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THE INFLUENCE OF ELECTROCHEMICAL BATTERY AGING PROCESS ON AN ELECTRIC VEHICLE'S RANGE

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Abstract

This article presents the influence of aging processes of the electric vehicle's electrochemical battery. The increasing number of hybrid and electric vehicles increases the demand for durable and efficient sources of energy storage for vehicles. The vehicle's declared range is reduced over time.

This is due to the aging of the battery that causes loss of its capacity and loss of its power. To minimize this phenomenon, manufacturers use counteracting solutions that include mounting additional cells in the battery that are switched on when the battery controller identifies a particular battery cell's failure or high degradation. This is due to the deep and shallow discharges of the battery, the number of charge and discharge cycles, and the age and technology of battery packs.

AMESim software was used for the simulation of the electric vehicle. The research was based on modelling the range of the vehicle whose cell capacity includes processes related to aging of the battery. An aging cell algorithm causes the capacity to drop and consequently reduces the range of one full charge. By modelling aging processes, it is possible to determine the battery's probable capacity loss during vehicle use and to estimate how these processes affect the vehicle's range.

Keywords: *battery, simulation model, electric vehicle,* $LiFePO_4$

1. Introduction

With the tightening of regulations and emission standards, manufacturers are constantly striving to fulfil increasingly stringent emission limits among vehicle manufacturers, including companies producing engines that power mechanical vehicles. In order not to exceed the set limits, manufacturers use different solutions, based on extensive exhaust gas treatment systems. One solution to meet emissions standards is the use of hybrid and electric drive systems.

The advantages of having electric and hybrid systems over exhaust-based systems are, among other advantages, the ability to recover energy while braking a vehicle, allowing for a slight increase in vehicle range, and lower CO_2 emissions by turning off an internal combustion engine under conditions where it would not operate efficiently. Optimized internal combustion engines are characterized by lower toxic emissions of exhaust gases [2].

There has a tendency to increase the capacity of electrochemical batteries in newly designed hybrid vehicles (Fig. 1). Presently there is a rapid development in energy storage systems technology. This applies in particular to the capacity and density of these cells. There is also a noticeable decrease in the cost of production of cells, prolongation of life and even an increase in safety (Fig 2) [1].

Despite such great development, it is impossible accurately to determine the lifetime of a lithium-based or metal-hydride battery. This is due to the lack of accurate models describing the nonlinear aging of cells of this type and the different effects and factors that cause the degradation of the cells. Vehicle drive controllers are based on inaccurate data and simple models. It is difficult to determine the technical condition and wear rate of lithium cells. Different degradation can occur even between vehicles of the same brand and model. This is influenced by the way the car is being driven or the conditions in which the cells are used, i.e. driving techniques, number of loads and full discharges, atmospheric conditions (temperature) and many others factors.

a) b)

