

## **How far can you get without a friction brake on rear axle? The RABBIT project**

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### **Summary**

By eliminating the mechanical friction brake, the wear parts in the power train are eliminated, which reduces costs, maintenance and also enables savings in weight and space. In addition, the emission of particulates by brake wear are eliminated. A braking resistor allows the use of the energy that is applied during braking to the thermal management of the entire vehicle, thereby extending the vehicle's driving range. This paper will present the concept of a fault-tolerant and functionally safe electric drive train with alternative energy sources that meets the brake requirements and at the same time enables a complete electrical and thermal utilization of the energy generated during braking.

*Keywords: powertrain, regenerative braking, thermal management, wheel hub motor, BEV (battery electric vehicle)*

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### **1 Introduction**

For the first time, electric vehicles with wheel hub drives offer the opportunity to operate without a mechanical friction brake system. This is due to the fact, that these drives can provide the required braking power completely electrical and at the same time allow a wheel-individual, independent control of the torque, which is a prerequisite for vehicle-dynamics control systems such as ABS and ESC for a purely electric brake. An alternative energy control device like a braking resistor is required, which ensures an additional regeneration of the brake energy besides the HV battery. Electric vehicle prototypes without mechanical brake system on the drivetrain axle have been presented before [1]. Many use cases can be covered, but such concept have not been seen for series applications, yet. Most likely, this is due to some important use cases, such as braking at full HV battery, which cannot be covered by such system. So the starting point of the RABBIT project had been both, legal requirements and typical car manufacturer requirements regarding braking and thermal comfort. A risk assessment was carried out as well as simulations of the high voltage DC link and the thermal system. Based from these analyzes the component requirements have been derived [2]. Fitting components are currently under development to run as a new system in a demonstrator vehicle. This vehicle will be used to proof the concept of the RABBIT project in real world driving, supplemented by examinations on a test rig.

As a result of the project, a drive system is integrated and tested in a demonstrator vehicle, consisting of a fault-tolerant wheel hub drive and a brake resistor as an alternative energy dissipater, which can be used to perform all the braking operations occurring on the rear axle. The underlying safety concept ensures a high reliability of the braking system and enables the fulfilment of all legal and manufacturer-relevant requirements. During normal driving operation, the brake resistor will be used for electro thermal recuperation to increase the vehicle's range [3]. Now, in the middle of the project, the analysis of the vehicle requirements and the risk assessment is executed. The development of the new components, the wheel hub drives and the brake resistor has started.

RABBIT is a German abbreviation for “Radnabenantrieb ohne Bremse – Bremswiderstand integriert in Thermomanagement”, i. e. “Wheel hub drive without brake – brake resistor integrated in thermal management” [4]. The presented project is funded by the German Federal Ministry for Economic Affairs and Energy.

## 2 Vehicle Requirements Analysis

### 2.1 Legal requirements

The main legal requirements for the braking system are defined by the ECE13H directive, which is valid for Europe, Australia, New Zealand and Japan and very similar to local regulations in China, India and US. The directive distinguishes between operating, auxiliary and parking brake systems. The main requirements for the various brake types are shown in Table 1.

Table 1: Requirements for the different brake types according to ECE13H

Description	Effect on	Min. deceleration	Actuator
Operating brake	Front and rear axle	5,76 m/s <sup>2</sup>	Brake pedal
Auxiliary brake	Front and rear axle	2,44 m/s <sup>2</sup>	Brake pedal
Parking brake	Typical rear axle	1,5 m/s <sup>2</sup>	Push-button or lever

### 2.2 Other requirements

In addition to the legal requirements, further requirements for the brake system are defined by industry standards (e.g. AMS test) and OEM development requirements regarding braking performance as well as durability, reliability, noise behavior, etc.

Typical use cases and tests used for brakes system development are show in Table 2. In these tests the required decelerations are significantly higher than legally required for the service brake system.

