected battery according to the specifications of the IEC 61951-1 norm. After selecting the automatic test function from the main menu, the tester checks the voltage on the testing cables, whether it is in the range of selected battery type. If the voltage is zero volts, or otherwise outside the selected battery type voltage range, a message will appear on the display. The device will display a message that the test is ready, and asks user for confirmation by pressing the OK button. The automatic test will at first load the battery with a current I_{BAT1} = 0.1C (where C - Capacity rating of the battery expressed in Ampere-hours) for 10 seconds, and at the end of this period, measuring the battery voltage U_{BAT1}. Next, the battery is loaded with current I_{BAT2} = 1C for 3 seconds, and again the voltage U_{BAT2} is measured. The EVBT calculates the battery internal resistance R_I according to the following equation:

(3) $$R_I = \frac{U_{BAT1} - U_{BAT2}}{I_{BAT1} - I_{BAT2}}$$

The manual test function allows to load the connected battery with a preset value of current for a preset time. After selecting and confirming the current value, the user sets time duration of the test, then the device displays the entered values and waits for confirmation. Pressing the OK button starts the test, which is performed until: the time elapsed reaches the value of preset time test, the user terminates the test by pressing the OK or ESC button, or (in order not to damage the battery) the voltage on the battery falls below certain critical value, corresponding to the set battery type. The measured values at the start of the test (the moment the OK button is pressed) and when the test stops, are plugged into the equation (4) with which the internal resistance of the battery is calculated.

(4) $$R_I = \frac{E - U_{BAT}}{I_{BAT}}$$

where: R_I – internal resistance, E – voltage on the battery without load, U_{BAT} – voltage on the battery with load applied, I_{BAT} – battery current with the load applied.

The function of battery capacity measurement allows to measure the true capacity of tested battery C_{BAT}[Ah] by integration of the function of current flowing out of the battery I_{BAT} in time t (5).

(5) $$C_{BAT} = \int_0^t I_{BAT}(t)dt$$

After selection of capacity testing function, the device asks the user to input the battery discharging current value, and after that, the low battery voltage setting U_{STOP}, which when reached, will stop the discharge and finish the test. Pressing the ESC or OK button also will stop the test. The EVBT will suggest the proper U_{STOP} value, according to the selected battery type, but the user has the liberty to change it at will. During the test, the actual value of charge given out by the battery and time elapsed from the beginning of the test are displayed. After the test concludes either by reaching the U_{STOP} voltage, or by user intervention, the tester displays a test results screen, containing, among others, the charge that the battery sourced expressed in Ampere-hours and as a percentage of nominal battery capacity, entered by the user before the start of the test. In the first line, the consecutive test number is shown, and it is used as an index number for accessing the test results stored in the tester's EEPROM memory. Ratio of the actual capacity to the nominal capacity is one of the factors used by the testing algorithm for determination of tested battery's SOH [17-25].

The purpose of the last function, measurement without loading, is to check whether the connection between the battery and the tester is properly made - by displaying the voltage seen by the tester, as well as displaying the temperatures measured by the battery and load unit heatsink sensors.

On the basis of performed test functions at the particular temperature, measured battery parameters: internal resistance, voltage at the battery terminals and rate of change of battery voltage during loading are taken into account when calculating the tested battery score.

$$SOH = \frac{R_{SOH0}(T) - R(T)}{R_{SOH0}(T) - R_{SOH100}(T)} \cdot 100\% \qquad (6)$$

where: $R(T)$ - internal resistance of tested battery at the given temperature, $R_{SOH0}(T)$ - internal resistance of battery of the same type as tested battery, with SOH=0% (worn battery), at the given temperature, $R_{SOH100}(T)$ - internal resistance of battery of the same type as tested battery, with SOH=100% (brand new battery), at the given temperature.