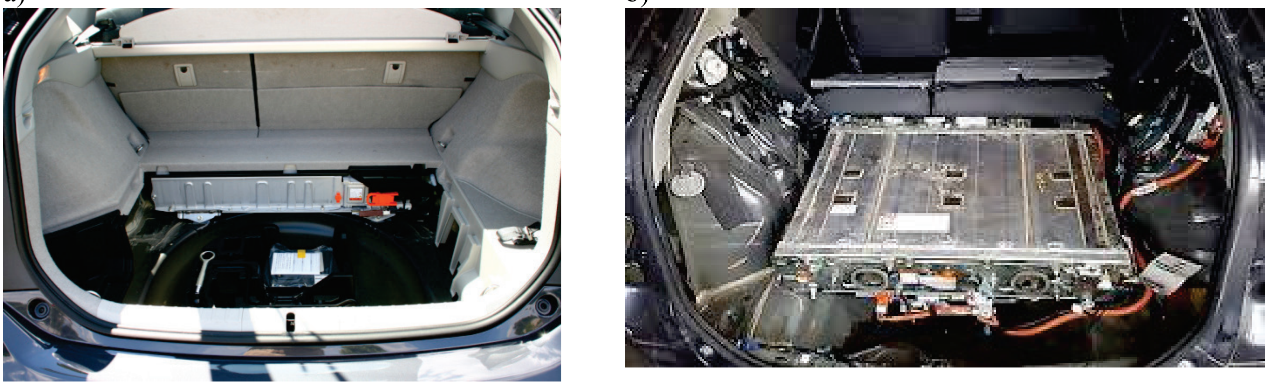


Fig. 1. A view of battery pack: a) Toyota Prius from 2004, b) Toyota Prius Plug-in from 2014 (source: a – author's archive; b – www.egmcartech.com)

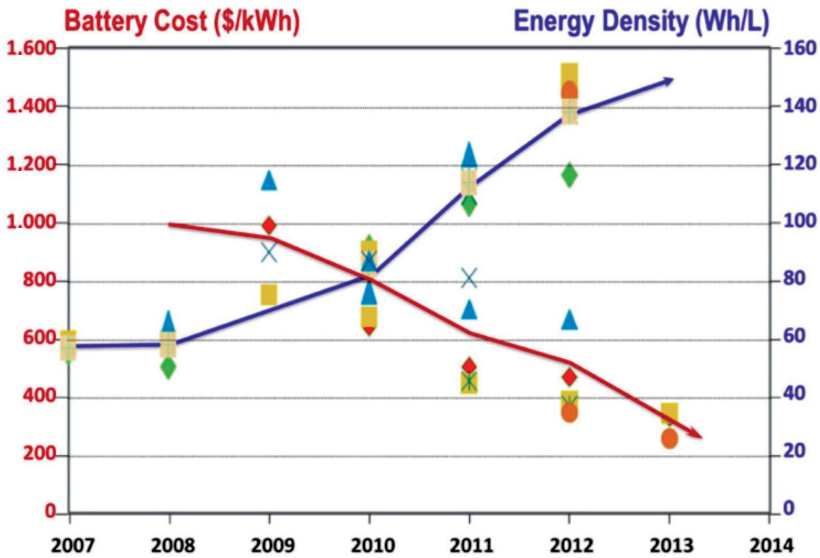


Fig. 2. Increase of battery capacity (blue line) and decrease of battery cells costs (red line) (source www.greencarreports.com)

Aging processes of a battery are mainly connected to [2, 3, 4];

– formatting/reformatting of cell electrolyte,
– contamination occurs during cell production,
– creating lithium layer on aa anode during use,
– corrosion of battery elements,
– migration of electrodes material to the electrolyte layer.

The loss of battery capacity can also occur due to, mechanical damage or improper vehicle maintenance.

These processes change the energy delivery process characteristics, which can cause a decrease in the cell's capacity as well as a decrease in power output. Depending on the type of vehicle, these processes may have a greater or lesser effect on the behaviour of the drive system. Hybrid vehicles are built to provide high power in a short time. This is due to high current consumption from the battery when starting the vehicle. A battery with noticeable aging processes will be less energy-efficient or even, in extreme cases, the entire high-voltage system of the vehicle will be shut down. Battery cells of electric vehicles are not loaded as high as they are in hybrid vehicles, because of their large numbers in vehicle. For them, the biggest problem is the decrease in capacity, resulting in reduced vehicle range and consequently more frequent charging, which as a result, further shortens the life of the cell.

By counteracting the processes of reducing energy storage efficiency, car or battery systems manufacturers use solutions designed to prolong the life of the battery without apparently changing its parameters. Some of these solutions are:

– renting batteries to the user of the vehicle,
– installing additional cells that are "turned on" when the battery driver detects a fault in the working cell,
– software and hardware limitation of nominal battery parameters, both charging/discharging currents and capacities to approximately 80-90% of the range of its operating characteristics is used,
– using all of the solutions mentioned above.

At present, the most popular solution is using hardware and software that limits battery capacity [6]. The battery operates in a narrower characteristic range. In case of aging, as long as battery values do not exceed the programmed parameters (f.i. maximum current, capacity, voltage drop), vehicle users will not notice any signs of system aging.

