Ultra Capacitor Storages for Automotive Applications

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Abstract

A research group at the Berlin University of Technology is engaged with the applications of Ultra Capacitors (UC) in automotive systems. Today Ultra Capacitors have the disadvantage of a too small operation area regarding the voltages and very low voltage levels of a single module. This leads to series connections of Ultra Capacitors which needs a high dynamic energy management to guarantee the lifetime.

A management system for a 42 V power net storage block is under development which includes a protection strategy for the Ultra Capacitors. The concept includes the handling of Peak Power Assistance (400 A at voltages levels from 40 V to 56 V) in combination with a DC/DC converter based (for a better utilization of the stored energy) delivery of medium power (100 A at steady 42 V). Regarding to easy-to-handle requirements the block has only a CAN bus interface and the power connector.

The Paper includes a detailed description and the test results of several UC storages in different power classes.

Keywords: power density, regenerative braking, resonant converter, ultra capacitor, energy density, PAS (power assist system),

1. Introduction

The power consumption of a future car will be several times higher than today. The advanced loads of today cars like air conditioning (1 kW), rear defroster (0,5 kW), windows lifter (4 x 0.35 kW), etc. can not be supplied simultaneously by the 14 V network. In addition there will be some new consumer loads in different power classes built into future vehicles:

For driver's comfort:	
Windscreen / rear defroster	(max. 2 kW)
Seat heating / positioning	(max. 2 kW)
Passenger compressor fan	(max. 0.5 kW)
Independent vehicle compressor	(max. 0.5 kW)
Vehicle management unit	(max. 0.3 kW)
Multimedia unit	(max. 0.3 kW)
For driving comfort:	
Power steering	(max. 0.6 kW)
Steering wheel heating	(max. 0.1 kW)
ABS	(max. 0.6 kW)
Brake-by wire	(max. 3 kW)
Electrical drive management	(max. 0.6 kW)
For motor management:	
Crankshaft motor starter/generator unit	(max. 20 kW)
Electrical valve injection	(max. 3.5 kW)
Turbo hole sluring	(3 kW - 7 kW)
Electrical vibration damping	(max. 5 kW)
Electrical driving (city crawling)	(max. 6 kW)
Electrical boost	(max. 6 kW)

The crankshaft motor starter/generator unit and recuperative braking are the only possibilities for supply the new consumer loads in the vehicle. Additional there are the normal loads like traffic lights and wiper, pumps, horns etc.

The consumer loads can be sorted in different kinds of loads. Some of them (especially units with lower power consumption like traffic lights, wiper, rear window defroster etc.) are continuous loads (up to 1 kW). The medium power class (up to 3 kW for windscreen defroster, seat heating / positioning etc.) has a dynamic availability up to 60 sec. The peak power class (all motor management units) have a power need up to 30 kW but less than 3 seconds.

All these loads are not used simultaneously but the peak power consumption will reach several 10 kW which can not be delivered by the 14 V network anymore. The new 42 V power net is able to supply this power but it needs several kinds of backup energy storages.

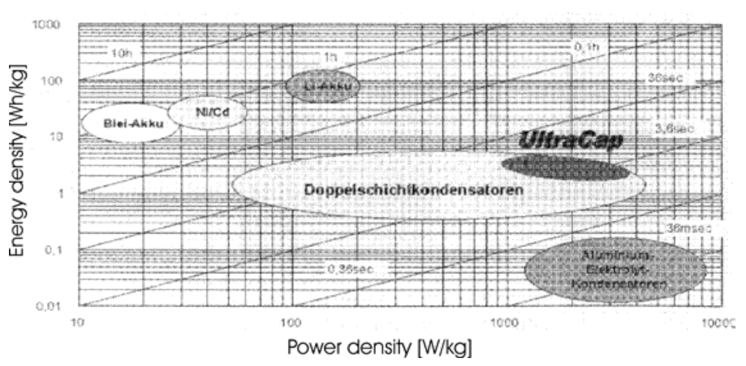

Figure 1: Comparison of energy storages technologies [1]

For the supply of the 42 V power net exist several kinds of storages systems (lead acid batteries, NiCd, NiMH, Lithium Ion, Fuel Cell, etc.). The possible storages have to be distinguished according to their power or energy capabilities: The lead acid battery has a medium energy density but low power density. Refer Figure 1 for details. The Ultra Capacitors (UC) have an opposite behaviour: very high power density but a low energy density. This means that the UC's are very useful for the peak power loads of the vehicle but can not supply the power for a long time. This leads to a minimal number of two kinds of storage system for a car. For example, a high energy density storage like lead acid battery for the steady energy supply and a high power density storage for the peak power loads.