Table 2: Use cases / tests for the design of the brake system

<b>AMS</b>	Acceleration to 110kph, Deceleration to standstill with 1g, 10 cycles
<b>Groß Glockner</b>	Speed constant 30 kph, Slope max. 14%, deceleration between 0.1g - 0.17g
<b>Single Stop</b>	Acceleration to 130kph, Deceleration to standstill with 1.2g

### 2.3 System requirements

The wheel torque required for the electrical drive and service brake system was determined using the above mentioned brake tests. A longitudinal dynamics model of the vehicle was implemented considering optimal braking force distribution between front and rear axle to derive torque/power profiles for the electric machine over time. In the simulation different initial conditions for HV battery SOC, electric machine and

inverter temperatures were considered as well. The vehicle data have been derived from the MEHREN technology demonstrator (B-car, GVM 1700kg) [5]. Table 3 shows the required torque per wheel.

Table 3: Required torque per wheel

Use Case	Drive torque [Nm]	Braking torque [Nm]	max rpm [1/min]
AMS	800Nm for 12,5s	800Nm for 5s	1000
Groß Glockner	50Nm for 100s	150Nm for 100s	270
Single Stop	800Nm for 12,5s	850Nm for 3s	1150

To meet all legal and OEM requirements with the RABBIT demonstrator vehicle, each wheel hub drive needs 850 Nm regenerative peak torque and 100 kW regenerative peak power. The resulting torque curve over speed for one wheel hub drive is shown in Fig. 4.

## 2.4 System Concept

The brake system of the demonstrator vehicle shall comprise the following functions:

1. Electro-hydraulic service brake system operating on the front axle, which decelerates the vehicle.
2. Electrical service brake system with recuperation and thermal brake resistor operating on the rear axle, which decelerates the vehicle.
3. Secondary brake system, which slows the vehicle in case of failure of the service braking system.
4. Parking brake system operating on the rear axle, which holds the vehicle.

Nowadays, regenerative braking is usually limited to 0.15g due to the restrictions generated by the HV battery system. A 50kW electric power at the rear axle through recuperative braking (approx. 0.2g) results in a charge rate of around 3 C. When a deceleration of up to 1.2 g exists, a maximum electric power of around 200 kW is generated through recuperation at the rear axle. Furthermore, the HV battery system cannot be charged at 10 C or more in any given ambient conditions, SOC and SOH. Therefore, an additional energy sink, e.g. a brake resistor, is necessary. Fig. 1 shows the system concept for the drive and brake system. It is defined by the interaction of the electric wheel hub drives (E-WD) on the rear axle, the HV battery, the brake resistor and the hydraulic brake system on the front axle. There are no rear hydraulic service brakes, however an electrically actuated mechanical parking brake (EPB) which will still be required to hold the vehicle at gradients during standstill. The concept assumes a regen capable vacuum less brake system (Continental MKC1) [5].

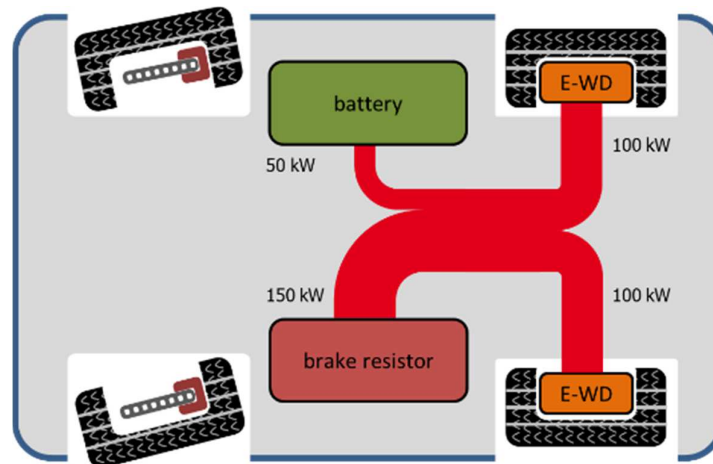


Figure 1: System concept

The combination of the HV battery system with a brake resistor as an alternative energy dissipater leads to a redundant concept. The HV battery system is charged with optimal charge rate in its actual “comfort zone”, as it can be seen in the picture above. Regarding the (additional) recuperated electric energy, it is dissipated through a brake resistor (Fig. 1) into the cooling system, where it can be used to heat up the cabin. In case of a HV battery failure the full electric braking power can be transferred to the cooling system (Fig. 2).

