CONSIDERATIONS ABOUT INCREASING THE Li-ION BATTERY EFFICIENCY BY USING THEM AS ENERGY SOURCE FOR VEHICLES

Cristina PITORAC[1]

This article proposes technical ways of reducing of the biggest disadvantages of using Li-Ion battery as traction batteries in the automotive world starting from the analysis of the battery behavior by its implementation in an electric vehicle and continuing with the case studies of hybrid systems based on battery - supercapacitor and battery - supercapacitor - fuel cell. The analysis will be done by comparing the power losses of the battery after running the FTP75 driving cycle. The influence of of the hybrid systems parts on the cost of the electric propulsion system it will also be detailed.

Keywords: battery, hybrid, power sources, super-caps, fuel cells

1. Introduction

The climate change is a reality and its impact on us has grown in the last years. The climate is changing because of the way of life of people, particularly in the richer and more developed economically countries (EU being included in this category). Vehicles, airplanes and factories are playing an important role in climate changes and are contributing to the growth of so called "greenhouse gases". A way to „greenhouse gases„ reduction consists in improvement of the electrical vehicle. [1]

The electric vehicle is designed for short distance daily trips (ca. 100 km) with periods of pause for charging, which is within the autonomy that currently electric batteries can provide. Thus the electric vehicle is more likely becoming the future way of transportation, at least in the terms of coverage of a certain market segments. [2]

The power source of the electric vehicles is mostly the Li-Ion battery. Following the last years of research and development, the lithium battery has become more reliable in operation providing a high capacity of energy storage at a reduced weight. The purchase price of such a battery has dropped in the recent years enabling the market development of electric cars with lithium battery, despite its disadvantages such as autonomy and lifetime. These disadvantages have direct influence on the cost of an electric vehicle, which is the reason why

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the percentage of the currently produced vehicles with classic propulsion systems is still very high. [3] [4]

This article proposes technical ways of reducing of the biggest disadvantages of using Li-Ion battery as traction batteries in the automotive world starting from the analysis of the battery behavior by its implementation in an electric vehicle and continuing with the case studies of hybrid systems based on battery - supercapacitor and battery - supercapacitor - fuel cell. The analysis will be done by comparing the power losses of the battery after running the FTP75 driving cycle. The influence of these systems on the cost of the electric propulsion system it will also be detailed.

2. Simulation model

2.1. Sizing and simulation model of the considered battery pack

The battery sizing is done for an electric vehicle with five places and a maximal speed of 160 km/h. The simplified schematic of the electrical vehicle is shown in fig 1. [5]

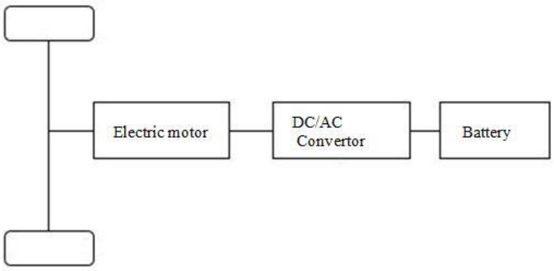

Fig. 1. Simplified schematic of the electrical vehicle

The periphery system of the electrical vehicle will not be considered in the calculation in order to simplify the simulation model. As result of the simulation the power losses of the battery through heat will be estimated.

The detailed calculation is described in [5] and the results are centralized in table 1.

Table 1

Speed dependency of the needed power of the electrical vehicle

Speed [km/h]	0	55	110	148	160
Power [kW]	0	16	32	43	45

Estimating a high voltage grid of 300 to 400 V for the electrical vehicle, the battery sizing can start from determining the cells number of one module of the battery with the condition that its voltage should achieve the grid voltage.

Considering the nominal voltage of a Li-Ion cell of 3.7V, the number of cells connected in series per battery module will be 90.

The electrical characteristics of the considered Li-Ion cell are shown in table 2. Based on this data, the total power of a battery module of 90 cells in series connected will be 9 kW. [6]

Table 2

Characteristics of considered cell

Type	Pouch
Capacity [Ah]	28
Voltage min/nom/max [V]	3.4/3.8/4.1
Current min /max [A]	-270 /120
Energy [Wh]	100

As shown in table I, the maximum needed power of the projected electric vehicle is 45 kW. Knowing this, the number of the battery modules connected in parallel will be 5. Therefore, the considered high voltage battery will have a 90s5p configuration. The battery characteristics are shown in table 3.

