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Possibilities to identify defective electric automobile batteries

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Abstract. A pack of batteries is one of the most important and expensive assemblies for an electric vehicle. A pack of batteries is comprised of several batteries connected in series. The number of the batteries connected depends on the operating voltage of the vehicle's on-board system as well as on the individual characteristics of the batteries used, e.g. the operating voltage of a single cell. One or several cells of a pack of batteries could be damaged if improperly exploiting an electric vehicle– excessively discharging the batteries or overloading the electric vehicle. If a self-converted vehicle does not use an intellectual BMS (battery management system) that can identify and register voltage drop for any individual cell in the high-load regime, e.g. when accelerating, it is difficult to identify and change the cells damaged. In case a cell does not demonstrate a complete failure, it is almost impossible to identify a defect in any regime other than the load regime.

The research developed and compared three different methods for identifying defective battery cells. The methods were approbated on a converted Renault Clio. The experiment involved making voltage measurements in road tests, running the electric vehicle on a roll test bench and making voltage measurements of maximally discharged batteries in the no-load regime. A comparison of the measurement results revealed that the measurements made in the road tests were the most accurate and useful. After the experiment, the defective battery cells were replaced, thereby restoring the performance of the battery pack.

Key words: electric vehicle, battery pack, battery voltage, test.

INTRODUCTION

Electric vehicles are known for more than 100 years. A century ago, vehicles with noisy and difficult to start internal combustion engines triumphed over electric vehicles, as it was a period when intercity road infrastructure began developing and a longer driving range per charge was needed. Relatively short ranges per charge are a problem of many modern electric vehicles. Electric vehicles have become more popular over the last decade, as they appeared in the assortment of models of almost any large auto manufacturer. The main field of application of vehicles is still cities where daily distances covered by the electric vehicles are insignificant. The popularity of electric vehicles is hindered by their relatively high prices.

In 2018 in Latvia, an electric vehicle mobility project was implemented, and 75 new fast-charging stations along trunk roads were opened (A network of ..., 2018). This gives a possibility to travel by electric vehicle almost across the entire Latvia. As the electric vehicle fleet becomes older, the performance of battery packs decreases, which, in its turn, reduces the range of electric vehicles. Since a battery pack consists of a number of cells connected in series, even one damaged cell can considerably impact the performance of the entire pack. Unfortunately, it is difficult to identify the damaged cell by simple no−load testing methods. For this reason, the present research analyses a number of practically approbated methods of testing for damaged battery cells.

Scientists place a large focus on how to test the batteries of electric vehicles for defective cells, addressing this problem in their research papers. Electric vehicles use lithium batteries, as such batteries are considered a progressive source of accumulated energy. A BMS system, which the base models of serial electric vehicles are equipped with, has to control the charge and discharge of batteries, collect data on each individual cell, provide thermal control and control the technical condition of the batteries. The key reasons of battery defects are overcharge, over discharge, high or low temperatures and a large number of cycles. There are model based and non-model based methods for diagnosing a battery. It is stressed that batteries connected in series make a complicated system with different electrical parameters in each individual cell. Therefore, it is possible to use diagnostics systems based on signals, e.g. voltage or current, yet such systems do not always produce fast and correct results. Using a BMS system, there is one more risk in diagnosing a battery, as the BMS itself might be damaged and inaccurate. Knowledge- and experience-based testing for a defective battery or the expert method is also regarded as a useful method (Wu et al., 2015).

In simulation, Kalman filters that modify a signal allowing identifying the performance of a particular battery are frequently used to test the battery for defective cells. Error scenarios and various measurement methods for testing a battery for defects based on simulation results have been developed as well (Singh et al., 2013).

A test of the performance of a battery pack could be performed in accordance with the USABC (United States Advanced Battery Consortium) Electric Vehicle Battery Test Procedure Manual. Such a test involves the discharge of a battery within three hours at a current of a third of the capacity of the battery. The test produces a voltage-capacity curve (BEV battery, 2012). For example, a 100 Ah battery has to be discharged at a current of 33.3 A. This method is useful for identifying the performance parameters of a battery pack, but not for testing individual cells for defects.

Research studies on BMS enhancement are done as well. A BMS includes an algorithm for measuring each battery cell, and the readings are compared with marginal parameters indicating a potential defect. Research studies analyse a number of logical diagnostics methods, yet no practically useful method is suggested (Marcicki et al., 2010; Lu et al., 2013).