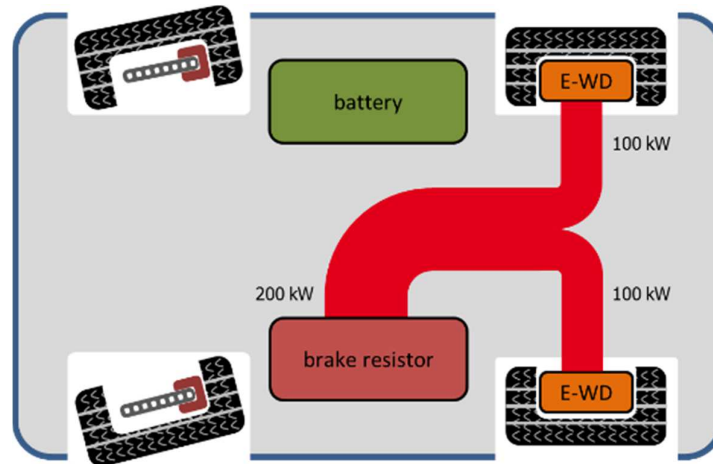


Figure 2: Redundant energy sink concept

## 2.5 Demonstrator vehicle

The planned RABBIT demonstrator vehicle shall be based on the Ford Fiesta demonstrator vehicle developed in the MEHREN project, which is shown in Fig.3. The vehicle has two electrical wheel hub drives on the rear axle and a HV battery system with 18.8 kWh energy capacity. Maximum weight is 1700kg and the maximum vehicle speed is 130kph [6].

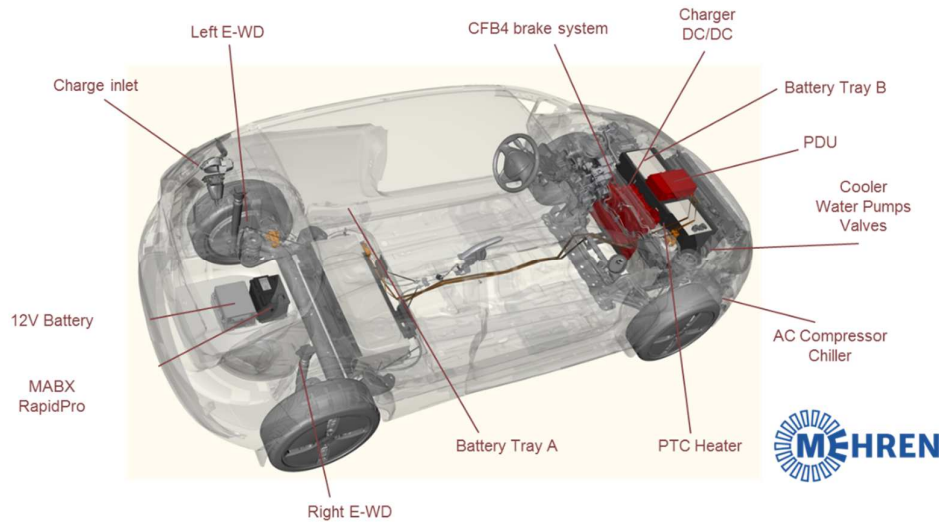


Figure 3: MEHREN Demonstrator vehicle

### 3 System Architecture

#### 3.1 Wheel Hub Drives

The system shall represent an innovative, HV battery-driven powertrain consisting of two wheel hub drives located on the rear axle. The wheel hub drives are integrated and evaluated in an assigned demonstrator vehicle provided by Ford and shall provide a compact construction volume. They are developed based of the work results from project MEHREN. In difference to MEHREN, the concept pursues the objective to eliminate the mechanical friction-brake due to recuperate the full electric and electro-thermic energy.

