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HyHEELS

Hybrid High Energy Electrical Storage

SPECIFIC TARGETED RESEARCH OR INNOVATION PROJECT

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Revision and history chart

Version	Date	Reason
0.1	21.11.2008	Initial template & structure by IMC
1.0	02.06.2009	Compiling of partner inputs.

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Executive publishable summary

The overall goal of HyHEELS was to provide an UltraCap energy storage system for the use in hybrid- and fuel cell vehicles, which satisfies all properties necessary to make an integrative component. Therefore, the development work comprised the optimisation of the electric properties of the basic cap, its combination into scalable modules with integrated power balancing within the modules, power prediction and the communication interface with the drivetrain.

The work programme consist of two technical work packages 1000 and 2000 for the development of the UltraCap modules and the UltraCap controller, and a work package 3000 concentrating on simulation & modelling as well as on testing & evaluation of the developed hardware.

After the kick-off meeting several workpackage meetings take place to achieve a fine tuning of the project.

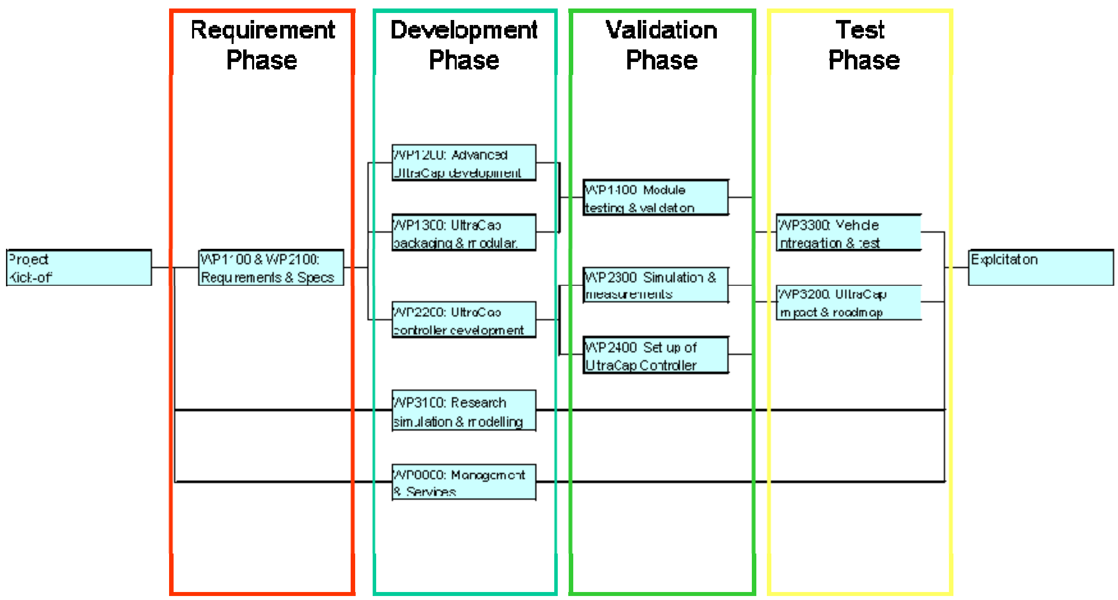


Figure 1: Project phases of HyHEELs.

The requirement phase of the UltraCap module specification as well as of the UltraCap Controller specification was finished in the first project year. Further activities were conducted in the development phase, which were part of WP 1200 and 1300 as well as WP 2200 and WP 3100 within the second project year. These activities covered the cell and the module development of the capacitors, the set up of the UltraCap controller prototype which will include cell balancing and voltage measurement and consideration regarding to design simulations of the power train. Furthermore the evaluation of modules based on traditional UltraCaps was conducted and simulations of the power losses of the UltraCap controller were performed and measurements were done.

As one partner left the consortium the tasks of this partner were shifted to internal partners of the consortium.

All partners proceed with their activities. However these discussions and additional deliveries results in a delay of the project as several activities could not started at time.

The actual project duration was prolonged until end of the year 2008. The final, total project period was 38 months.

Results of WP1000

Within the HyHEELS project a newly cell/stack technology was developed and a new module was designed. The stack is made of one positive cell and one negative. On one side the positive electrode is connected to the lid and the other side to the bottom can. The 2 bottom can thickness, once laser welded together, have the same thickness as the lid. A plated connection is laser welded between the 2 cells to give a very low resistive connection for voltage measurement. A thermal shrink tube insulates the stack.

Figure 2: A completed stack with two aluminum connectors (+) and (-), shrink sleeve.

			HyHEELS Cell		
	Unit	Initial	Current	Improved	Target
Nominal cell voltage Un	V	2.5	2.7	2.7	2.7
Maximum cell voltage Umax	V	2.7	2.85	2.85	2.85
Gravimetric energy density at Umax	Wh/kg	3.7	6.6	7.5	7.5
Volumetric energy density at Umax	Wh/l	5.0	9.0	9.0	9.5
Gravimetric power density at Umax	kW/kg	3.5	10.3	15.6	15.0
Volumetric power density at Umax	kW/l	4.7	14.0	18.8	19.3

Table 1: HyHEELS cell current data, improved versus initial and target.

The Table 1 shows the very good positioning of the HyHEELS cell according today's standard product. The energy density, one of the major HyHEELS projects' technical targets, is already as good as a future cell with 2,85V nominal voltage.

If the tests will qualify the cell for this 2,85V voltage, the results would be even better. And the building of a 3000F cell would also increase the power and energy densities, as the increasing weight and volume is proportionally lower!

The HyHEELS final module version is presented in Figure 3.

Figure 3: HyHEELS module 54V 100F in final version, including the controller

The ESR used for the maximum power corresponds to the value measured at 1kHz. This value is about 66% of the DC ESR, which correspond to 8.35mOhms.

The possible mass of the module, using lighter plastic bases, has been evaluated to 8370g.

Using these evaluations, the calculated results are given on the line "HyHEELS possible", depending on the 2 assumptions above. (red numbers in the table)

			HyHEELS Module		
	Unit	Initial	Current	Improved	Target
Nominal cell voltage Un	V		54	54	54
Maximum cell voltage Umax	V		57	57	57
Gravimetric energy density at Umax	Wh/kg		4.9	5.4	5.0
Volumetric energy density at Umax	Wh/l		4.9	4.9	6.3
Gravimetric power density at Umax	kW/kg		7.8	11.6	10.0
Volumetric power density at Umax	kW/l		7.9	10.6	12.9

Figure 4: HyHEELS final module: measured vs targeted values

Results of the Controller development WP2000

UltraCaps are available on the market. However, there are restrictions with regard to automotive applications when looking on max. voltage and max. working temperature and packaging requirements. As the max. voltage of a single capacitor is only 2.5 V, several capacitors have to be connected in serial to a module if higher supplying voltages are required. This makes it necessary to develop an advanced UltraCap module packaging with optimised thermal behaviour, weight and cost. Furthermore, caused by different self-discharge of the single capacitors, the individual voltages of the module will drifting away. Finally, the capacitor module will be mismatched in voltage. Battery systems will be usually overcharged to keep it balanced in charge and voltage. However, capacitors could not be overcharged. Therefore, special charge balancing systems were developed in the past. These charge-balancing systems exchange the energy between the single capacitors in such a manner, that all capacitors achieve equal voltages. However, additional information about the UltraCap module and functions are necessary for a secure operation under automotive conditions.

Within WP2000 all requirements of an UltraCap controller were compiled. The prepared document "Controller requirements" was the basis for the development of the UltraCap Controller.

According to the requirements only a recharging balancing concept from an external source was possible. Therefore the following concept was chosen for the UltraCap Controller realization.

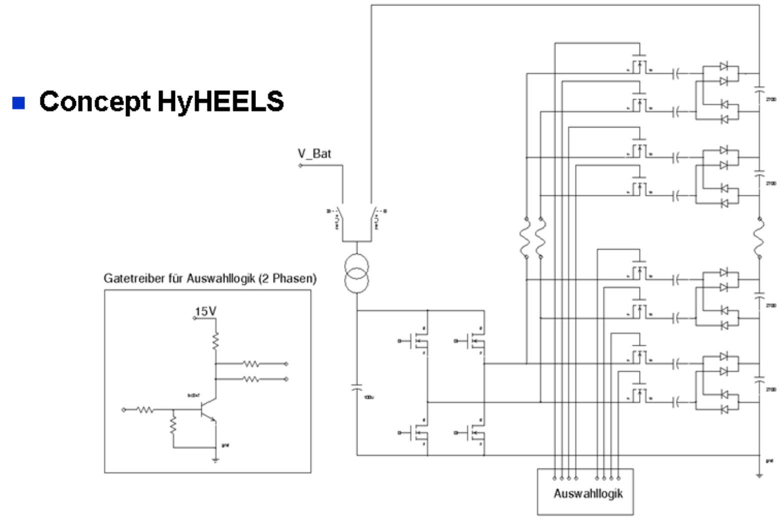


Figure 5: Selected concept for the UltraCap Controller.

This concept provides the cell voltage measurement and the recharging of weak cells with up to 1 A. Of cause additional functions were necessary for the controller. Finally the following architecture was developed to realize all requirements.

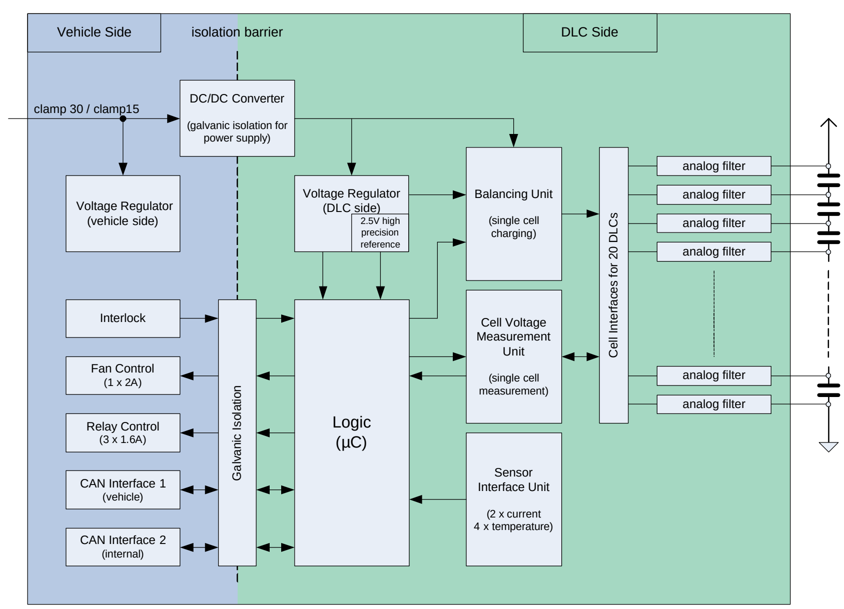


Figure 6: Architecture of the UltraCap Controller.

The UltraCap Controller has a sampling rate of 10 ms for 20 cells (voltage channels). The average failure in the voltage measurement was in the relevant voltage area better than 10 mV. Furthermore the Controller is able to calculate the ESR and the capacitance of the capacitor and therefore also provides the usable and restorable energy.

The final design of the controller is shown in the following figure.

Figure 7: Picture of fully assembled UltraCap controller

The performance as well as the mechanical design of the controller ensure the reliable operation of the module and satisfy the future requirements of all automotive applications in this area.

Results of WP3000

New simulation models were developed to design and configure the Ultracap modules for different vehicles. The simulations were validated by experimental results. The modular ultracap packs were virtual designed and recommendations for these configurations as well as for the power management strategies were provided to the OEM's of WP1000.

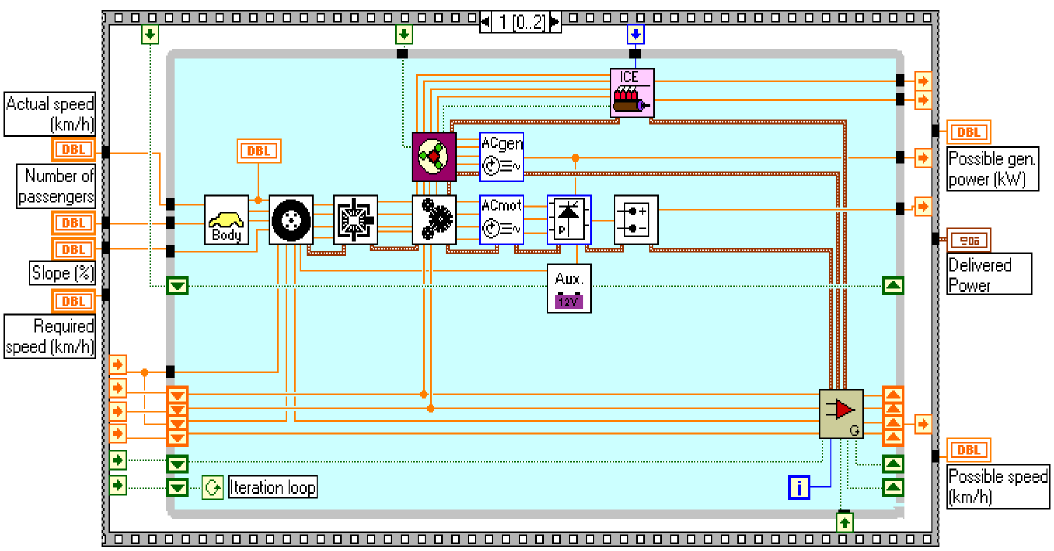


Figure 8: Representation of system modelling.

The test platform at Vrije Universiteit Brussel was applied to verify the configuration the super capacitor based energy storages for passenger cars and heavy duty vehicles, with respect to the voltage variation, maximum charging/discharging current, power losses in speed cycles (e.g. NEDC, FTP and so on).

After 55000 km equivalent driving distance on the experimental test rig, there were no over temperature, mechanical deviation or significant change in the self discharging observed.

The driving cycle tests have confirmed very good electrical stability even in the pre-series UltraCap modules. As a result, the super capacitor modules developed in the HyHEELs project are suitable for the automotive applications.

A Life Cycle Assessment was done to compare the environmental impact of ultracaps with batteries. The uncertainty analysis was performed through a Monte Carlo analysis. The ultracapacitor scored better than all the assessed battery technologies. The relatively low weight of the super capacitor and the high recyclability rate of its main material (aluminium) are the most important reasons for this. Recommendations were formulated to further improve the environmental performance of ultracapacitors.

1 Goals and objectives

Background and motivation

Since the deployment of fuel cell cars in the European fleet will constitute a process of decades (it takes more than 20 years for standard functions to reach a 90% fleet penetration) and CO_2 problems are present and demanding, the industry favours solutions with both, future potentials with innovative power trains and the possible realisation of short term benefits in combination with state of the art power train technology.

In this regard it is necessary to stress the fact that automotive technology has grown to be more and more complex in the recent years by the addition of a growing number of functionalities. OEMs addressed this challenge by decreasing the production of in-house parts and by the supply of black box like system components, the integration of which still constitutes a big challenge in terms of handling complexity. This is why the HyHEELS consortium considered it to be appropriate to focus on providing an UltraCap storage function comprising all properties necessary to make it an integrative component. This is the unanimous view of both, the supplier and the OEM regarding manageable interfaces.

Therefore the HyHEELS project comprises the optimisation of the electric properties of the basic cap, its combination into scalable modules and an integrated power balancing within the modules. By either parallel or sequent combination of these basic modules, it will be feasible for an OEM to realise various solutions that may differ in voltage and/or capacity. For the suppliers it will thus be feasible to cover a broad market with one basic component.

However, it has to be noted that this projects also carried potential and substantial technological risks for the manufacturers of UltraCapacitors because of controversial targets, like

low weight – high mechanical stability – high charging and discharging currents.

High ambient temperature and extremely dynamic driving profiles cause accelerated aging processes of the cells/modules this is contrary to the life time demands of the car manufacturers.

State of the art

A passenger vehicle is one of the most widespread decentralised and non grid connected stand alone systems in our modern society. Its energy supply has to be provided internally by the vehicle itself, for decades, the drivetrain was powered by an internal combustion engine and the electrical energy supply of the car has been performed by a combination of a generator and a starter battery.

Future vehicles will be powered by either fuel cells in combination with an electrical machine or - in the medium term- by hydrogen powered internal combusting engines, both using pure Hydrogen. These are the most promising approaches for future transportation tasks, as Hydrogen fuel cells do not emit CO_2 provided that the Hydrogen will be generated by renewable energy.

Fuel cells for vehicles will supply energy to the drivetrain with the electrical machine as well as to the board net with all its loads. One major problem of the fuel cell technology is the degree of the today's technical realization. Fuels cells have still technical problems, which have to be solved. However, there are some additional system limitations. The full performance of the fuel cell will be only achieved if the fuel cell is heated up, e.g. for PEM fuel cells roughly 80 °C. Caused by this during start up phase the fuel cell is limited in power for several minutes. Therefore an additional energy storage system is needed which covers the start up phase, as a reduced function is not acceptable for the customer.

In addition, the dynamics of real load profiles often are faster than the response capability of the fuel cell requiring an energy/power buffer, unless the fuel cell is unacceptably over-dimensioned. In summary, because of these boundary conditions vehicle applications of fuel cells without an energy/power storage system of some kind are impossible.

The energy storage system will be used for restoring of vehicle kinetic energy (regenerative braking) at deceleration, as the energy conversion process of the fuel cell is not reversible. This regenerative braking saves energy and extends the range of the fuel cell vehicle. In some cases, even the size (power) of the fuel cell can be reduced if the user profile is proper and the energy storage system is powerful and strong enough.

Regenerative braking is a well know approach that offers energy savings for full hybrid vehicles (cars up to 12%, van's up to 15%, and buses up to 17%).

At present NiMH- or Li-Ion battery systems will be used for these tasks. However, these battery systems are limited in power at low operating temperatures (-40 to 0 °C). Furthermore, these battery systems can not be recharged with the same power as previously discharged with high power. At normal conditions, brake power is higher as accelerating power. Caused by this circumstances energy will be lost during regenerative braking. This results in reduced functionality of the overall fuel cell vehicle.

All of the above described power requirements may be covered by UltraCapacitors at the lowest cost, compared to battery or fuell cell.

The way ahead and general HyHEELS objectives

As already described in the section state of the art, fuel cells have some basic system limitations. These limitations should be neutralised by powerful energy storage systems. However, standard storage systems could not cover these tasks, especially at lower operating temperatures and for the required number of charge/discharge cycles.

An UltraCap provides much more power at low temperatures and accepts more power during recharge. UltraCaps could be charged and discharged with the same power, even at a temperature working range from -30 to +70 °C and exhibit a superior cycle life. Therefore, the UltraCap fulfils the most requirements on an energy storage systems used in a fuel cell electric vehicle. The only disadvantage is the limitation of the energy content compared to battery storage systems. However, during the start up phase, the fuel cell delivers some energy. As the fuel cell efficiency is roughly 50 % and caused by the fuel cell loads, the fuel cell heats up itself by losses. During this phase, the fuel cell delivers energy, however, only with less power. Therefore, the disadvantage of the reduced energy content of the UltraCap could be eliminated if the start up phase will be managed well and additional information about the UltraCap will be available.

UltraCaps are available on the market. However, there are restrictions with regard to automotive applications when looking on max. voltage and max. working temperature and packaging requirements. As the max. voltage of a single capacitor is only 2.5 V, several capacitors have to be connected in serial to a module if higher supplying voltages are required. This makes it necessary to develop an advanced UltraCap module packaging with optimised thermal behaviour, weight and cost. Furthermore, caused by different self-discharge of the single capacitors, the individual voltages of the module will drifting away. Finally, the capacitor module will be mismatched in voltage. Battery systems will be usually overcharged to keep it balanced in charge and voltage. However, capacitors could not be overcharged. Therefore, special charge balancing systems were developed in the past. These charge-balancing systems exchange the energy between the single capacitors in such a manner, that all capacitors achieve equal voltages. Prototypes were already developed in former EC projects e.g. SUPERCAR. However, additional information about the UltraCap module and functions are necessary for a secure operation under automotive conditions. These are:

- capacity determination,
- Overvoltage detection/protection,
- Mismatch detection (unbalanced module),
- Power prediction,
- Maximum single voltage,
- Diagnosis of the module status (ageing, decreased capacity, increased IR),
- Communication to Super Visor.
- Low manufacturing cost, low mass production cost,
- High power density, small volume, low weight,
- Low EMI and acoustic noise, poor noise emissions,
- High reliability, high robustness, fail-safe,
- Good thermal behaviour/tolerance
- Efficient controllable regenerative braking,
- Little maintenance or maintenance free,
- Application oriented lifetime,
- Universal installation.

This information and functions are only achievable if the charge balancing system and the single capacitor voltage measurement is available. In total the following function blocs are necessary:

- Charge balancing,
- Single voltage measurement,
- Diagnosis,
- Power prediction,
- Communications interface.

These functions were compiled by an UltraCap Controller in the project. The development of this UltraCap Controller with all its function blocs and the definition of the electrical and mechanical interface between the Controller and the UltraCap Module was one of the advanced development targets for the STREP HyHEELS. Now the improved UltraCap together with the new developed UltraCap controller enables the secure and reliable function of this energy (power) storage system in combination with fuel cells in automotive applications.

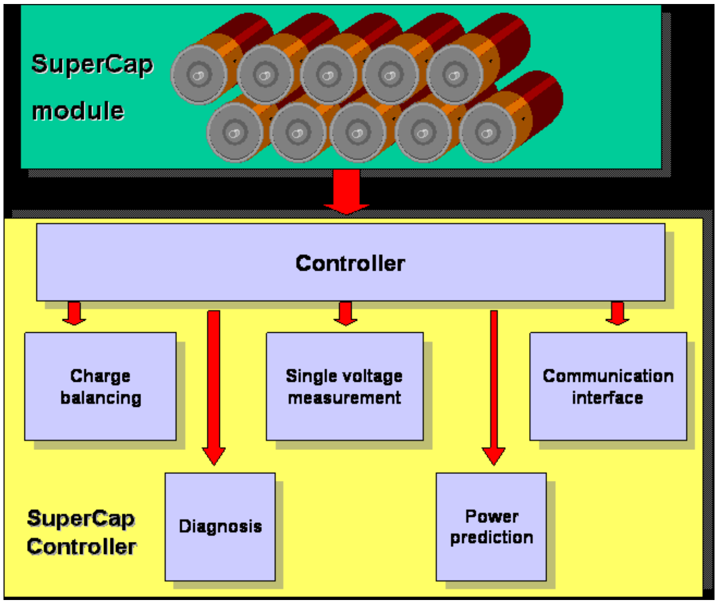


Figure 9: Modules of the UltraCap Controller

The main goals of HyHEELS may be summarized with the expected performance which must be reached in the next years. The values are given in Table 2. In other words, we had to focus on the power density which allows the weight reduction, the increased voltage which allows the serial connection number reduction and the temperature which allows to cover the full range requested by the car manufacturers.