In primary diagnostics of a battery, the most important parameters are as follows: potential power, internal and external temperatures of a cell, charge-discharge time, internal resistance, voltage of the cell and the voltage of the entire battery (Wang et al., 2017; Omariba et al., 2018).

A decrease in the performance of the entire battery pack could be caused by a partial failure of a single cell. Even if battery packs are commented in parallel, the pack with a damaged cell can cause a malfunction of the other packs, which could be identified by using a mathematical model. Measurements were taken of 504 battery cells with a total capacity of 9 kWh. Tests were done on a power bench in the 3–second advance mode. The results were recorded by means of a standard BMS. The internal resistance of batterie's were calculated based on the experimental results. The experiment performed a 15-minute discharge cycle by running the vehicle on a dynamometric bench. The battery cells were selectively tested also individually (Offer et al., 2012).

The charge of a battery could be tested at various ambient temperatures, e.g. from +5 to +45 °C. Besides, the physical-models approach, the Thevenin model, the runtime-based electrical model, the combined electric model, the data-driven approach, the neural network and fuzzy logic methods are recommended for diagnostics, prognostics and health management of batteries (Rezvanizaniani et al., 2014).

The performance of batteries could be estimated based on the number of battery cycle life, recording the number of charge-discharge cycles as well as battery capacity measurements (Yan et al., 2015). Old batteries could be recycled; however, to protect the environment, a lot of work is done on technologies allowing using old electric vehicle batteries for stationary equipment needing no high current output (Cready et al., 2003).

Most of the methods reviewed in the paper are used for testing a battery pack for defects, yet methods for determining the performance of each individual cell are little analysed in the literature.

The research novelty represents the approbation of a battery pack testing methodology for an electric vehicle through measurement of individual battery cells in the load regime and the no-load regime.

The research aim is to analyse, select and approbate the simplest method of diagnosing the performance of a battery pack in the converted electric vehicle.

MATERIALS AND METHODS

An electric vehicle Renault Clio was converted from an internal combustion vehicle to an electric one. The conversion was done at the Faculty of Engineering, Latvia University of Life Sciences and Technologies. During the conversion process, a number of experiments were carried out as well as system enhancements were made. The battery pack was equipped with a battery management system (BMS) that had to ensure a proper charging process for individual battery cells. During charge, the voltage of an individual cell might not exceed 4.1 V, while in discharge regimes it might not decrease below 2.4 V. At the initial stage of the conversion, the system did no function properly because the BMS was programmed inaccurately, and there were cases where the minimum and maximum voltages were exceeded multi-fold. The key technical parameters of the converted vehicle are presented in Table 1.

After the BMS software had been reprogrammed, the maximum charging voltage was set at 3.8 V and the minimum allowable discharge voltage was set at 2.6 V. However, during road tests when accelerating fast, the BMS often engaged the minimum battery voltage limiter, which indicated that the performance of one or several battery cells decreased. The BMS was capable of identifying voltage drops within 0.015 s, yet it could not determine which particular cell out of 30 ones was faulty. After the voltage drop had been registered, the BMS limited the maximum speed of the electric vehicle, which could be set, for example, at 60 km h^{-1}.

Table 1. Key technical parameters of the electric vehicle Renault Clio

No	Parameter characteristics	Parameter value
1	Vehicle category	M1
2	Motor nominal power	30 kW
3	Gearbox	5−speed manual
4	Used gear	3rd gear
5	Maximum speed	120 km h^{-1}
6	Battery cells	LiFePO4, 30 pcs.
7	Total battery voltage	96 V
8	On-board power	10.5 kWh
9	Nominal voltage of a battery cell	3.2 V
10	Voltages set in the BMS	U_{min} = 2.6 V; U_{max} = 3.8V
11	Range per charge	60 km
12	Minimum BMS response time	0.015 s
13	Battery charging time	3.5 h
14	Battery capacity	100 Ah
15	Maximum discharge current	1,000 A

In previous road tests of the electric vehicle, data were recorded by means of a data logger. When accelerating fast, the data logger registered a voltage drop of battery pack from 98 to 89 V. In each battery cell, the voltage dropped, on average, from 3.27 to 2.97 V. Since the BMS engaged the limiter, such a voltage drop was due to the battery's inability to supply a high current, as the current could exceed 400 A in this regime (Berjoza et al., 2018).