Table 3

Characteristics of considered battery

Battery	90s5p
Capacity [Ah]	140
Voltage min/nom/max [V]	306/342/369
Energy [kWh]	45

The schematic of the battery model is presented in Fig. 3.

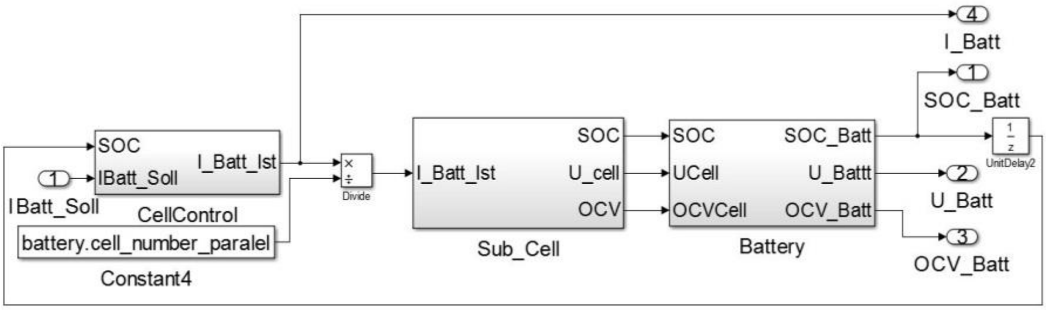

Fig. 2. Battery model schematic

The model consists of three main blocks:

- Cell control block - determines the applied current to the battery, function of SOC and maximal and minimal allowed values of battery pack currents; [7]
- Sub_Cell block – calculates the electrical characteristics of the battery cell; [8]

- Battery block – calculates the electrical characteristics of the battery pack.

The resistance values are integrated in the Sub_Cell block. For the internal resistance, a temperature correction factor was applied, as shown in table 4, where the reference temperature is 23°C. [9]

Table 4

Correction temperature factor for the internal resistance of Li-Ion Battery

Temperature [°C]	-25	-10	0	10	23	45	50
Correction factor [-]	1.1	1.07	1.065	1.035	1	0.975	0.96

2.2. Sizing and simulation model of the considered super-caps pack

For the simulation are considered the battery cell HE 40Ah from firma Li-Tec Battery GMBH and the double layer capacitor BCAP 3000 from Maxwell GMBH, with the specifications shown in table 6. [10] [11]

Table 6

Technical data of the chosen ultra-caps

Typ	Double-Layer
Resistance [mOhm]	0,29
Voltage [V]	2,7
Lifetime [cycle]	1.000.000
Max. discharge current[A]	2200
Max. charge current [A]	2200
Capacity [F]	3000

The simulation model was realized in Matlab Simulink, after the schematic, shown in Fig. 9.

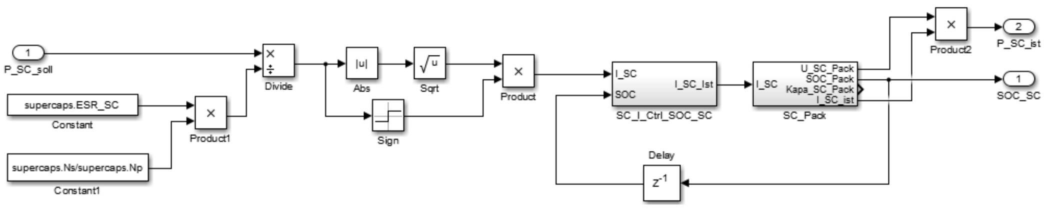

Fig. 3. Simulink model of the ultra-caps

2.3. Sizing and simulation model of the considered fuel cell pack

The fuel cell model in Simulink is presented in Fig. 4.

