A simple, reliable, cost and volume saving DC-link discharge device for electric vehicles

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A simple, reliable, cost and volume saving DC-link discharge device for electric vehicles

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***Abstract*-This paper describes a DC-link discharge device that is smaller and cheaper than conventional resistor or PTC-based solutions. The basic idea is to use the switching element (IGBT, Mosfet), that is usually controlling the PTC or resistor, in a linear mode and decrease the maximum power by shifting the discharge curve from an uncontrolled square voltage dependent curve to a roughly constant power characteristic. The advantages in volume and costs are described and the technical setup is explained and compared to the conventional solutions.**

I. INTRODUCTION

In all power electronic components of electric, hybrid and hydrogen vehicles that are connected to the HV-DC-link like drive inverter, battery charger, auxiliary supply converter and traction DCDC-converter, large capacitors are used, to stabilize the voltage, filter ripple currents, suppress oscillations and simplify control loops. In case of an accident and other unexpected error those capacities have to be discharged from the DC-link voltage (120-850 V) to harmless voltage levels (typically <60V). Therefore discharge units are applied. Conventional solutions are built up with a switched resistor (either constant value or PTC behavior). PTC solutions use the resistor's thermal capacity and need after one discharge triggering quite a long time (2-10 minutes) until they are ready for a new discharge cycle. Resistor solutions that are designed for continuous operation become quite big since the resistor has to cope with high discharge power if it is mistakenly triggered at maximum voltage and switched on battery contactor.

A. Approach

The approach is is to use the switching element (IGBT, Mosfet), that is usually controlling the PTC or resistor in a linear mode and decrease the maximum power by shifting the discharge curve from an uncontrolled square voltage dependent curve to a roughly constant power characteristic. For a better comparison a standardized DC-link voltage of 450 V is used and an intermediate circuit capacitance of 1 mF. Former converters and inverters mentioned in [1] and [2] still have higher capacities, but as shown in [3], storage capacities are decreasing with a continuous improve in ripple current capability of modern high voltage DC-link capacitors. So 1 mF is a good value for a comparison of future power electronics. If more capacity is despite used, a paralleling of discharge devices' power parts is still possible. The DC-link capacitor has to be discharged to 60 V within less than 5 s. Therefore a constant current discharge device with an IGBT and a small bipolar npn-transistor in the emitter path is used and extended with an additional pnp-transistor to increase the discharge current with falling DC-link voltage (Fig.2).

B. Results and Significance

The build-up device shows a far more voltage independent discharge behavior than the compared resistor and PTC-based solutions. The discharge current can be adjusted freely according to the cooling possibility, DC-link voltage and DC-link capacitor size. The cublic volume (5.0 cm³) and the material price (2.78 €) of the presented solution is far smaller than the compared PTC and resistor solution (Tab.4). The only disadvantage of the IISB CP-DU 450 compared to a resistor based solution is the need for a cooling possibility. Having a closer look at the geometry of power electronics in electric vehicles, it can be clearly seen, that the need for a cooling power of less than 50 W is no real disadvantage, since the small size of the shown solution of less than 5cm³ allows a mounting almost everywhere at the already cooled power electronic casing (e.g. drive inverter, auxiliary supply converter, traction DCDC-converter, et al.). The measured discharge time of 2.2 s is even quicker than the automobile manufacturer's requested 5 s, so the discharge power can even be decreased and the necessary thermal resistance increased or the device can be used for larger DC-link capacities than 1 mF. Field tests with a big German car manufacturer have improved the presented design and shown a reliable and safe operation under harsh conditions.

II. DISCHARGE SOLUTIONS

In this chapter the conventional discharge solutions are displayed and the new developed rougly constant power discharge solution is displayed.

