Design report for eWD2 and in-wheel motor component

HORIZON 2020

H2020-LC-GV-2018-2019-2020/H2020-LC-GV-2018

GA No. 824250

EVC1000

Electric **V**ehicle **C**omponents for **1000** km daily trips

Deliverable No.	**D3.1**
Dissemination level	**Public**
Written by	I&M, ELAPHE, Fraunhofer

"This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 824250".

EVC1000 is co-funded by the European Commission, DG Research and Innovation, in the HORIZON 2020 Programme. The contents of this publication are the sole responsibility of the project partners involved in the present activity and do not necessarily represent the view of the European Commission and its services nor of any of the other consortium partners

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Abbreviations

Abbreviation	**Long Version**
ABS	Anti-lock braking system
AC	Alternating Current
BATT	Battery powers electric vehicle and stores energy
BLDC	Brushless DC Motor
BMS	Battery Management System
CAN	Controller Area Network
CMTI	Common Mode Transient Immunity
DC	Direct Current
DIDIMO	Dual Inverter Developed at Ideas & Motion
DPT	Double-Pulse Test
DSP	Digital Signal Processor
DUT	Device Under Test
ECE	Economic Commission for Europe
ECU	Electronic Control Unit
EMC	Electromagnetic Compatibility
EPB	Electric Parking Brake
ESP	Electronic stability program

EV	Electric Vehicle
eWD^2	Electric Wheel Dual Drive
FEM	Finite Element Modelling
FSM	Finite State Machine
GDB	Gate-Driver Board
GVW	Gross Vehicle Weight
HEV	Hybrid Electric Vehicle
HS	High Side (Switch)
HV	High Voltage
HVIL	high voltage interlock loop
I/F	Interface
ICE	Internal Combustion Engine
Id	Direct current
IGBT	Insulated-Gate Bipolar Transistor
IMU	Inertial measurements unit
INV	Inverters drive electric motors with power from the batteries or can power the batteries in regenerative braking.
Iq	Quadrature current
ISO	International Standard Organization
IWM	In-wheel electric motor is integrated in two or four wheels.
LS	Low Side (Switch)
LV	Low Voltage
MCU	Micro Controller Unit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NPN	NPN (Bipolar Transistor)
NTC	Negative Temperature Coefficient
NVH	Noise, vibration, and harshness
OEM	Original Equipment Manufacturer
PCU	Propulsion Control Unit
PHEV	Plug-in Hybrid Electric Vehicle
PM	Permanent Magnet

PMSM	Permanent Magnet Synchronous Machine
PNP	PNP (Bipolar Transistor)
PSD	Power Spectral Density
PSEN	Position sensor measures motor position
PTC	Positive temperature coefficient
PWM	Pulse width modulation
RMS	Root Mean Square
RPM	Revolutions Per Minute
SVM	Space Vector Modulation
SW	Software
UVLO	Under Voltage Lock Out
VMU	Vehicle Management Unit consist of all logic contents involved in processing driver requests and system status to calculate the torque(s) value(s) to be requested to powertrain unit(s).
WLTP	Worldwide-harmonized Light-vehicles Test Procedure

History

Version Number	**Comment**
_final	Final version submitted on November 7th.
_V02	Updated version submitted on December 3rd.
_V03	Updated version submitted on December 16th.

Authors

Name, Partner	E-mail
Paolo Santero	paolo.santero@ideasandmotion.com
Andrea Recce	andrea.recce@ideasandmotion.com
Maurizio Tranchero	maurizio.tranchero@ideasandmotion.com
Claudio Romano	claudio.romano@ideasandmotion.com
Riccardo Groppo	riccardo.groppo@ideasandmotion.com
Roberta Peroglio	roberta.peroglio@ideasandmotion.com
Jože Buh	joze.buh@elaphe-ev.com
Tomaž Motaln	tomaz.motaln@elaphe-ev.com
Martin Strojnik	martin.strojnik@elaphe-ev.com
Alexander Otto	alexander.otto@enas.fraunhofer.de
Eberhard Kaulfersch	eberhard.kaulfersch@enas.fraunhofer.de

1 Publishable executive summary

1.1 Aim of EVC1000 project

The EVC1000 project addresses powertrain efficiency as well as reduced needs for raw materials and rare earths challenges by developing brand-independent components and systems, and demonstrates them through an integrated wheel-centric propulsion architecture and EV management approach implemented on two second generation EVs – a JAC iEV6S and an AUDI e-tron.