In accordance with the instructions for serial electric vehicles, the entire battery pack is changed after a standard maintenance operation or repair, while the old one is recycled. In the case of a self-converted electric vehicle, only the damaged battery cells could be changed, thereby reducing repair cost even 30-fold (in case only one cell has to be replaced).

The potential ways of diagnosing lithium-ion batteries are as follows:

1) by means of the BMS if it is possible to specify an address for each cell;
2) measuring the voltage of an individual cell by means of multichannel loggers;
3) taking measurements of an individual cell during different driving regimes;
4) taking measurements of an individual cell under no load in a stationary vehicle;
5) visually examining the battery (a considerably damaged battery might have changed its geometrical dimensions, e.g. it could be swollen).

For a battery that does not supply enough power, the very last way of diagnostics is not useful.

The first experimental stage was performed with the battery discharged to the minimum allowable level. The battery was discharge by road testing the electric vehicle. During the road tests, the electric vehicle's average range per charge decreased from 65 to 55 km. It was easy to access the battery pack in the converted electric vehicle. It was required to only remove the cover over the battery pack to take measurements. The measurements were made by a digital multimeter Fluke 87. The device's resolution was 0.01 V.

The electric vehicle was road tested for a distance of 55 ± 1 km under similar conditions. The road tests were done in September at an average ambient temperature of +15 ± 2 °C. To record the data, a data logging protocol for a pack of 30 batteries and their position addresses was prepared. Right after the vehicle was stooped, the voltage measurements of all the battery cells were made, logging the data in the protocol. The test was replicated three times.

The second experimental stage involved a roll test bench Mustang 1700. The key parameters of the bench were as follows: maximum power – 1,700 hp, maximum speed – 300 km h^{-1}; the brake mechanism was powered by electromagnetic eddy currents. The experiment was done at the Alternative Fuels Research Laboratory, at an ambient temperature of +16 ± 1 °C. Before the experiment, the electric vehicle was fully charged and left inside the laboratory for at least 5 h. The electric vehicle was fastened to the bench and its batteries were warmed up by running it idle at a speed of 50 km h^{-1} for three minutes. After the warm–up, the electric vehicle was run at a speed of 80 km h^{-1} and the wheels were subject to a load of 30 kw. One of the experimental operators simulated the driving of the electric vehicle, while the other one made measurements of individual cells of the batteries. Each cell was measured for on average 5–8 seconds. The data were manually recorded in accordance with the methodology described above. To make the measurements faster, the data were recorded by the operator who simulated the driving. The test was replicated three times. Since a significant decrease in voltage was observed after the second replication, the first two replications were taken into account; the batteries were fully charged and then the third replication was performed.

A sequential scheme of the experiment is shown in Fig. 1.

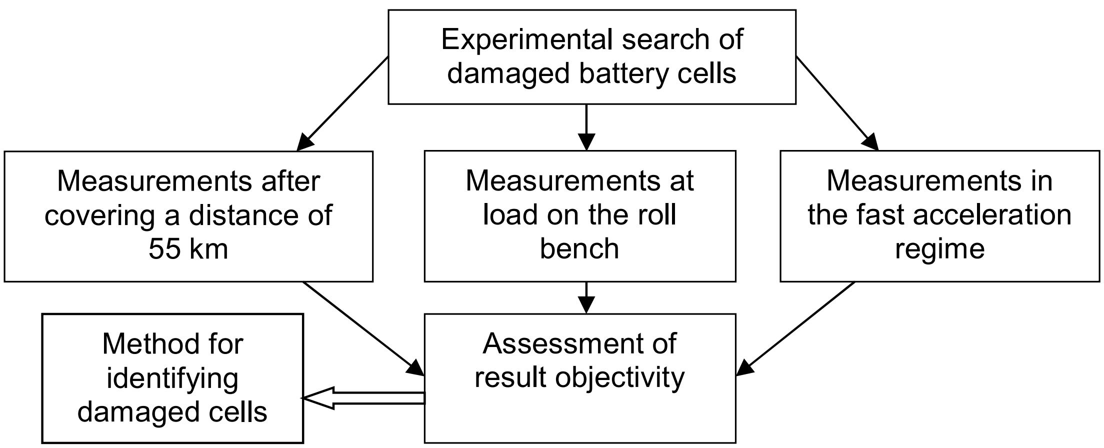

Figure 1. Sequential scheme of the experiment.