A. Conventional Solutions

Conventional discharge solutions are build up with a signal isolation (magnetic or optical coupler) and a switched resistor or PTC to dissipate the stored energy in the DC-link capacitor. A resistor based solution needs a 2.48 kΩ resistor to discharge a 1 mF capacitor from 450 V to 60 V within 5 s. In the implemented design, a 2.2 kΩ resistor is used since it is the next purchasable product with 100 W.

$$U(t) = U_0 \cdot e^{-\frac{1}{RC}t} \tag{1}$$

$$R = -\frac{t}{C \cdot ln\frac{U(t)}{U_0}} = -\frac{5s}{1mF \cdot ln\frac{60V}{450V}} = 2.48k\Omega \tag{2}$$

$$P_{max} = \frac{{U_{max}}^2}{R} = \frac{(450V)^2}{2.2k\Omega} = 92W \tag{3}$$

Fig. 1a) and b) show a possible schematic of conventional discharge devices. The signal isolation is done with an optocoupler and the switching is done with a very small n-Mosfet (600 V 8 Ω) in a) and a small IGBT (600 V 3 A) in b). The gate supply is done with a resistor divider and a z-diode since it is the cheapest available supply.

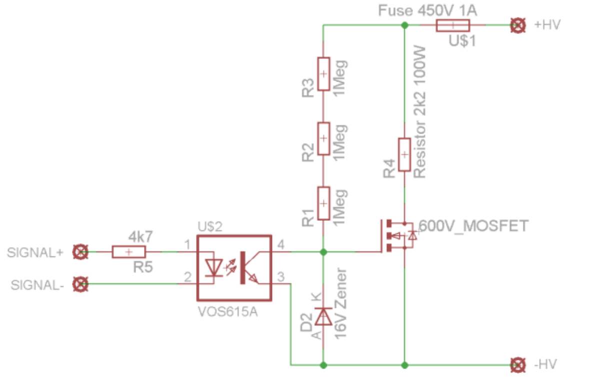


Fig.1a. Possible schematic of a conventional resistor based discharge unit

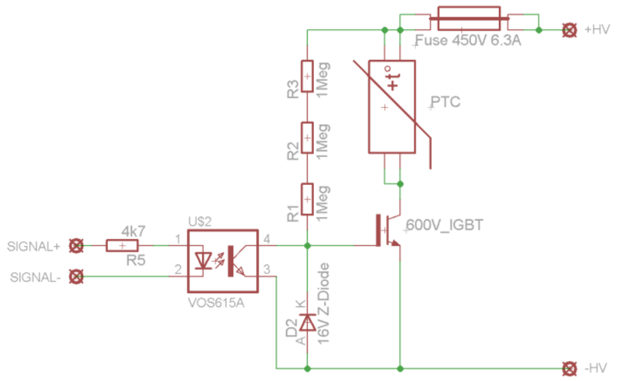


Fig.1b. Possible schematic of a conventional PTC based discharge unit

The dissipated power in a resistor increases with the square of the applied voltage. So if the discharge resistor is designed for a continuous operation in case of an error (false triggering with switched on battery contactors) a square voltage dependent power curve like the one of a resistor is not a very good choice since the resistor has to be designed for high power, that can be buffered with the resistor's thermal capacity in normal operation, but requires a tough setup in the described error case. Therefore PTCs have been designed and applied since they are quick discharge solutions in normal operation, but limit the discharge current automatically in the case of an error. The disadvantages PTCs still have, are a quite low resistance at low temperatures (typically 20 – 100 Ω) and a long cooling time after triggering (typically 2-10 minutes). The quite low resistance and the still square voltage dependent power curve lead to high maximum currents and therefore require stronger switching elements, protection devices and cables. The long cooling time decreases the safety level if a multiple triggering is necessary during and after a car accident. So the PTC is a better and cheaper solution than the commonly used resistor but still has some disadvantages that are solved with the presented IISB CP-DU 450 solution in the next chapter.

B. IISB CP-DU 450

The basic idea of the IISB CP-DU 450 is to drive the 600 V switching element (Mosfet/IGBT) that is already applied not as a switching element, but in a linear mode. The big advantage to a resistor is besides the cost and volume arguments the controllability of the discharge curve. So the discharge power graph can be shifted from an uncontrolled square voltage dependent one to a roughly constant power characteristic. A completely constant power characteristic would be possible as well, but would require a control loop with integrated multiplier that would be far out of cost and volume budget.