2. Drivetrain's mathematic model

The aim of the study was to compare drivetrains parameters of a vehicle in two different cases of battery state of health conditions, and how battery capacity will influence to the vehicle's drivetrain behaviour.

The vehicle's drivetrain model was developed in the AMESim environment of SIEMENS Company. This is a complete computational system for the simulation of multi-mechatronic systems. Fig. 3 shows the main components of a model set. Used elements such as vehicle (3) with electric power transmission system, driver model (2) mapping selected road test (5). Power transmission system consisted of controller (1), electric engine (4) with engine controller and battery (6). In presented model, there is the possibility to take into account parameters such as wind speed and slope angle during testing.

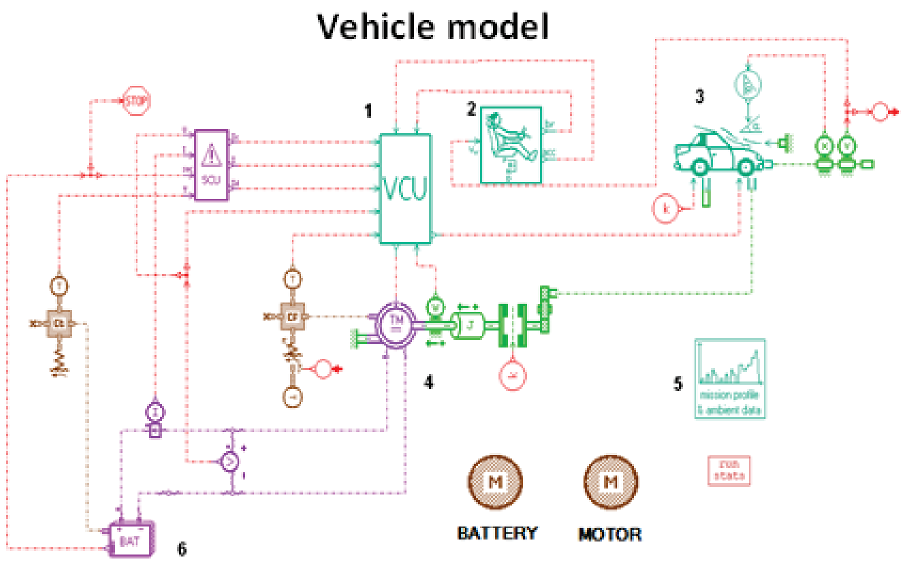


Fig. 3. Model of a vehicle's drivetrain presented in AMESim

During simulations, a model of an electric vehicle, introduced on a figure 3 was used. The chosen vehicle parameters were as follow:
- vehicle's mass: 1695 kg,
- electric engine power: 60 kW,
- battery cell capacity: 2.3 Ah,
- battery voltage: 330 VDC.

A key element of the mathematical model was the correct identification of the characteristics of the cells used in the study. For this purpose, the characteristics of the new $LiFePO_4$ cells of 2.3 Ah capacity, and the cells, which had been subjected to multiple cycles of loading and unloading in laboratory conditions were used. The vehicle's battery consisted of 100 cells connected in series and 10; these modules are connected in a parallel formation (100S x 10P x 2.3 Ah). Due to the fact that it is difficult to predict the aging process of cells with the same parameters and the same manufacturer, but used differently (fi. different loading and depletion), the technical condition of the battery of a real vehicle may differ from that used in the simulation.