The UltraCapacitor price targets are related to new technology and to production volume. Table 2 gives a summary of the actual UltraCapacitor development roadmap.

Year	Volume [ccm]	Weight [g]	C [F]	ESR [mOhm]	Voltage [Vdc]	Power density * [kW/kg]	Energy density [Wh/kg]	Temper [°C]	Cycle life [Millions]
2005 (actual data)	425	525	2600	0. 5	2.5	6	4.3	-45 +65	0.5
2007	375	475	2600	0.35	2.7	12	5.8	-45 +65	1.0
2009 (Project goals)	350	450	3000	0.3	2.85	15	7.5	-45 +70	1.5
2011	325	425	3200	0.28	3.0	19	9.4	-45 +75	2.0

***Power density = V2/4xESR/weight**

Table 2: Modules of the UltraCap Controller

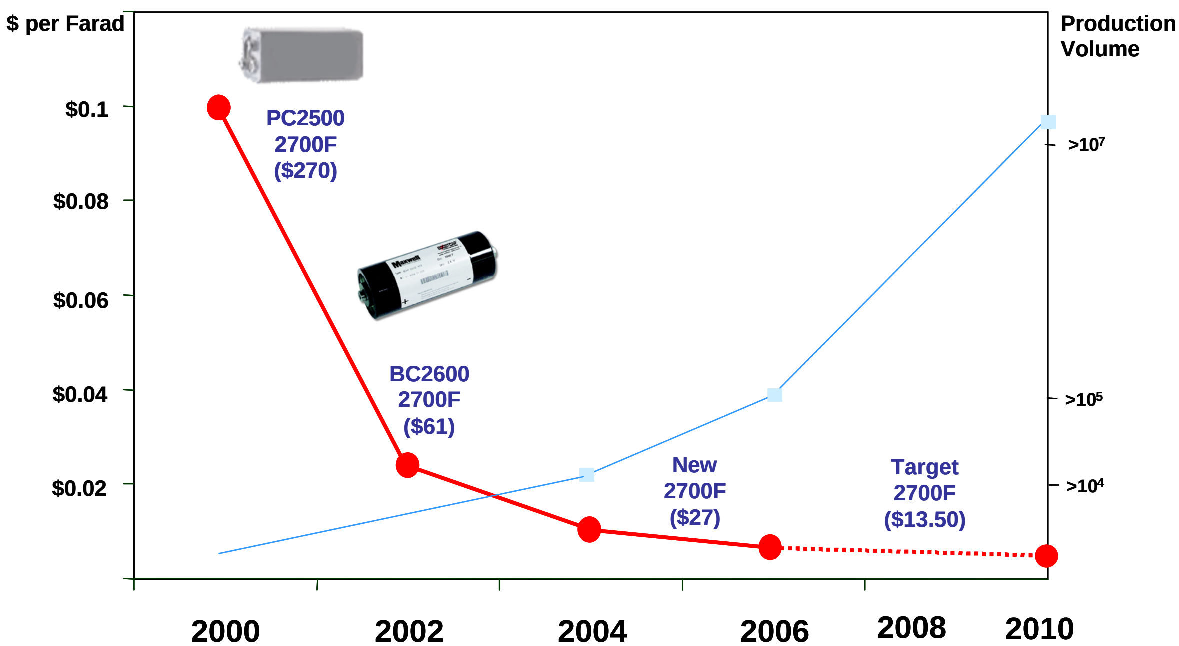


Figure 10: UltraCapacitor development roadmap

Scientific and technology objectives

The project's detailed scientific and technical objectives are thus the result of a thorough analysis of the challenges in the energy supply architecture of Hydrogen fuel cell vehicles. A Hydrogen fuel cell has to be provided with power and energy during start up phase as well as during continuously operation. High power is needed for the acceleration of the vehicle and for high power auxiliary fuel cell loads like compressors. A powerful and reliable energy supply is crucial to fulfil the requirements of the future passenger cars generation, which will be powered by Hydrogen fuel cells.

Sometimes batteries are not able to supply enough power. These could be high power charge and discharge conditions as well as operating at low temperature e.g. -20 °C. UltraCaps could fill up the power gap. The approved UltraCap storage technology is available but needs to be adapted to future automotive Hydrogen applications, satisfying the demands on cost- efficiency, safety and reliability.

Aim of the project was the development of an improved cost efficient energy supply concept for fuel cells based on an advanced, powerful UltraCap. The project had the following development targets:

- Increasing of the max. operating voltage of UltraCaps from 2.5 V to 2.7V. High cell voltage which requires an electrochemical stability of the electrode, the electrolyte and the packaging materials.
- Cost reduction of the electrodes by new production technologies
- Cost reduction of cells and modules by industrialization
- Advanced UltraCap component electrode and packaging. All the material need to have a high electrochemical stability in order to operate the components at a higher voltage during a long time. The component packaging weight must be minimized. A special attention must be paid to the packaging tightness and to the mechanical resistance.
- Advanced UltraCap module packaging with optimised thermal behaviour, weight and cost
- Development of an UltraCap controller, including a single cell voltage measurement and a cell balancing, providing extended UltraCap information to the Fuel cell system Super Visor.

Final goal of the project is the installation of an advanced reliable and cost efficient UltraCap module, providing all necessary information, which enables the integration into the fuel cell vehicle architecture.

Installation, testing, and evaluation of several UltraCap modules were done, besides bench testing, on one existing Series Hybrid Vehicles.

From this vehicle extensive data has been captured in the past and was used as baseline.

2 Technology and applications

During the HyHEELS project new UltraCap cells were developed and a new module.

The overall objective was to develop storage systems consisting of UltraCaps that are suitable for cost-efficient, automotive applications. Another focus was the packaging and industrial manufacturing of the modules. Therefore the workpackage had the overall responsibility on the specification, development, packaging, testing and validation of energy storage by advanced capacitors.

Furthermore an UltraCap controller was developed which is necessary for all applications with several UltraCap cell or modules in serial. The basic research was on the development of a potential free voltage measurement and to enable the balancing of the cells. Balancing of the cells is necessary to avoid overcharge which resume into overvoltage during normal operation of the system. The HyHEELS controller is able to handle all requirements for mobile applications.

The basic for the voltage measurement and the balancing is the usage of a coupling capacitor. This set up provides all flexibility and ensures a potential free connection between controller and cells.

Due to this flexibility the UltraCap controller could be used of several cell as well as modules of UltraCaps. However, even more, this device could be also used for Lithium cells as similar requirements were identified.

This newly designed UltraCap module in combination with the UltraCap controller is suitable for all automotive applications with high dynamic charge and discharge load profile.

3 Scientific and technical description of the results

3.1 WP1000

MAXWELL

Maxwell focused on the Ultracapacitor development of the activated carbon, the electrolyte, the separator, binder materials and electrode construction. Figure 11 illustrates an ideal porous carbon-based Ultracapacitor where electrodes store ions in pores and the separation of charges in the ionic species at the interface produces a standing electric field.

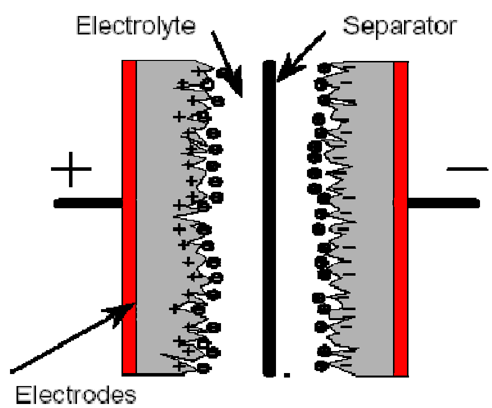


Figure 11: Porous carbon-based Ultracapacitor.

Activated carbon.

Maxwell's proprietary activated carbon has been successfully created. Using H_2SO_4 as catalyst, the stage I carbon showed high capacitance, low ESR, high impurity content and hence short lifetime. The major impurity was sulphur, which is residual from the sulphuric acid that is used as a dehydration catalyst. By replacing sulphuric acid with an acid that does not contain sulphur, Stage II carbon was prepared that does not contain sulphur. The original stage II carbon has a high volumetric capacitance, slightly higher ESR and longer lifetime performance compared to stage I carbon. By adjusting the processing parameters, a new stage II carbon was synthesized and shows high coin cell capacitance, low ESR, high purity and long DC life, which are similar to the best Ultracapacitor carbon S1 and S2 currently available. The major problems with current best carbons are that their pore size distribution and structure are not sufficiently optimized for liquid electrolytes and they are very expensive. Maxwell's proprietary carbon starts from inexpensive carbohydrate based precursors. The use of low-cost feedstocks and processing steps greatly lowers the production costs of Ultracapacitor while retaining the high performance.

Future work will be improving the production method and optimizing the pore size distribution as well as structure with the goal of making a highly pure carbon with increased capacitance and/or reduced ESR. The following approaches will be explored for further improvement of capacitance:

- Adjusting the process parameters, such as temperature, ramp, gases, gas flow rate and dwelling time for carbonization and activation to optimize the pore size distribution of activated carbon.
- Using heterocyclic organics as additives to the formulation of carbon synthesis to achieve doped activated carbon.
- Using hard or soft templates, most commonly surfactants as additives to the formulation of carbon synthesis to achieve local organization of activated carbon structure.

Electrolyte.

Small ion electrolyte plays an important role in enhancing Ultracapacitor performance, specifically in reducing Ultracapacitor ESR and improving Ultracapacitor cycle life due to fast speed in entering and leaving activated carbon pores. It is important to develop electrolytes with smaller ion size but without solvating with solvent molecules. Implementation of TEMA electrolyte into Maxwell Ultracapacitor system is underway. Continuing study in this area has been started. Electrolyte under study includes Me_4N^{+}, with the ion radius of 0.283 nm, slightly smaller than TEMA ions. Ionic liquid presented a new chapter in Ultracapacitor electrolyte development to possibly achieve high voltage applications. It's higher thermal stability and greater electrochemical stability are important characteristics for developing high performance Ultracapacitors.

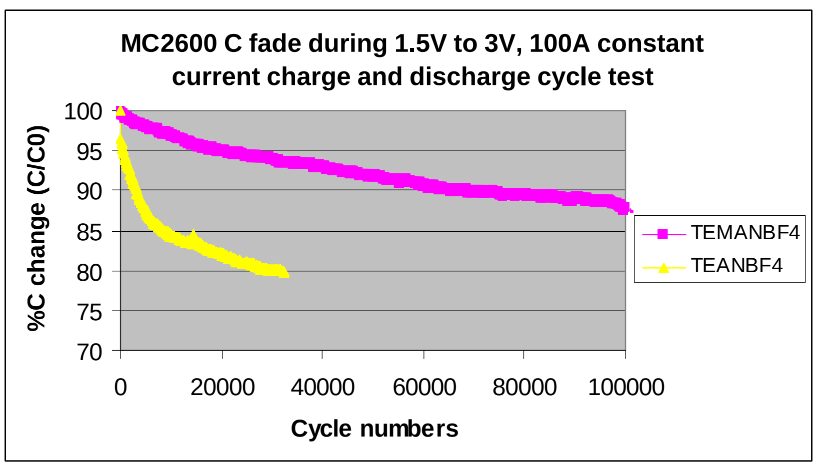


Figure 12: MC2600 Ultracapacitor Capacitance fade during 100A constant current charge/discharge cycle test at 1.5V to 3V voltage range with 2 different electrolytes.

Separator

The separator in Ultracapacitors is often considered to be the least important component, as it does not provide the active functions. The separator acts as an insulator between the positive and negative electrodes to prevent the electrical short circuit between the two, yet it provides a path for ions inside the electrolyte to pass through during charge and discharge process and in this function it is a very important contributor to Ultracapacitor performance. The common knowledge is that as long as the separator functions well in the above two aspects, and the ionic ESR increases due to ion passing resistance will be small, and the separator would be considered a good separator. Figure 13 shows gas generation inside of a cell depending only on separator thickness.

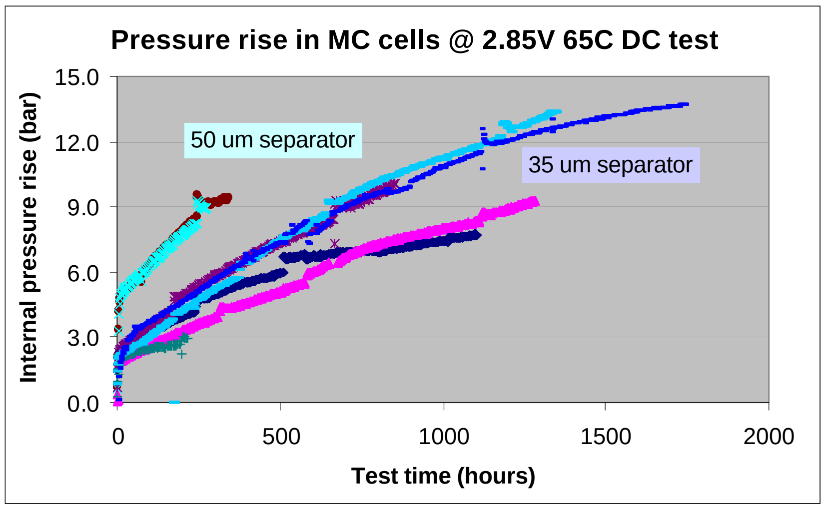


Figure 13: Gas generation rates for the Ultracapacitor cells made by using 50 um separators and 35 um separators.

Electrode

Eleven new primer material samples were evaluated in the Maxwell lab. Two primer materials EB-036B and K were selected for large scale evaluation. The initial cell tests show that the cells with EB-036B and K have ~5% improvement in cell ESR. Both EB-036B and K have similar life performance as the control samples. But EB-036k has better DC life performance than control primer material. More EB-036K is ordered for qualification test. The 2 following figures show the Capacitance fading and ESR increase for the both best 2 samples developed in the HyHEELS project.

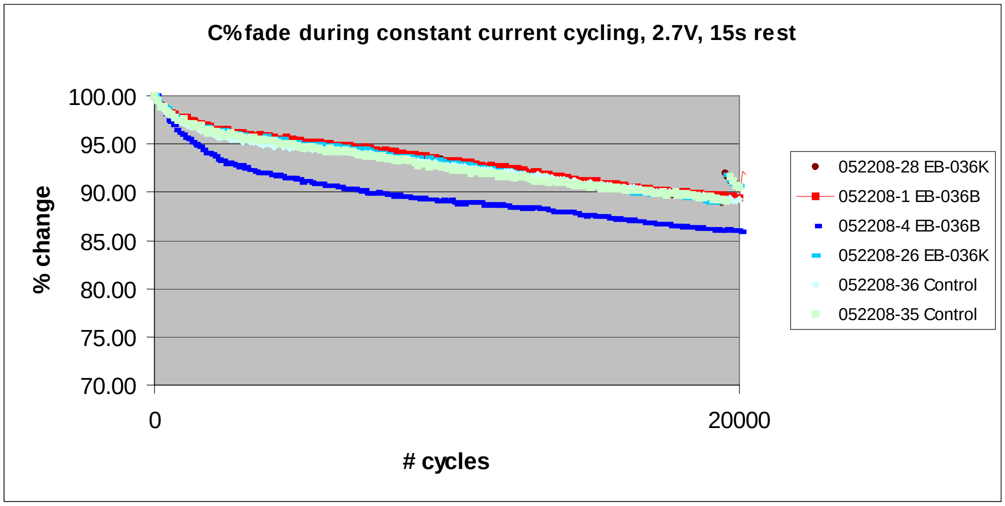


Figure 14: Cycle life of cells made with EB-036B and K.

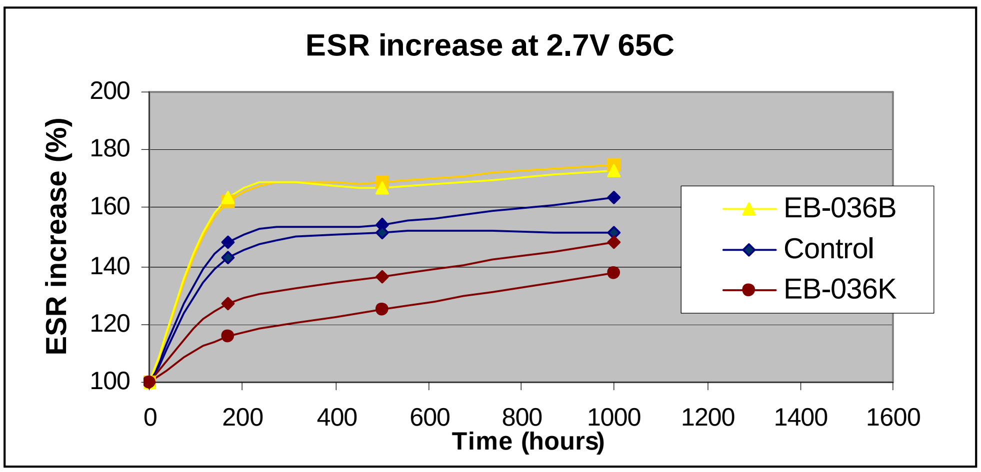


Figure 15: ESR increase of cells tested at 2.7V 65C.

Research and Testing

VUB

Methods identifying voltage differences of UltraCaps and the principle of voltage balancing were analysed. It was concluded that balancing at high voltage gives the most representative values for the voltage difference between cells (see Figure 16). Prohibiting high voltage differences increases the total amount of available energy of an UltraCap module and reduces the required power rating of the voltage balancing circuit. The bench test results confirmed and completed the scientific analysis from UTMB and were applied into the simulations (see WP3000).

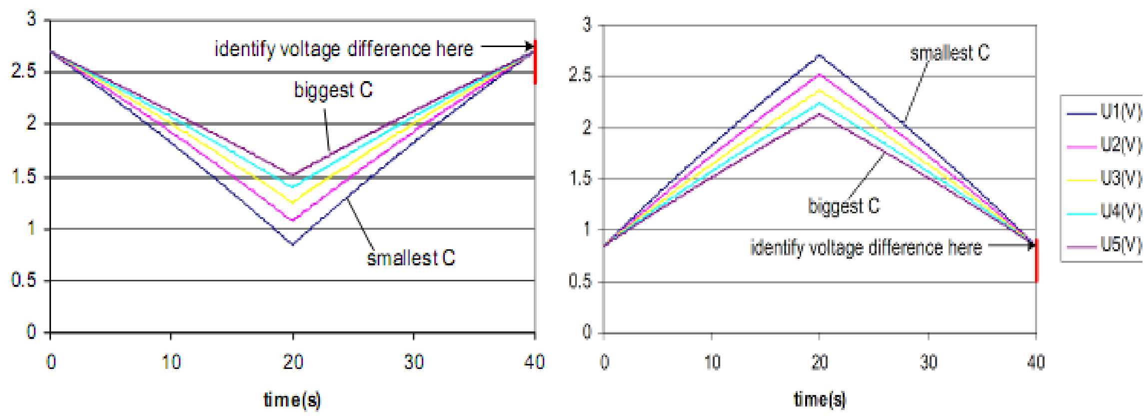


Figure 16: Identifying voltage difference method at high (left) and low (right) voltage point (method 1 and 2).

The energy capacity of a finale (UC stack based) module in comparison with a previous module was increased by approximately 33% (from 90KJ to 120KJ per module) within the same voltage range (between 5V and 105V). The test results also prove that reducing the voltage range would reduce the energy losses especially at high currents (80A). Based on this fact we suggest adjusting the operating voltage range carefully in order to limit the losses at high power levels in real applications.

The results of the pulse current tests prove that the energy losses depend on the series resistance and variation of capacitance in charging state and in discharging state. This conclusion suggests that the variation of capacitance should be treated as an important attribute during the evaluation of different types of super capacitors.

Taking into account the losses due to the variation of capacitance, the results show that the ESR of the final modules is slightly lower than the ESR of the previous UC modules. The test results also show that the super capacitor cells or stacks in 2 final modules have very similar electrical characteristics. These results verify the advance in the development of super capacitor cells, stacks and modules at Maxwell. Finally the test results show that the electrical stability of the tested super capacitor modules is good enough for automotive applications, after 2785 worst-case driving cycle (55700 km equivalent driving distance) were proceeded, there was no over temperature, mechanical deviation or significant change in the self discharging feature (Figure 17) observed.

Current (A)	E_{input} per cycle (kJ)	Efficiency of energy	ESR (mOhm)
20	240	0.97	40
40	240	0.95	32
80	234	0.91	32

Table 3: The results for the 2 final Ultracap modules in fully charging/discharging cycles.

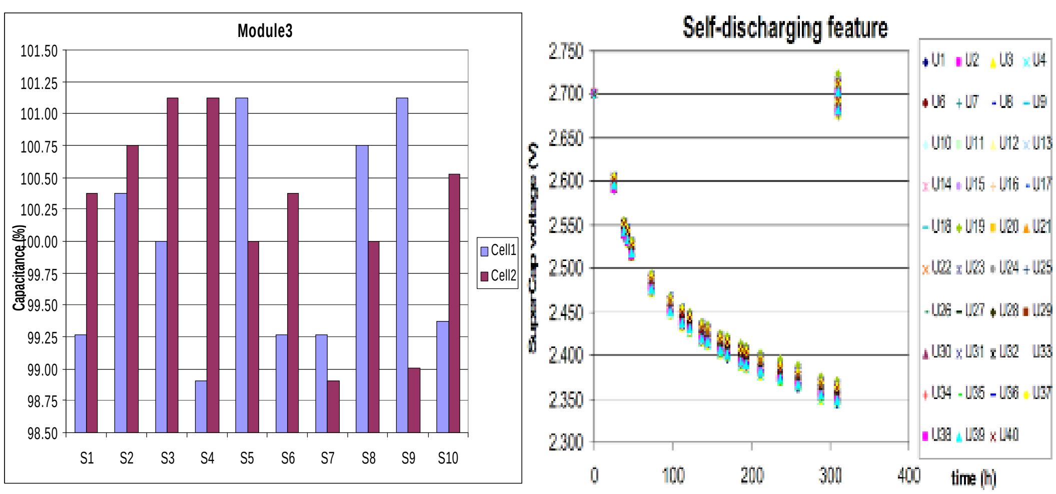


Figure 17: Capacitance differences and self discharging feature.