The SOH evaluation of the tested battery is performed by an expert system with a fuzzy rule-based inference database (fig.5), developed on the basis of numerous practical tests, and data provided by battery manufacturers. The battery can be considered eligible for replacement when its SOH is below 65%. The device provides the ability to modify and update the database by direct editing or by saving actual test results performed on reference batteries. Due to the fact, that the battery's internal resistance rises as the battery is discharged, it is required to perform the battery test only after it is fully charged.

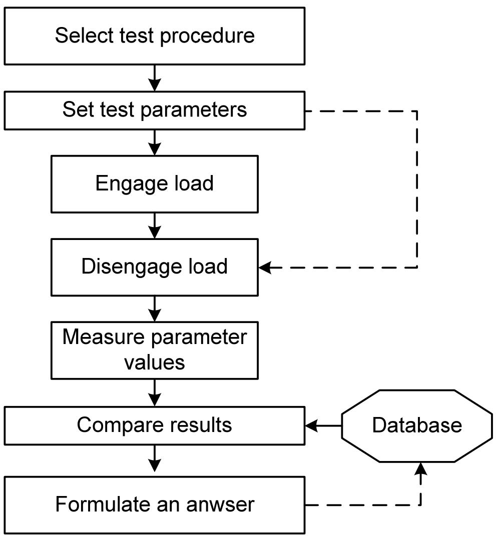


Fig.5. Structure of the reasoning algorithm

The accuracy of EVBT measurement depends mostly on the accuracy of measurement of voltage on the tested battery (±1%), heat phenomena occurring in the electrical circuit(±1%), measurement of voltage on the load resistor (±1%) and its tolerance (±5%). Taking these factors into consideration, it can be assumed, that the overall accuracy of measurement is less than 10%.

Results

The suitability of EVBT was tested on a battery pack of 160Ah LiFePO4 batteries from a Fiat Panda EV car [16], which was manufactured in 2010. The ambient temperature during testing was 20°C, the batteries were loaded with current rating of 1C.

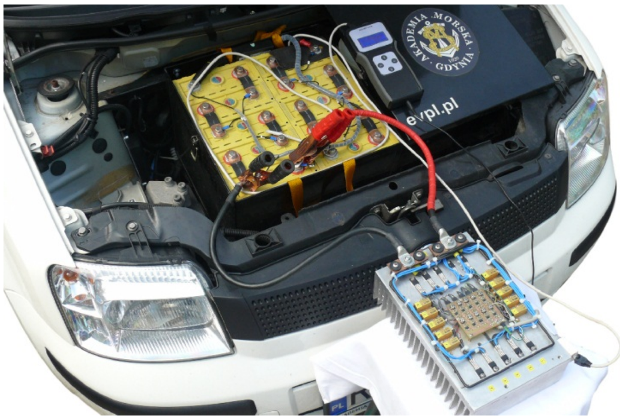


Fig.6. Electric Vehicle Battery Tester during test of the battery pack in a Fiat Panda EV car

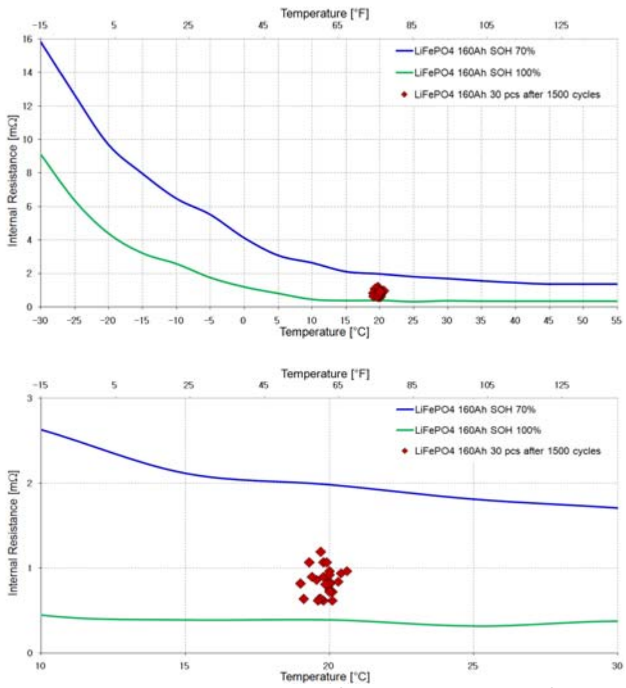


Fig.7. Temperature dependence of internal resistance of a 160Ah LiFePO4 battery (1C rated load current)