The roughly constant power discharge solution is shown in Fig.2. The isolation with an optocoupler and the gate supply with a resistor and a z-diode is the same as in the last chapter. In the emitter path of the IGBT there are two resistors R6 and R14 and a npn-bipolar transistor added. This setup leads to a constant current discharge. The resistor divider of R1-R3 charges the 600 V IGBT gate to a z-diode limited value of 16 V. As soon as the emitter current of the 600 V IGBT rises above ~25 mA, the voltage drop at R14 reaches 0.7 V, opens T1 and decreases the gate voltage of the 600 V IGBT. So the gate voltage is adjusted dynamically to reach a constant current through the power IGBT.

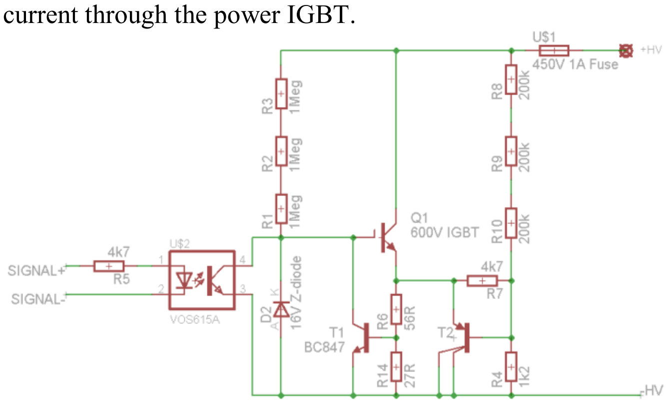


Fig.2. Schematic of the constant power discharge unit IISB-CP-DU 450

The discharge curve of the device is now no longer dependent on the square of the applied voltage, but linear dependent. This device is now extended with an additional pnp-transistor T2 to increase the discharge current with falling voltage by bypassing the two resistors R6 and R14 dependent on the divided HV-voltage of resistors R4 and R8-R10. In order to have a better adjustment possibility a high gain transistor is used for T2 and the gain is then reduced with resistor R7. The discharge current is now set by a constant and a voltage dependent part. By adjusting resistors R6 and R14, the constant current part can be changed, and the voltage dependent part can be changed by adjusting resistors R4 and R7. Consequently the discharge power and the characteristic can be set to the applications needs. Possible design targets are for example a quite constant power curve, but as well a characteristic with a power maximum at high voltages to decrease the DC-link voltage as fast as possible to lower values, or a power minimum at nomnal DC-link voltage to run the unit without any triggering all the time.

III. Measurements

In order to prove the proposed layouts all three devices have been tested with a 450 V 1 mF foil capacitor that has been charged to 470 V, then has been disconnected from the supply and then each discharge unit has been triggered. Measurements have been done at room temperature. Discharge voltage and current are displayed over the discharge time in diagrams a) and discharge power and discharge voltage over discharge voltage in b). The critical 60 V line is indicated in diagrams a). The diagrams are based on oscilloscope measured values.

A. Resistor based solution

The resistor solution is based on a 2.2 kΩ resistor as shown in fig.1a. Discharge current and time are as expected. After 4.3 s the capacitor is discharged beneath 60 V. The maximum discharge power of ~90 W is reached at 450 V and decreases to ~2 W at 60 V. The discharge current decreases linear with decreasing voltage from ~200 mA at 450 V to ~28 mA at 60 V.