The high energy capacity, low energy losses and very similar electrical characteristics of the super capacitors are evidence for the Maxwell enhanced technique in the development of the super capacitors and their assembling (e.g. laser welding). The super capacitor modules developed in the HyHEELS project are suitable for the automotive applications, particularly when many modules are required in series connection to reach high DC voltage (e.g. 400V~550V).

UTBM

A thermal characterization of the old generation and the new generation of Ultracapacitor stacks was performed. The experimental results have shown that the temperature distribution in the new generation stack is uniform; the maximum value is stabilized in steady state at 48°C when the stack is charged and discharged at 100A. For the old generation, in the same conditions, the temperature is not uniform and the maximum value is at the lid+. It is in order of 70°C (Figure 18 and Figure 19). The new generation technology presents a better temperature behaviour compared with the old one.

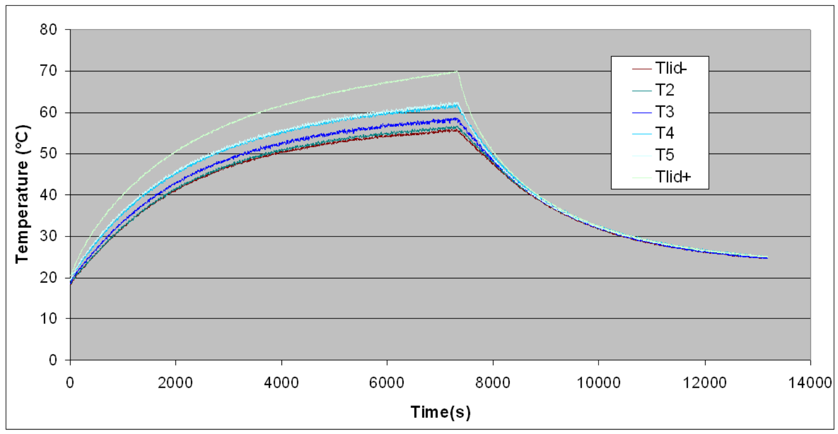


Figure 18: Old stack temperature versus time.

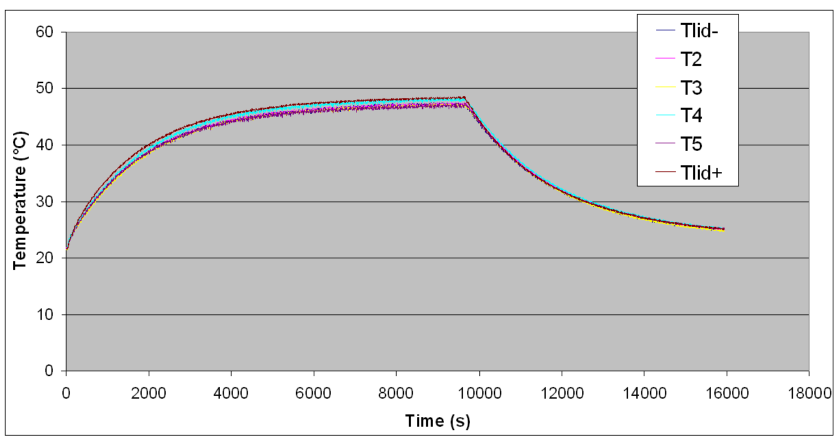


Figure 19: New stack temperature versus time.

The series resistance of the new generation of the Ultracapacitor stacks is lower. Table 4 gives the difference between the two stacks generations.

I(mA/F)	5	10	50	100
Old stack ESR (mΩ)	1.33	1.43	1.26	1.29
New stack ESR (mΩ)	0.909	0.893	0.909	0.911
Variation	- 31 %	- 37 %	- 28%	- 29%

Table 4: Old and new stack generation ESR for different currents during discharge at constant current.

We can conclude that the ESR is decreased by ~30%. Consequently, the power losses are reduced. A comparison was performed by discharging the two stack generations. At constant power it was observed that the energy of the new generation is higher.

During charge and discharge it was shown that the stack must be equipped with a balancing system in the two cases (new and old generation). For thermal shock tests, the experimental results have shown that after 100 thermal shocks, only the stack's ESR is affected.

Electric characterization in positive and negative voltage was realized. It was shown that the Ultracapacitor is reversible. Figure 20 represents a 1500F cell's ESR and C evolutions as a function of voltage. Due to the UC's reversibility, the energy stored in a Ultracapacitor can be increased by factor 2. However, the tests performed by DLR have shown that the UC's lifetime decreases considerably when the Ultracapacitor is operated at negative voltage.

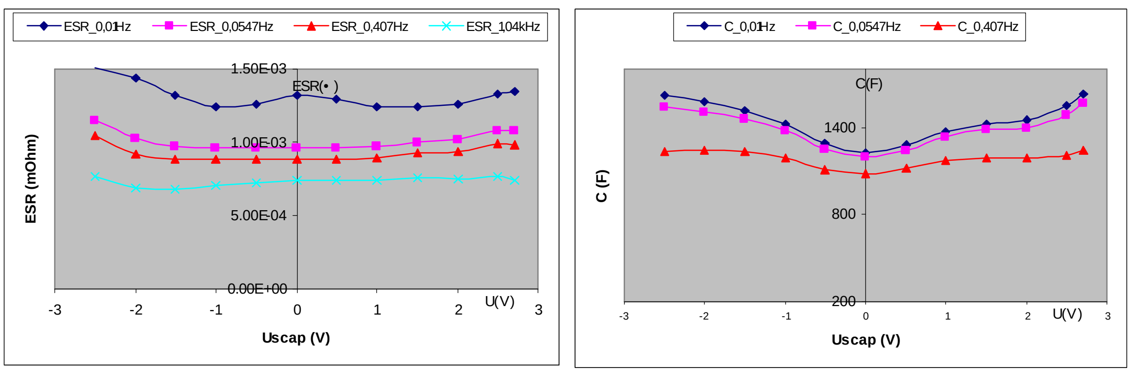


Figure 20: ESR and C versus voltage for 1500F.

DLR

Negative Voltage cycling

The negative voltage cycling test was performed on 350 F cells of the "old" technology.

During the negative voltage cycling tests we have inverted the cell's voltage during a charge-discharge-cycle to -0.1, -0.4 and -2.5 V. The results show that the cell's life time is affected by inverting the voltage. The degree of life time degradation depends on the depth of the inversion.

While inverting the cells to -0.1V one specimen reached the failure criterion (reduction of capacity by 30% or increase of ESR by a factor of 2) after approximately 190.000 cycles. The two others did not reach the end of life until 250.000 cycles. Figure 21 shows the results for the -0.1V-inversion test.

During the inversion to -0.4 V all cells tested reached the defined failure criterion. The lifetime was between 125.000 and 200.000 cycles. Figure 22 shows the results for the -0.4 V-inversion test.

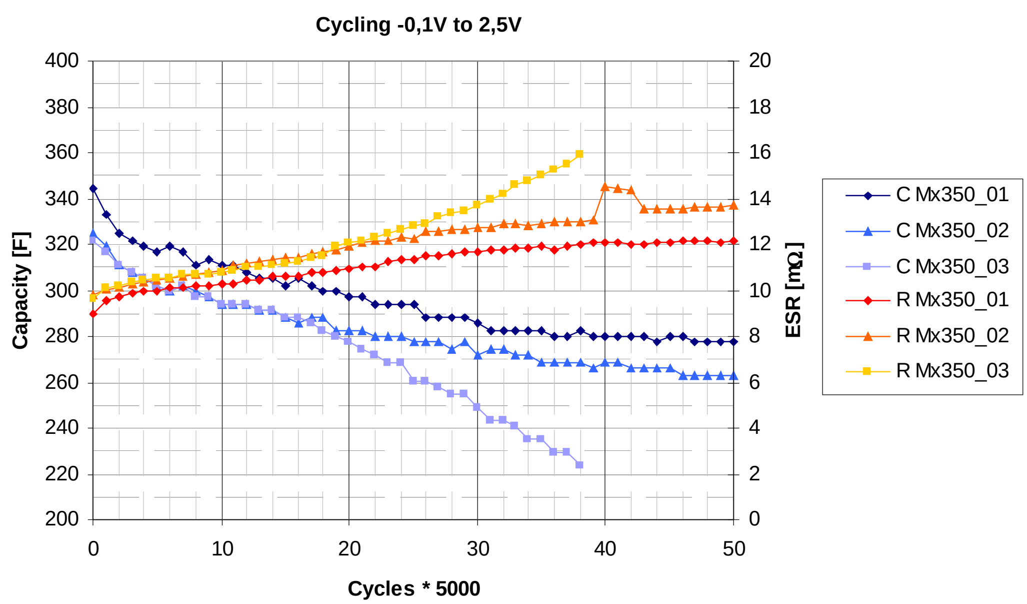


Figure 21: Evolution of C and ESR during negative voltage cycling – depth of inversion = -0,1V.

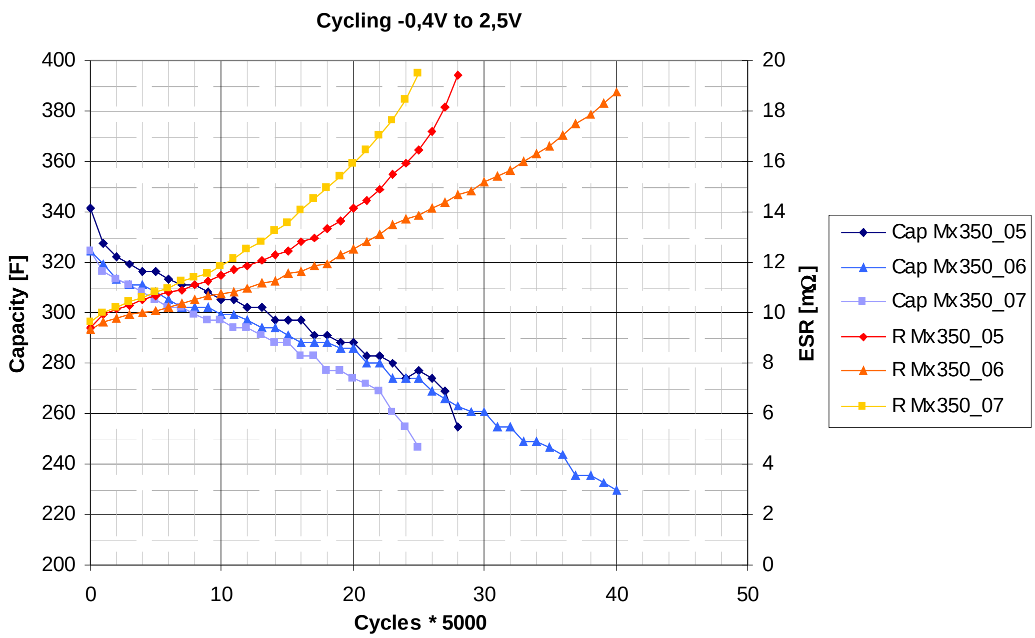


Figure 22: Evolution of C and ESR during negative voltage cycling – depth of inversion = -0,4V.

Inverting to -2.5 V was the worst case. During this test the cells reached a lifetime of approximately 2.000 to 3.000 cycles. Figure 23 shows the results for the -2,5V-inversion test.

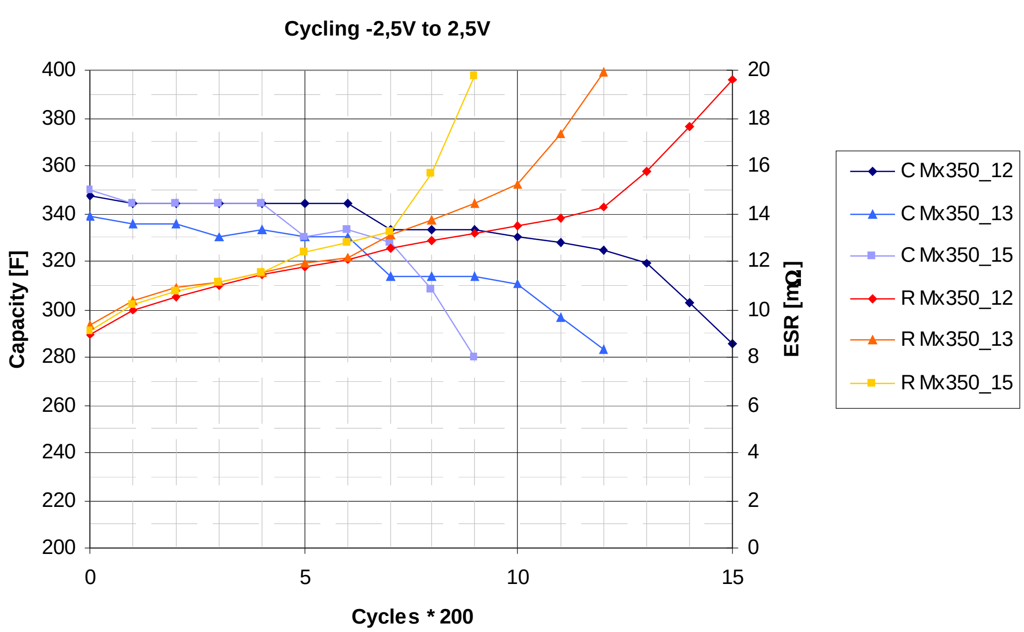


Figure 23: Evolution of C and ESR during negative voltage cycling – depth of inversion = -2,5V.

Alternating temperature test

The alternating temperature test was performed with six 1500 F cells of the new generation. The initial capacitance measurements showed that the capacitance of the new generation cells is approximately 30% higher (1900 F) than the targeted capacitance (1500 F). The internal resistance of the cells was between 0.7 mΩ and 0.9 mΩ.

During the alternating temperature test the cells were exposed to a cyclic temperature change between -40°C and +60°C. During the constant phases at low and high temperatures respectively the cells were charged and discharged. After each temperature cycle the internal resistance and the capacitance was automatically determined.

During 40 days under test (= 120 temperature cycles) the cell's internal resistance did not show significant change (Figure 24). The capacitance dropped from approximately 1870 F to 1730 F which represents a loss of 7.5% (Figure 25).

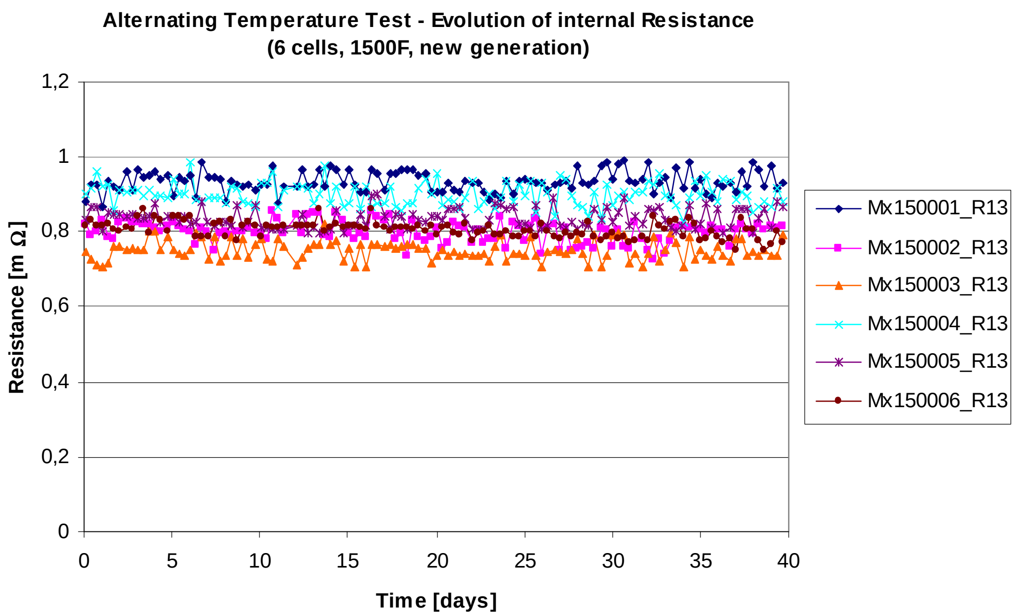


Figure 24: Evolution of internal resistance of new generation 1500 F cells during alternating temperature test.

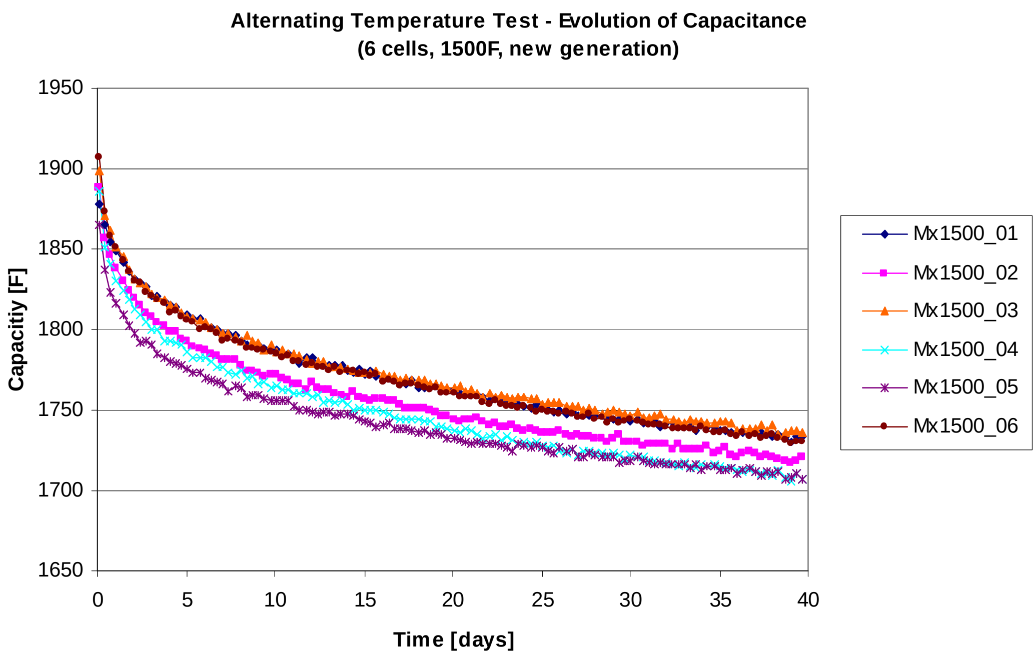


Figure 25: Evolution of capacitance of new generation 1500 F cells during alternating temperature test

Moist-heat-cycling test

The moist-heat-cycling test was performed with six 1500 F cells of the new generation.

During this test the cells have been exposed to a temperature and moist profile. Due to the late delivery of the cells, the climate chamber foreseen for this test was already occupied by another project. Therefore the originally planned profile, as described in deliverable D1, could not be applied. Instead we applied a very similar profile, according to Volkswagen AG's standard PV 1200. This profile is applied for parts, usually placed in the motor compartment, thus being exposed to high humidity and temperature cycles. Each time during the constant temperature phases (at high and at low temperatures) in the cycle, an impedance spectroscopy measurement was performed.

The cells under test showed a significant rise in ohmic behaviour of about 10 % (see Figure 26) during the moist-heat-cycling.

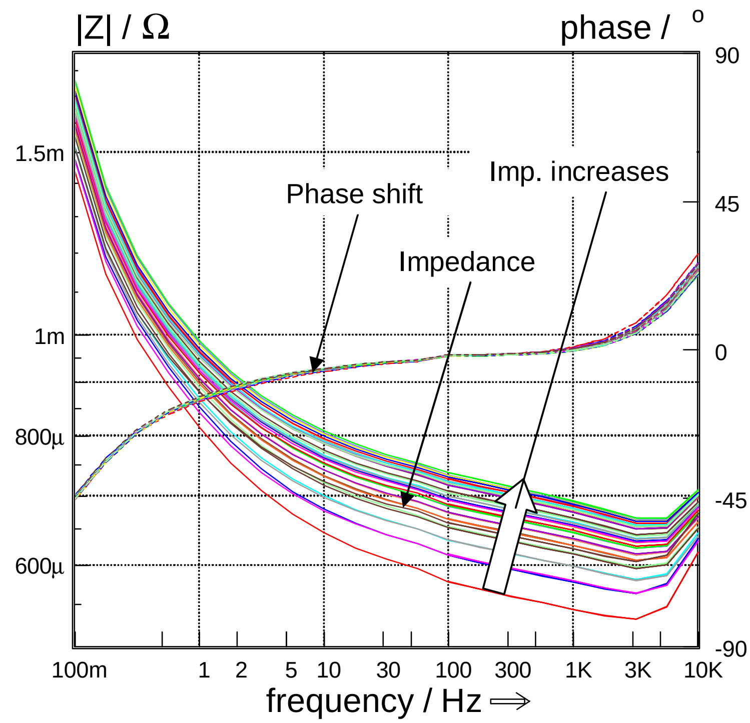


Figure 26: Evolution of the impedance during the moist-heat-cycling test.