Due to its higher power density, improved fault tolerance, and reduced phase currents, six-phase motors with two independent three-phase systems are used. With a six-phase machine, the required braking torque can be reached with less than half the phase current required with the three-phase machine. In this respect, the torque requirements alone were reason enough to make a six-phase machine meaningful. Furthermore, with a 6-phase machine, the RMS current stress and the voltage ripple of the DC-link capacitors can be reduced compared to the three-phase system by implementing an interleaving of the carrier signals for the pulse width modulation.

In additional six-phase drives with two electrical independent three-phase systems can provide an increased fault-tolerance. In case of a failure in a sub-machine or its associated power electronics, it is possible to switch off the sub-system and to continue operating with the second sub-machine only. This has a direct positive effect on the availability of the electric brake. In this case, there is still 50% available, which, under security aspects is only half as high – but not 0.

Fig. 4 shows a comparison of torque gradients (motor and generator driven) for different voltage levels. Due to the increased DC-link voltage the field weakening area starts at a speed close to the maximum speed. Thus, the torque requirements during braking can be fulfilled.

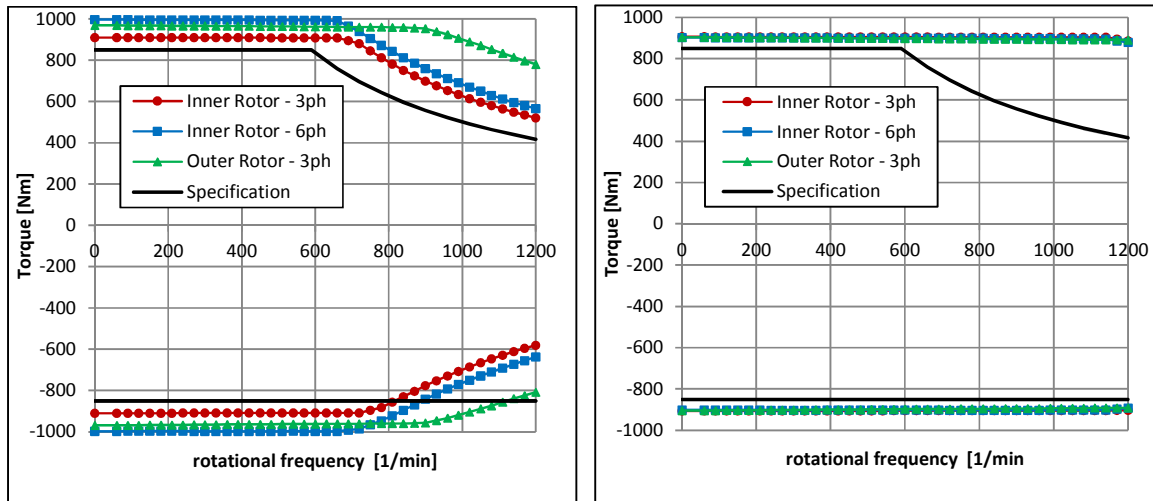


Figure 4: Torque gradient at originally HV battery voltage (left) & increased DC-link voltage (right)

#### 3.2 Brake Resistor

The HV battery is not always able to absorb the electric power during regenerative braking. Regarding to the brake requirements, the brakes shall be always available. As it is necessary to have fault tolerant drivetrain it is also necessary to guarantee the absorption of the electric energy. There are different ways to absorb this energy parallel to the HV battery. In this project the decision was done for the electro thermal energy sink. In the following the electro thermal energy sink is named as brake resistor. In [7] the brake resistor was tested in the vehicle for the first time. It was proofed that the regenerative braking works also

with a full HV battery. If the brake resistor is integrated in the cabin heating circuit there is a potential at cold temperatures to save heating energy and increase the range of EVs.