Ultra Capacitors are very suitable to solve the peak power need of a future car, but they have to be handled according to their characteristics.

2. Characteristics of Ultra Capacitors

2.1. Low single module voltage

Depending on their physical structure, the voltage of a single UC can not be increased to more than 2.7 V. Technical realisations of UC's reach today 2.4 V. For the 42 V power net more than 18 single modules in series connection are necessary. Exceeding of this voltage will lead to a reduction of the lifetime. For this reason a voltage regulation for each module is necessary. In the following section this problem will be discussed in detail.

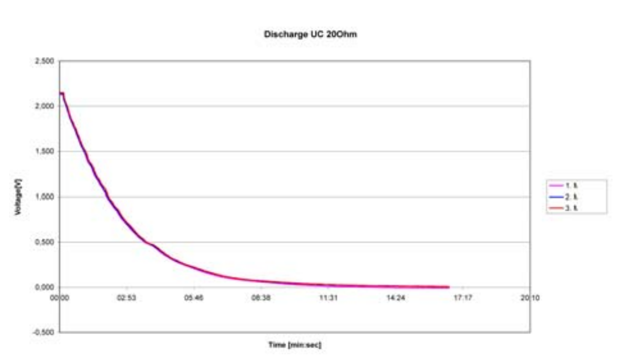

Figure 2: Constant resistor discharging of one UC

2.2. Capacitive voltage behaviour

Figure 2 shows a normal voltage discharge behaviour of a capacitor. At the beginning the capacitor has the energy of:

$$W_0 = ½ * C * U_0^2$$

After a short time the voltage falls below 70%

of the nominal voltage. In the case of a 12 V Ultra Capacitor storage unit this voltage is about 9 V or for a 42 V power net 29.4 V. The Energy is now:

$$W_{70\%} = \frac{1}{2} * C * \left(\frac{3}{4} * U_0 \right) = 9/16 * W_0 \approx 56\%$$

Below this voltage level the efficiency of the loads will be decreased extremely resp. the loads will stop working. But at this voltage level over the half of the energy content is still inside of the UC.

For the use or conservation of this energy there exist a few possibilities:

- Charging back from the UCs into the batteries after using.
- Overdimensioning of the UC storage in a way that more energy can be used at the same voltage.
- Using a DC/DC Converter for boosting the rest energy to a higher voltage level.

The second point is too expensive today but could be a solution if the prices for UC modules are decreasing. For the first point a special charger is necessary which has the same topology like the DC/DC converter which has to be installed in case of point 3. This DC/DC Converter has to be designed for the greatest possible power of the loads.

An alternative structure of an UC's storage with a DC/DC Converter which has not the full power range is shown in Figure 3. By using a full voltage range UC storage, a direct peak power extraction is possible. After the minimal voltage is reached (e.g. 9 V / 30 V) the DC/DC Converter can lift up the voltage level and using the rest UC storage energy. This DC/DC Converter can be designed for medium power applications and is less expensive.

An additional advantage of this structure is that the energy of recuperative braking can be saved. The braking energy will be fed into the peak power connector without causing switching losses in the DC/DC Converter.