3.2 WP2000 UltraCap controller

UltraCaps are available on the market. However, there are restrictions with regard to automotive applications when looking on max. voltage and max. working temperature and packaging requirements. As the max. voltage of a single capacitor is only 2.5 V, several capacitors have to be connected in serial to a module if higher supplying voltages are required. This makes it necessary to develop an advanced UltraCap module packaging with optimised thermal behaviour, weight and cost. Furthermore, caused by different self-discharge of the single capacitors, the individual voltages of the module will drifting away. Finally, the capacitor module will be mismatched in voltage. Battery systems will be usually overcharged to keep it balanced in charge and voltage. However, capacitors could not be overcharged. Therefore, special charge balancing systems were developed in the past. These charge-balancing systems exchange the energy between the single capacitors in such a manner, that all capacitors achieve equal voltages. Prototypes were already developed in former EC projects e.g. SUPERCAR. However, additional information about the UltraCap module and functions are necessary for a secure operation under automotive conditions. These are:

- capacity determination,
- Overvoltage detection/protection,
- Mismatch detection (unbalanced module),

- Power prediction,
- Maximum single voltage,
- Diagnosis of the module status (ageing, decreased capacity, increased IR),
- Communication to Super Visor.
- Low manufacturing cost, low mass production cost,
- High power density, small volume, low weight,
- Low EMI and acoustic noise, poor noise emissions,
- High reliability, high robustness, fail-safe,
- Good thermal behaviour/tolerance
- Efficient controllable regenerative braking,
- Little maintenance or maintenance free,
- Application oriented lifetime,
- Universal installation.

This information and functions are only achievable if the charge balancing system and the single capacitor voltage measurement is available. In total the following function blocs are necessary:

- Charge balancing,
- Single voltage measurement,
- Diagnosis,
- Power prediction,
- Communications interface.

These functions will be compiled by an UltraCap Controller. The development of this UltraCap Controller with all its function blocs and the definition of the electrical and mechanical interface between the Controller and the UltraCap Module is one of the advanced development targets. The improved UltraCap together with the new developed UltraCap controller enables the secure and reliable function of this energy (power) storage system in combination with fuel cells in automotive applications.

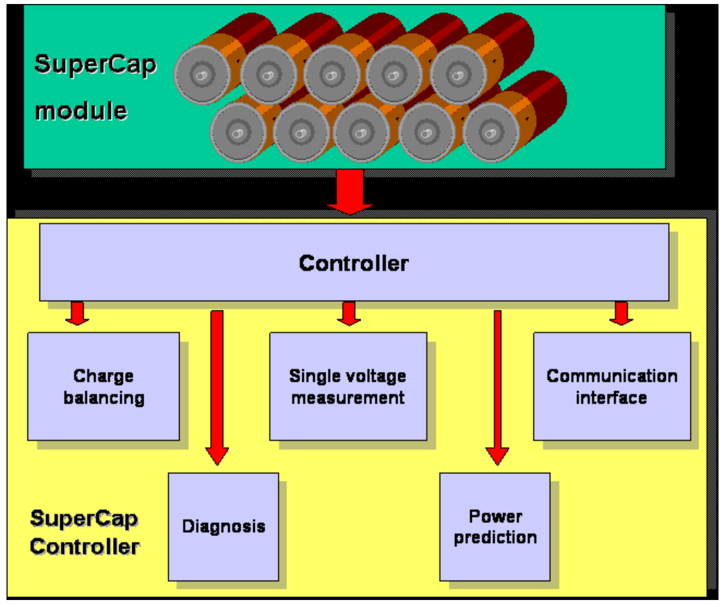


Figure 27: Modules of the UltraCap Controller

The WP2000 had four sub-chapters which the following title:

- Requirements & specifications
- UltraCap controller development
- Simulation and measurements of power losses
- Set up of UltraCap controllers suitable for mass production

The performed work within WP2000 is described below.

3.3 WP 2100 Requirements & specifications

As already stated, an UltraCap controller is essential for the secure and reliable operation of the UltraCap module. The balancing of the cells in the module is the main function of the controller. However why are the cells within the module unbalanced?

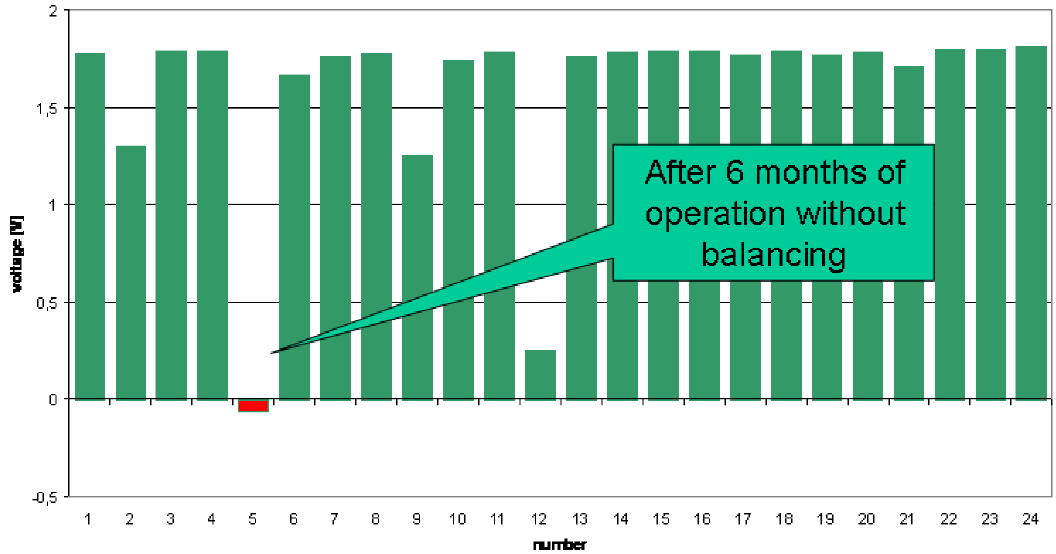


Figure 28: Individual cell voltage after 6 month of operation without balancing.

The answer on this question is important for the requirements on the controller and the requirements on the electronic part of the balancing device. These main requirements were investigated and analysed at the beginning of the project. Two points were identified. The first one is based on the different capacities distribution within the module caused by

- production tolerances
- aging

In any case this has to be covered by the balancing system of the UltraCap controller. Production tolerances are almost 30 % at present. Series production promises better accuracy. However aging is a factor which could not be calculated. A capacitor is at its end of life if the capacitance is 80 % of the initial capacity. This is also the maximum difference which has to be balanced. As the capacitance is decreasing slowly the differences or the necessary load which has to be recharged is small. Caused by this the balancing current is high at the initial balancing and afterwards small as only the differences in capacitance must be adapted.

The second is based on the different self discharge rates of the individual cells within the module caused by

- production tolerances
- different temperature distribution
- different aging

Also in this case these have to be covered by the balancing system of the UltraCap controller. In particular this is in the focus of the development because balancing current must be high enough to keep the system in a secure operating area! Production tolerances are influencing the self-discharge rate. This is well known. E.g. small quantities of iron increase the self-discharge rate enormous or water in the cell which has the same effect. Therefore during the production process these effects on the self-discharge must be controlled and has to be guaranteed to be minimized. If this could not realized no balancing system will strong enough to compensate this and keep the UltraCap module in operating conditions. However the maximum value of these production tolerances were investigated and fixed in WP1000. The different temperatures in the module are one issue which could also be influenced by production tolerances in this case by the internal resistance of the cell. If the internal resistances of the individual cells are different also the temperature distribution within the module will be wide spread. The internal resistances are responsible for the losses and these losses will heat up the cell. If the resistance is different also the temperatures will be different. Last but not least the different temperatures in the cells will also influence the aging. According to the Arrhenius law the lifetime of the cell will be reduced to the half if the cell temperature increases at 10K. The necessary balancing current was investigated within WP1000. According to these investigations the minimal balancing current should be more than 100 mA for a cell with 1500 F. Even more the accuracy of the voltage measurement of the individual cells was investigated and fixed. Caused by this primarily investigations and evaluations the overall requirements of the UltraCap controller was described. These requirements were summarized in deliverable D2 "Requirement documentation on the UltraCap controller". These requirements were split up in five sub groups indicated below.

- Mechanical requirements
- Environmental requirements
- Electrical requirements
- Functional requirements
- Interface requirements

In the next step the method of balancing was investigated as balancing of cells could be performed in different ways and by different technical solutions.

The focus was on the different balancing possibilities and methods of potential free voltage measurement.

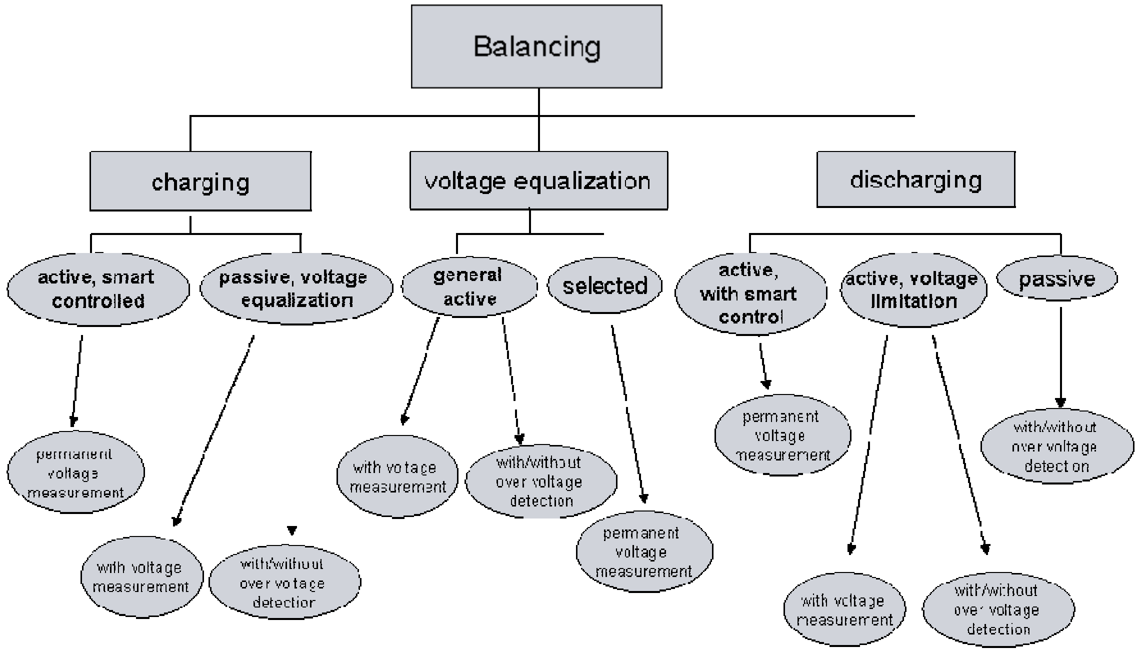


Figure 29: Different possible balancing methods

The picture above shows the different balancing methods, split up into balancing by charging, discharging and voltage equalization. As the energy content of a single UltraCap is limited up to max. 5 Wh (~5000 F) the focus is on charging. Charging from an external source, this will be dominated by the strongest cell. Discharging is dominated by the weakest cell and voltage equalisation needs a very high efficiency of the balancing circuit. Caused by these investigations a first electronic evaluation board with a micro-controller was designed. This evaluation board offered maximal flexibility for the testing of different balancing methods with the focus on charging.

WP2200 UltraCap controller development

The main electronic part of the project was done in the WP2200 UltraCap controller development.

According to the guidelines already compiled in WP 2100 the UltraCap Controller was developed. The special focus on this development was a simple and efficient cell balancing device, providing an easy installation on the module (no manual installation work, focus on automated factoring) and a scalable, modular approach. The control unit also provides the diagnosis of the UltraCap module (e.g. capacitance determination), the communication interface and a power prediction. Especially the power prediction is necessary for the overall system management e.g. in automotive application forecast of power contribution for acceleration and possible recharge prediction during regenerative braking phases as well as providing power during warm up phase. The development had a special focus on an overvoltage protection to ensure the compatibility with the cell and module design of the capacitor manufacturer. A study of the overvoltage capabilities of the cells as a function of time provides detailed information of the design of the overvoltage protection function. Finally the UltraCap controller was designed for a low cost mounting technology focusing on high volume production.

Hardware development

Different charge balancing methods were investigated in WP2100. However methods which enables balancing by discharging were not taken into account as normally only few cells within a module will be weak and therefore all other cells has to be discharged for balancing. Due to this only recharging methods were in the focus.

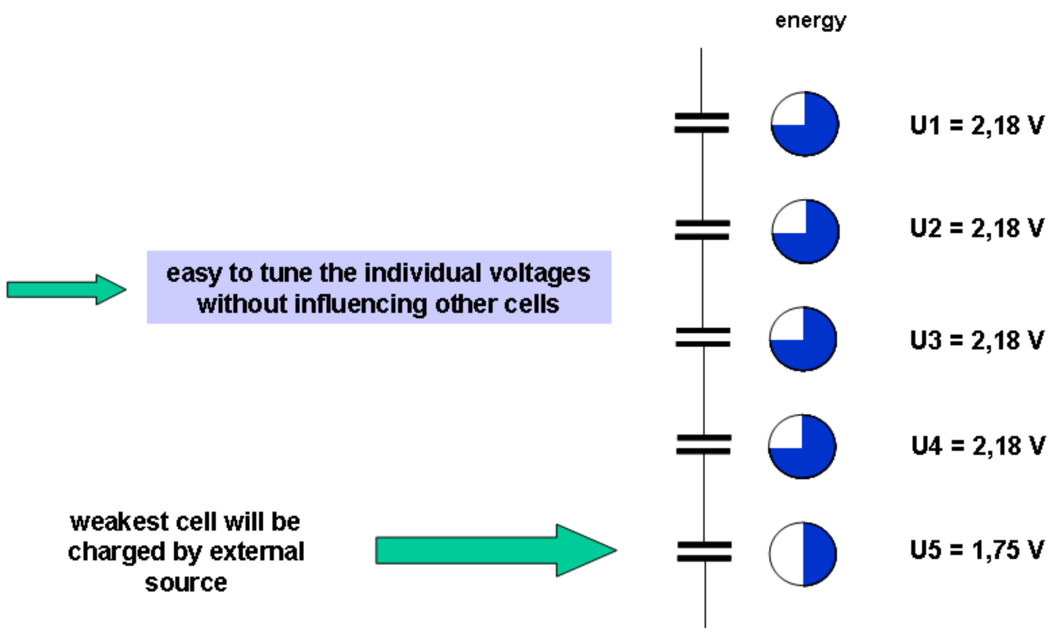


Figure 30: Balancing via recharge by external source.

On the basis of this requirements and the first draft of the specification an evaluation board was designed. This board was able to recharge cells via an external source. The basic idea was used from a former EC project which was called "Supercar".

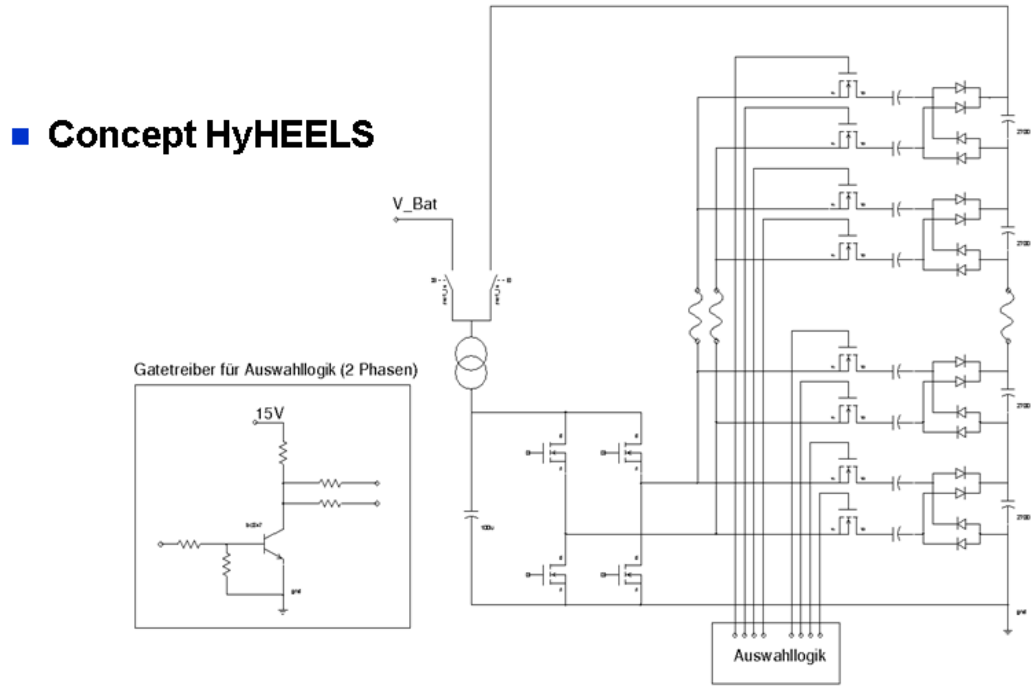


Figure 31: Selected balancing HW concept.

In the chosen concept the energy for the balancing process has to be supplied by an external source. A small step down converter reduces the input voltage of the source to roughly 4 V. This DC-voltage will be converted into an AC-voltage via H-bridge (4 Mos-Fets). The output voltage of the H-bridge is the basis for the AC-bus system which has a frequency of roughly 25 kHz. If one UltraCap is selected by the MosFets, the UltraCap fixes the voltage in the AC-Bus. Due to this the UltraCap will be charged caused by decoupling of the energy via the coupling capacitors and the rectifier at each UltraCap. The function is equal to a charge pump. If an other capacitor should be recharged than the MosFETs will be switched off and the new preferred path with MosFETs will be switched on. Due to this the new capacitor is connected to the AC-Bus which results in a recharged of the capacitor until the MosFETs will be switched off again.

On the same principle the voltage measurement is working, however with reduced, extremely small current. This small current ensures that the UltraCap will not be recharged but the AC bus voltage reflects the voltage of the UltraCap. The following figure explains the voltage measurement process more in detail.

- **apply a measuring current with square waveform**
- **measure cell ratiometric**
- **measure reference cell**
- **determine cell voltage by:**

$$U_{Cell} = U_{CC} + 2 \cdot U_D + U_{UC}$$

$$U_{RefCell} = U_{CC} + 2 \cdot U_D$$

$$U_{UC} = U_{Cell} - U_{RefCell}$$

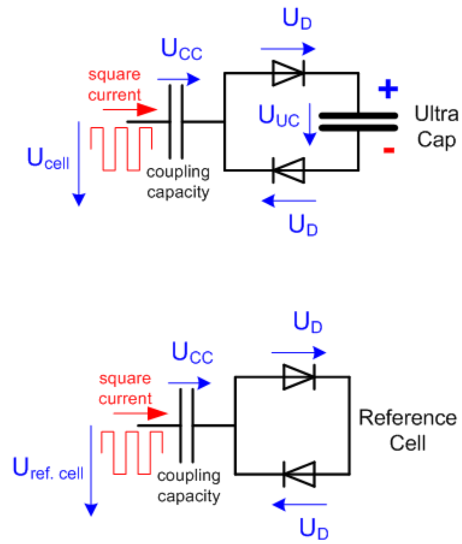
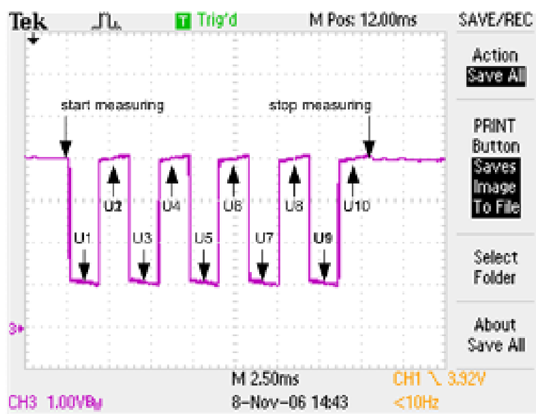


Figure 32: Principle of the potential free cell voltage measurement.

The next figure shows the signal of the measurement on the micro controller port. As a voltage drop occurs via the rectifier diodes a reference cell has to be included which eliminates in the calculation this failure in measurement.

- **Plot of AD-port of µC signal**
- **Ratiometric cell voltage measurement (e.g. U_1-U_2)**



$$U_{cell} = \frac{(U1-U2)+(U3-U4)+(U5-U6)+(U7-U8)+(U9-U10)}{5} - U_{RefCell}$$

Figure 33: Cell voltage measurement, realisation.

The board was equipped with a 16 bit micro-controller, a recharging balancing device which voltage measurement. To provide a maximum on flexibility the board was design for high charging currents (Up to 3 A) and up to 12 cells. The actual configuration could be changed via jumper. The communication with the environment was realized by a CAN communication. The complete board has a galvanic isolation of more than 500 V.

The architecture for the UltraCap Controller evaluation board and the set up of the PCB is shown in the following two figures.

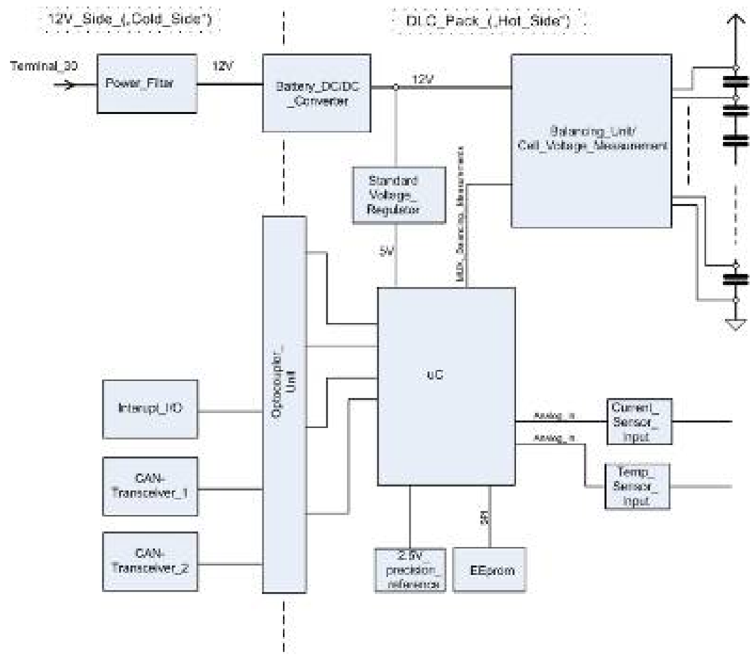


Figure 34: Architecture of the UltraCap controller device.