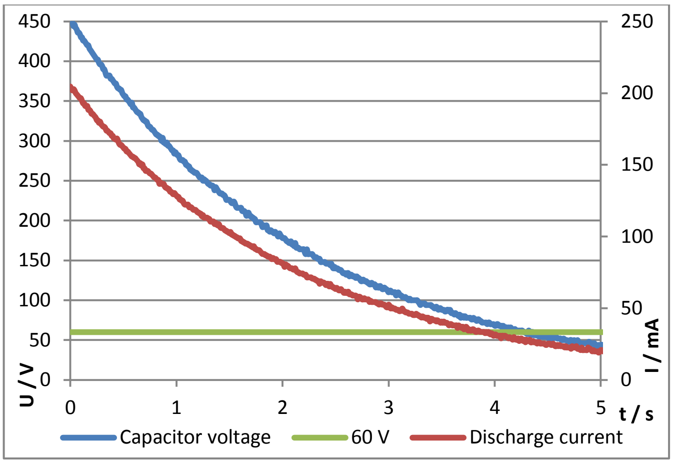


Fig.3a. Measured discharge curve over time of the resistor based solution

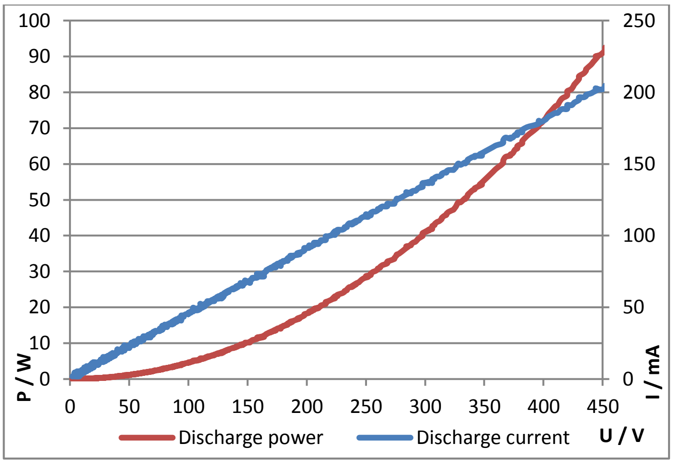


Fig.3b. Measured discharge curve over voltage of the resistor based solution

B. PTC based solution

The PTC solution is based on a 100 Ω resistor as shown in fig.1b. The discharge current is higher than expected and consequently the discharge time is shorter as well. It can be explained by the voltage dependence of a PTC reistor's value. After 1.3 s the capacitor is discharged beneath 60 V. The maximum current of ~9 A is reached at 450 V and decreases with the applied voltage to ~0.76 A at 60 V. The thermal capacity of the PTC is heated up with a maximum of 4.1 kW at 450 V and decreases to ~50 W at 60 V. The current curve is not any more linear dependent on the applied voltage because of the voltage and temperature dependence of a PTC resistor's value.