3. Simulation test

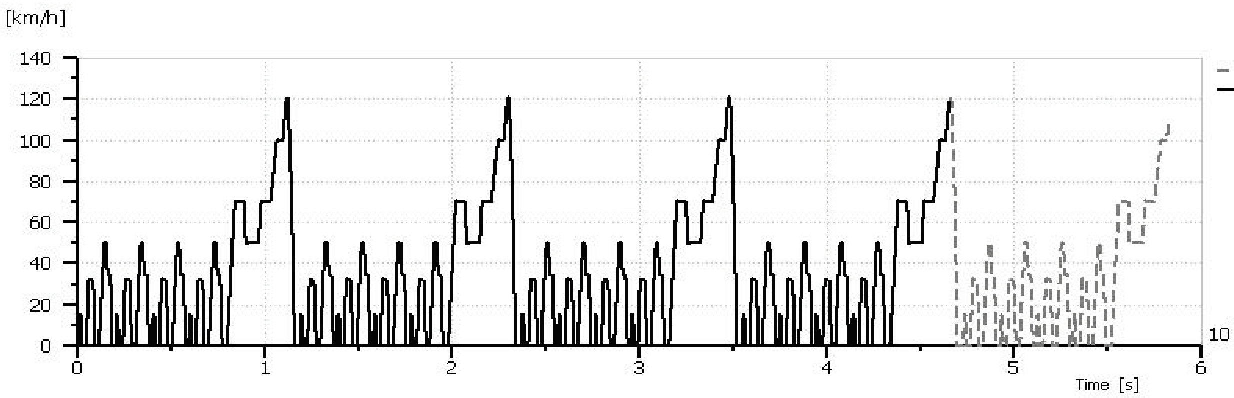
Simulation test consisted of passing a NEDC road test by a vehicle. NEDC test was selected for the study, due to Regulation ECE R83.03, EU directive 98/68 EC. It is a standard test procedure for testing vehicles up to 3500 kg.

The average vehicle speed during the test was about 16 km/h. The vehicle was required to perform the test repeatedly from 100% state of charge, until the battery was completely discharged. Set limit was 10% SOC.

Two variants were tested. First, it was assumed that the parameters of the vehicle and its propulsion system would be the same as that of a new vehicle. In the second variant, it is assumed that the battery parameters will change, the capacity of which will be reduced by approximately 18%. This level of cell wear is usually around 8 to 10 thousand charging cycles [5]. The vehicle was equipped with 2.3 Ah capacity cells, cells connections (100S x 10P) gave 330 VDC and 230 Ah capacity. For 18% of the capacity drop gives 1.9 Ah. Others test parameters remained unchanged, including the configuration and charge level of the battery pack and the parameters of the vehicle's propulsion system. The test ended when the vehicle reached set limit of battery state of charge. The results of the comparison of selected parameters of the propulsion system and vehicle performance are presented in Fig. 4-9.

The difference in ratio of the number of cycles of the road test (Fig. 4a), between the two technical conditions of the battery is one NEDC road test. The graph ends when the vehicle is running at the highest speed and emergency shutdown of the HV system is added, which can further endanger the vehicle and road users. Fig. 4b presents the range covered by the vehicle with a new battery (grey colour) and with a reduced capacity battery (black colour). The range of the vehicle with a new battery is about 54 km, which the vehicle travels in about 97 minutes, with a variant of 18% less capacity, the difference is about an 8 km decrease in distance, with percentage drops of about 15%. Fig. 5a shows the charge status of the battery as a function of distance travelled by the vehicle. In the model presented, the charge of the new and aging battery is similar. The difference is a faster decrease in the battery level and the differences between the new battery (grey colour) and subjected to aging processes (black colour) are caused by a decrease in its capacity. A programmed 18% depletion of battery cells results in a faster decrease in battery charge, in proportion to the capacity of the battery. For the first travelled kilometres the difference is barely noticeable and at the end of the test, when the battery is fully discharged, the difference is about 20% of the charge, which translates into a shorter range of about 8 kilometres. This can be seen in Fig. 5b, where voltage of a single cell is presented. Open circuit voltage of a new cell is 3.360 VDC in respect to old cell which OCV equal 3.355 VDC. Lithium and NiMH cells characteristics gave similar voltage level for the new and aged battery. A new cell can be discharged deeper, and discharge processes cause less temperature increase (Fig. 6).

a)



b)