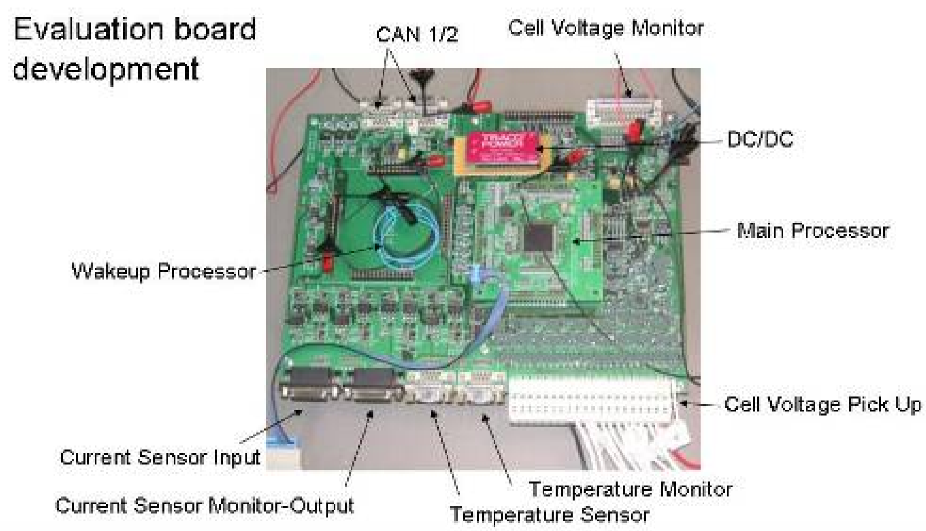


Figure 35: Evaluation board UltraCap controller

The main building blocs of this architecture are

- the Battery DC/DC for the power supply
- the optic-coupler unit
- the micro controller
- the balancing unit
- the voltage measurement unit as well as
- the communication blocs with the CAN transceiver

One focus was on the cell voltage measurement as the voltage measurement must be potential free and should have an efficient accuracy at the same time which is a special challenge. The following figure shows the realized voltage measurement based on coupling capacitors already described above. For a better overview only the voltage of 3 cells are plotted and compared with a high resolution AD converter.

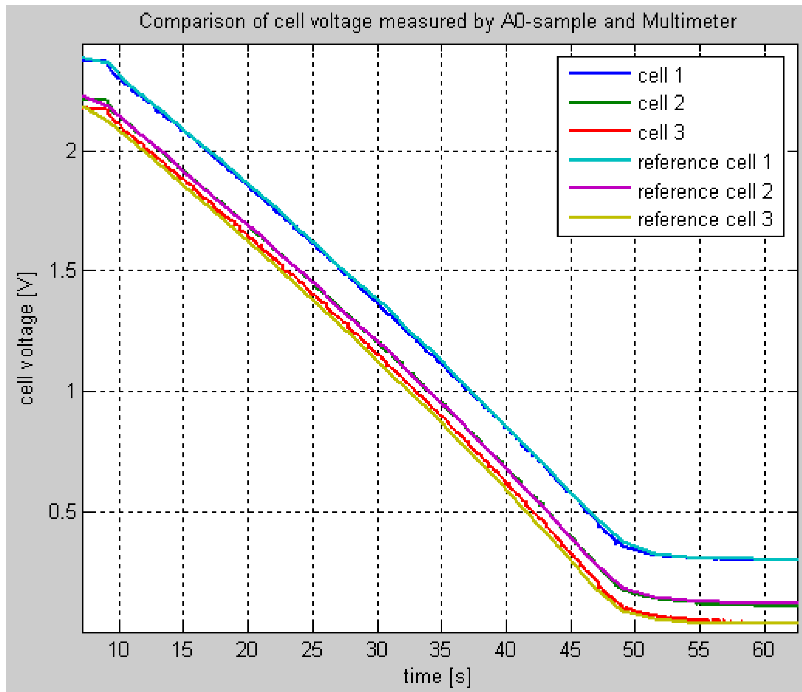


Figure 36: Comparison voltage measurement with high precision voltage measurement.

The results were satisfying. During the development process the sampling rate could be further improved. Finally the controller design was able to sample 20 cells with 10 ms.

Also the accuracy was sufficient. The average absolute failure is depending on the voltage however is in the range of 16 to 8 mV.

stack voltage	cell voltages	maximum absolute failure	average absolute failure
20V	1V	0,023V	0,016V
40V	2V	0,021V	0,014V
50V	2,5V	0,017V	0,008V

Table 5: Table of comparison voltage measurement.

Software development

In the chapter before the Hardware of the system was described. However the UltraCap controller includes also several software modules which realize the functionality of the Hardware and prepares the necessary information for the vehicle supervisor. In this chapter the focus is on the second part, the preparation of the information.

As the control unit should also provide the diagnosis of the UltraCap module (e.g. failure, capacity), the communication interface and a power prediction necessary functions and software modules were developed. Especially the power prediction is necessary for the overall system management e.g. in automotive application forecast of power contribution for acceleration and possible recharge prediction during regenerative braking phases as well as providing power during warm up phase. The development will be a special focus on an overvoltage protection to ensure the compatibility with the cell and module design of the capacitor manufacturer. A study of the overvoltage capabilities of the cells as a function of time provided detailed information of the design of the overvoltage protection function.

- Charge balancing,
- Single voltage measurement,
- Diagnosis,
- Power prediction,
- Communications interface.

These functions were compiled by the UltraCap Controller. The following figure shows the overall structure of the software with the different layers

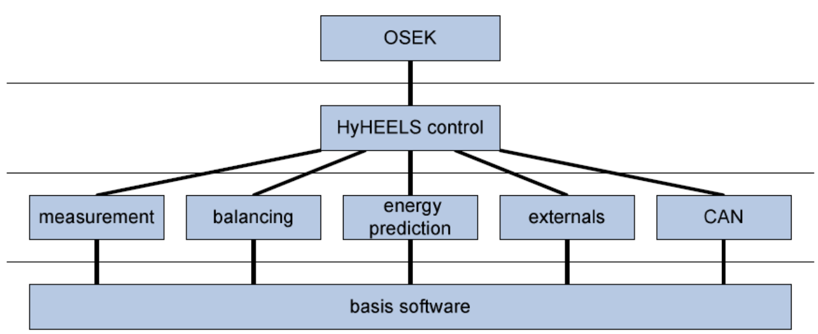


Figure 37: Software architecture.

From bottom to the top there are four layers. On bottom the basis software which includes the IO driver for the peripheries of the controller which is a STAR 12 from Motorola. The basis software is common used software module of Continental. However this module was adapted for the application. The second layer is the application software. The application software includes the software for the diagnosis of the UltraCap module, the communication via CAN and the interaction with the externals e.g. current sensor, temperature sensor or fan if applicable. The third layer is the HyHEELS control. Together with the forth layer the OSEK layer the overall software will be coordinated. Especially the OSEK (open systems and the corresponding interfaces for automotive electronics) is responsible for the proper working of the software. OSEK provides the task manager for the application software.

As the first and the forth layer is more standard software the focus is more on the application layer in this description. The application layer includes the HyHEELS control with the diagnosis and the following modules:

- Measuring and balancing
- ESR calculation and energy prediction
- CAN communication

Measuring and balancing

The most important and critical task of the software is the cell voltage measurement, because the overall performance of the UltraCap Controller is mainly depending on the ability of performing a fast and accurate voltage measurement of every single cell.

All other functions of the UltraCap Controller (communication of measurement values / over voltage signalling / balancing / power prediction / ...) need the output of the cell voltage measurement module and have to rely on the precision and reliability of this measurement module.

A detailed description of the measurement process of a single cell for the UltraCap Controller is depicted in Figure 38 below.

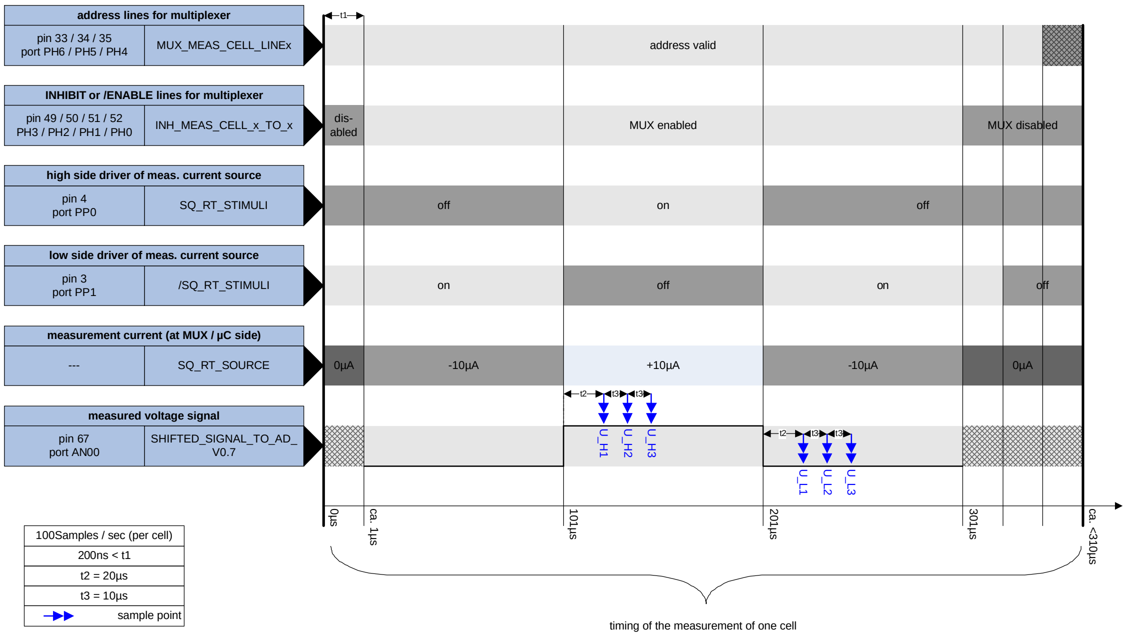


Figure 38: Measurement process of a single cell

The timing diagram in Figure 38 explains that the SW has to control three addresses and four enable lines to select a certain DLC cell. Besides this the SW also controls the current source and sink for producing the square wave measurement current.

For measuring a DLC cell as fast as possible only 1.5 periods of a full square wave are used. Measuring one cell lasts less than 310µs.

The sequence starts with a low phase to bring the circuit into a defined initial state. Afterwards there is one full period with a high and a low phase in which the SW collects six A/D samples. The measurement value for this DLC cell is calculated with the following equation.

$$Umeas = \frac{U_{H1} + U_{H2} + U_{H3} - U_{L1} - U_{L2} - U_{L3}}{3}$$

The voltage measurement of all DLC cells is done in two 5ms tasks. See Figure 39 for a detailed timing of the overall voltage measurement process.

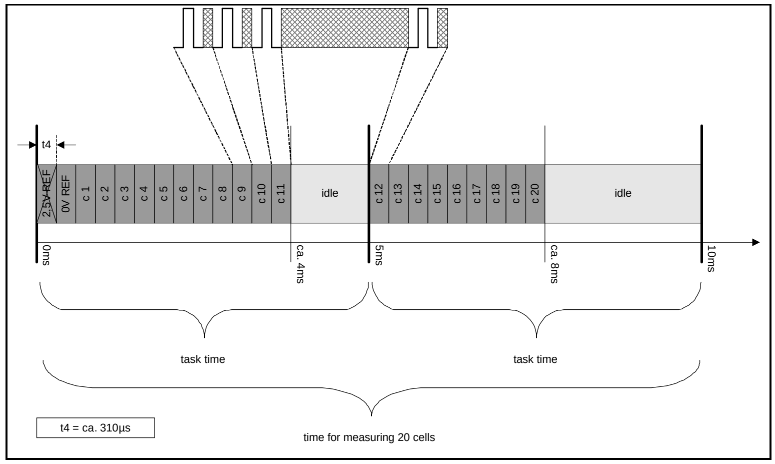


Figure 39: Timing of the complete voltage measurement

For the overall voltage measurement process SW has to measure a 0V reference cell and 20 DLC cells. The total time for these measurements is approx. 6.8ms (means too long for one task time with 5ms). Therefore the measurement is split into two 5ms tasks. The 2.5V reference is not used anymore to enhance the calculation performance of the µ-controller.

With this measurement process SW is able to collect 100 samples per second per cell. This sampling rate enables the UltraCap Controller to measure voltage signals of all DLC cells up to a bandwidth of 50Hz.

The following Figure 40 shows two oscilloscope screenshots of the cell voltage measurement signal.

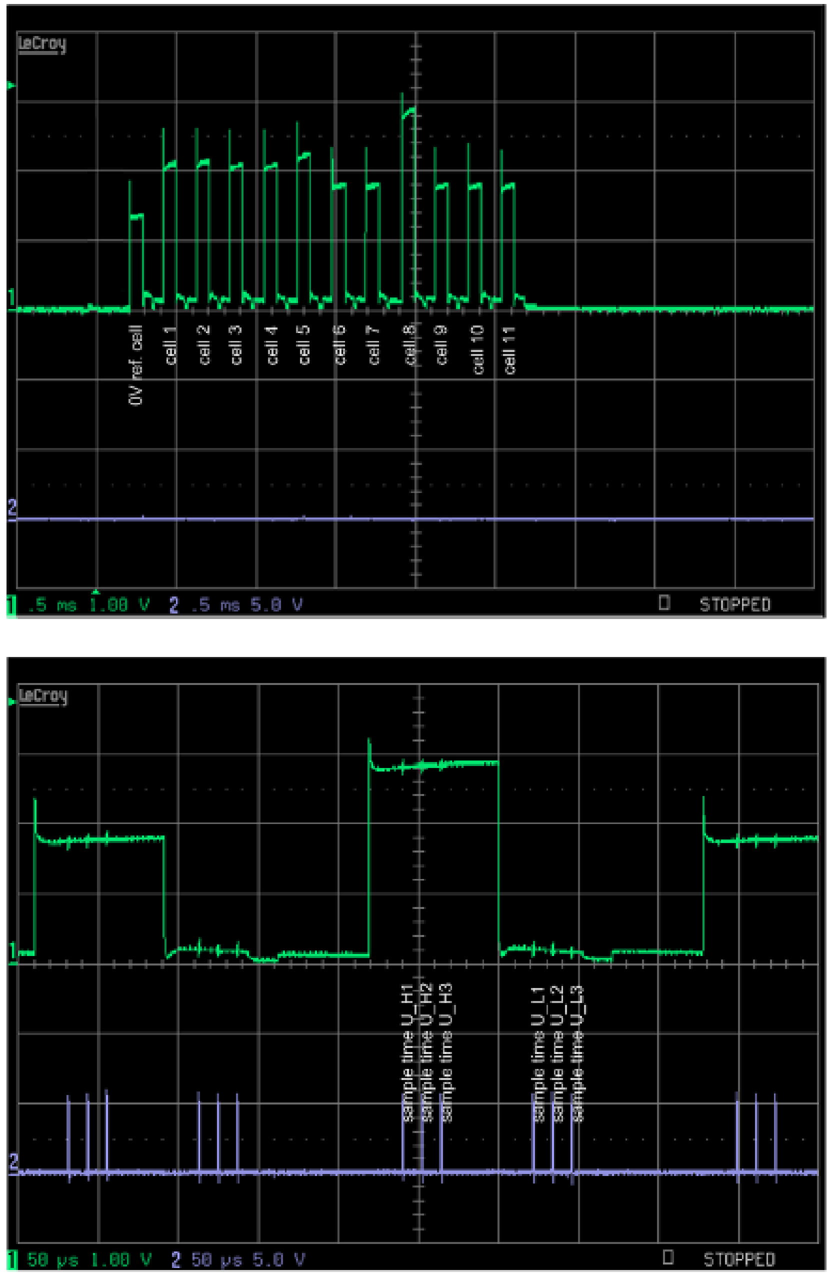


Figure 40: Oscilloscope screenshots of cell voltage measurement

The upper screenshot shows an example of the correct timing behaviour of the cell voltage measurement module.

The lower screenshot shows the same example more detailed (shorter time basis) and with an additional test signal on channel 2, which shows the correct timing of the ADC sample points.

The following table shows the characteristics of this measurement:

Name	cell_volt_1 ... cell_volt_20
Type	analog
Sampling rate	100 samples/sec
Resolution	1digit = 5V/(2^{10}) = 4.9mV
Measurement range	0V ... 3.5V

The balancing of the cells is working vice versa as the cell voltage measurement. However as described in chapter 3.2.2.1, the hardware path is separate and the coupling capacitors are bigger to ensure a high balancing current. From the software point of view the procedure is easy and simple. Furthermore the software step will be not controlled from outside. It is an internal process and not visible on the CAN. Only the desired cell has to be selected and the H-bridge with the DC/DC converter has to be activated by the software. If the parameters are set the selected cell will be recharged. All cells except that with the highest voltage (i = g) get a calculated charge correction DQ[i]. All cells get the same additional charge • Qmax until the energy storage is full:

Q@2.5[i] = Q[i] + • Qmax + DQ[i]

The balancing will be switched off as soon as the mismatched cell has the target load. Afterwards the next weak cell will be selected and recharged. This procedure is going on until all cells have the target charge which guarantees a balanced module. The calculation for the necessary charge will be done within the software modules ESR calculation and energy prediction. These both modules will be explained below.

ESR calculation and energy prediction

The ESR is very important for the determination of the state of health and for the prediction of the energy. However this determination is tricky especially during normal operation as this value is extremely low. During the project different possibilities were investigated. The figures below show the internal resistance determination of a real measurement, derived from current and voltage of a test drive with a demo car.

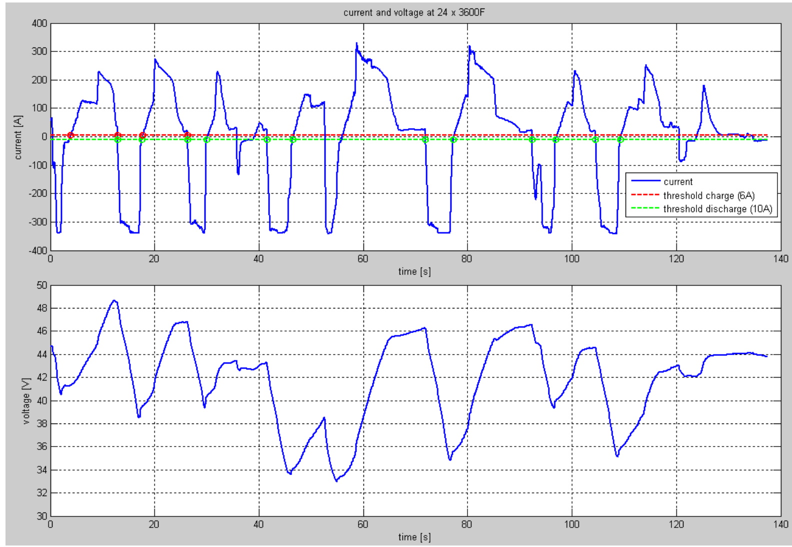


Figure 41: Measurement of current and voltage during a test drive with car, equipped with a UltraCap module.

The result was very satisfying as the ESR of the capacitor is extremely low (only 150 µOhm) and this value could be detected during normal operation. Even weak capacitors could be identified at this example (50 µOhms higher ESR of cell 20 compared to the others).

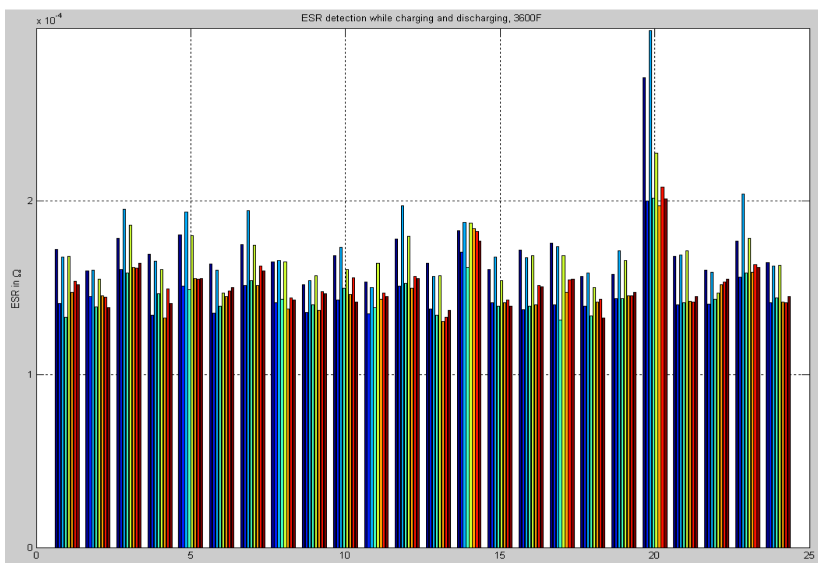
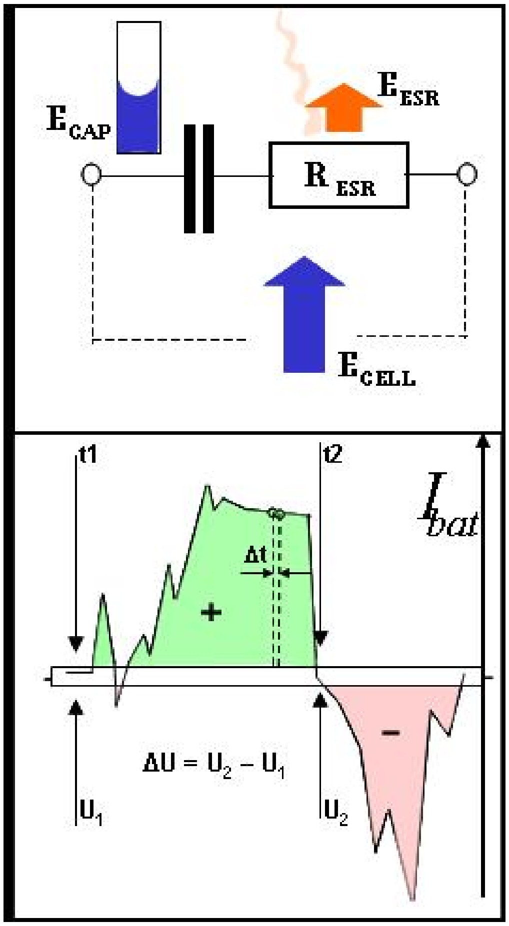


Figure 42: Calculated ESR on the basis of the test drive data.