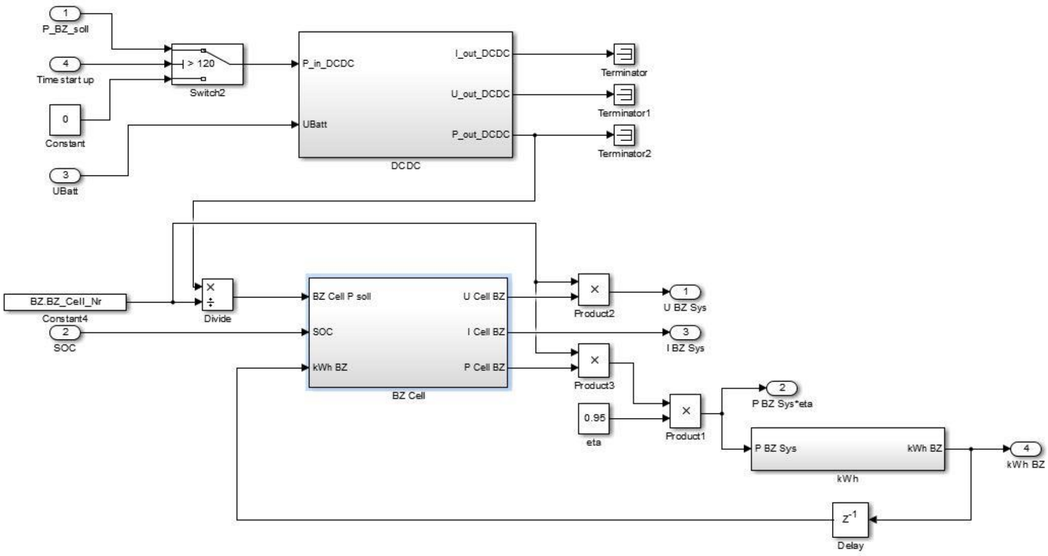

Fig. 3. Fuel Cell pack Simulink model

The fuel cell system will need 120 seconds to start time in which the generated power will be null. Using fuel cell is not possible without using a voltage convertor due its low voltage. For the simulation, will be considered a fuel cell pack of 55 cells and a ramp-up of the current of 5 A / s. The efficiency of the voltage converter shall be presumed to be 95%.

Through the “DCDC” Block will be calculated the needed power of the fuel cell system in order to overcome the efficiency of 95% of the voltage converter. The “BZ cell” block generates the electrical values of the fuel cell system and through “kWh” block is calculated the amount of energy consumed by the fuel cell system.

2.4. Battery efficiency analysis

Battery behavior will be analyzed through estimation of its power losses at different temperatures by simulation of the driving cycle FTP75. [12]

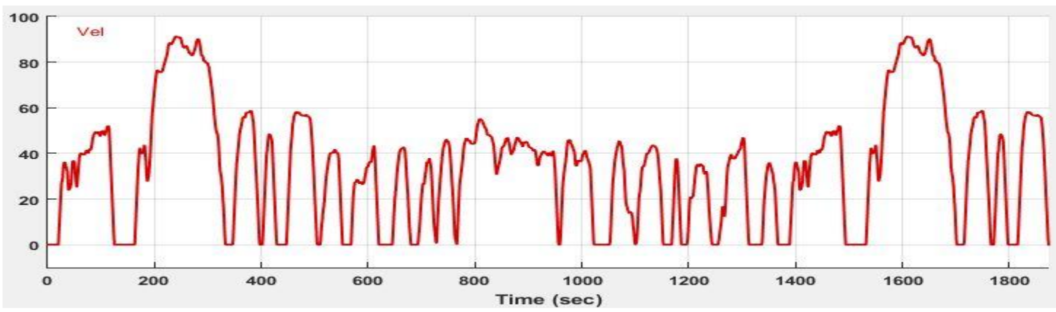

Fig. 4. Driving cycle FTP75

The considered factors for the estimation of the battery lifetime will be:

- DOD (depth of discharge) of the battery which influences the battery lifetime as shown in Fig. 6; [6]

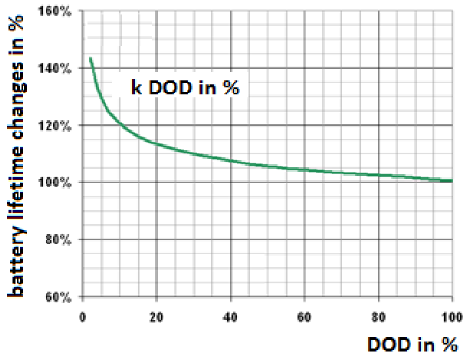

Fig. 5. Battery lifetime changes vs depht of discharge of the battery

- Dy, measured in %, depending on the dynamic of the power changes which influences the battery lifetime as shown in Fig. 7. [6]