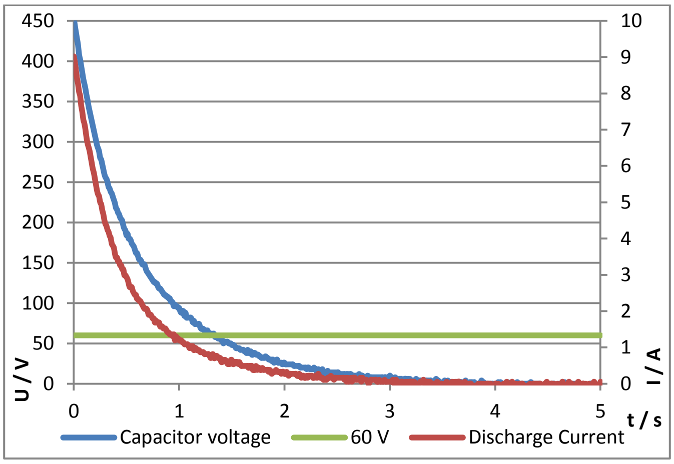


Fig.4a. Measured discharge curve over time of the PTC based solution

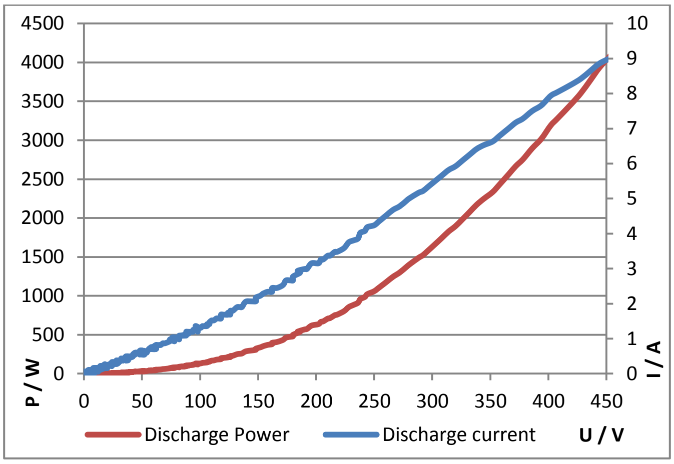


Fig.4b. Measured discharge curve over voltage of the PTC based solution

C. IISB CP-DU 450

The presented discharge solution IISB CP-DU 450 with the presented dimensioned components (fig.2) shows a roughly constant power behaviour. The discharge current rises with decreasing capacitor voltage from 80 mA at 450 V to a maximum of 280 mA at 60 V. The maximum discharge power of 50 W is reached at ~300 V and varies between ~36 W at 450 V and ~17 W at 60 V. Different discharge characteristics are possible as well and can be adjusted with the resistor values mentioned in chapter II.B, so the shown characteristic is an example that has been reached with the components shown in fig.2 and that can be changed according to the requirements of the application. After 2.2 s the capacitor is discharged beneath 60 V. Since the necessary discharge time is 5 s, the discharge power could still be reduced in order to match higher thermal resistances.

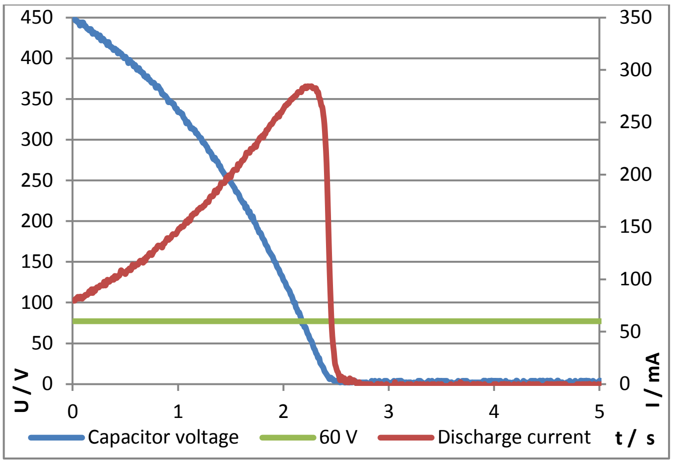


Fig.5a. Measured discharge curve over time of the IISB CP-DU 450

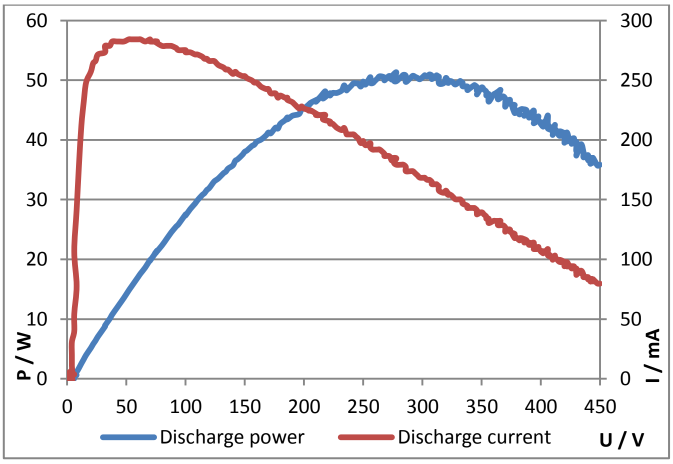


Fig.5b. Measured discharge curve over voltage of the IISB CP-DU 450

D. Temperature dependence

The measurements have been done at room temperature. In an automotive application the ambient temperature can be lower and higher. The resistor based solution doesn't show a real temperature dependence, The PTC based discharge unit has a slight temperature dependence concerning the discharge time and the maximal storable discharge energy. For the presented 450 V 1 mF capacitor the chosen PTC can store enough energy for an ambient temperture of up to 85 °C. The IISB CP-DU 450 operates the transistors in a linear mode and therefore has with the presented dimensioned components a temperature dependent discharge curve because of the threshold voltages of especially the base-emitter channel. The base-emitter threshold voltage is decreasing with approximately ~2 mV/K. If necessary, this temperature dependence can be compensatied with a 6.2 V Z-diode (temperature coefficient of approximately +2 mV/K) in series to the base-emitter channel. Measurements have shown a decrease in temperature dependence to less than 10% within a range of -40 to +85°C. The disadvantages of such a compensation are higher component costs and an increased voltage level between the source contact of the power Mosfet and –HV which requires stronger and better cooled bipolar transistors and resistors. But having a closer look at the temperature dependent discharge curve in fig.6 one can see, that the negative temperature coefficient of the IISB CP-DU 450 isn't a real disadvantes since it protects itself against a thermal destruction with a rising ambient temperature.