Simplified the brake resistor is an over-dimensioned heater. The main difference lies in the requirements for the performance as well as the availability. While the power requirements of the interior heater are quasi-static, the power requirements for the brake resistor are more peaks than quasi-static. A further new requirement is the fast and precise controllability of the needed power. This requirement excludes some electro thermal conversion types, e.g. PTC, for this project. The heating layer provides the best characteristics regarding the requirement [8] and was chosen for brake resistor in the project. From the control point of view, the heating layer is an electrical resistance at which heat is generated by current flow. The amount of heat depends on the height of the current.

For the component design, two essential properties must be taken into account and designed regarding the requirements. Considered shall be on the one hand the electrical properties and on the other hand the thermal properties.

The electrical design depends on the applied voltage  $U$  and the desired power  $P$ . The maximum power of the brake resistor is specified by the maximum power of both E-WDs (see chapter 2). The voltage is set constant by the boost converter. So the needed resistance value  $R$  can be calculated by the following equation.

$$R = \frac{U^2}{P} \quad (1)$$

The resistance must be applied to the maximum peak power, thus the peak power is also equal to the continuous power. If a lower power is requested, this must be adjusted by chopping the applied voltage. As with the pulse width modulation, the needed voltage is controlled by electronic switches e.g. IGBT, MOSFET. The advantage of this method is the good controllability of the desired power over the frequency or the duty cycle.

For the thermal design there is the freedom to optimize the component on either the continuous power or the peak power. Since the peak power is the critical requirement, the thermal behavior is designed for the maximum peak power. The limiting sizes are on the one hand the maximum temperature in the heating layer and on the other hand the maximum coolant temperature. If the heating layer temperature exceeds a critical value the heater can be destroyed. Also if the coolant exceeds the boiling temperature the heater could be destroyed due to lack of cooling. These states shall be avoided. In [3] a sensitivity analysis of the design parameters from a brake resistor was made. Although it is a resistance heater, the heat transfer mechanisms are the same as for the layer heater. Thus the findings from this analysis could be taken over. The head knowledge is, to reduce the maximum coolant temperature peaks the cooler has to be design with a high mass.

### 3.3 HV Architecture

In this section, the architecture of the HV system is described, and different topologies for the connection of the HV battery to the drives are compared. An overview of the architecture is given in Fig. 5. The HV system consists of two electrical wheel hub drives (E-WD) with integrated power electronics. The drives are connected to the primary energy source (here: a HV battery) and to the brake resistor. Furthermore, three different approaches for the connection of the drives to the HV battery are shown in **Error! Reference source not found.** The first one is the direct connection (Fig. 5a). In this case, the DC-link voltage of the inverter equals the HV battery voltage. The second approach is a semiconductor-based HV battery disconnecter (Fig. 5b). It consists of a controllable power semiconductor (e.g. IGBT or MOSFET) and an anti-parallel diode. In addition a free-wheeling diode and a small capacitor are necessary to limit the over voltage during turn-off of the semiconductor. Under normal conditions, the semiconductor is turned ON and the DC-link voltage equals the HV battery voltage. Only if the DC-link voltage is too small to provide the requested braking torque the semiconductor is switched OFF. Due to the regenerated energy from the drive system, the DC-link voltage increases. In this case the brake chopper controls the DC-link voltage to the voltage limit and no energy can be stored into the HV battery. Therefore, the maximum phase voltage during braking can be increased in comparison to the directly connected topology. In combination with the higher torque requirement during braking than during driving, this enables an

improved motor design. The boost converter (Fig. 5c) can be used similarly to the HV battery disconnecter. The advantage is that it can boost the voltage to a higher level during driving as well.