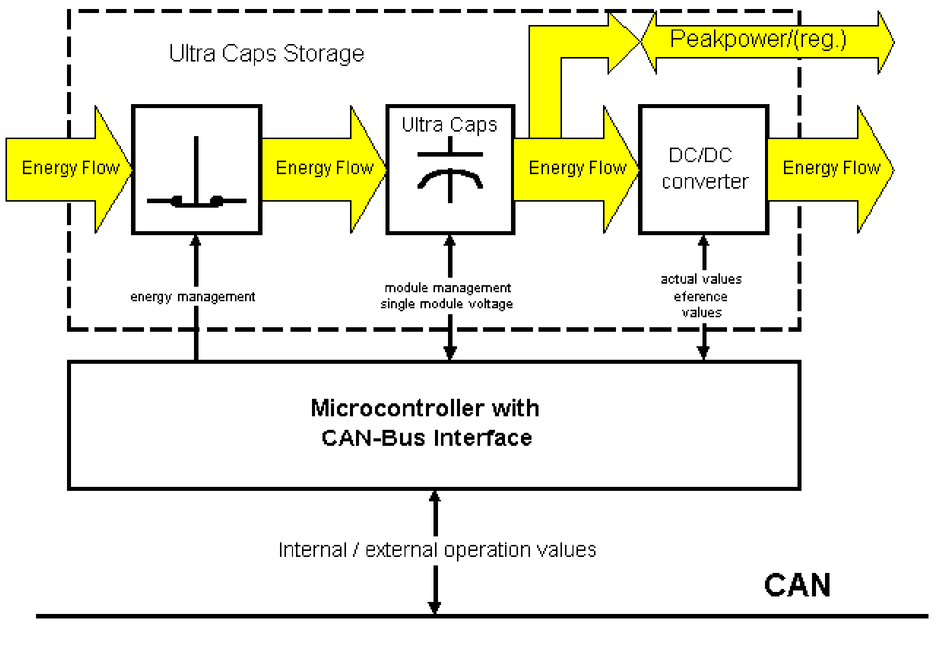

Figure 3: Management structure of an Ultra Capacitor storage block

Additionally the structure of Figure 3 takes care of other requirements of a module for automotive applications. Most of the components of a modern vehicle are modular designed. It is easy-to-handle, universal applicable and has a standardized communication interface. The complete application is composed of the UC series connection, the DC/DC Converter and the microcontroller with CAN-Bus interface, all included in one box. This box has only the CAN-Bus and the power line connector (see Figure 3) as input / output. The storage module is cascadable. All regulations like control of the DC/DC Converter, voltage balancing or error handling will be done by the microcontroller, depending on the measured data (6x single module voltage, 1x current, 1x temperature). The communication to the host controller (Vehicle Management Unit) is only necessary for the reference values and for the visualization of the state of charge and for error messages.

3. Voltage Balancing

One problem of a capacitors series connection is the asymmetrical balance of the voltage. The reason for the aberrations are the tolerance of the internal charge resp. discharge resistances and of the capacitance (+/- 40%!) of the UC's.

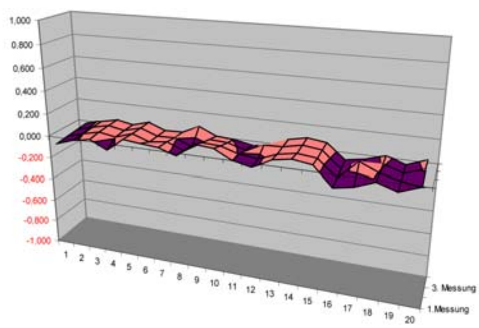

Figure 4: Voltage distribution of 42V UC storage

In Figure 4 the voltage distribution of an UC 42 V power storage is shown after a few charge/discharge cycles. After the last discharge phase each UCs should have 0 Volt. The difference to 0 Volt is shown in Figure 4. The voltage aberrations will be increased with additional cycles and lead to an asymmetrical voltage distribution with possible transgressions of the single module maximum voltage.

The best solution for avoiding this behaviour is the charging of parallel connected UC's. Depending on the small single module voltage the parallel connection has to be converted into a series connection after charging. This will cause extremely high costs for the power switches needed, especially in the case of high current applications (e.g. recuperative braking or acceleration).

The alternative with less costs is to balance the voltage after charging. Figure 5 and Figure 6 show two versions of voltage balancing circuits.

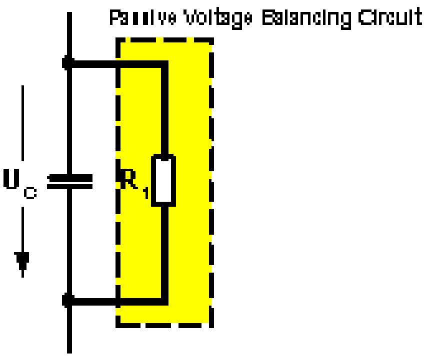

Figure 5: Passive Voltage Balancing

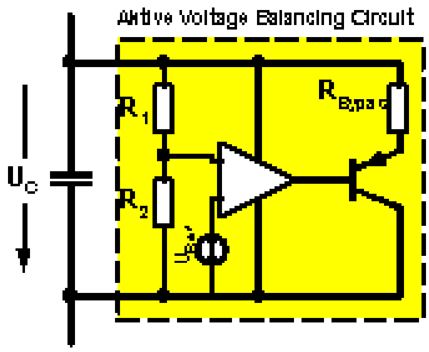

Figure 6: Active Voltage Balancing

3.1. Passive Voltage Balancing

Passive Voltage Balancing is the simplest way to balance the UCs. This principle uses external low tolerance resistors for forcing the single module voltages. The resistors are several thousand times higher than the internal discharge resistors of the UCs. During the charging of the UCs the internal resistor of an UC defines the size of the current (and the resulting voltage). After charging the UCs the internal self discharging resistor is the determining component. By using a smaller parallel resistor it is possible to balance the voltage differences between the UCs. The value of the parallel resistor should be much higher than the internal resistor (to limit the current and the losses in the parallel resistor) but smaller than the internal self discharging resistor. Depending on this value the voltage balancing process can take a time from several minutes up to several hours. The power dimension of this resistor increases by reducing the balancing time.