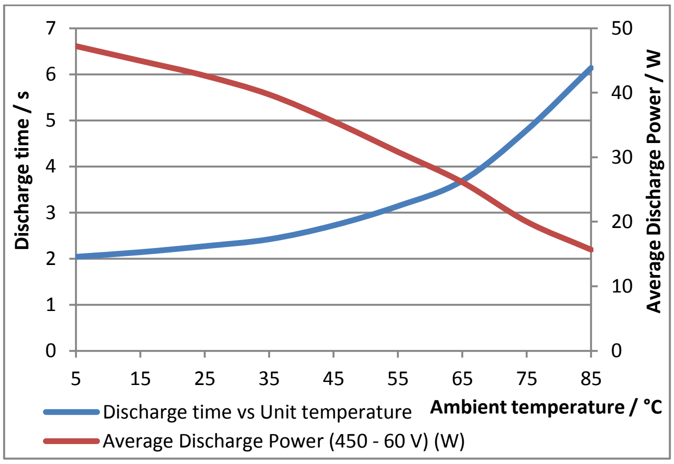


Fig.6. Measured discharge power and time over the ambient temperature

IV. VOLUME COMPARISON

Volume is a very important factor in the automotive industry. The last chapter showed the electrical advantages of the IISB CP-DU 450. In fig.8, the cubic volumes are compared and in fig.7 pictures of the different built-up discharge solutions are shown. As a comparison a 1 € coin has been placed next to the units.In all three built-up discharge units, there have not been mounted any plugs, because there are many different possible HV-plugs, the discharge devices are usually mounted inside of an isolated housing, and for a volume and cost

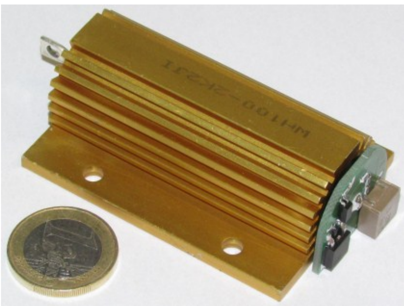
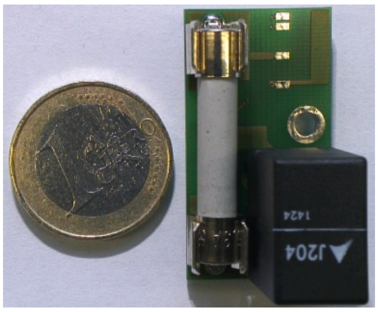
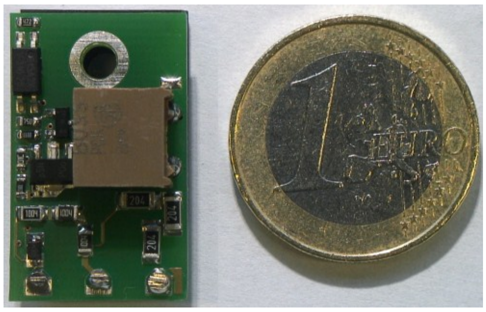
Resistor	PTC	IISB CP-DU 450
		

Fig.7: Pictures of the three discharge solutions for size comparison

comparison it is not necessary, since all units need the same type and amount of plugs (2 x HV 450 V and 2 x LV for triggering).