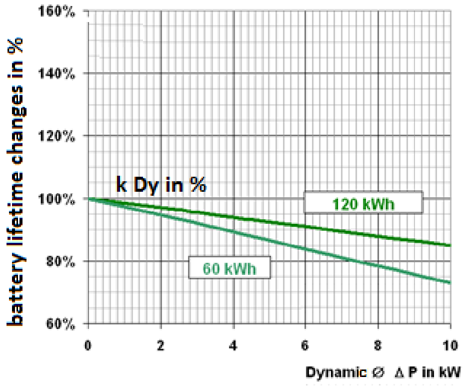

Fig. 7. Battery lifetime changes vs dynamic of power changes

3. Simulation results

3.1. Simulation results of the battery behavior by functioning in simple battery system by applying the FTP75 driving cycle. Lifetime estimation

Applying the cycle FTP75, the requested power from the battery will take the form shown in Fig. 8.

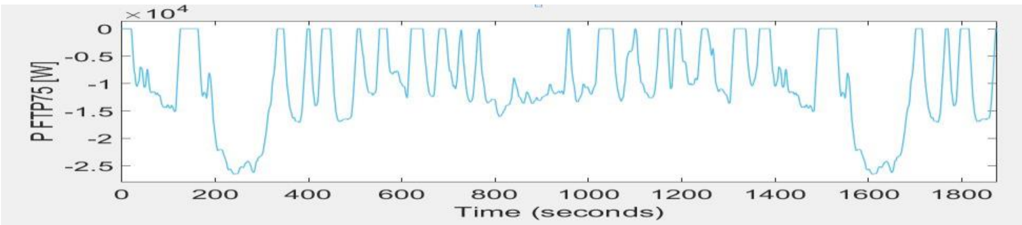

Fig. 6. Requested power of the battery

Simulation results of the battery by driving the FTP75 cycle are presented in Fig. 9.

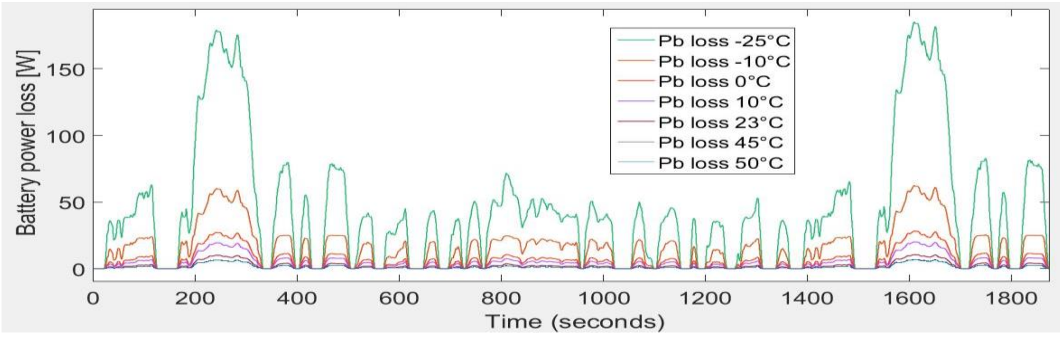

Fig. 7. Simulation results - battery power losses - battery system - FTP75 driving cycle

The battery pack power loss will be reduced by operating at positive temperatures. Yet, functioning at high temperatures can bring the battery in unsafe state. Recommended temperature range for the functioning of the battery is 10°C-30°C. All other temperatures will alter the battery, shorting the life time.

Based on the considered factors for the battery lifetime estimation described above, the simulation result can be centralized as in table 5.

Table 5

Simulation results - battery lifetime estimation - battery system

Simulation results	Battery
Battery capacity	45 kWh
Number of complete discharges in one year	800
Normal battery lifetime [lifetime = 3000 cycles]	3,75 years
Battery lifetime	100%
Φ P_V Battery	200 W
Heating per 200W	7,4 K
Battery lifetime: factor k P_V	84%
ΔDOD	11 %
Battery lifetime:factor k DOD	120 %
Battery lifetime: factor k Dy	87 %
Expected battery lifetime	3,5 years
Battery costs: 1000€ / kWh	45.000 €
Costs of the storage system per 10 years	120.000 €

The power peaks, as well the dynamics changes of the power request will be ensured by the Li-Ion battery. Needing 10% DOD to run one time the FTP75 cycle, the electrical vehicle will ensure autonomy of 108 km.