The ESR will be determined between two zero current events according to the following equations.



$$E_{ESR} = E_{cell} - E_{CAP}$$

$$R_{ESR}[i] = \frac{\int_{t1}^{t2} U[i] * I(t)\ dt - (E_2 - E_1)}{\int_{t1}^{t2} I^2(t) dt}$$

$$E_{cell}(U) = \left\{ \tfrac{3}{4} a * U[i]^4 + \tfrac{2}{3} b * U[i]^3 + \tfrac{1}{2} c * U[i]^2 \right\} [Ws]$$

$$E_2 = E_{cell}(U_2[i])$$

$$E_1 = E_{cell}(U_1[i])$$

Figure 43: Principle method of the ESR calculation.

The ESR for each cell will be estimated in the range of [0..5] mOhm and the resolution is 1digit = 0.02mOhm. That means, for each cell, the ESR value will be an 8bit integer value in the range of [0..250], as this calculation is much easier and faster than the calculation in floating point.

As soon as the ESR and the capacitance are well known also the energy prediction is possible because this value could be derivate from these values.

CAN communication

CAN module handles the CAN communication between UltraCap Controllers and the vehicle. In the following subchapters two important messages for observing the UltraCap Controller are described. The complete message set is defined in the HyHEELS DBC (database container), which can be retrieved from Continental Automotive GmbH.

The following CAN signals could be received:

- T_ist (temperature)
- I_ist (current)
- U_ist (stack voltage)
- Cell_Voltage_max (maximum cell voltage)
- Cell_Voltage_min (minimum cell voltage)

The structure of the CAN message is according to the following frame. As an example for T_ist, I_ist and U_ist:

Message Name	USSI_SpTech
Purpose	Message which periodically (10ms) lays certain measurement values on the CAN bus
Message ID	200h
Data length	8bytes
Message type	cyclic message
Carried signals	• T_ist (temperature) • I_ist (current) • U_ist (stack voltage)
Data layout	(see below)

	bit 7	bit 6	bit 5	bit 4	bit 3	bit 2	bit 1	bit 0
byte 7	FFh							
byte 6	T_ist							
byte 5	I_ist (high)							
byte 4	I_ist (low)							
byte 3	xxh							
byte 2	U_ist (high)							
byte 1	U_ist (low)				xxh			
byte 0	checksum							

All signals will be updated every 10 ms. Of course further signals available but not indicated as necessary and therefore not provided.

WP2300 Simulation and measurements of power losses

The power losses were simulated in order to guarantee the well-functioning of the UltraCap Controller under all circumstances. In a special focus of these simulations was the charge balancing system, which transfers the most of the power. But also the single voltage measurement was checked because this unit has to be extremely low in power consumption as otherwise the UltraCap module will be discharged in a very short time (Increased "self-discharge" of the UltraCap module). The simulations provided necessary information for the design of the cooling concept as the simulations showed that cooling is essential but could be by natural air convection.

The complete UltraCap controller has several parts which could be observed in separated blocks. These blocks could be simulated independently. The individual blocks are show in the figure below. The main blocks are

- the buck converter,
- the voltage link,
- the DC/AC converter and
- the balancing electronic.

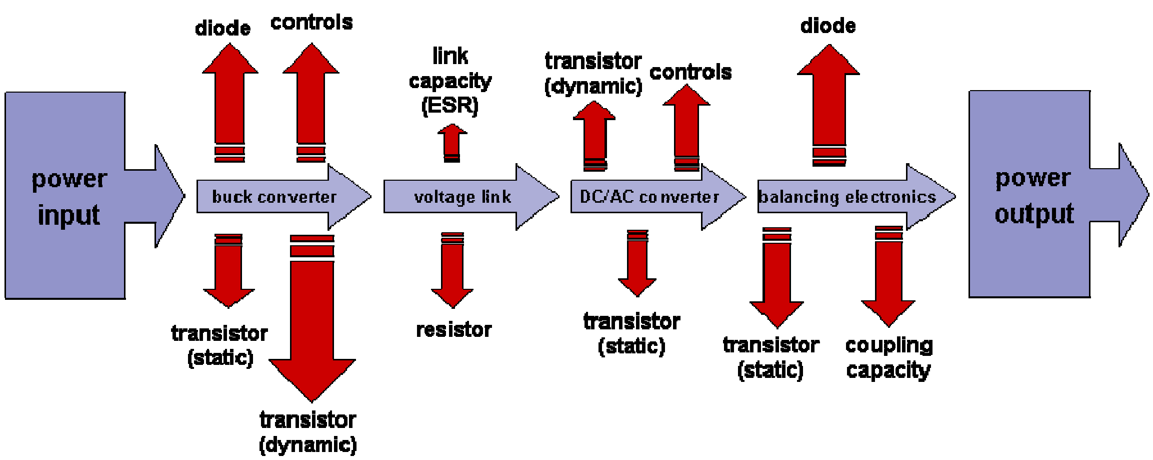


Figure 44: Structure of the UltraCap Controller, part of the power losses simulations.

The simulation of the power losses were done according to this structure. The main part in the UltraCap controller is the buck converter. Therefore the result sheet of this simulation part is shown in the following figure.

Power losses BuckConverter

Data FET:

Ron	0,026 Ohm	PLUS_BUCK	12 V
Qg	7,70E-09 C	Irms (out)	0,443289 A
tr	5,00E-09 s		
tf	3,00E-09 s		

Data Gate IC:

Io+	0,09 A
Io-	0,18 A
t_tot_max	1,00E-07 s

Power Losses:

TOPFET:

Pvstat	1,49E-03 W	
Pvdyn	1,284E-01 W	(ton, toff, 12V-Uzk)
Pvges	1,299E-01 W	

BOTFET:

Pvstat	3,62E-03 W	
Pvdyn	5,29E-02 W	(ton, toff, Uzk)
Pvges	5,650E-02 W	

Transfer Power:

eta	89,27 %	
Pin	1,738E+00 W	(Pout-Pvg1-Pvg2)
Pout	1,55 W	

Comparison:

eta	89,27 %
t_tot	1,00E-07 s
t_on	9,06E-08 s
t_off	4,58E-08 s

Data Buck:

L	3,30E-05 H	
Imax	6,27E-01 A	
Imin	0,00E+00 A	
Irms	4,43E-01 A	(only for Imin=0)
di	6,27E-01 A	
f	5,00E+05 Hz	
Uzk	3,5 V	
dt1	5,83E-07 s	
dt2	1,42E-06 s	
T	2,00E-06 s	
ftest	500000 Hz	
d	0,29	(Uzk/12V)
ton	9,06E-08 s	
toff	4,58E-08 s	
Iin	1,448E-01 A	(Pin/12V)
U11_top	8,5 V	(12V-Uzk)
U12_bot	3,5 V	(Uzk)

Figure 45: Result of the buck converter simulation.

These estimations and simulations result in at least 61 % efficiency of the electronic. The complete chain of power losses is shown in the following figure.

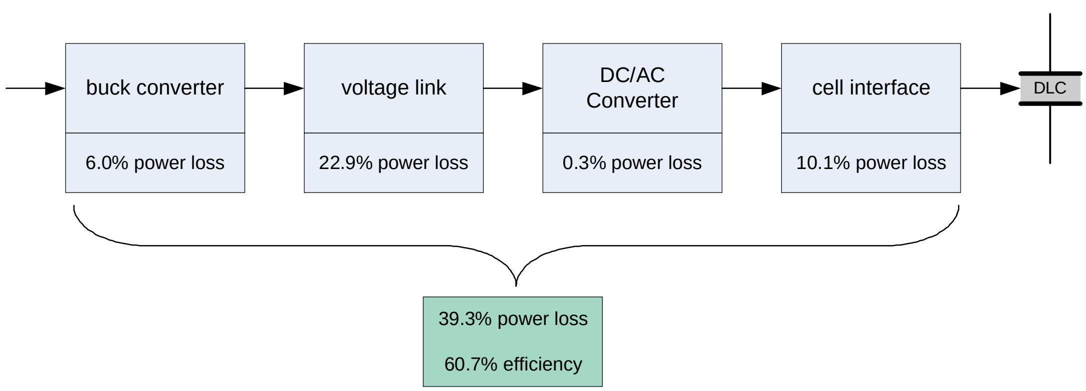


Figure 46: Result of the simulation, power losses chain.

The main part of the losses will be generated in the voltage link capacitor. This improvement could be easily identified by the simulation. The counter-measurement against these losses was the using of different DC link capacitor with lower ESR. In the last version of the UltraCap controller a ceramic capacitor was used instead of an electrolyte capacitor.

Based on the simulations and improvements a final efficiency of 70 % will be assumed.

WP2400 Set up of UltraCap controllers suitable for mass production

The developed UltraCap Control units were set up and combined with an adequate UltraCap module. Experiences of the capacitor manufacturer had an important influence in this set up. The focus was on the easy assembly of the Controller with the module.

As the responsible partner for the module design left the consortium after one project year, this task was transferred to the partner MAXWELL. Caused by this additional task of this partner the module design had not the maturity as original planned. However this design reached a final status which enabled possible tests in vehicle.

During the development phase several improvements were done. These improvements were the result of four design loops of the electronic. Therefore more than 50 UltraCap controllers were set up with different performance. These four different developments steps are shown in the following figure.

The figures shows the several steps during the development which are:

- On the left upper side: A0 sample for development
- On the right upper side: A sample
- On the left lower side: A sample with filter board
- On the right lower side: final prototype with own DC/DC

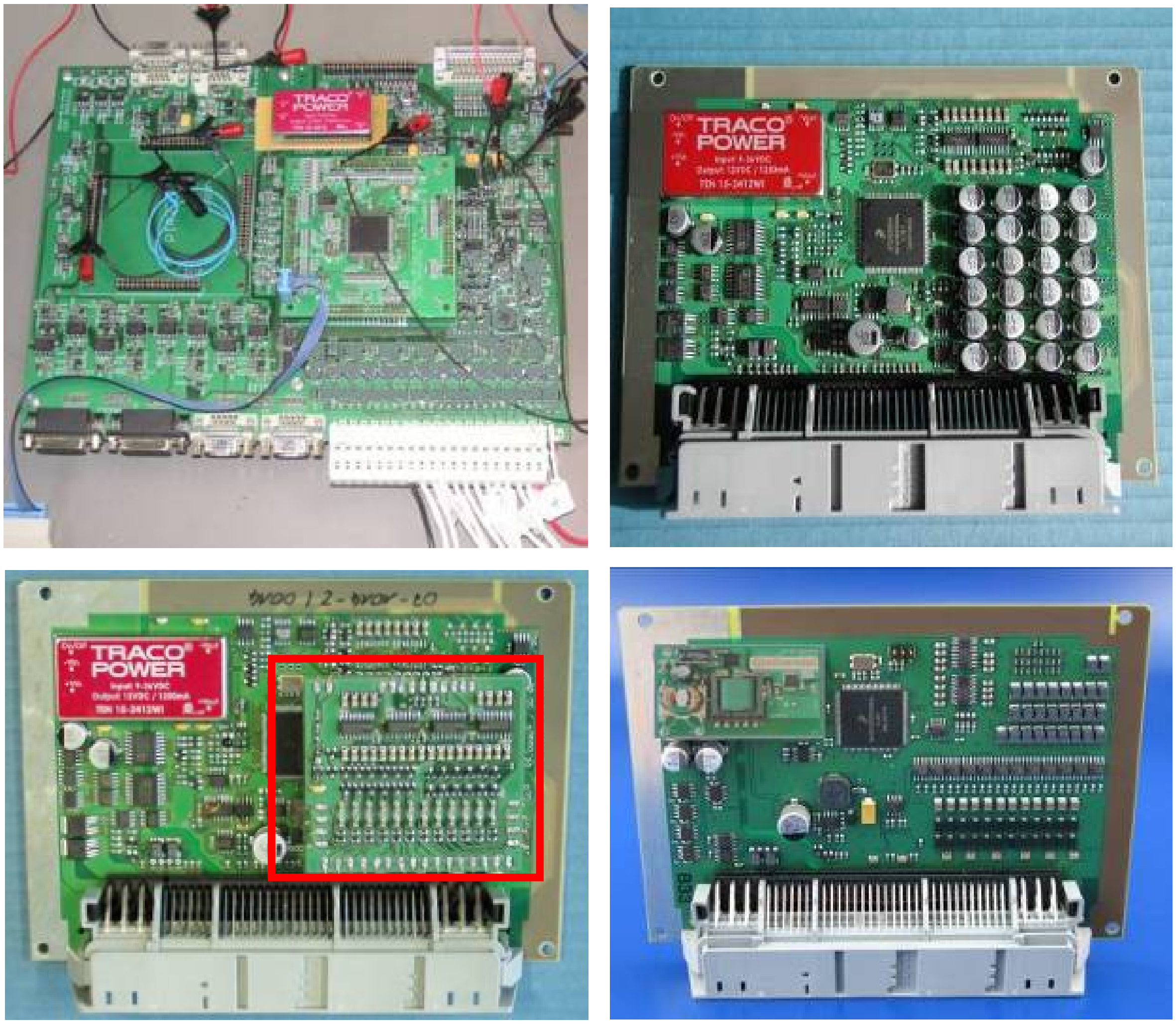


Figure 47: Four different development steps of the UltraCap controller.

The first picture upper left was the A0 sample. This board had additional functionality. Especially a second controller for safety reasons (redundancy). Furthermore this sample had a very big printed circuit board PCB, which guaranteed easy access to the individual pins for measuring. The focus on the A0 sample was to test and optimize the cell voltage measurement and the cell balancing/energy transfer via the isolation barrier.

Based on the results of the A0 sample the first A-sample was set up. Compared to the A0 sample the size of the PCB was smaller. The dimensions of the board had already the target size of the controller. Many of the used components had automotive standard and were released. Only the DC/DC was a commercial product and not released for automotive products. The functionality of the controller was smaller than the functionality of the A0-sample. However all requirements were taken into account but could not fulfilled in total. With this sample many tests were performed. Especially the voltage measurement and the balancing were tested. The design showed some disadvantages regarding temperature drift (heating up of the coupling capacitors) and disadvantages caused by the parallel use of the measuring path for balancing. This disadvantage was based on timing problems. As the same path was used for both functions the cell voltage could not observed during balancing. Finally this disadvantage results into balancing of the module at parking. However if the balancing is only enabled during parking the vehicle controller could not switched off and the power consumption of the vehicle was too high.

The next evolution step was the splitting of the path into two parts. One path for balancing which was able and strong enough to transfer more than 1 A and one measuring path able to sample the 20 cells within 10 ms. Furthermore the temperature problem was solved by this separation. Therefore the accuracy of the voltage measurement could be fundamentally improved. This new A-sample board showed very good performance in the laboratory. However during high current charge and discharge of the module aliasing effects occurred on the voltage measurement.

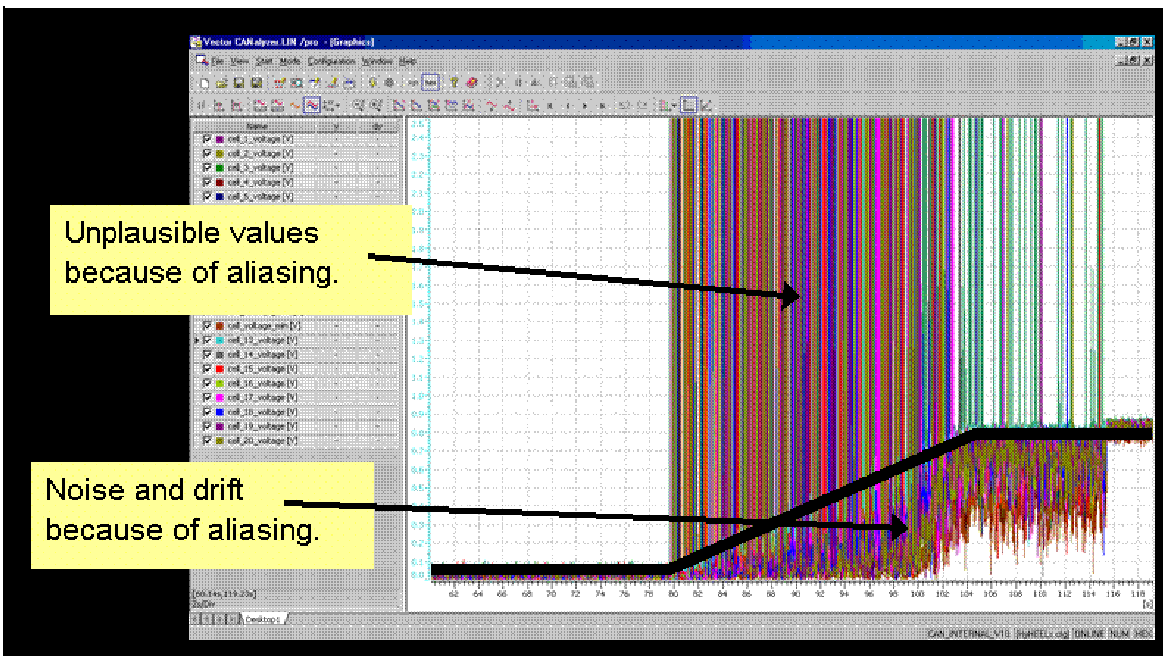


Figure 48: Aliasing effects during voltage measurement at high current charge.

This aliasing was provoked by the switched DC power supply for charging the UltraCap module representing the worst case. However additional counter measurements had to be installed to keep the device stable in measurement. These were in the first step an analogue filter board at each voltage channel, which was realized by low pass filter at a cut-off frequent of 50 kHz, in the second step in a software filter of the analogue inputs and last but not least in an increase of the measurement current from 10 µA to 500 µA.

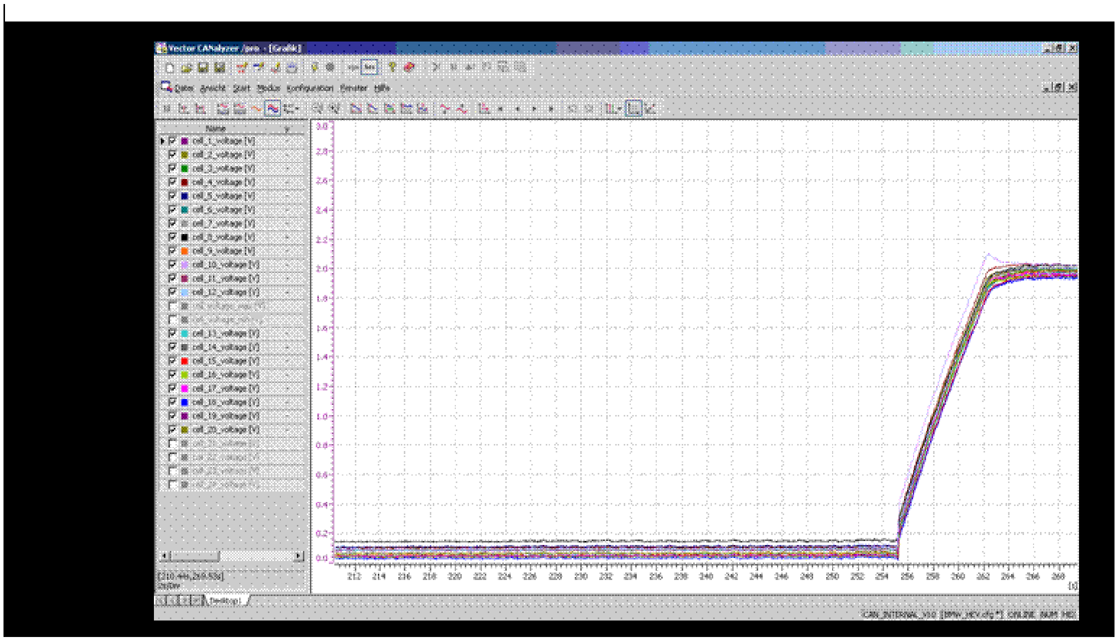


Figure 49: Voltage measurement test at 300 A charge.

The test results after integration of the filter board were satisfying.

A final step in the industrialization of the UltraCap controller is the cost reduction of components. In special focus was the DC/DC converter. This component was as an expensive bought-in part from TRACO-POWER which was used in the first batch of UltraCap controller. A marginal step into the industrialization of the UltraCap controller was the exchange of this isolated DC/DC converter by a DC/DC converter designed by Continental.

Figure 50: Further Industrialization step forward by exchange of the DC/DC from TRACO by an own development.

The last version of the controller, the final prototype, was equipped with this own DC/DC development. However this was a single board were the Traco Power DC/DC was exchanged by the own. This was possible as the footprint of both DC/DC has the same. An additional improvement from the A-sample to the final prototype was the exchange of the electrolytic capacitors by ceramic capacitors. This step was implemented as the simulations within WP2300 showed high improvement of the efficiency by using of ceramic capacitors. The final design of the controller was assembled by automotive qualified components which are very important regarding to reliability and last but not least regarding to costs. The compiled requirements of workpackage WP2100 were almost completely fulfilled.

Mechanic development

The housing of the UltraCap Controller consists of two deep-drawn parts (housing and bottom plate). Both parts are made of aluminium alloy which guarantees good heat dissipation. When assembling the housing, the PCB and the bottom plate is screwed together with four "3.5x12 Powerlok-" screws.

The protection class with plugged or unplugged harness is according to DIN 40050 IP5K0 / IEC529 - IP50.

Figure 51: Picture of fully assembled UltraCap controller

For comfortable mounting of the UltraCap Controller at the UltraCap module or the desired installation space in general, mounting brackets have been designed. They can be viewed in Figure 51 at the left and right of the controller provided with 4 hexagon socket screws.

The connector of the UltraCap Controller is a 134pin connector (18pins for higher currents) with 5 chambers from Tyco-AMP (drawing number: 967288). See also Figure 52.