The goals of the EVC1000 components are to match/exceed the ERTRAC efficiency targets for EV2030+, see Table 1; to reduce cost by at least 20%; and to increase convenience and comfort of long range travel.

Efficiency	Inverter AC/DC	Power electronics DC/DC	Motor-to-wheel (NEDC)	Motor-to-wheel (WLTP)
EV2016	0.95	0.91	0.85 to 0.9	0.86 to 0.91
EV2030+	0.96	0.92	0.86 to 0.91	0.87 to 0.92
EVC1000	**0.96**	**0.92**	**0.89 to 0.94**	**0.90 to 0.95**

Table 1: Efficiency values of current and future EV generations (from [2]) and EVC1000

At the core of EVC1000 is the in-wheel electric motor architecture because of its advantages in terms of active safety and drivability and because of its unique benefits of packaging and modularity that will significantly enhance flexibility and adaptability of future EV architectures. At the same time, the EVC1000 participants acknowledge the perceived drawbacks of in-wheel motors – but the recent documented progress in terms of efficiency, durability, scalability and cost-reduction makes in-wheels motors a promising alternative to on-board motors. Also, the fact that two major car makers, AUDI and JAC, are investing resources here is a clear sign of the innovation potential of this technology.

Despite the high level of integration within EVC1000, full flexibility in the commercialization of the individual components will be retained. This will facilitate the widespread introduction of the EVC1000 outputs on the automotive market in short term, and overcome the limitations of some of the previous integrated electric corner solutions.

EVC1000 will assess the energy efficiency benefits of the new technologies compared to existing EVs. This will include demonstration of long distance daily trips of up to 1000 km across different Member States with no more than 90 minutes additional travel time due to charging, and without additional degradation of the components.

1.2 Aim of Work Package 3

Within the WP3 the e-traction axle system components are designed and realized, leveraging on the latest in-wheel motor technology. The coupled custom dual inverter rely on wide band gap switches, whose performances perfectly match the requirements of the proposed in-wheel motors.

1.3 Aim of this report

This document provides a publishable report of all activities performed in Task 3.1. This task covers the detailed design requirements definition for the e-traction axle components. The information provided in this deliverable reflects the current development in EVC1000 at Month 9; it is expected that few aspects mainly related to mechanical interfaces (e.g. subcomponents fixing points, cooling circuit hoze fitting) will be consolidated during the validation and integration phase. These consolidations will be reported in Deliverable D3.5.

1.4 Structure of this report

This report is divided in four chapters, mainly describing interfaces of DIDIMO inverter:

- section 2 describes at high level the electrified axle concept;
- section 3 details the in-wheel motor specifications;
- section 4 details the eWD^2 specifications;
- section 5 summary of the activities related to functional safety analysis;
- section 6 conclusion.

1.5 Deviations from the plan

All objectives addressed to Task 3.1 have been fulfilled. There are neither deviations with respect to timing nor content deviations from original plan in GA Annex 1 – Part A.

2 The electric axle concept

The e-axle integrates the latest ELAPHE in-wheel motor technology and the electric wheel dual drive (eWD²) provided by I&M. The eWD² is based on wide band gap switches, perfectly matching the requirements of the proposed in-wheel motors.

Figure 1: e-Axle concept.