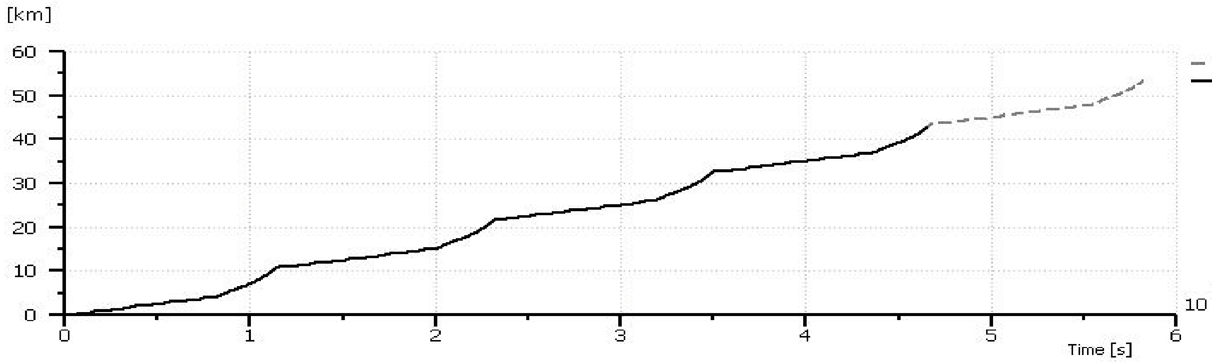


Fig. 4. Vehicle's range investigation: a) NEDC test profile and number of overcomes road tests b) range of the vehicle (time vs. range characteristic) during examination

The difference in cells voltage occurs because of cell active area degradation. As mentioned before, this difference can be greater or smaller during normal conditions, because of different mechanism that cause aging processes.

As the load increases due to higher vehicle speed, the battery cell temperature rises (Fig. 6). The higher the battery load and the longer the battery life, the higher the temperature of the battery. Figure 6 shows temperature changes during test in respect to the test profile (dotted line in background). In new cells, the increase is about 4°C, from 20°C to 24°C (grey), and for the old battery (black), the rise in temperature in the cells are between 20 and 27°C and are associated with higher load currents, internal cell processes, the increase in internal resistance is also significant, as shown in Fig. 7. Moreover, increased temperature cause faster cell degradation.

The change in internal resistance of the cells is shown in Fig. 7. In the background, test profile is shown. Ohmic resistance of a new cell is within the range of 0.08 to 0.11 Ω during the entire battery SOC. For the old cell the increased internal resistance can be observed during the entire state of charge range, which at the beginning is 0.13 Ω and increases to 0.26 Ω during the test. This value is greater, the greater is the degree of discharge of the battery, and the peaks shown in the graph are associated with increased battery load resulting from increased vehicle speed (increase in motion resistance), causing higher power consumption to achieve the required vehicle speed.