This principle is useful for uninterruptible power supplies (UPS) for increasing the lifetime of the UCs because the charging currents are not so high (and the charging time very long). For automotive applications it will be applicable if the recharging time is long enough for the balancing process. But peak power recharging processes will cause overvoltages which are not controlled (or limited) in this circuits.

3.2. Active Voltage Balancing

An active Voltage Balancing (or bypass circuit like in Figure 6) needs less time than a Passive Voltage Balancing. This circuit detects the voltage across the UC which will be bypassed by a small power resistor parallel to the UC if the limit voltage is reached. This resistor has the same task as the parallel resistor in Passive Voltage Balancing but the balance process is faster because the balancing current is higher (due to the smaller resistance). Under the limit voltage the resistor is not active and the charging current can be very high. After the bypass switching the current can be higher but it is limited by the bypass resistor (up to 1A). For this reason the circuit can not be used for automotive application because the charging current can be much higher than 1A (in the case of recuperative braking) which would destroy the circuit. An exception is in case of using an intelligent DC/DC Converter which could limit the current nearby of the critical voltage.

In the Management Structure (Figure 3) a combination of Passive Voltage Balancing and overvoltage protection is used: The energy management (symbolized by a switch) detects every single module voltage and switches off the power supply line from the UCs if the critical voltage of only one module is reached. After the security switch off the voltage balancing process (Passive Voltage Balancing) is starting. In this way it is possible to save the high current power peaks (like from recuperative braking) without the risk of having overvoltages and to balance the voltage of all UCs.

4. DC/DC Converter

For the DC/DC Converter several topologies are possible. In the following Figures two of them are shown and described in short. The criteria for the choice are costs, bidirectional energy flow possibility, peak power ability and physical dimensions. Each of the different types will get an separate microcontroller resp. will be controlled by the UC storage microcontroller (shown in Figure 3). Parameters are input voltage, output voltage and output current. The temperature will be checked for emergency shutdown. The target is to develop a DC/DC Converter for an UC storage with a stable output voltage of 14 V (based on 6 UCs) or of 42 V for a power net storage (based on 20 UCs). The minimum input voltage is 30% of the nominal voltage and the calculate output power will be 1 kW (14 V) resp. 5 kW (42 V).

4.1. Buck / Boost Converter

The Buck / Boost Converter works in forward direction as a Boost Converter and in backward direction as a Buck Converter. Both converters are based on an inductor which stores the energy during half of a period. The Boost Converter lifts up the energy stored to a higher voltage level during the second half of the period via the freewheel diode. The Buck Converter reduces the energy by a chopping process and uses the inductivity for current smoothing.

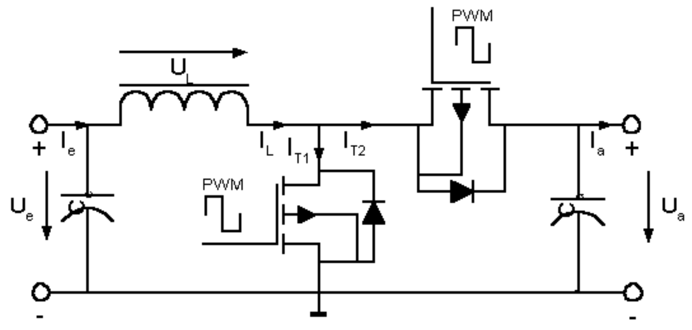

Figure 7: Topology of Buck / Boost Converter

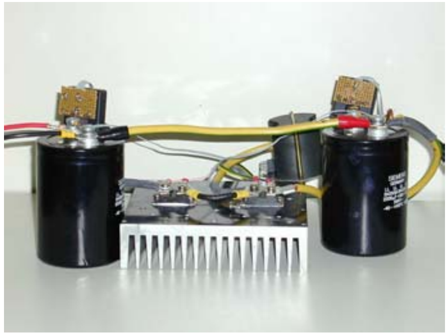

Figure 8: Buck / Boost converter

This converter have the following advantages:

- Small number of components and a simple topology
- easy peak power possibility (only by a Diode)
- multiple component use (compared to the buck or the boost converter)
- bidirectional energy flow (compared to the buck or the boost converter)

There are the following disadvantages:

- high voltage spikes at the output
- high output capacitance
- semiconductors drain-source maximum voltage must be higher than voltage spikes
- no capability of output current control

The main points of the advantage / disadvantage table are the low costs depending on the small number of components and, in contribution, high voltage spikes. Depending on these spikes the semiconductor switches need high voltage operation areas. Due to the principle of this kind of converter, the efficiency of voltage boost relations higher than 1:3 (e.g. from 4 V to 12 V or from 14 V to 42 V) is very less.

4.2. Bidirectional Full Bridge Converter

The Bidirectional Full Bridge Converter (Figure 9) is based on the normal transformer principle. The first H-Bridge modulates the DC voltage to a sinusoidal voltage which is transformed by the transformer to a higher voltage. Depending on the energy flow direction the primary side of the full bridge acts as an inverter and the secondary side as an rectifier. The output voltage can be controlled by the PWM of the first H-Bridge switches. Two circuits with this topology power versions have been setup (400W and 1 kW) and tested.

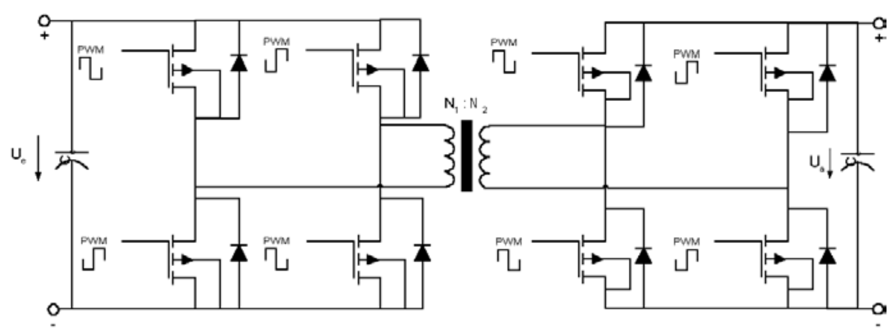

Figure 9: Topology of Bidirectional Full Bridge Converter

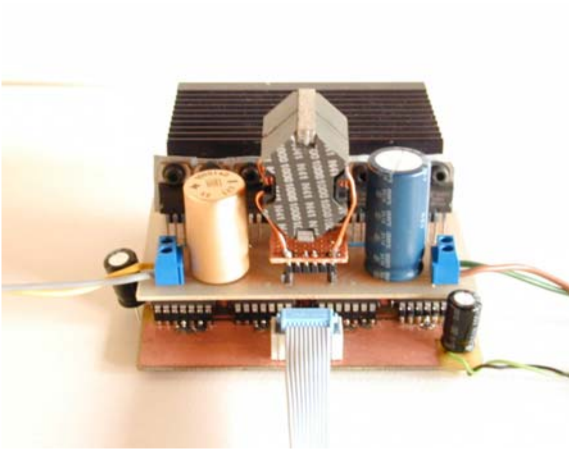

Figure 10: Full Bridge Converter (400W)

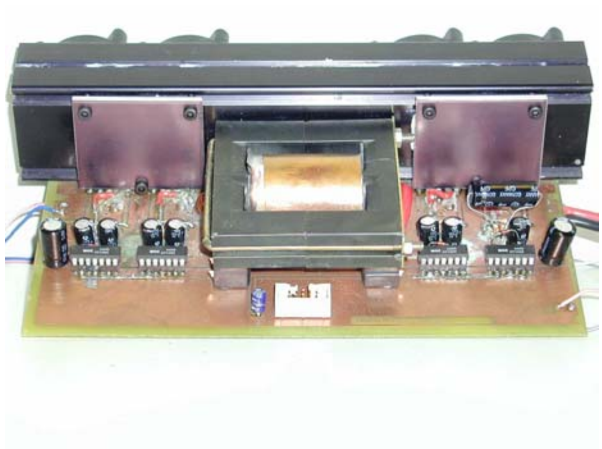

Figure 11: Full Bridge Converter (1 kW)

This converter have the following advantages:

- no symmetry problems (compared to other half bridge topologies)
- semiconductors drain source voltage maximum must be only as high as the input voltage
- galvanic isolation through the HF Transformer
- full output and input current and voltage control capability
- better use of the core material due to the bipolar use of the transformer hysteresis
- multiple component use (compared to simple full bridge converters)
- bidirectional energy flow (compared to simple full bridge converter)