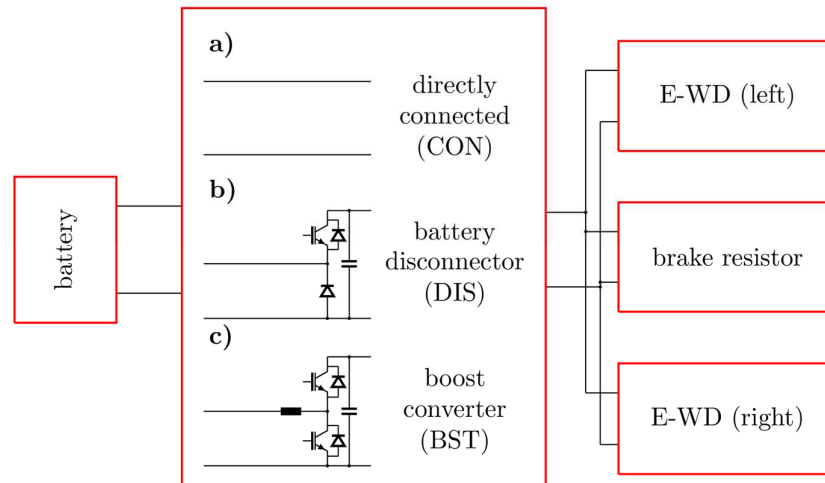


Figure 5: Overview of the HV architecture

For the investigation and the comparison of these topologies, scalable models of the HV battery, the motor, and the power electronics are developed. The components (HV battery, motor, power electronics) are designed by these models, and in the next step, the energy consumption of the topologies are determined for various drive cycles. A short overview of the designs of the components and a comparison of the overall system size and efficiency are given in the following paragraphs. More detailed results are presented at the European Conference on Power Electronics and Applications 2017 [9].

For the comparison of the architectures, three different HV battery designs are developed. The first one uses the maximum DC-link voltage of the inverters as maximum open-circuit voltage (OCV) and is suitable for all investigated topologies. The second one supplies the drive system during driving operation without the need of an increased voltage. The voltage must be increased for braking with high braking torques in higher speed range only. Thus, it is not qualified for the directly connected drive system. The third HV battery provides a sufficient DC-link voltage in urban speed range. For higher speeds, the voltage must be boosted. Therefore, it requires a boost converter for driving and braking.

The motors must be designed considering the torque capability during braking. Therefore, the maximum phase voltage under braking conditions is the main design criterion. The maximum phase voltage of the directly connected drives results from the minimum OCV of HV battery 1. The maximum phase voltages for the other topologies depend on the maximum DC-link voltage. Therefore, two different motor designs are necessary here: Motor 1 for the directly connected drive system and motor 2 for the other topologies. The motors are scaled via the number of turns per winding. Therefore, the reduced maximum phase voltage of Motor 1 leads to an increased phase current (here: 160 A instead of 132 A). Due to the scaling of number of turns and the motor current, the magnetic flux of the motor remains constant in the constant torque area. Thus, the motor losses remain nearly constant as well.

The optimum designs of the power semiconductors are determined by scaling the semiconductor chip area [10]. Different constraints like equal maximum temperature or equal maximum losses for all topologies are possible for the scaling of the semiconductors. In this paper, the scaling factor is selected in a way that the scaled semiconductors meet the thermal requirements under maximum load conditions. Due to the higher maximum current, the chip area of the inverter is larger for the directly connected system (approximately 22%). The needed chip area of the HV battery disconnecter is smaller than the area needed for the boost converter because only one IGBT is necessary and no switching losses occur in the HV battery disconnecter. For topologies with lower HV battery voltages, larger chip areas are necessary. This results from the higher currents in HV battery and DC link. The resulting overall chip areas for the power train are given in Fig. 6 (black crosses). The smallest overall chip area is needed for the combination of semiconductor-based HV battery disconnecter and HV battery 1.