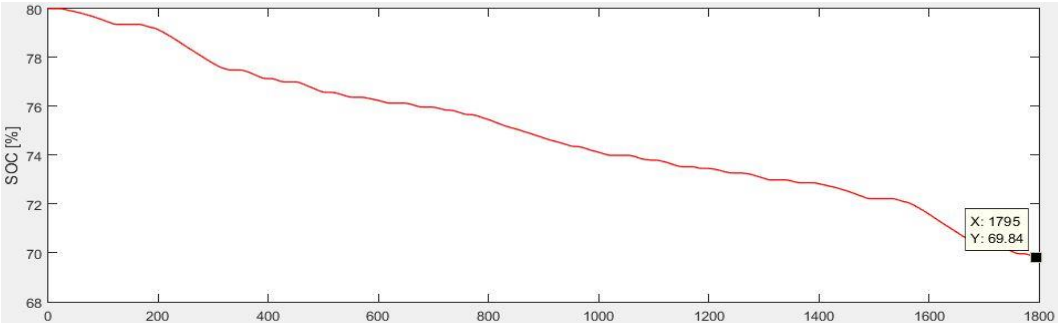

Fig. 8. Battery state of charge - FTP75

The battery cost is directly influenced by its lifetime. The urban regime trips are requiring many and dynamic changes of the speed values which reflect in a high stress applied to the battery. When running in urban areas is remarkable frequent changes in the value of the speed of electric vehicle, with frequent acceleration and braking, transposing them to the battery level in a high stress applied to it. Stress applied to the battery will decrease its storage capacity and will directly influence life and its autonomy.

As the required power changes are more pronounced, the internal resistance of the battery pack is higher. Battery stress reduction will result in a reduction of power losses of the battery. Simulating the operation at different temperatures highlights the power losses of the battery at dynamic changes of the power request. Power losses have direct influence on the battery lifetime. In addition to a classical battery cooling system, this article proposes the introduction of the super-caps in order to reduce the battery stress.

3.2. Simulation of the battery behavior by functioning in hybrid system battery- ultra-caps by applying the FTP75 driving cycle. Lifetime estimation.

Frequent changes of power demand will deplete the battery, will decrease its DOD limit, and will be reflected in denial of charge because of its inside chemical changes, thus reducing the electric range of the vehicle.

Reducing the battery stress will result in a longer battery lifetime and cost reduction as shown through the simulation of the Li-ion battery behavior in hybrid system battery- ultra-caps.

The results were obtained by applying the power profile of the analyzed driving cycle, shown in Fig. 2.

The biggest advantage of introducing the super-caps consists in reduction of the battery stress. The power peaks are taken over by the ultra-caps, which have a long lifetime immune to dynamic power changes. The curve of the power losses of the battery by running in a hybrid system is shown in Fig. 11

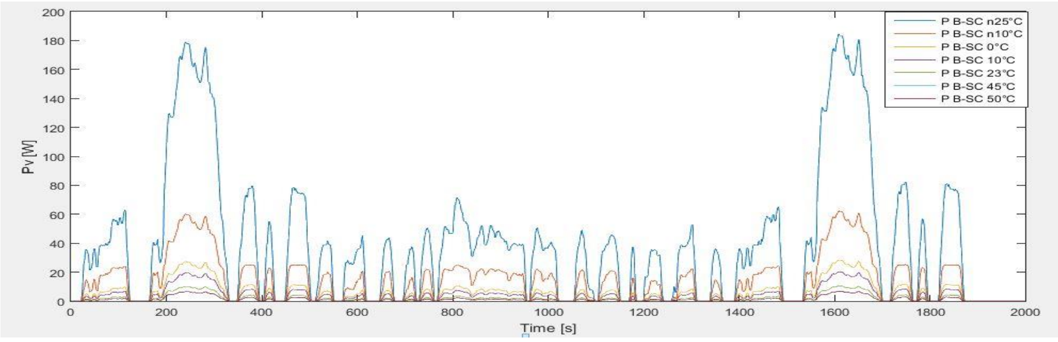

Fig. 9. Simulation results - battery power losses - hybrid system battery - ultra-caps - FTP75 driving cycle

Based on the considered factors for the battery lifetime estimation described above, the simulation result can be centralized as shown in table 7.