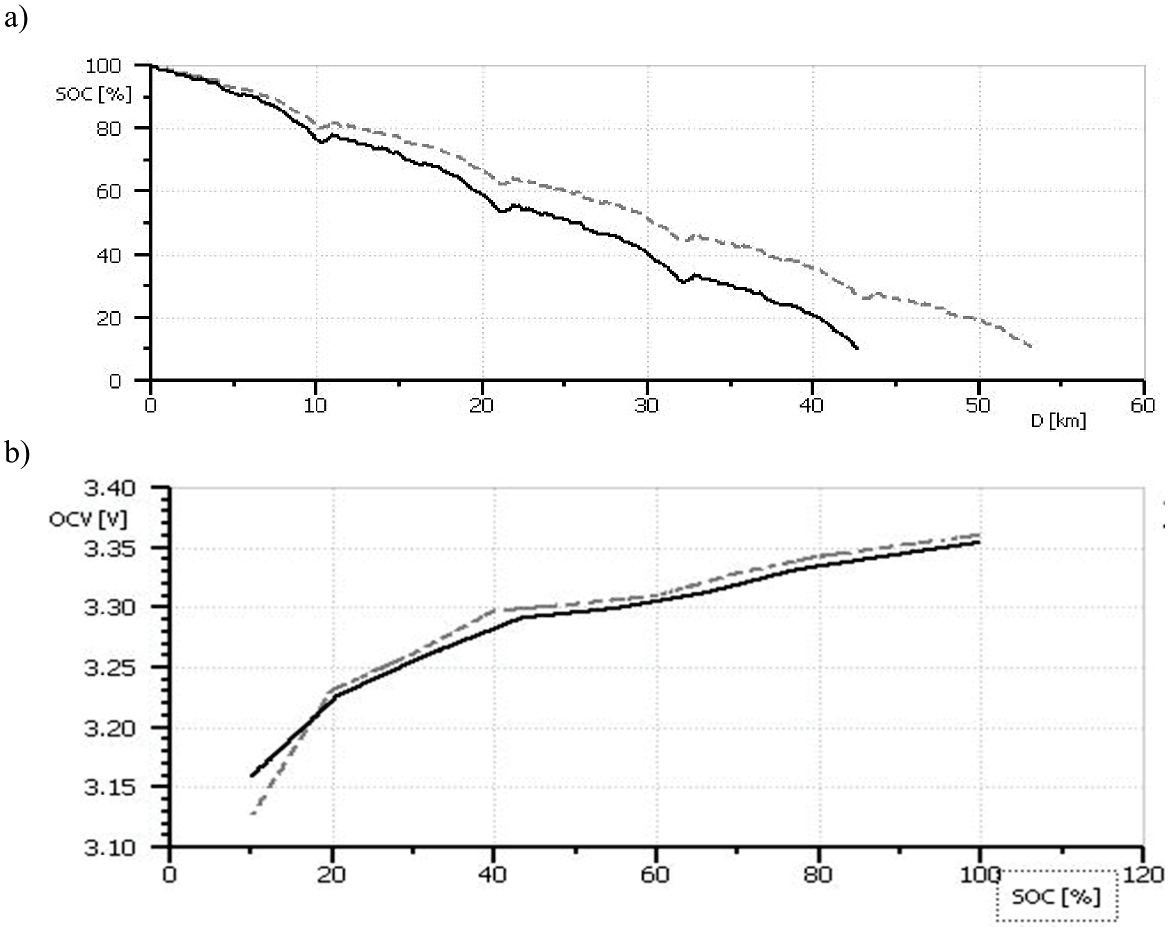


Fig. 5. Battery capacity and vehicle's displacement during test

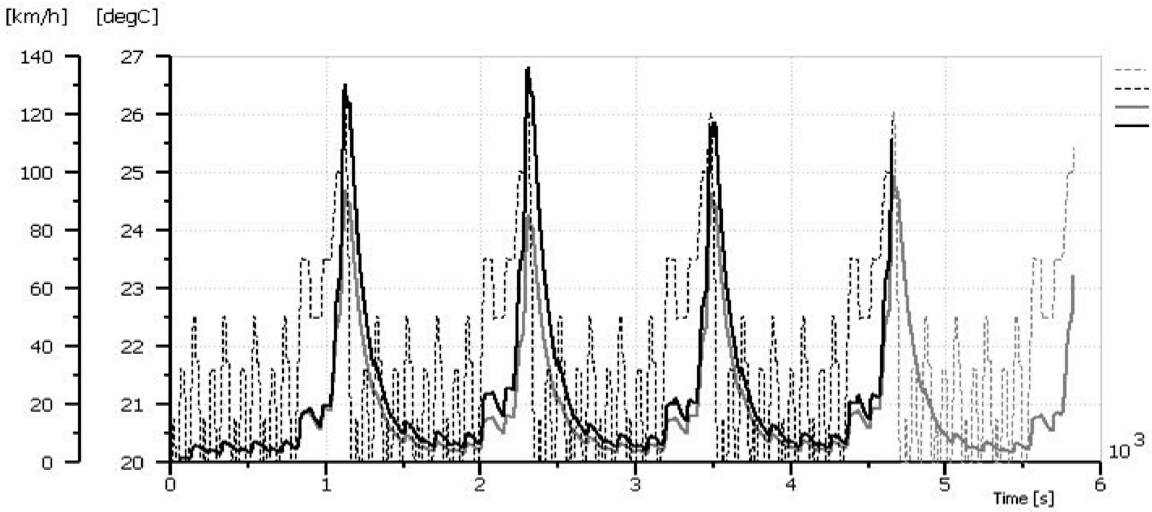


Fig. 6. Temperature changes of new (grey) and old cell (black) during test

4. Conclusions

- Battery aging processes are dependent on a number of factors, which makes it difficult to determine the technical condition of the battery considering the age of the battery or the number of charge cycles,
- The research shows that even a small battery capacity loss (in the presented model – 18%) affects the range of the vehicle (about 15%),