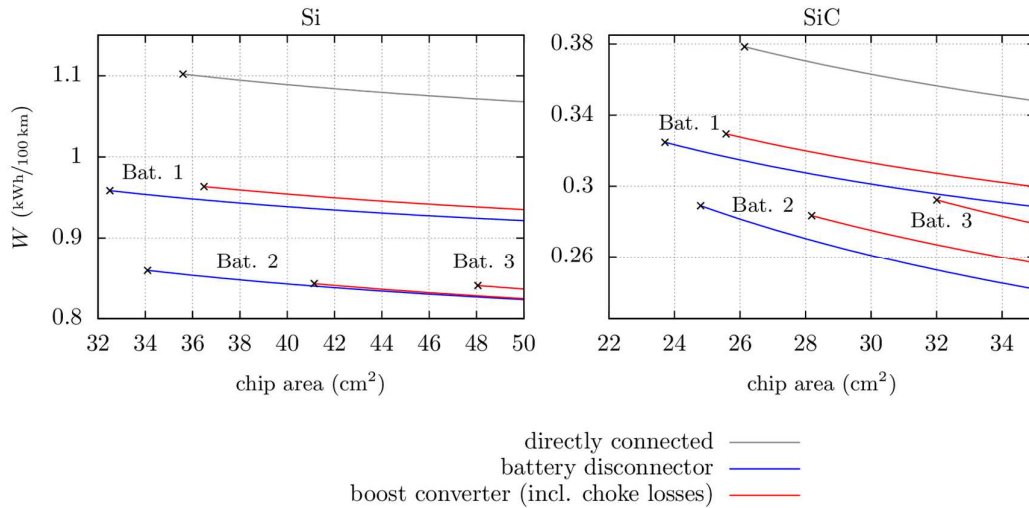


Figure 6: Energy consumption over semiconductor chip area

The overall energy consumption is the sum of the vehicle driving losses (drag, rolling resistance) and the losses in the HV components (battery, motors, converters). The losses of HV battery and motors are nearly equal for all topologies. Thus, the focus of the comparison is on the converter losses. In Fig. 6 the overall converter losses over the overall chip area are presented (black crosses). Furthermore, the estimated power losses for larger chip areas are shown (lines). The comparison is given for silicon-based (Si-based) and silicon-carbide-based (SiC-based) semiconductors. The lowest power consumption is given for the topology with HV battery disconnecter and HV battery 2. For the boost converter, the estimated power consumption is slightly higher. Due to the high power consumption, the directly connected topology is not the optimal solution for this application. The advantages of the boost converter over the HV battery disconnecter are that it enables more functionality for the full system and already developed and tested devices are available. Furthermore, the HV battery disconnecter can be evaluated by the boost converter as well. Therefore, for the prototype, the HV architecture with a boost converter is applied.

### 3.4 Thermal Management System

By the usage of a redundant energy sink for the HV battery in shape of a brake resistor the thermal management get an important role in the project. For the first time in the development, the coolant cycle must be considered in the brake design. This means that the requirements for the thermal management getting higher. Peak power of about 200 kW (see. chapter 2) must be absorbed by the coolant and released to the environment. Further challenges are different preferred temperature levels of the components. One more requirement is to develop an efficient vehicle. In [3], [11] it was shown that, especially in winter, the usage of the braking energy with a brake resistor can increase the range. By this fact the free braking energy shall be used in the project to heat up the cabin or bring the components, e.g. the HV battery, in a much more efficient set point. All this requirements were considered in the development of the thermal management architecture. The outcome is the architecture shown in Fig. 7.

The coolant thermal management circuit consists of two independent coolant circuits. The connection of the two circuits is over a coolant /coolant heat exchanger. With this component it is possible to exchange heat or cooling energy between the circuits.