Dimensions:				
	Length (mm)	Width (mm)	Height (mm)	Volume (cm^3)
Resistor	75.5	47.0	23.9	84.8
PTC	38.8	21.2	28.0	23.0
IISB CP-DU 450	27.5	16.2	11.2	5.0

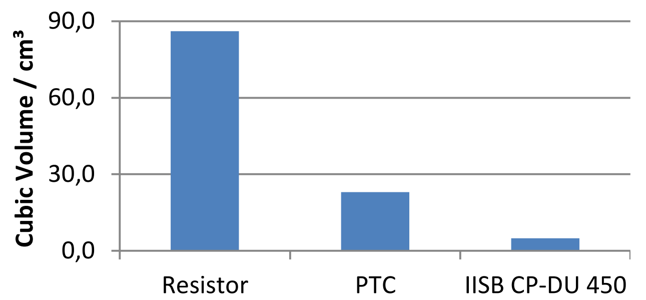


Fig.8. Volume comparison between the three discharge solutions

V. COST COMPARISON

The calculations are based on prices for 10000 units. The prices have been compared at the distributors Mouser, Farnell, Digikey, Reichelt for delivery in Europe. The cheapest one has been used for the calculations. The PCB-board price has been calculated with a price per m^2 extracted from calculators of MultiCB, Aetzwerk and Leiton of 144.30 €/m^2. The PCB-board area has been calculated out of the dimensions of the build-up prototype and an added 2mm milling width. Tab.1-3 list prices and component information. Fig.9 shows the main cost factors of every device. At the resistor based solution, the main cost is caused by the power resistor (86%) since those resistors are not produced in high volumes and therefore are quite expensive. At the PTC discharge unit, the main costs are caused by the PTC (40%) and the fuse (38%). The PTC is not manufactured in high volumes as well, and the fuse needs to be stronger (6.3 A) than at the other discharge units because the PTC causes high inrush currents of up to 9 A. The main costs of the IISB CP-DU 450 are caused by the power IGBT (54%) because the IGBT needs to be much stronger than at the other discharge solutions because it is used in linear mode.

Resistor

Quantity	Item	Part Number	Housing	Price/unit	Price
1	Resistor 0603		0603	0.00117 €	0.00117 €
3	Resistor 0805		0805	0.0008 €	0.0024 €
1	Optocoupler	VOS615A	SSOP-4	0.176 €	0.176 €
1	16V Z-Diode	MM3Z16VT1G	SOD-323	0.01963 €	0.01963 €
1	Fuse 450V 1A	BK/PCC-1-R		0.768 €	0.768 €
1	n-MOS 600V 8 Ω	TSM1NB60CP	TO-252	0.156 €	0.156 €
1	Resistor 2.2 kΩ 100 W			7.47 €	7.47 €
6.7cm²	Dual layer PCB			144.30 /m²	0.10 €
					8.69 €

Tab.1: Price calculation of a resistor based discharge solution

PTC:

Quantity	Item	Part Number	Housing	Price/unit	Price
1	Resistor 0603		0603	0.00117 €	0.00117 €
3	Resistor 0805		0805	0.0008 €	0.0024 €
1	Optocoupler	VOS615A	SSOP-4	0.176 €	0.176 €
1	16V Z-Diode	MM3Z16VT1G	SOD-323	0.01963 €	0.01963
1	Fuse 450V 6.3A	35816300029	6.3x32	1.39 €	1.39 €
2	Fuseholder Clip	01020074Z		0.066 €	0.132 €
1	IGBT 600V 3A	FGD3N60UNDF	TO-252	0.352 €	0.352 €
1	PTC 100 Ω 2 J/K	B59204J130B10		1.48 €	1.48 €
9.4cm²	Dual layer PCB			144.30 /m²	0.14 €
					3.69 €

Tab.2: Price calculation of a PTC based discharge solution

IISB CP-DU 450

Quantity			Housing	Price/unit	Price
5	Resistor 0603		0603	0.00117 €	0.00585 €
3	Resistor 0805		0805	0.0008 €	0.0024 €
3	Resistor 1206		1206	0.00232 €	0.00696 €
1	Optocoupler	VOS615A	SSOP-4	0.176 €	0.176 €
1	16V Z-Diode	MM3Z16VT1G	SOD-323	0.01963 €	0.01963 €
1	Fuse 450V 1A	BK/PCC-1-R		0.768 €	0.768 €
1	NPN Transistor	BC-847B	SOT-23	0.013 €	0.013€
1	PNP Transistor	PBSS301PX	SOT-89	0.162 €	0.162 €
1	IGBT 600V 350 W	FGH40N60SMD	TO-247	1.50 €	1.50 €
1	Glimmer Isolation			0.05 €	0.05 €
5.2cm²	Dual layer PCB			144.30 /m²	0.08 €
					2.78 €