In order to accelerate the electric vehicle (EV), the e-axle system employs two electric motors directly coupled with the vehicle wheels to generate torque by converting electric energy into mechanical. The process is reversed during regenerative braking, when energy is recovered with braking torque that decelerates the vehicle. Total requested torque represents a reference for the propulsion system control and is obtained from the driver over the accelerator and brake pedal positions. The in-wheel propulsion system enables an independent torque control for each driving wheel, whereas distribution of the torque between the driving wheels can be fixed or dynamic. The latter is used in the case of active propulsion systems with yaw control functions (torque vectoring) and/or anti-slip function. Active systems also employ steering wheel data as an additional reference for intended lateral motion from the driver.

The eWD² control board is based on latest Infineon 32-bit TriCore™ AURIX™ providing a top level computing performance and offering best in class features in term of safety. Main microcontroller consists of different cores: two of them are fully dedicated to the motors control, the remaining cores are available to integrate application dependent control strategies. The EVC1000 E/E architecture has been designed to be flexible enough to guarantee a two steps approach during the development of the application. In the experimental phase an external rapid prototyping unit is used in order to be faster in application update and tuning. Once the control algorithms will be stable enough the same application software will be synthesized. The resulting source code will be integrated directly on the eWD² control board.

Figure 2 and Figure 3 are showing this two steps approach.

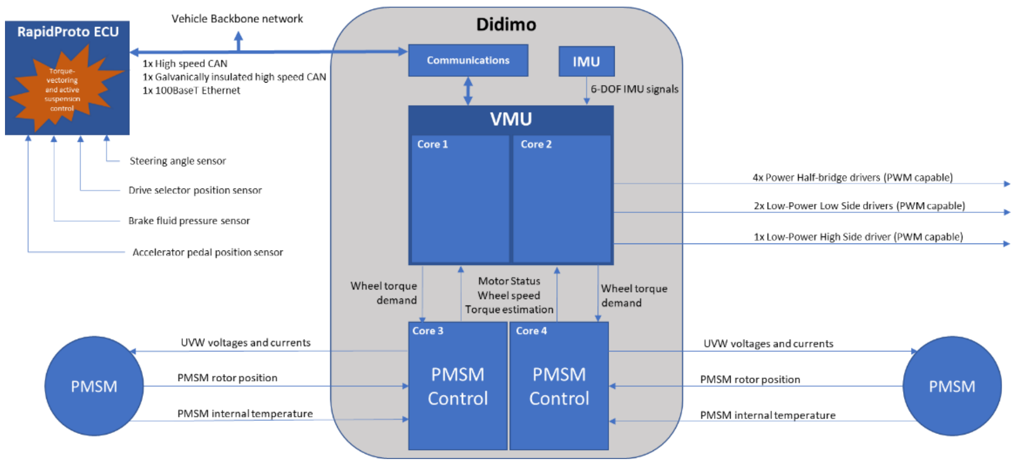


Figure 2: eWD² integration (development)

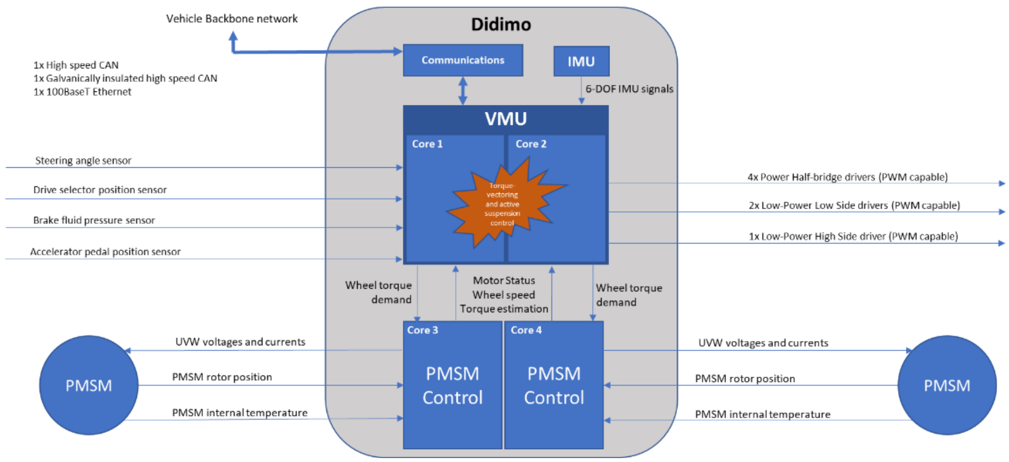


Figure 3: eWD² integration (final)