The first cooling circuit is the low temperature circuit. The temperature limits are set from the HV battery. The primary task of this circuit is to cool the HV battery. This could be done in two different ways. The first possibility is to exchange the waste heat with the environment by the radiator. If the cooling power is not enough the HV battery could be cool down active by the chiller. In this possibility, the waste heat is transported to the environment by the refrigerant circuit of the vehicle. The secondary task is to cool the charger during charging and also keep the 12 V DC/DC in the preferred temperature range. At cold temperatures the radiator and the chiller are shorted with the target to keep all the waste heat in the coolant circuit to heat up the components very fast. In this mode it is also possible to use the waste heat of the E-

WDs, DC/DC or from the brake resistor via the coolant heat exchanger. At very cold temperatures the HV battery could also be heat up active by the brake resistor.

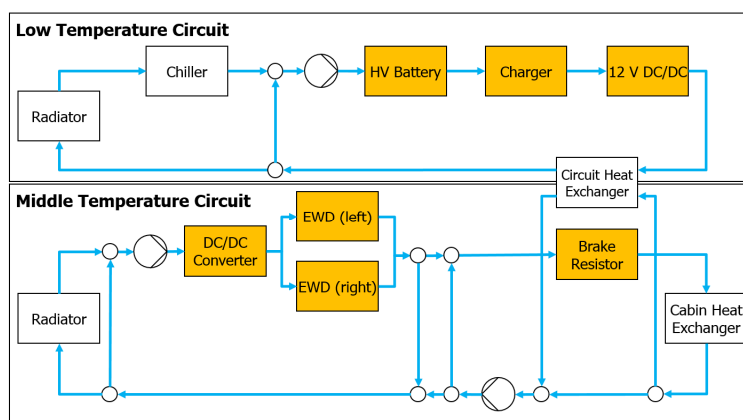


Figure 7: Thermal Management Architecture

The second cooling circuit is the middle temperature circuit. The tasks of this circuit are to cool the drivetrain (DC/DC, E-WDs and brake resistor) and to heat the cabin. Regarding this two requirements it is feasible to divide the circuit in two independent circuits. With this interconnection, the cabin could be heat up very fast because the high thermal mass of the drivetrain is not in the circuit. At cold temperatures it makes sense to use the wasted heat of the components to bring the drivetrain into a comfort temperature range where the efficiency is better. This mode can be activated with bypassing the radiator not to lose the waste heat to the environment. If there is free heat from the brake resistor during braking which could not be used by the cabin, this heat can be used to heat up the drive train or transfer this heat to the HV battery. With this strategy the components works much faster in their optimum operating point to save energy and increase the range.

The drivetrain and the brake resistor gets more in the focus of a brake by wire system, this leads to much higher requirements for the thermal management. For this a second coolant pump was installed in the middle temperature circuit. In case of failure of one coolant pump, the second pump can guarantee the coolant flow through the drive train and the brake resistor.

## 4 Conclusion

For the first time, a concept for a brake by wire system realized by wheel hub drives is presented. During the development phase OEM and customer requirements were taken into account in addition to the legal requirements. The goal was not to have any restrictions compared to a conventional system. This only works if the wheel hub drives take over the complete braking power at the rear axle. For the design it means that the torque in generator mode must be constant over the entire speed and does not drop as usual with increasing speed. Furthermore a fault-tolerant operation of the wheel hub drives must be guaranteed. For this purpose, a six-phase machine is designed. In addition to a fault-tolerant drivetrain, a redundant power sink in addition to the HV battery is required. The system should also work when the HV battery is not able to absorb the energy, e.g. at high state of charge. For the redundant energy sink a braking resistor is used. He converts the electrical energy into thermal energy. The brake resistor shall be designed for the maximum power of the drivetrain to cover the use case where the HV battery is not able to absorb any power. The single stop leads to a peak power up to 200 kW. This requirement challenges on the one hand the component brake resistor and on the other hand the thermal management. The concept of a thermal system which meets all component requirements was presented. In addition, this system has been designed so that the braking resistor takes over two functions. On the one hand the dissipation of the electric power during regenerative braking and on the other the function of the cabin heater. The thermal architecture enables also the use of free braking energy to heat the cabin and safe expensive energy from the HV battery. With this strategy it is expected to save heating energy and thus increase the range.

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