Table 7

Simulation results - battery lifetime estimation - hybrid system battery - ultra-caps

Simulation results	Battery	Battery + Ultra-caps
Battery capacity	45 kWh	45 kWh
Ultra-caps	-	138 × 3000F
Number of complete discharges in one year	800	1983
Normal battery lifetime [lifetime = 3000 cycles]	3,75 years	5 years
Battery lifetime	100%	133 %
Φ P_V Battery	200 W	170W
Heating per 200W	7,4 K	4 K
Battery lifetime: factor k P_V	84%	95%
ΔDOD	11 %	10 %
Battery lifetime:factor k DOD	120 %	118%
Battery lifetime: factor k Dy	87 %	98%
Expected battery lifetime	3,5 years	5,2 years
Battery costs: 1000€ / kWh	45.000 €	20.000 €
Ultra-caps + DC convertor costs:	-	15.000€
Costs of the storage system per 10 years	120.000 €	70.000 €

Power peaks will be taken over by the ultra-caps and the remaining requested power will be provided by the battery pack. Because of their capacity of saving energy only for a few seconds, the ultra-caps will have no bigger influence on the autonomy of the considered electrical vehicle.

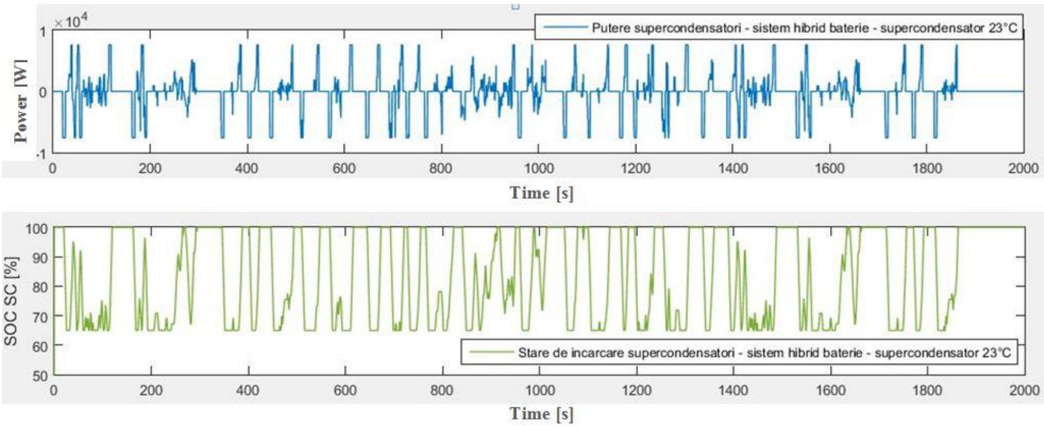

Fig. 10. Simulation results - Super-caps power curve and SOC curve - FTP75 - 23°C

Is to be observed the rapid response of the super-caps changing their SOC between the admitted limits in time intervals of seconds. Their capacity of rapid charge permits to save a bigger part of energy recovered by braking the vehicle. Based on the simulation results, the battery stress is reduced through the presence of the super-caps with 30%, due the fact that the power peaks are taken over by the super-caps.

The autonomy could be increased by introducing in the hybrid system battery - ultra-caps of a fuel cell system. The Ultra-caps will reduce the battery stress and the fuel cells will increase the electrical vehicle autonomy by charging the battery.

3.3. Simulation of the battery behavior by functioning in hybrid system battery- ultra-caps - fuel cell by applying the FTP75 driving cycle. Lifetime estimation.

In order to integrate the fuel cell pack as range extender the electrical drive system it will be so design that the requested power will be covered by the super-caps and battery and the fuel cell pack will work with the minimal power in order to determine the maximal autonomy of the electric vehicle. The fuel cell pack will maintain the state of charge of the battery between the operating limits.

The simulation results are shown in the figure below by representing the power curves of each component of the hybrid battery - supercapacitor - fuel cell system. The chosen temperature for the simulation is 23 °C.