2.1 System interfaces

External Interface ID	Description	Comment
ACC_PDL_POS	Accelerator pedal position	Can be provided by external ECU or directly from the pedal
BRK_PDL	Brake fluid pressure/pedal position	Can be provided by external ECU or directly from the pedal
DRV_DIR	Driving direction selection information	Can be provided by external ECU or directly from the gear selector
STEER_ANGL	Angle of the steering wheel	Can be provided by external ECU or directly from the steering system

Table 2: External interfaces to the system

3 The L1500 In-wheel motor

For EVC1000 an efficiency optimized variation of the L1500 in-wheel motor will be developed with the aim to fit the same motor on both EVC1000 demonstration vehicles. There is quite some difference between the vehicles in terms of vehicle weight (3130 kg GVW for e-tron and 1835 kg GVW for JAC) so the resulting performance will also be different. For appropriate performance the e-tron could in the future have 4 in-wheel motors or a front e-axle or ICE driven axle.

General project constraints:

- 19-inch rims - as these are the largest rims that will fit on the JAC vehicle;
- Weight of the e-tron vehicle and with this the needed space in the interior of the motor for mechanical brake of sufficient size;
- Nominal Battery voltage 396 V;
- Peek current from the inverter 400 A_{rms};
- SiC inverter switching frequency will be 50kHz;
- Two-wheel drive on each vehicle on rear axle.

Both OEM partners in the project have given their respective vehicle performance expectations. These OEM expectations are gathered in the Table 3 below. Actual performance of the EVC1000 demonstration vehicles equipped with L1500 efficiency optimized motors are listed in Table 5 at the end of this chapter.

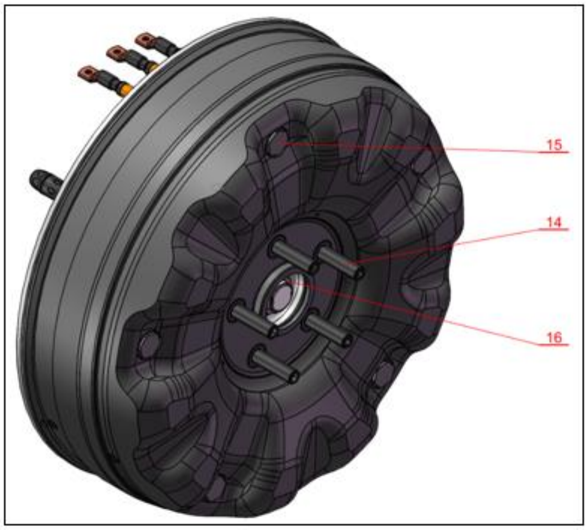
Basic vehicle requirements		AUDI e-tron	JAC iEV7S
1.	**Total vehicle mass [kg]**	FULL: 3130 EMPTY: 2660	FULL: 1835 EMPTY:1460
2.	**Frontal surface area [m2]**	2,65	2,16
3.	**Air drag coefficient**	0,28	0,37
4.	**Rolling resistance coefficient**	0,006	8,5
5.	**Wheel radius [m] (tire radius)**	0,371 m	0,307
6.	**Number of in-wheel motors per vehicle**	2 (RWD)	2 (RWD)
7.	**Max speed [km/h] of target vehicle**	150	130
8.	**Continuous speed [km/h] of target vehicle**	150	130
9.	**Hill-climbing ability (in %)** PEAK: CONTINUOUS: HILL-START:	 Performance for 2 x L1500 Performance for 2 x L1500 Performance for 2 x L1500	 30 / 30
10.	**Speed in peak % grade [km/h]**	performance for 2 L1500	5
11.	**Expected acceleration [s]:** a. Accelerate time from 0 to 30km/h[s] b. Accelerate time from 0 to 50km/h[s] c. Accelerate time from 0 to 100km/h[s]	 performance for 2 x L1500 performance for 2 x L1500 performance for 2 x L1500	 2,5 4,5 12
12.	**Battery data**	95 kWh gross, 83 kWh net, 396 V nom.	80 kWh gross, 399 V nom. (after conversion)
13.	**Driving cycle (driving cycle for benchmark, if different than WLTP)**	NEDC & WLTP	WLTP