The third experimental stage involved road tests. One operator drove the electric vehicle, while the other one made measurements. The measurements were consecutively taken for all the 30 cells. The measurements were made at an ambient temperature of +15±2 °C. The electric vehicle was road tested in non-urban driving at an average speed of 50 km h^{-1}. The measurement operator gave a command at a moment when he was ready to take readings and had connected the multimeter to a particular cell. The electric vehicle was accelerated to a speed of 80 km h^{-1}, and the measurement operator took the lowest voltage reading for each cell and recorded that in the protocol. The acceleration was repeated 30 times for each road test replication and for each series of measurements. Totally, there were three replications.

At all the experimental stages, the batteries were assigned numbers from 1 to 30 according to a scheme presented in Fig. 2.

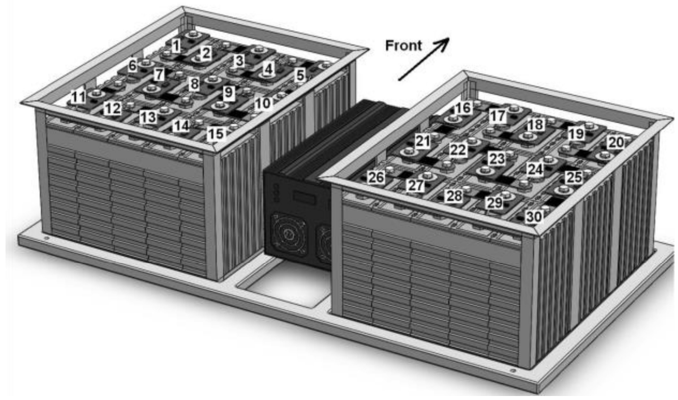

Figure 2. Numbers and positions of the batteries.

The data were aggregated and analysed after each series of tests. Based on the experimental data, the batteries were tested for defects and replaced.

RESULTS AND DISCUSSION

First of all, the experimental data on the measurements taken after the vehicle had covered a distance of 55 km were processed. The average readings of the mentioned measurements are presented in Fig. 3. The measurement results shown in the graphs have a confidence level of 95%, i.e. a confidence interval falling within two standard errors (Figs 3–5).

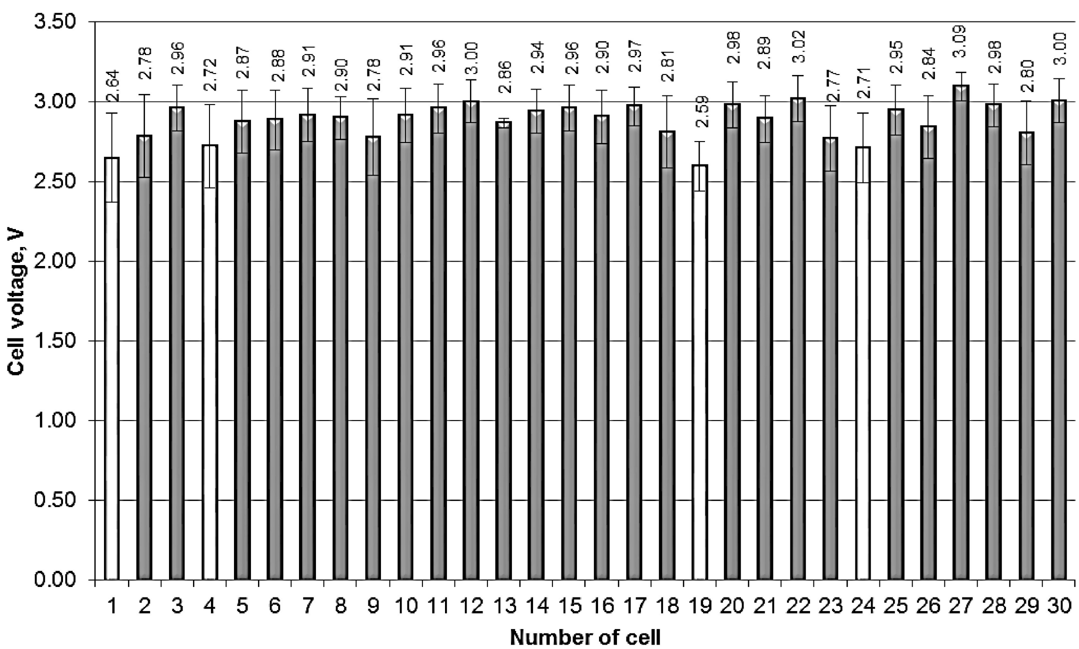

Figure 3. Average readings of the voltage measurements taken after the electric vehicle had covered a distance of 55 km.