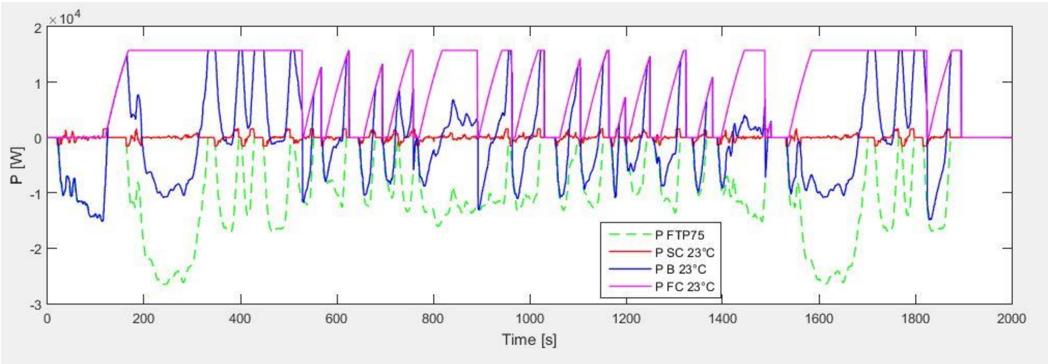

Fig. 11. Simulation results – power curves - 23°C

Due the presence of the fuel cell pack, the state of charge of the battery will be at the end of the simulation of the driving cycle FTP75 at 80%.

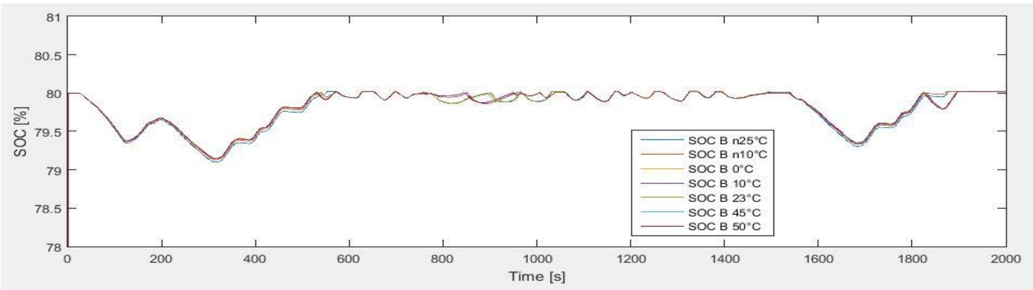

Fig. 12. Simulation results – battery state of charge vs simulation temperature

The battery power losses by functioning in the hybrid system battery - ultra-caps - fuel cell is shown in Fig. 15.

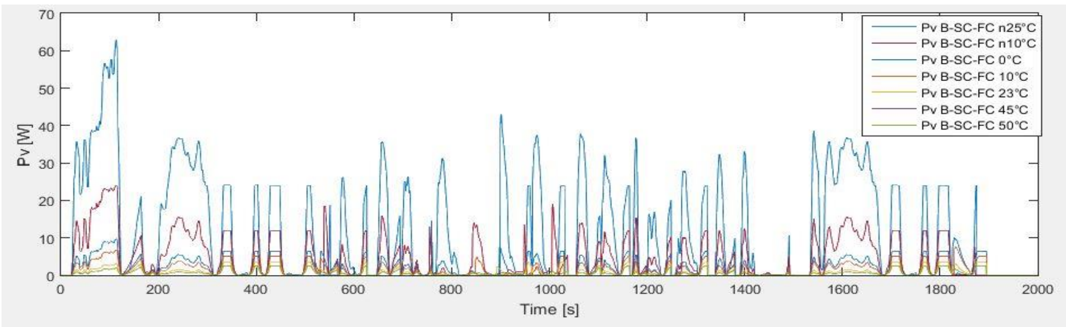

Fig. 13. Simulation results - battery power losses - hybrid system battery - ultra-caps - fuel cells - FTP75 driving cycle

Because the battery state of charge of the battery is maintained at a constant value through the fuel cell pack, the battery power losses are much lower than the simulation results battery- super-caps hybrid systems.

The implementation of the fuel cell pack in the hybrid system battery - ultra-caps will reflect in a at least double autonomy of the electrical vehicle. This advantage will be seen in 10-year battery price calculation, as shown in the following table.