Table 3: OEM performance expectations for the demonstration vehicles.

Main efficiency validation criterion within EVC1000 project will be WLTP cycle efficiency. This is in-line with the 1000 km demonstration trip goal, where reduced energy consumption will be the main influencing factor. Motor electromagnetically active part will be optimized with this validation goal and above listed requirements in mind.

3.1 Motor parts and dimensions

The L1500 disc brake version with calliper configuration and electric parking brake (EPB) is shown in Figure 4. This motor configuration is to be used with the JAC iEVS7 demonstration vehicle.



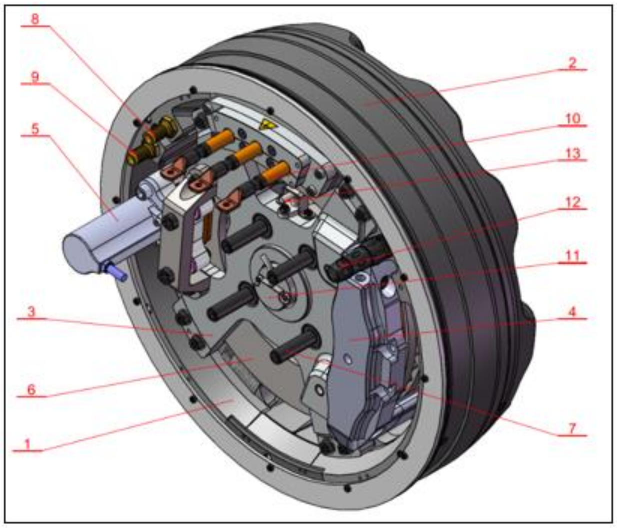


Figure 4: Front view (left) and rear view (right) of the L1500. 1 – Stator, 2 – Rotor, 3 – Stator Plate, 4 – Main Calliper, 5 – EPB, 6 – Brake Disc, 7 – Stud Bolts for vehicle mounting, 8 – Coolant - Inlet, 9 – Coolant - Outlet, 10 – Phase Cable, 11 – Position Sensor, 12 – Temperature Sensor Connector, 13 – ABS Sensor, 14 – Stud Bolts for Rim mounting, 15 – Sealing Plug, 16 – Bearing Nut.