There are the following disadvantages:

- a high number of components needed (and therefore higher costs)
- 8 driver signals – complex control structures
- no peak power capability

The main points of the advantage / disadvantage table are the galvanic isolation of both sides and the harmonic voltage behaviour (without spikes) in contribution to the high costs depending on the high number of components. Additionally this kind of converter is able to reach a high voltage boost relation and can be used to boost small UC storages (e.g. less UC's than for the vehicle voltage net necessary) to high voltage areas. A possible application will be the use of a 12 V UC storage connected to a 42 V power net (without the possibility of peak power assistance).

4.3. DC/DC Converter results

Both types of converter can be used for UC storages. Due to the costs the Buck / Boost Converter will be better for the use in small UC storages (like 12 V storages) or for high current applications because of the uncomplicated inductivity. The Full Bridge Converter has a more complicated structure but is the better choice for operations with higher voltages. Additionally this principle can be used for applications with low voltage UC storages (like a 14 V UC storage for a 42 V power net).

The following Figures give an overview about the results of the first DC/DC Converters (both topologies).

Figure 13 shows the improved voltage behaviour of the UC storage unit of Figure 12. The DC/DC Converter starts working if the UC voltage is fallen under 12 V. It can stabilize the voltage up to an input voltage of 4.5 V. This limit is a result of the working limits of the voltage regulator which supplies the electronic of the storage.

Figure 12: 14V UC storage with 140W DC/DC Converter

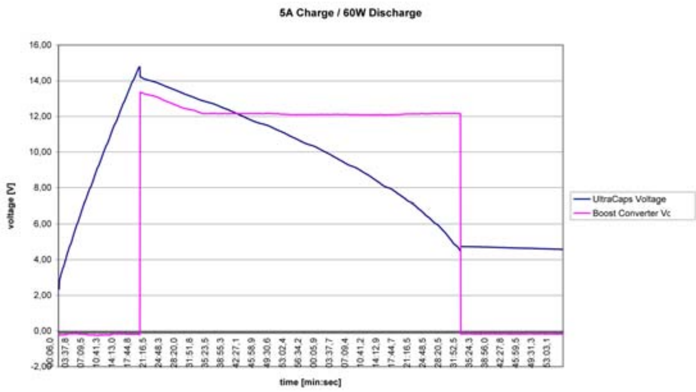

Figure 13: Voltage improved UC storage output (60W)

Figure 14 shows the 14 V UC storage with microcontroller, voltage scanner, CAN-Bus interface and DC/DC Converter (400W). The voltage output of the DC/DC converter during a full charge / discharge cycle of the UC's is shown in Figure 15.

The final versions of the DC/DC converters and the results especially about efficiency and dynamic behaviour will be presented at the EVS19.

Figure 14: 14V UC storage with 400W DC/DC Converter

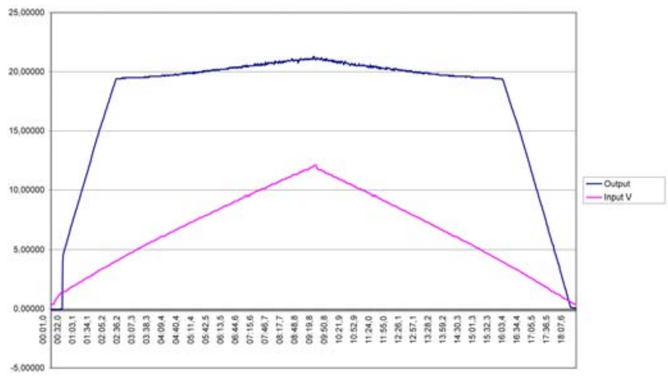

Figure 15: Voltage output with variable voltage input (150 W Output)

5. Conclusion

The paper has defined the requirements of a power storage system for automotive applications. Application problems of Ultra Capacitors are analysed and possible solutions are discussed. A new concept which takes care of these requirements is presented. The necessary circuit structures are presented, built up and results are shown. The final versions for different voltages (14 V and 42 V power net) and results regarding the efficiency and dynamic behaviour will be presented at the EVS19 in Busan.

6. References

[1] T. Dietrich, B. Staib, Eigenschaften von Doppelschichtkondensatoren, 1. Anwenderforum Doppelschichtkondensatoren (1999), p. 24 - 40

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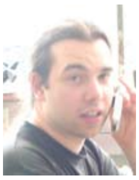

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