- The linear dependence of the cell resistance assumed for the simulation is related to the aging model of the $LiFePO_4$ cell – multiple charge and discharge cycles,
- As long as battery will produce significant capacity loss during its lifetime, the best solution to keep nominal capacity is software limitation of the battery pack operating capacity. During cell aging, battery management system (BMS) will augment its characteristic.

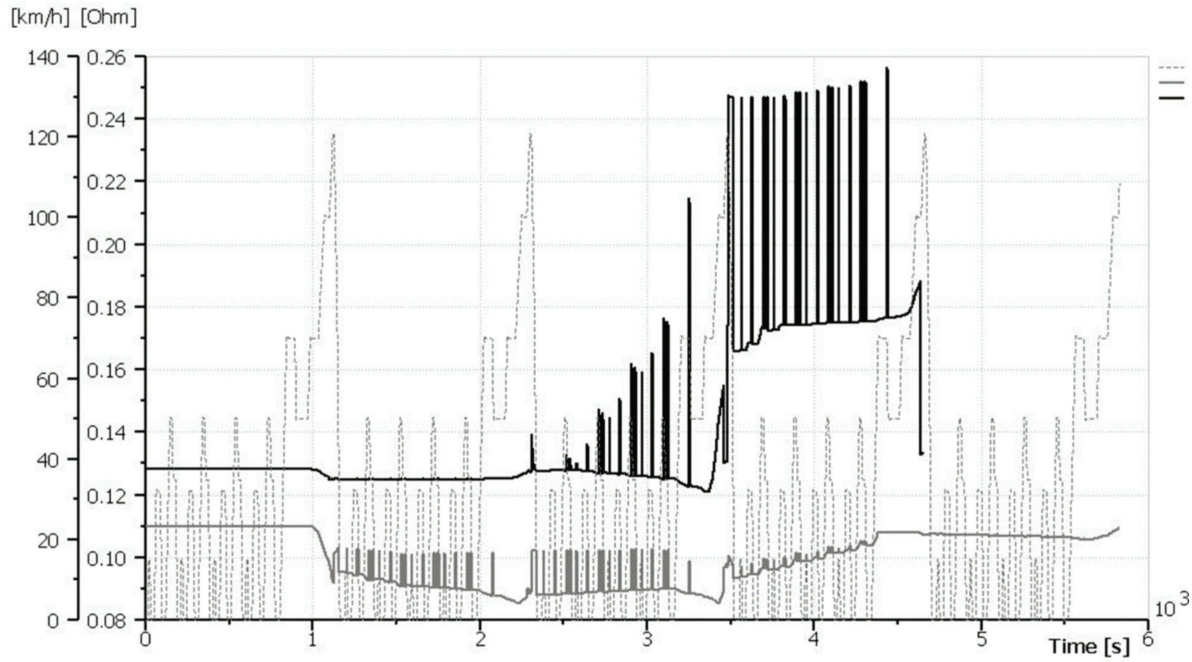


Fig .7. Internal resistance changes of new cell (grey) and old cell (black)

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