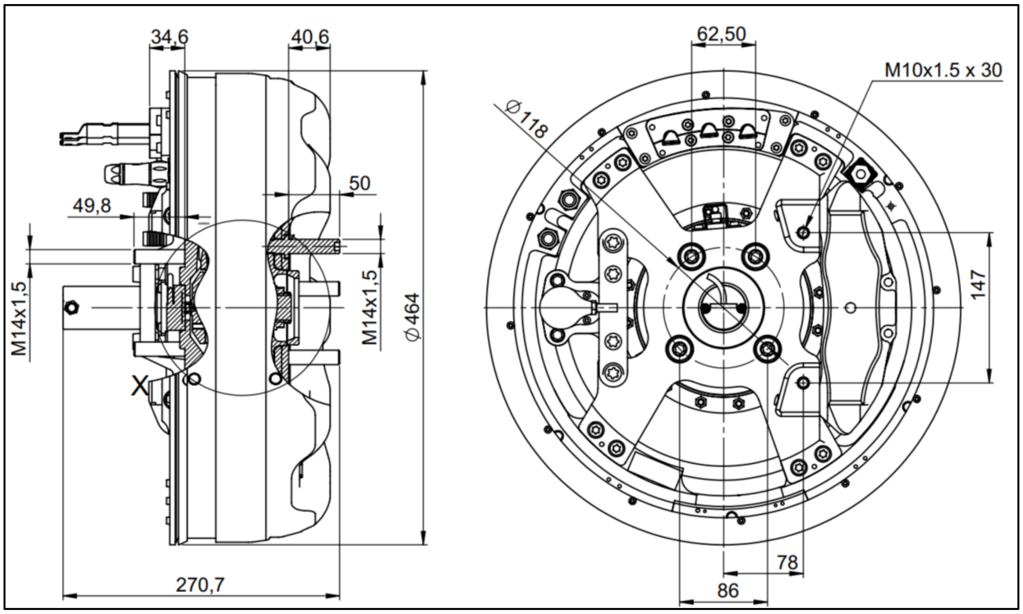


Figure 5: Outer dimensions and mounting feature

Audi e-tron demonstrator will be equipped with Brembo Brake-by-wire system while for JAC vehicle an electric parking brake and a standard fixed calliper will be used show on Figure 6.

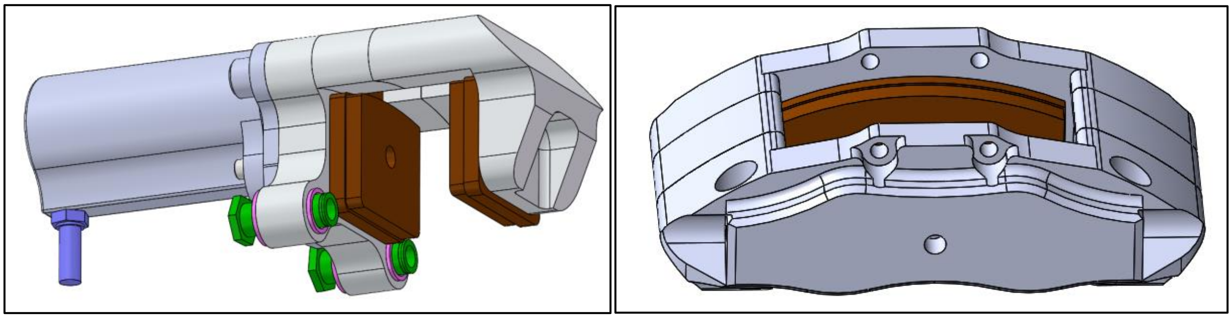


Figure 6: Left: Electric parking brake. Right: Fixed standard calliper.

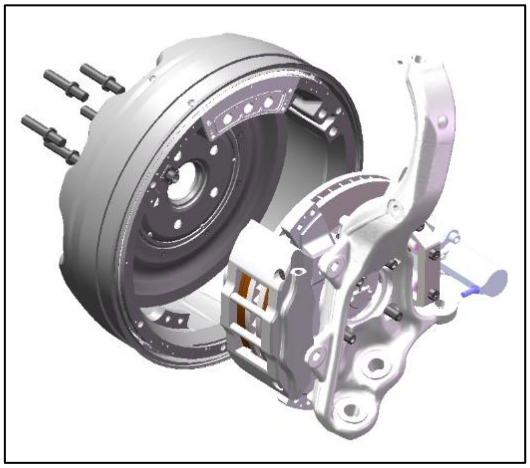
3.1.1 Motor mass

Motor mass will influence the design and tuning of the suspension system. Weight of the motor active part and motor as a whole is shown in Table 4.

Electromagnetically active mass	14.7	kg
Total motor mass (excluding brake, bearing, cables, stator plate)	34.8	kg

Table 4: Overview of the mass

3.1.2 Customization of attachment points



The motors are decupled from the mechanical brake, bearing and knuckle assembly.