The counterparts for the wiring harness are freely available at Tyco-AMP (see table 1 'pin assignment' for part numbers)

The assembly of the connector on the PCB is done with a snap mechanism for mechanical fixation and with through-hole technology for electrical connection.

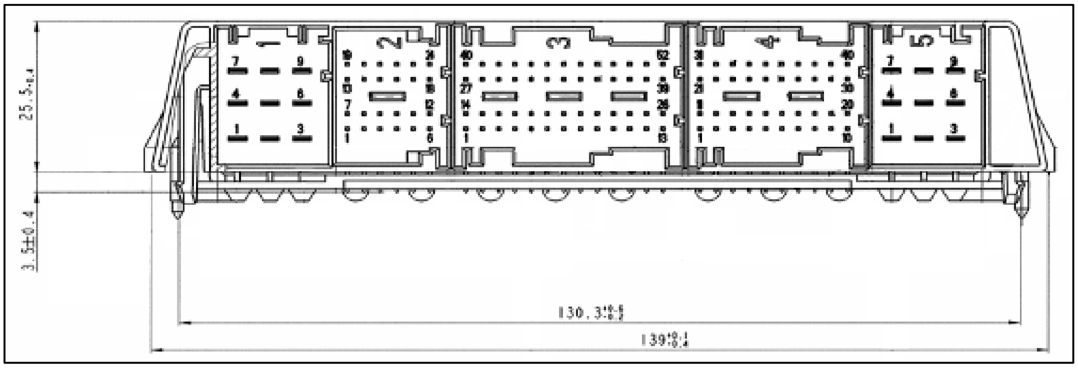


Figure 52: Connector drawing and pin definition

3.4 WP3000

WP3100

Based on a dedicated power profile of the energy storage in a passenger car, the UltraCap based energy storage is configured and evaluated with simulation tools (Figure 53) at differently aged UltraCaps. The energy capacity of an UltraCap energy storage is dependent on the different voltage difference besides the rated capacitance in different ages. Applying the methods of identifying and balancing voltage differences the energy capacity of the storage can be ensured until the end of the UltraCap life

Simulations were carried out for light duty vehicles (VUB) as well as for heavy duty vehicles (WUT). In a first step simulations were performed with a vehicle simulation tool to assess the power load profiles to be delivered by a ultracap stack. More detailed analysis were done in Matlab in order to configure and design the ultracap packs. The analyses were based on based on these load profiles as well as based on load profiles provided by BMW and Scania.

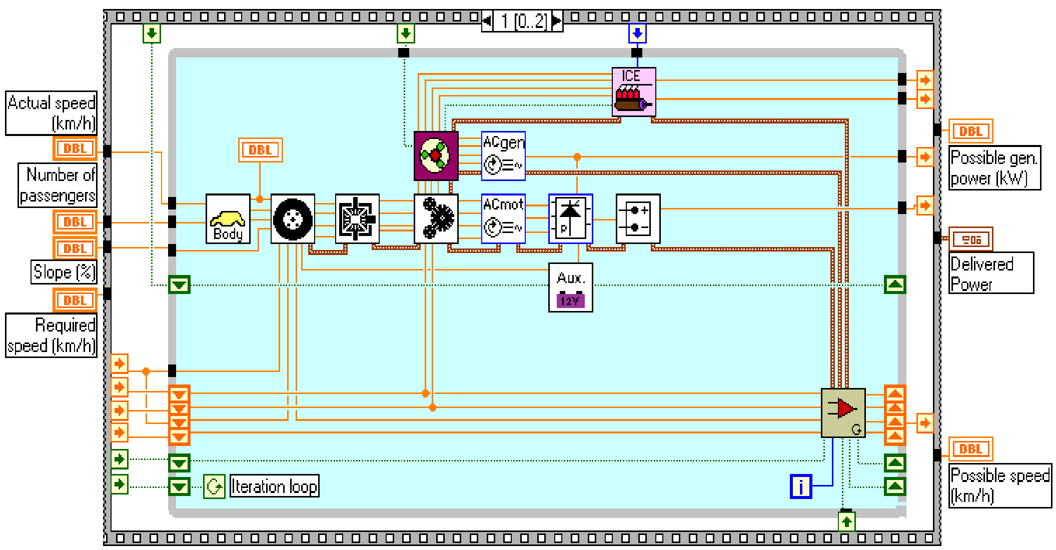


Figure 53: Representation of system modelling.

According to the power profiles provided by the OEM's a structure of 170~180 total cell levels (single-cell string or double-cell strings) energy storage can be functioning well in NEDC and FTP test cycle for passenger cars. Structures of 200 total cell levels can be functioning well in the SORT and the Braunschweig cycle of heavy duty buses. Instantaneous current and power losses of UltraCaps corresponding to the test cycle of passenger car and heavy duty vehicle were obtained. This information was very useful for further analysis of voltage unbalance and thermal behavior of UltraCaps.

Using the determined power profile of the UltraCap, the initial and final voltage of the UltraCaps are not equal. This resulted into increased power of the primary source to cover the differences. This unbalance is caused by the non-linearity and different individual level of energy losses. With repeated drive cycles, carried out in an experimental test set-up, this voltage unbalance accumulated up to achieve critical values (tests were done without balancing circuit).

On vehicle level, the simulation results for different driving cycles (SORT, Braunschweig, Leuven, DUBDC) show that a system of 2x11x20 cells fulfil the requirements for the driving cycles with a fully balanced system (no exceeding of 12% of the short-circuit current value, voltage kept between limits of 50% to 100%). Simulations on vehicle level indicated that operation in ambient temperatures up to +45°C feasible without an additional active cooling system. Furthermore the results obtained were the base for several publications and presentations of papers by the partners at international conferences and symposiums (see dissemination).

WP3200

If different technologies are used for the same purpose, the environmental quality can be used as a criterion of choice. Using the Life Cycle Assessment methodology (Figure 54), a comparative environmental assessment covering the complete life cycle of a Ultracapacitor and of different battery technologies was performed in this study. From a global point of view, the Ultracapacitor scored better than the assessed battery technologies. The relatively low weight of the super capacitor and the high recyclability rate of its main material (aluminium) are the most important reasons for this. The uncertainty analysis was performed through a Monte Carlo analysis which allows comparing different products on the basis of the variation of their specific parameters between two extreme values.

Additionally, an improvement opportunity assessment has shown that the overall environmental impact (Figure 54) of the Ultracapacitor could be further reduced by more than 30% if the aluminium is replaced by 80% recycled aluminium.

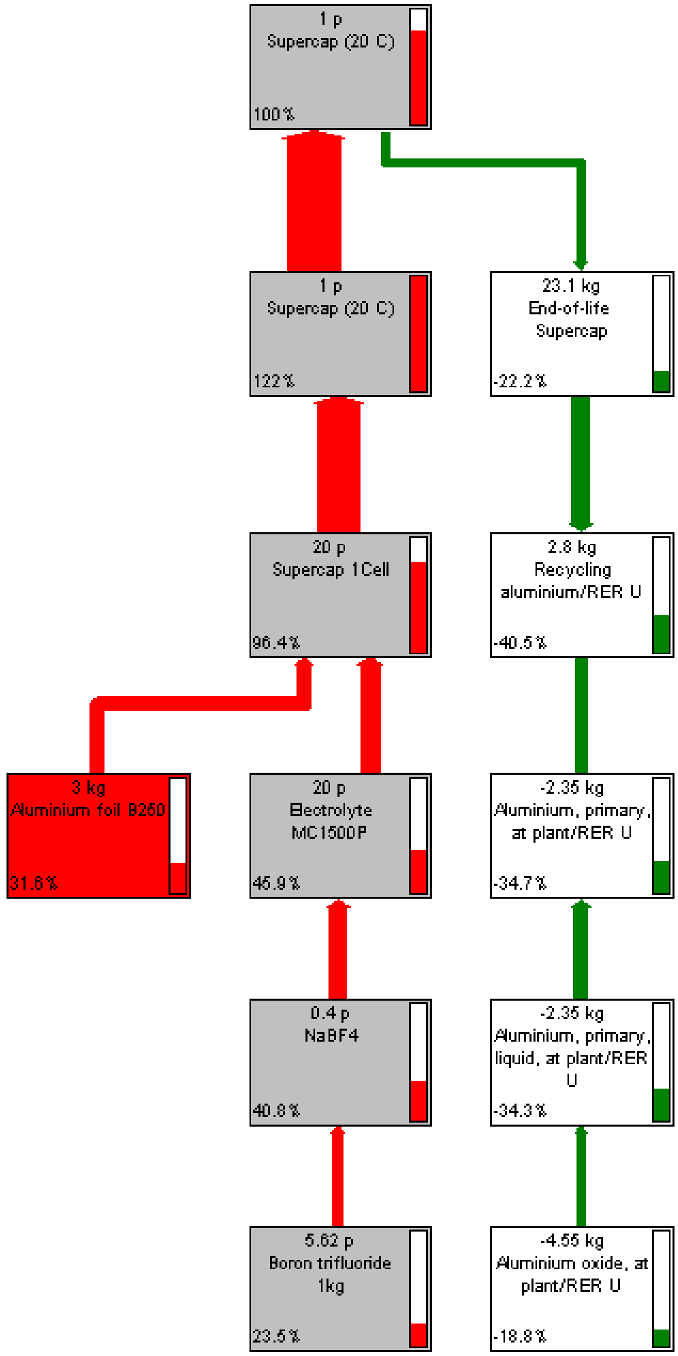


Figure 54: Environmental impact tree of the MC 1500P Ultracapacitor according to the Eco-indicator 99(H) calculation method (only contributions of more than 18% of the total are shown).

Detailed uncertainty data concerning all the components of the different technologies allowed producing useful results during the sensitivity analysis, helping the decision maker in his or her choice amongst technologies which seem to have the same environmental burden.

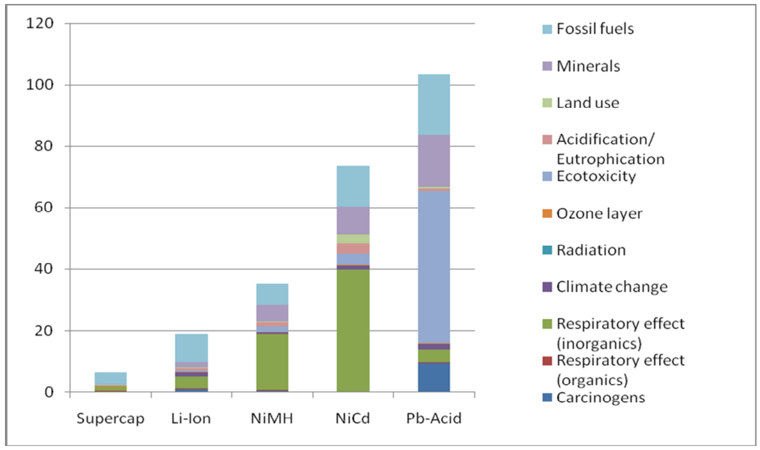


Figure 55: Comparative LCA results (Eco-indicator points).

WP3300

A test setup was developed at the VUB to test the ultracap packs under real load profiles (see Figure 56).

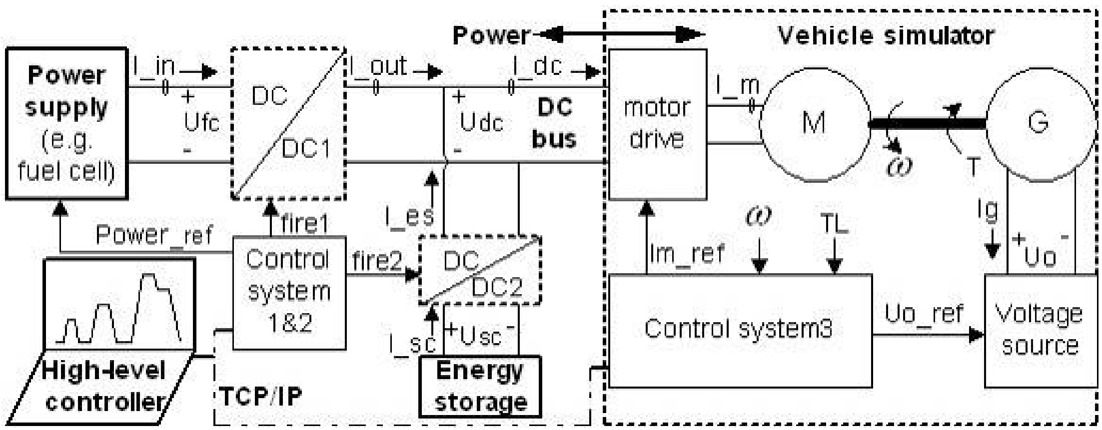


Figure 56: Research and test platform of hybrid electric vehicle

In order to acquire input data for the simulation model and model validation, Ultracap modules were tested at VUB.

The required parameter values of super capacitors for the simulation model have been acquired from these. The simulation model was also validated in the test setup.

Furthermore, vehicle driving cycle tests were done. One example of such a driving cycle is the Worst-Case cycle from BMW depicted in Figure 57. The test results of the voltage variation tests (around 100%~50% rated voltage) are shown in Figure 57, which proves that the SC modules are efficiently applied. The configuration (see WP3100) is thus validated.

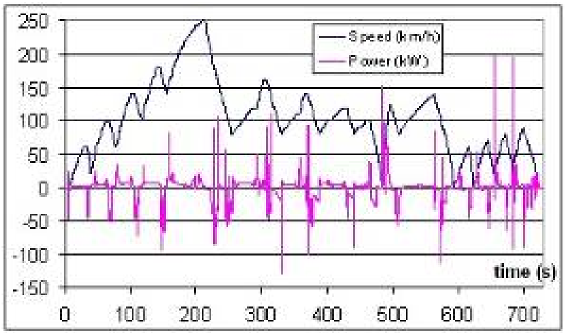


Figure 57: Speed and power profile during Worst-Case cycle.

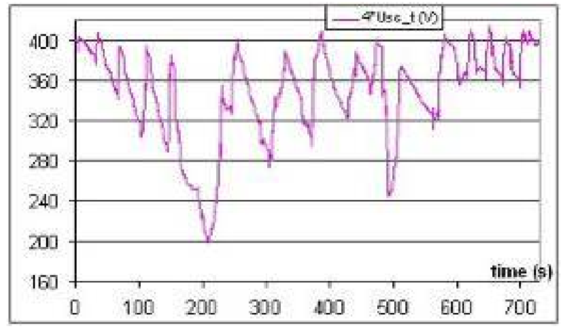


Figure 58: Voltage variation during Worst-Case cycle.

During experiments by cycling the Ultracap modules many times the parameter values of the modules were traced as a function of the number of driving cycles. For this purpose, the worst-case cycle is repeated at room temperature. The equivalent driving distance is about 20km per Worst-Case cycle. After each 500 cycles, the parameter values of SC modules were evaluated. Particularly, the energy losses vs. the input energy are tested. It was concluded that the energy losses are higher in big voltage range (1.7~105V) even at low current (20A) than in small voltage range (8.5~98V) at high current (80A). This is because the energy losses are strongly dependent on the operating current and voltage range of the SC modules. The test results show that the energy losses increased during the test procedure. At the end 2785 Worst-Case cycles equivalent to 55700 km driving distance were executed. The losses at the end doubled compared to the losses at the beginning of the cycle test. However, there was no over temperature or mechanical deviation observed. The modules could still be used for other tests or applications.

4 Deliverables and other output

During the HyHEELS project several deliverables and other output were generated. These were reports, samples and presentations on conferences.

4.1 Deliverables

The deliverables were predefined before project start. All deliverables were fulfilled however some of them with a delay. This delay was mainly caused by the early withdrawal of EPCOS and a planning failure at begin of the project. In total only in 3 deliverables was a bigger shift of the delivery date.

Deliverable No	Deliverable title	Planned Delivery date	Actual delivery date	Delay	Status
D1	Requirements document UltraCap (WP1100)	M9	M11	2	J
D2	Requirements document UltraCap controller (WP2100)	M9	M11	2	J
D3	Sample modules based on traditional UltraCaps	M12	M25	13	L
D4	Report on recommendations from other research (WP3100)	M12	M12	0	J
D5	A0-sample UltraCap controller (WP2200)	M16	M16	0	J
D6	A0-sample UltraCap component (WP1200)	M18	M18	0	J
D7	Evaluation of modules based on traditional UltraCaps	M18	M23	5	L
D8	Prototype UltraCap component available (WP1200)	M24	M40	16	L
D9	Prototype UltraCap module packaging available (WP1300)	M24	M37	13	L
D10	Prototype UltraCap controller and documentation (WP2200)	M24	M28	4	K
D11	Report on simulations and modelling (WP3100)	M24	M25	1	J
D12	Pre-series UltraCap module (WP1200)	M36	M39	3	K
D13	Report on test bench results on UltraCap modules (WP3200)	M36	M38	2	K
D14	Report on simulation and measurements (WP2300)	M36	M42	6	L

Deliverable No	Deliverable title	Planned Delivery date	Actual delivery date	Delay	Status
D15	Pre-series UltraCap controller (WP2400)	M36	M38	2	K
D16	Assessment and outlook report (WP3200)	M36	M38	2	K
D17	Report on vehicle test results on UltraCap modules (WP3300)	M36	M39	3	K
D18	Website operational (regular updates) (WP0400)	M9	M11	2	K
D19	Technology implementation plan (WP0400)	M36	M42	6	L
D20	Final report (WP0100)	M36	M42	6	L

4.2 Dissemination

Date	Event/venue	Location	Distribution	Partner
15.06.2006	Conference paper	ESSCAP'2006	International	
15.08.2006	Carbon 44 (2006) 2523–2533Paper		International	
06.09.2006	Paper	Windsor, England	International	
05.10.2006	3rd HFP Brussels		International	VITO
24.10.2006	EVS22 Conference	Yokohama, Japan	International	VUB, VITO
02.-03.11.2006	ESSCAP 2006 Papers	Lausanne	International	VITO, VUB, Maxwell, UTBM
01.06.2006	Poster	Hydrogen & Fuel Cells brochure		IMC, VITO
12-15.06.2006	TRA 2006, Gothenburg	Poster session		IMC, VITO
31.08.2006	Website operation	www.vito.be/HyHEELS	Visibility worldwide	VITO
02.11.2006	Publication and Presentation Paper on HyHEELS	ESSCAP' 2006 HyHEELS	International	VITO, VUB, Maxwell, UTBM
22-25.01.2007	XX Conference "Trends in the Development of Heavy Duty Machines"	Zakopane, Poland	National	WUT
12-14.04.2007	International Conference on Power Engineering, Energy and Electrical Drives (POWERENG)	Polytechnic Institute of Setúbal; Setúbal; Portugal	International	WUT
15.04.2007	Scientific Paper "Thermal modelling and	Submitted to IEEE Transactions on Industrial	International	UTBM, MXWL

	experimental characterization of Ultracapacitor for hybrid vehicle applications"	Electronics		
14.05.2007	Large Ultracapacitor Technology and Applications	Long Beach, California	International	VUB
31.05.2007	Web site up-date	www.vito.be/HyHEELS	International	VITO
30.05.-02.06.07	European Ele-Drive Transportation conference 2007	Brussels, Belgium	International	VUB
04.06.-07.06.07	2007 IEEE International Symposium on Industrial Electronics	Vigo, Spain	International	VUB
03.-05.09.2007	12th European Conference on Power Electronics and Applications	Aalborg (Denmark)	International	VUB
22.09.2007	MobiDays Conference	London	International	VITO
23.-27.09. 2007	IEEE-IAS, 2007 Annual Meeting	New Orleans (USA)	International	UTBM, MXWL
26.-27.9.2007	Automotive Power Electronics APE2007 conference	Paris (France)	International	SVDO
4.-5.10.2007	Formula Electric and Hybrid Italy	Pollein (Italy)	International	CRF
16.-19.06.2008	Paper "UC adjustment for hybrid bus" (in Polish)	Sarbinowo, Poland	National	Warsaw
14.06.2008		Warsaw Poland	International	Warsaw
06-07.10.2008	ECPE Conference	Stuttgart	International	Continental

Publications related to Energy storage

Articles in scientific journals with an international referee system related to energy storage

- Methods of Configuring and Managing Super Capacitor Energy Storage as Peak Power Unit, Edition: European Power Electronics and Drives Journal (EPE Journal), Volume: 18, N° in volume: 4, pp: 198 - 207, published by: European Power Electronics and Drives Association, ISBN-ISSN: 0939-8368, 2008, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire Impact factor: 0.200, impact year: 2008
- Methods of Modelling and Identifying the Electrical Characteristics of Super Capacitor Energy Storage, Edition: International Review of Electrical Engineering (IREE), Issue: January-February 2008, Volume: 3, N° in volume: 1, pp: 198 - 207, published by: Praise Worthy Prize S.r.l., ISBN-ISSN: 1827-6660, 2008, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire Impact factor: 1.000, impact year: 2008
- Test Bench of Hybrid Electric Vehicle with the Super Capacitor based Energy Storage, Edition: International Review of Electrical Engineering (IREE), Issue: May-June 2008, Volume: 3, N° in volume: 3, pp: 466 - 478, published by: Praise Worthy Prize, ISBN-ISSN: 1827-6660, 2008, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire Impact factor: 0.200, impact year: 2008
- Test Platform for Hybrid Electric Vehicle with the Super Capacitor Based Energy Storage, Edition: International Review of Electrical Engineering (IREE), International Review of Electrical Engineering, Issue: May-June 2008, Volume: 3, N° in volume: 3, pp: 466 - 478, eds:

Praize Worthy Prize S.R.L., published by: Praize Worthy Prize S.R.L., ISBN-ISSN: 1827-6660, 2008, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire

- Peak Power Based Fuel Cell Hybrid Propulsion System, Edition:WEVA Journal, Issue: May 2007, Volume: 1, N° in volume: 1, pp: 54 - 61, published by: Japan Automobile Resaerch Institute, ISBN-ISSN: 978-4-931196-00-1, 2007, Joeri Van Mierlo, Jean-marc Timmermans, Gaston Maggetto, Peter Van Den Bossche

- H. Gualous, H. Louahlia-Gualous, R. Gallay, ? Thermal modelling and experimental characterization of supercapacitor for hybrid vehicle applications? IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 45, NO. 3, MAY/JUNE 2009

Communications at international congresses / symposia integrally published in proceedings related to energy storage

- Comparative LCA of Ultracapacitors and different battery technologies, ESSCAP 08, Italy, Edition:ESSCAP 08, , 2008, Faycal-siddikou Boureima, Julien Matheys, Vincent Wynen, Nele Sergeant, Joeri Van Mierlo
- Evaluation and Validation of Super Capacitor Energy Storage applied in Hybrid Electric Vehicles, Edition:PCIM China 2008, Issue: March, 2008, published by: Power Electronics Intelligent Motion Power Quality Association, , 2008, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire Impact factor: 1.000, impact year: 2008
- Method of Identifying the Electrical Characteristics of Super Capacitor based Energy Storages, Edition:EET-2008 European Ele-Drive Conference, published by: European Association for Battery, Hybrid and Fuel Cell Electric Vehicles aisbl/ivzw (AVERE), , 2008, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire Impact factor: 3.000, impact year: 2008
- Methods of testing the super capacitor energy storages at the application level, Edition:ESSCAP2008 (3rd European Symposium on Ultracapacitors and Applications), , 2008, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire
- Modélisation et management thermiques des supercondensateurs pour des applications véhicules, Edition:EPF, , 2008, Monzer Al Sakka, Hamid Gualous, Joeri Van Mierlo, Yonghua Cheng
- Configuration and verification of the super capacitor based energy storage as peak power unit in hybrid electric vehicles, Edition:EPE2007(12th European Conference on Power Electronics and Applications), Issue: September 2007, , 2007, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire, Michael Lieb, Erik Verhaeven, Rainer Knorr
- Control principle and modulation method for bi-directional and dual-coupled series resonant converters, Edition:EPE2007 (12th European Conference on Power Electronics and Applications), Issue: September 2007, , 2007, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire
- Designing Control principle and modulation method for bi-directional and dual-coupled series resonant converters, Edition:ISIE2007 (IEEE industrial electronics society conference), , 2007, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire
- Method of identifying voltage difference of super capacitors and principle of voltage balancing, Edition:EPE2007 (12th European Conference on Power Electronics and Applications), Issue: September 2007, , 2007, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire, Mathias Buechel, Rainer Knorr, Roland Gallay
- Research and test platform for hybrid electric vehicle with the super capacitor based energy storage, Edition:EPE2007(12th European Conference on Power Electronics and Applications), Issue: September 2007, 2007, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire
- Test Bench of Hybrid Electric Vehicle with the Super Capacitor based Energy Storage, Edition:ISIE2007 (IEEE industrial electronics society conferece), Vigo, Spain, , 2007, Yonghua Cheng, Joeri Van Mierlo, Philippe Lataire

- H. Gualous, H. Louahlia-Gualous, R. Gallay, ?Supercapacitor Thermal Characterization in Transient State? IEEE-IAS, 2007 Annual Meeting, September 23-27, New Orleans USA.