According to the readings, the average voltage of battery 19 was the lowest at 2.59 V, which was 10.1% lower than the average for all the batteries (2.88 V). Battery 1 demonstrated the second lowest voltage – 2.64 V, which was 8.3% lower than the average. Batteries 24 (2.71 V) and 4 (2.72 V) also had low voltages, 5.9% and 5.6%, respectively, lower than the average.

The best performers were batteries 12, 22, 27 and 30, the voltages of which were in the range of 3.00–3.09 V – 4.2–7.3% higher than the average.

The experimental data on the measurements taken on the roll bench are presented in Fig. 4.

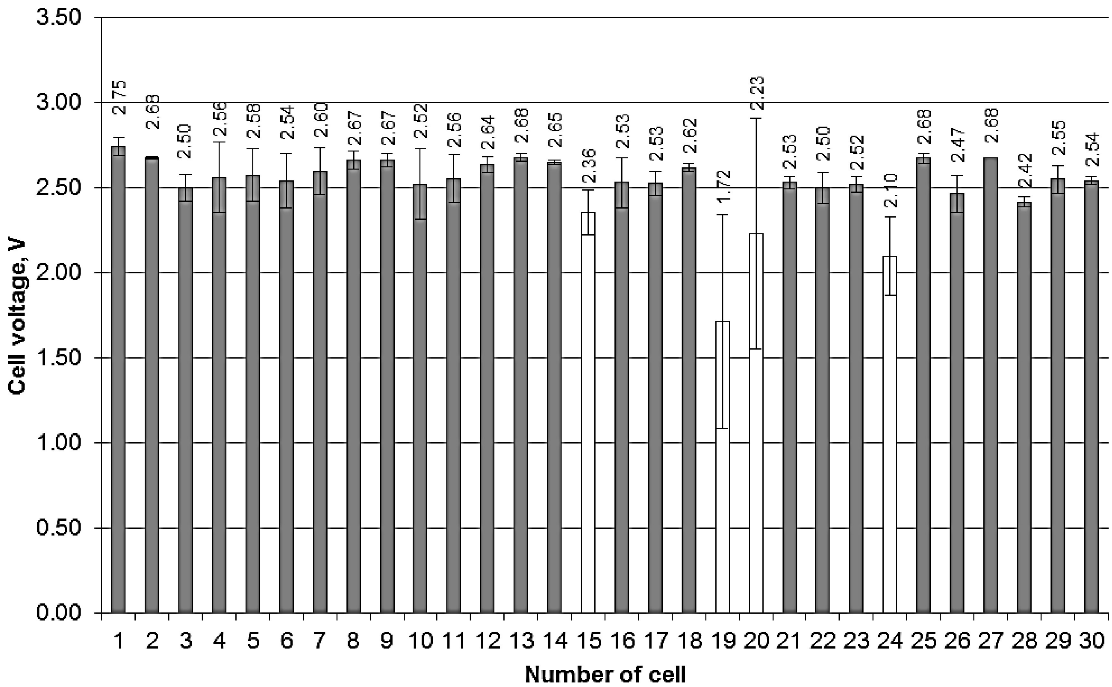

Figure 4. Average readings of the voltage measurements taken on the roll bench.

The lowest average voltage (1.72 V) was demonstrated by battery 19, which was 31.7% lower than the average for all the batteries (2.52 V). The second lowest voltage was observed for battery 24 (2.10 V), which was 16.7% lower than the average. The voltage of battery 20 was 2.23 V, which was 11.5% lower than the average. Battery 15 demonstrated a voltage of 2.36 V, which was 6.3% lower than the average. The voltages of the analysed batteries were lower the allowable voltage of 2.4 V, and the batteries were not capable of operating in such a regime for a long time, otherwise the batteries might get irreversibly damaged.

The best results acquired on the roll bench were demonstrated by batteries 1 with 2.75 V (9.1% higher than the average) and 2, 13, 25 and 28, the voltages of which were equal to 2.68 V (6.3% above the average).