For comparison of properties of LiFePO4 batteries, a relationship of internal resistance and temperature of a traction Lead-Acid battery is presented on figure 8.

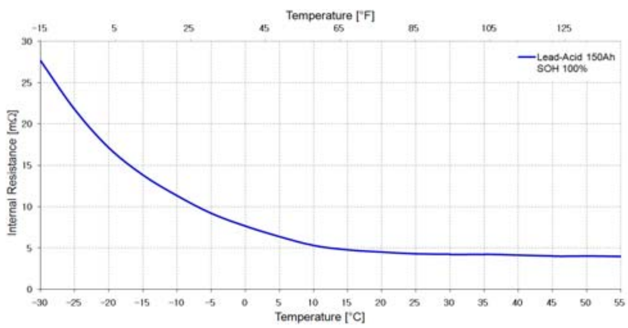


Fig.8. Temperature dependence of internal resistance of a 150Ah Lead-Acid battery (rated current 1C)

View of EVBT display during the example test of a 160Ah LiFePO4 battery are presented in the figure 9.

Battery setup screen is shown, followed by an automatic test and a full capacity test with a load of 0.5C.

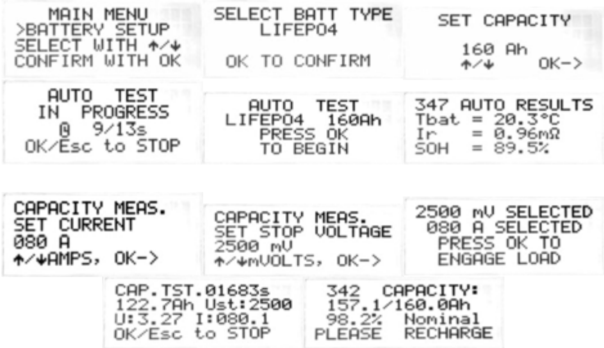


Fig.9. View of EVBT screens of battery setup, auto test and capacity test functions

Conducted testing of a 30 LiFePO4 cell battery pack have shown, that SOH was between 95 to 85%. Bearing in mind, that the tested vehicle used a passive Battery Management System - without the possibility of individual cell balancing mechanism, the result confirms that an important factor impacting the increase of internal resistance of a battery is the way the battery is being operated. The optimal operation conditions for LiFePO4 battery are: maximal charge voltage 3.6V, minimal discharge voltage 2.8V, maximal charge current 1C, maximal discharge current 3C, temperature of battery more than 5°C.

On the basis of these tests it can be stated that with rising internal resistance, the battery's usefulness is falling (the battery efficiency is falling).

The testing confirmed, that the internal battery resistance is dependant on several factors, such as:
- battery temperature (lower temperature causes increase of internal resistance),
- battery State of Charge (discharged battery has higher internal resistance),
- battery size (the bigger the battery, the smaller the internal resistance. The accepted internal resistance range for one battery size can be different for a battery of smaller or larger capacity).

Conclusions

The article presents the EVBT device, which is designed to evaluate the battery health of single cells in a battery pack, used with an electric powertrain of a vehicle.

Application of a fuzzy expert system allows to determine the SOH of tested batteries, which facilitates quick and precise diagnostics of an electric vehicle battery pack.

The configuration capabilities of the EVBT allow to add reference parameters for tested batteries by direct input into the device's database or by testing reference batteries.

The conducted testing on a Fiat Panda EV car proved the practical usefulness of the device to evaluate the SOH of a battery pack.

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