Table 8

Simulation results - battery lifetime estimation - hybrid system battery - ultra-caps - fuel cells

Simulation results	Battery	Battery + Ultra-caps	Battery + Ultra-caps + Fuel cells
Battery capacity	45 kWh	45 kWh	45 kWh
Ultra-caps	-	138 × 3000F	138 × 3000F
Fuel Cells			max 30 kW
Number of complete discharges in one year	800	1983	300
Normal battery lifetime [lifetime = 3000 cycles]	3,75 years	5 years	7 years
Battery lifetime	100%	133 %	190 %
Φ P_V Battery	200 W	170W	170W
Heating per 200W	7,4 K	4 K	2 K
Battery lifetime: factor k P_V	84%	95%	100%
ΔDOD	11 %	10 %	3 %
Battery lifetime:factor k DOD	120 %	118%	140%
Battery lifetime: factor k Dy	87 %	98%	98%
Expected battery lifetime	3,5 years	5,2 years	7 years
Battery costs: 1000€ / kWh	45.000 €	20.000 €	20.000 €
Ultra-caps + DC convertor costs:	-	15.000€	15.000€
Fuel cells + DC convertor costs:	0 €	0 €	50.000€
Costs of the storage system per 10 years	120.000 €	70.000 €	90.000 €

4. Conclusions

This article proposes an analysis of battery behavior by its implementation in electric vehicles, as well case studies of hybrid systems such as battery - super-caps and battery - super-caps - fuel cells, in order to highlight the reduction of the disadvantages of using Li-Ion batteries by reducing them applied stress and thus increasing their lifetime.

Battery life is directly influenced by temperature. Power losses generated through the operation of the battery will be transformed into heat thus increasing the internal temperature of the battery. The higher the demand of the battery power is, the greater are the battery power losses.

Power losses have direct influence on the battery lifetime. In addition to a classical battery cooling system, this article proposes the introduction of the super-caps in order to reduce the battery stress.

The simulation results are showing that the introduction of the super-caps pack will almost double the lifetime of the battery, likewise a cost reduction of 30%.

The effect of using super-caps consists in reducing the battery stress through reduction of its power losses. The decreased ramp of the power request through the presence of super-caps permits the battery to operate for a shorter time and to decrease the requested power peaks. The biggest advantage of introducing the super-caps consists in reduction of the battery stress. The power peaks are taken over by the ultra-caps, which have a long lifetime immune to dynamic power changes.

Because of their capacity of saving energy only for a few seconds, the ultra-caps will have no bigger influence on the autonomy of the considered electrical vehicle. The autonomy could be increased by introducing in the hybrid system battery - ultra-caps of a fuel cell system. The ultra-caps will reduce the battery stress and the fuel cells will increase the electrical vehicle autonomy by charging the battery.

The implementation of the fuel cell pack in the hybrid system battery - ultra-caps will reflect in a at least double autonomy of the electrical vehicle.

The power peaks will be taken over by the super-caps system. The fuel cell system will operate in its optimal range of functioning. The super-caps SOC will decide the battery function and the battery SOC will activate the fuel cell system operation.

The evolution of the power management of the hybrid energy source is presented below. Its aim is to reduce the focus on reducing the battery stress which will reflect in a bigger battery lifetime and lower costs of the energy source.

If considered a waterfall strategy, in which the power changes in seconds range will be taken over by the super-caps, the power changes in minutes range will be taken over by the battery and the power changes in hours range will be taken over by the fuel cells, the operating strategy could be graphically represented as shown in Fig. 16.

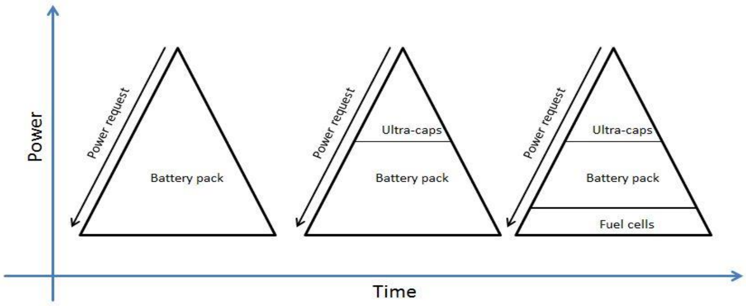

Fig. 14. Power management strategy

By simulating the driving cycles FTP75 is to see that the implementation of the hybrid system battery-ultra-caps-fuel cell has at least three big advantages: bigger life time of the battery, bigger autonomy and smaller prices for the clean tech technology.

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