The data acquired in the road tests, accelerating the electric vehicle from 50 to 80 km h^{-1}, are presented in Fig. 5.

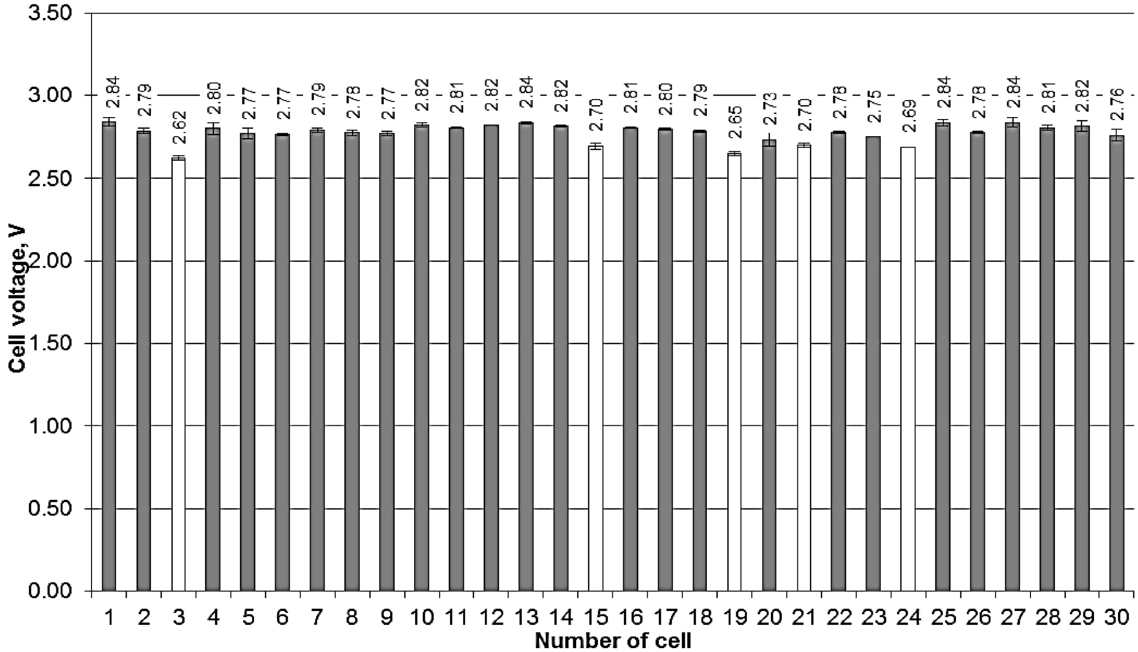

Figure 5. Average readings of the voltage measurements taken in the acceleration regime.

The lowest average voltage recorded when accelerating the electric vehicle was observed for battery 3 at 2.62 V, which was 5.4% lower than the average for all the batteries. The voltage of battery 19 was equal to 2.65 V, which was 4.3% lower than the average. The voltage of battery 24 was 2.69 V, while that of batteries 15 and 21 was 2.70 V, which differed from the average by 2.9% and 2.5%, respectively.

In the acceleration regime, the highest average readings of voltage were demonstrated by batteries 1, 13, 25 and 27 at 2.84 V, which was 2.5% higher than the average for all the batteries.

To accurately diagnose the batteries, out of the three series of tests only the tests on the batteries under load were taken into account. The data were processed to identify the average voltages of the batteries; the data are presented in Fig. 6.

According to the average readings of the voltage measurements taken in two series of tests of the electric vehicle – on the roll bench and when accelerating – the lowest voltages were demonstrated by batteries 3, 15, 19 and 24. The average voltage ranged for 2.18 to 2.56 V. The research compared the results on defective batteries shown in Figure 6 with the results shown in Figs 4 and 5. In view of the fact that the results shown in Figures 6 and 5 had greater consistency, the research assumed that the voltage measurements taken in the acceleration regime were the most accurate and this method would have to be employed in the future.

Taking measurements according to the above-analysed methods requires free access to the batteries measured while driving the vehicle, otherwise another method has to be chosen. A more accurate but more expensive method is the application of a multichannel data logger that accurately takes measurements in different regimes. However, the cost of using a multichannel data logger with at least 30 channels is high, and the connection of the logger to the battery pack to be measured is very labour intensive.