Tab.3: Price calculation of the presented constant power discharge solution

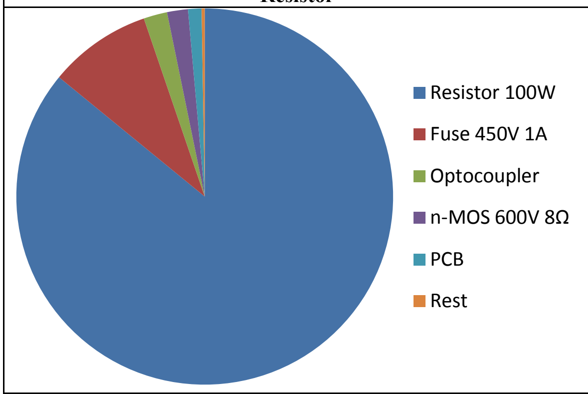
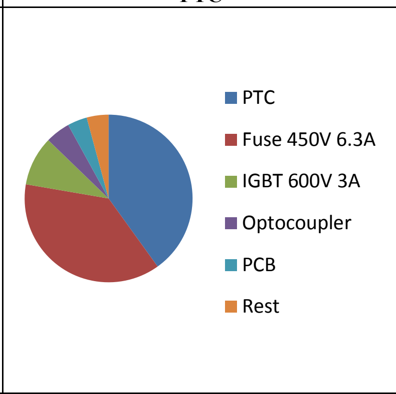
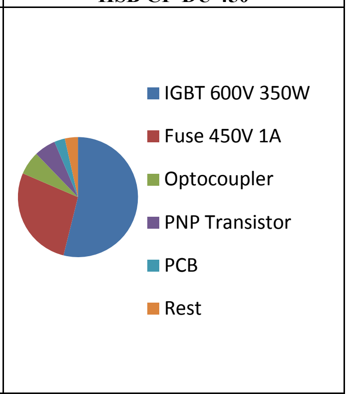
Resistor	PTC	IISB CP-DU 450
		
8.69 €	**3.69 €**	**2.78 €**

Fig.9 Cost distribution of the three discharge solutions

VI. SUMMARY

Tab.4 shows a summary of the presented discharge solutions. Keeping in mind, that the required cooling can be realized by mounting the discharge device at the casing wall of a vehicles power electronic device (drive inverter, auxiliary supply converter, traction DCDC-converter, et al.), one can conclude, that the presented IISB CP-DU 450 discharge device is the smallest, most cost efficient and best adjustable solution. It can operate in continuous operation and doesn't need any cooling time, so is always ready for service.

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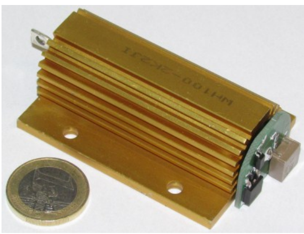
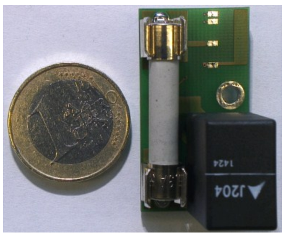
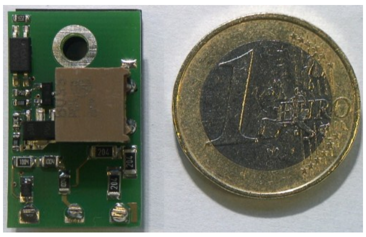
	Resistor	**PTC**	**IISB CP-DU 450**
			
Continuous operation possible	Yes	No	Yes
Cooling required	Yes	No	Yes
Rectangular Volume	84.8 cm³	23.0 cm³	5.0 cm³
Material Price (10000 units)	8.69 €	3.69 €	2.78 €

Tab.4: Comparison between the three different discharge solutions