- G. Alcicek, H. Gualous, P. Venet, R. Gallay ?Experimental study of temperature effect on ultracapacitor ageing? 12th European Conference on Power Electronics and Applications 2 - 5 September 2007, Aalborg, Denmark.

5 Assessment of results and conclusions

5.1 WP1000

MAXWELL

The stack is made of one positive cell and one negative. On one side the positive electrode is connected to the lid and the other side to the bottom can. The 2 bottom can thickness, once laser welded together, have the same thickness as the lid. A plated connection is laser welded between the 2 cells to give a very low resistive connection for voltage measurement. A thermal shrink tube insulates the stack.

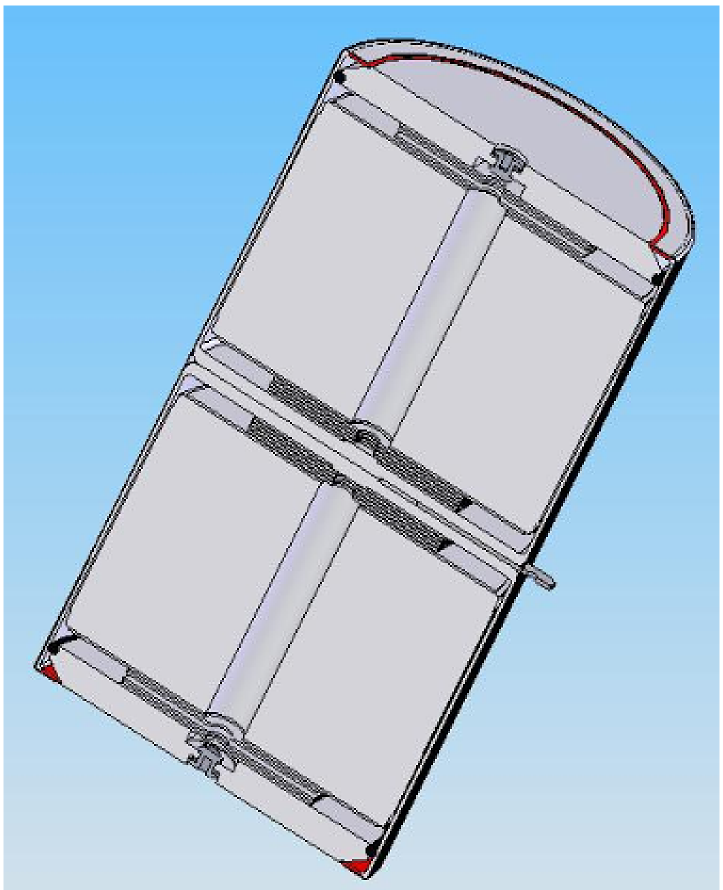


Figure 59: A 2 cells stack 5,4V 1000F with plated tab for wire connection to the controller board.

Figure 60: A completed stack with two aluminum connectors (+) and (-), shrink sleeve and Maxwell logo.

The Table 6 shows the technical evolution for a Maxwell standard product, a 2600F cell for 2004 and 2005, a 3000F cell for 2007 (actual data) and a supposed 3200F from 2009.

Power density [W/Kg] = V^2/(4xESR)/weight

Energy density [Wh/Kg] = (½ CxV^2)/3600/weight

Year	Relative Volume cc/F	Weight gram	F	ESR mOhm	Voltage	Power density kW/kg*	Energy density Whr/kg**	Temp C	Cycle life Millions
2004	0.161	525	2600	0.5	2.5	6.0	4.3	-40 +65	0.5
2005	0.138	453	2600	0.35	2.7	11.8	5.8	-40 +65	1.0
2007 (actual data)	0.130	550	3000	0.29	2.7	14	5.6	-40 +65	1.0
2009	0.120	550	3200	0.27	2.85	16.3	6.6	-40 +75	1.5
2011	0.116	500	3200	0.24	3.0	18.8	8.0	-40 +85	2.0

Table 6: Cell main data past, present and future.

			HyHEELS Cell		
	Unit	Initial	Current	Improved	Target
Nominal cell voltage Un	V	2.5	2.7	2.7	2.7
Maximum cell voltage Umax	V	2.7	2.85	2.85	2.85
Gravimetric energy density at Umax	Wh/kg	3.7	6.6	7.5	7.5
Volumetric energy density at Umax	Wh/l	5.0	9.0	9.0	9.5
Gravimetric power density at Umax	kW/kg	3.5	10.3	15.6	15.0
Volumetric power density at Umax	kW/l	4.7	14.0	18.8	19.3

Table 7: HyHEELS cell current data, improved versus initial and target.

The Table 7 shows the very good positioning of the HyHEELS cell according today's standard product. The energy density, one of the major HyHEELS projects' technical targets, is already as good as a future cell with 2,85V nominal voltage.

If the tests will qualify the cell for this 2,85V voltage, the results would be even better. And the building of a 3000F cell would also increase the power and energy densities, as the increasing weight and volume is proportionally lower!

The HyHEELS final module version is presented in Figure 61.

Figure 61: HyHEELS module 54V 100F in final version, including the controller

The average measured values from the 6 HyHEELS modules final version gives following results:

Module	Voltage [V]	Voltage Max [V]	Capacitance [F]	ESR (1kHz) [mOhms]	Mass [g]	Volume [l]
HyHEELS current	54	57	100	11.2	9300	9.18086
HyHEELS possible	54	57	100	**8.35**	**8370**	9.18086

Table 8: Average electrical values, weight and volume of modules SN1 to 6

Module	Emax [Wh]	Pmax [W]	Emax [Wh/kg]	Emax [Wh/l]	Pmax [kW/kg]	Pmax [kW/l]
HyHEELS current	45.1	72'522	4.9	4.9	7.8	7.9
HyHEELS possible	45.1	97'275	5.4	4.9	11.6	10.6

Table 9: Average energy and power density values of modules SN1 to 6

The ESR used for the maximum power corresponds to the value measured at 1kHz. This value is about 66% of the DC ESR, that corresponds to 8.35mOhms. The measured value by UTBM may correct a little bit this result.

The possible mass of the module, using lighter plastic bases, has been evaluated to 8370g.

Using these evaluations, the calculated results are given on the line "HyHEELS possible", depending on the 2 assumptions above. (red numbers in the table)

			HyHEELS Module		
	Unit	Initial	Current	Improved	Target
Nominal cell voltage Un	V		54	54	54
Maximum cell voltage Umax	V		57	57	57
Gravimetric energy density at Umax	Wh/kg		4.9	5.4	5.0
Volumetric energy density at Umax	Wh/l		4.9	4.9	6.3
Gravimetric power density at Umax	kW/kg		7.8	11.6	10.0
Volumetric power density at Umax	kW/l		7.9	10.6	12.9

Table 10: HyHEELS final module: measured vs targeted values

The electrical life tests proved that this technology corresponds to a 54V module at nominal voltage and 57V at maximal voltage.

The gravimetric energy density is currently slightly under the target value, but the improved module, with weight sparing, would be slightly above the goal.

The volumetric density is lower than targeted. But on this point, the current technology does not allow to reach a 6.3 Wh/l.

The gravimetric power density of 10kW/kg may be reached in an easy way by moulding the 2 base plates of the module. The gain on the weight would most probably be higher than 11kW/kg!

As the volume of the module can not be reduced so much, the volumetric power density is under the targeted value.

According to the module results, most of goals are reached, even if the target defined in 2005 was very aggressive!

Only the volume improvement on the UltraCapacitors is lower that what was expected a few years ago!

Research and Testing

VUB

The task of VUB was to verify the design and functionality of the pre-series UltraCap module for automotive applications, and to assess the electrical stability and lifetime of the super capacitor modules. In this case, the characterization of super capacitor modules is the essential procedure, to estimate the energy capacity and energy losses not only during the configuration phase but also during the service time.

The series resistance is detected according to the response of a stepwise discharging current on the fully charged super capacitors. According to IEC 62391, different types of super capacitors are compared with respect to the detected capacitance, series resistance and other parameters.

However, the detected parameters (capacitance, series resistance) are not sufficient to dynamically represent the energy of the super capacitors at different voltage levels in real applications. This is because the capacitance of super capacitors is dependent on the voltage. Moreover, the capacitances of super capacitors are not always the same in charging state and in discharging state even at same voltage level, (this has been observed in the lab test at VUB). Due to the nonlinearity of the super capacitors, it is not sure whether the power losses could be represented only by the series resistance (which is detected by using the method of IEC 62391) or not.

Therefore, the enhanced methods of characterizing super capacitor energy storage in the real applications have been developed at VUB. The super capacitor modules were tested in constant current charging-discharging cycles, in pulse current charging-discharging cycles and in driving cycles. Additionally the electrical characteristic differences of the stack super capacitors in 2 final super capacitor modules were assessed.

In conclusions, the energy capacity of the super capacitors at different voltage levels can be represented as a function of the capacitance. The power losses of the super capacitors at different power levels can more precisely be represented by the series resistance and the capacitance variation. The high energy capacity and low energy losses of the super capacitor modules are evidence for the Maxwell new technique in the development of the super capacitors and their assembling, in particular, the stack super capacitors and laser welding.

Table 11 summaries the main results of comparing the different tested modules and cells.



	cell	cell	cell	2 modules
Voltage	2,7V	2,7V	2,7V	108V
Capacitance	450F	1500F	1850F	45F
mass	215g	320g	350g	14kg
Energy	1,6kJ	5,5kJ	6,7kJ	268kJ
Energy density	8kJ/kg	17kJ/kg	19kJ/kg	19kJ/kg
Efficiency		89-96%		91-97%
ESR*		23m•		30-40m•
Voltage difference		<2%		<2%
Capacitance difference				<1,5%
Self discharge in 2 weeks		300mV	300mV	12V

* Note: ESR is not measured by method of IEC 62391, but on the methodology proposed by VUB as described in D13.

Table 11: Evolution of the cells.

DLR

At DLR the voltage inversion tests were executed according to the definitions in D1 of WP1100. The tests have shown that inverting the voltage lowers the cell's life time. Thus, deep inversions of the voltage should be prohibited by a suitable controller / controller function. Slight voltage inversions hardly affect the cells life time and might be acceptable if, for instance, it reduces the costs of modules.

Ultracapnr.:	Initial parameters		Stop parameters		Lifetime		Cycling
	C [F]	R_{im} [m•]	C [F]	R_{im} [m•]	Cycles	Hours	[V]
Mx350_01	344,4	9,0	277,2	12,2	> 250.000		-0,1 to 2,5
Mx350_02	324,8	9,8	263,2	13,8	> 250.000		-0,1 to 2,5
Mx350_03	322,0	9,7	**224,0**	15,9	190.000	2592	-0,1 to 2,5
Mx350_05	372,4	9,4	254,8	**19,4**	140.000	2163	-0,4 to 2,5
Mx350_06	358,4	9,3	229,6	**18,6**	200.000	2972	-0,4 to 2,5
Mx350_07	355,6	9,6	246,4	**19,5**	125.000	1882	-0,4 to 2,5
Mx350_12	378,0	9,0	285,6	**19,5**	3.000	**125**	-2,5 to 2,5
Mx350_13	369,6	9,3	282,8	**19,3**	2.400	**98**	-2,5 to 2,5
Mx350_15	380,8	9,1	280,0	**19,8**	1.800	**76**	-2,5 to 2,5

Table 12: Life time reduction according to voltage inversion.

The environmental tests (moist heat cycling and alternating temperature) performed at DLR showed that the actual reached capacitance of the new generation cells is much higher (+25%) than originally planned (1900 F vs. 1500 F). The tests showed also that the initial capacitance of approximately 1900 F is decreasing during temperature and moist cycling, but at the end of the test still remains far above the nominal value (1700 F vs. 1500 F). During the temperature cycling the internal resistance did not notably change. During the moist-heat-cycling the impedance of the cells showed a distinct increase of about 10%. The different behaviour of the resistance during the alternating temperature test and the moist-heat-cycling might occur due to the changed profile for the moist-heat-cycling. The maximum temperature during the test, as it was actually performed, was much higher (80°C) than stated in the originally planned test (55°C) and lies very near to the capacitors electrolytes boiling point.

UTBM

Try to track and evaluate the technical enhancements of the technology.

The tasks performed at UTBM were: measurement of UCs ESR and C using different methods, UC cells thermal modelling and heat management in UC modules, thermal shocks and life test at constant temperature and simulation of high current load with vibration superposition.

It was shown that it is very difficult to establish a method of ESR and C measurement because of their dependence on the operating frequency. Plus, the ultracaps capacitance depends on the voltage. However, at low frequency, and as a first approximation, the capacitance and ESR can be measured according to the IEC 62391.

For Ultracaps thermal analysis it can be assumed that the capacitance variations according to the temperature can be neglected. So, the ESR increases at low temperature especially at negative ones. This effect is due to the electrolyte ionic conductivity variations according to the temperature. Using a special ultracapacitor cell including four thermocouples manufactured by Maxwell Technologies, the experimental results have shown that the hot spot is at the lid+. The thermal modeling of ultracapacitors was done using the thermal-electric analogy. Relying on this model, thermal management in ultracapacitor modules was studied for vehicle applications. It was shown that the cooling system, for ultacapacitor modules, depends on the ambient temperature and on the power cycles. It was shown that the temperature effect can introduce an unbalancing in the ultacapacitor modules.

The experimental results of ultracaps ageing in floating and by cycling have shown that the ageing process depends on temperature and operating voltage. The two ageing modes have the same evolutions of the capacitance according to the time when the temperature is the same. For thermal shocks, the experimental results have shown that only the ESR is affected by this effect. This is due to the fact that the capacitance variation with temperature can be neglected and the ESR varies according to the temperature. The experimental results have shown that there is no influence of vibration on the ultracaps ageing in the given vibration profiles.

5.2 WP2000

During the HyHEELs Project the level of maturity of the UltraCap Controller has constantly improved and satisfies now the requirements defined for the UltraCap Controller at the beginning of the project.

The goals of the work are listed in the Table 13 below and the fulfilment is declared.

Description of work WP2000	**Accomplished**
The UltraCap Control units will be set up and combined with an adequate UltraCap module.	✓
The focus is on the easy assembly of the Controller with the module.	✓
Keeping in mind that a low cost volume production will be the final target.	✓
The module with the controller should be one unit.	✓
Perform an internal energy management of the UltraCap module.	✓
Provide all necessary information for an overall vehicle management to the Super Visor system.	✓
The target is an easy integration of an UltraCap module into the environment of a vehicle.	✓
Twenty UltraCap systems will be prepared for tests according to automotive standards.	✓

Table 13: Goals of WP2000

The goal of a fast, precise and cost effective cell voltage measurement, as well as an energy efficient balancing by charging the UltraCaps individually was achieved. The possibility to measure temperatures inside the UltraCap module and on the UltraCap Controller is given. Furthermore the UltraCap Controller can measure current, can handle several external interfaces (e.g. relay, interlock) and two communication interfaces.

Besides the functionality we can highlight, that the maturity of the UltraCap Controller has reached now the maturity of a pre-series automotive product, see Figure 62.

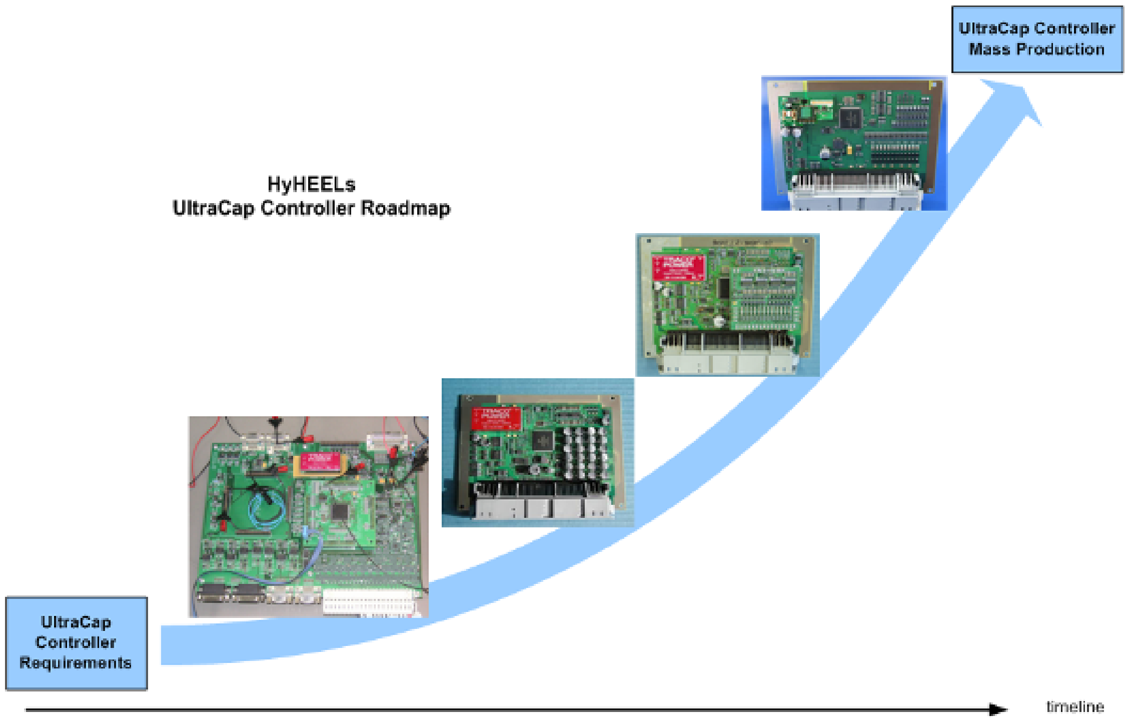


Figure 62: UltraCap Controller Roadmap

With the fully developed UltraCap Controller at the present status the HyHEELS goals regarding the UltraCap Controller have been reached.

The UltraCap Controller can now be used as a very good and well engineered basis for series development. Also the UltraCap Controller provides a very basic possibility, platform respectively to measure cells that are suitable to store electrical energy, for example fuel cells or Lithium-Ion, Lithium-Polymer or Lithium-Titanat cells.

5.3 WP3000

New simulation models were developed to design and configure the Ultracap modules for different vehicles. The simulations were validated by experimental results. The modular ultracap packs were virtual designed and recommendations for these configurations as well as for the power management strategies were provided to the OEM's of WP1000.

The test platform at Vrije Universiteit Brussel was applied to verify the configuration the super capacitor based energy storages for passenger cars and heavy duty vehicles, with respect to the voltage variation, maximum charging/discharging current, power losses in speed cycles (e.g. NEDC, FTP and so on).

After 55000 km equivalent driving distance on the experimental test rig, there were no over temperature, mechanical deviation or significant change in the self discharging observed.

The driving cycle tests have confirmed very good electrical stability even in the pre-series UltraCap modules. As a result, the super capacitor modules developed in the HyHEELs project are suitable for the automotive applications.

A Life Cycle Assessment was done to compare the environmental impact of ultracaps with batteries. The uncertainty analysis was performed through a Monte Carlo analysis. The Ultracapacitor scored better than all the assessed battery technologies. The relatively low weight of the super capacitor and the high recyclability rate of its main material (aluminium) are the most important reasons for this. Recommendations were formulated to further improve the environmental performance of Ultracapacitors.