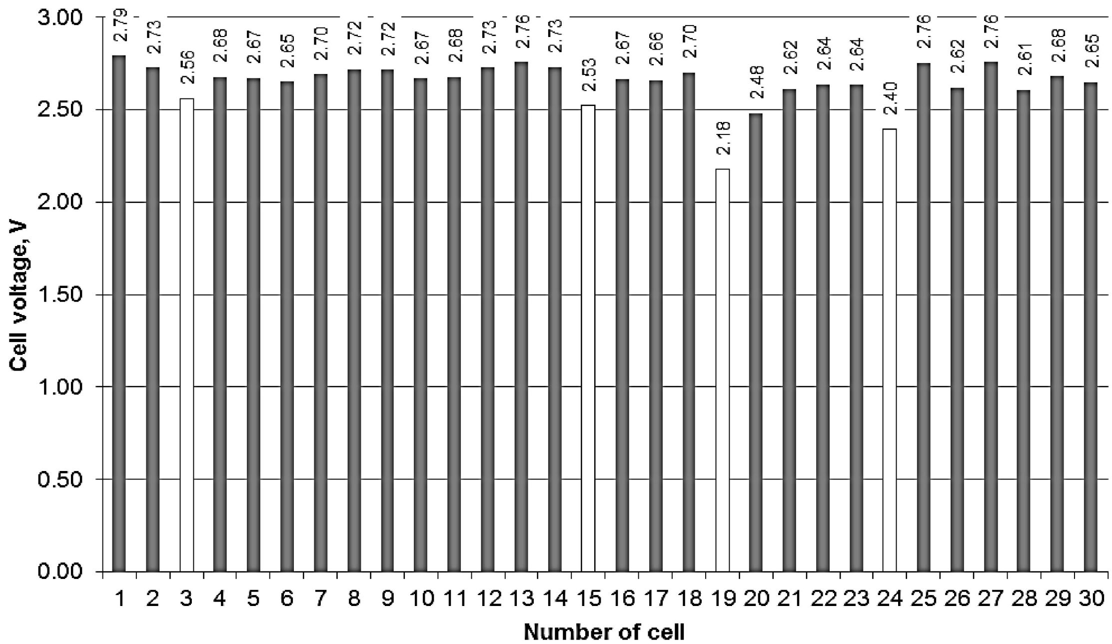

Figure 6. Average readings of the voltage measurements of the batteries under load.

After the experiment, four defective batteries were changed, thereby restoring the initial driving range of the electric vehicle (60 km).

CONCLUSIONS

1. For serial electric vehicles, regular testing for defective batteries involves identifying and changing the entire battery pack, which is an expensive and environmentally unfriendly way.

2. No simple method for identifying a defective battery cell, which could restore the normal performance of the entire battery pack, is available. Expensive data loggers could be used to identify a defective cell, or simple measurements by means of a multimeter could be taken. A defective cell could be accurately identified by also modern BMS systems having the address of each particular cell.

3. The research developed three different methods for testing batteries for defective cells. The first one was the least reliable, as it involved testing a battery after the vehicle had covered a distance of 55 km and did not represent a load regime for the battery.

4. The second method involved testing of the electric vehicle on the roll bench at a constant load. The choice of a proper loading regime on the roll bench could take a lot of time, and the regime could be very different from real operational conditions. The voltage measurements of battery cells taken in a regime different from the real operational conditions might lead to inaccurate results on the actual technical condition of the cells.

5. The defective cells identified in each series of tests were not the same, yet cells 19 and 24, the lifespan of which was undoubtedly about to end, were identified as defective.

6. The measurement readings taken while accelerating the electric vehicle were more reliable and consistent with the real voltage drop during the operation of the

vehicle. In this driving regime, the largest voltage drop in the range of 2.62–2.70 V was observed for five batteries.

7. An analysis of the average readings of the voltage measurements taken when accelerating the electric vehicle and on the roll bench revealed that the highest correlation was observed for the road tests in particular. For this reason, this method is recommended as the main method for testing the Renault Clio Electric and analogues for defective battery cells that provide direct access to their battery cells.

8. Since the batteries were connected in series, the damaged cells affected the performance of the entire battery pack and their internal resistance hindered the proper operation of the entire battery pack.

9. Four defective batteries were changed in the experimental electric vehicle, thereby restoring the performance of the battery pack and increasing the driving range of the vehicle by 20%.

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