The knuckle assembly is comprised of the stator attachment points, and vehicle knuckle. The knuckle assembly can be customized to be a single part (optimization and FEM validation of the part to load cases is required prior to manufacturing).

3.2 Electrical and cooling liquid interfaces

The L-Type in-wheel motor has five outlet cables and two cooling liquid connections:

- three (3) phase cables;
- one (1) position sensor cable;
- one thermal (1) protection cable;
- Cooling inlet and cooling outlet.

3.2.1 Phase cables

On the motor side, the shielding of each phase cable is connected to the motor housing. On the inverter side, the use of EMC cable glands is suggested. The cable shield shall be connected over EMC glands to the inverter housing.

The phase cables used are Class D (according to ISO6722) automotive grade shielded power cable for road vehicles with cable diameter 12.7 mm and cross-section 35 mm2.

3.2.2 Position sensor

The signal from position sensor travels through a cable to the inverter. The sensor cable used is a double shielded cable with a diameter of 5 mm. On the sensor side the cable is integrated into the sensor housing and the inner shield is not connected. The outer shield is connected to the sensor housing. The motor position sensor cable is equipped with DSUB9 connector.

3.2.3 Thermal protection sensors

Thermistors are integrated inside the motor for thermal protection of the motor during operation. There are three NTC thermistors placed in different parts of the motor. One thermistor shall be connected either to the inverter or the PCU, which allows for temperature monitoring and ensures that the motor temperatures remain below maximum operating temperatures. Other two thermistors present a redundant state, and are used for the motor thermal behaviour verification during the testing process. Those two temperatures can be observed on an external monitoring device. These thermistors are connected to the PCU.

3.2.4 Connection of the cooling circuit

There are two cooling connections, one for the inlet and one for the outlet. Design of cooling ducts ensures acceptable pressure losses in the cooling circuit. The cooling connections are shown in the Figure 7. The flow direction at each connection is represented with arrows.

The minimal required coolant flow for a water-glycol mixture (50%-50%) is 8 l/min with the maximal allowed inlet temperature of 65 °C for full performance of the motor.

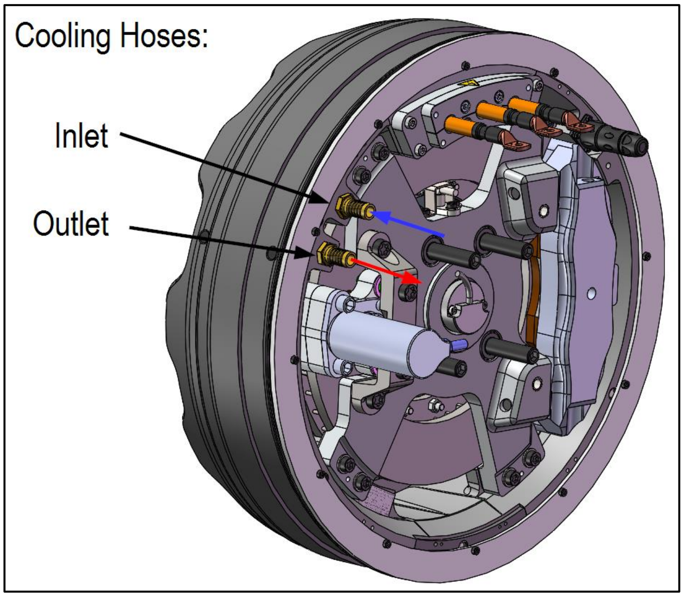


Figure 7: Cooling connections on the inner side of the stator. Flow direction is represented with arrows. Blue arrow: inlet, cold; red arrow: outlet, hot.

3.3 Vehicle integration

The rear axle of JAC demonstrator features a torsion beam suspension setup, which is accessible and requires less modification in the mechanical integration point of view than more complex setups like the one on the Audi demonstrator – integration for both cases is shown in Figure 8.

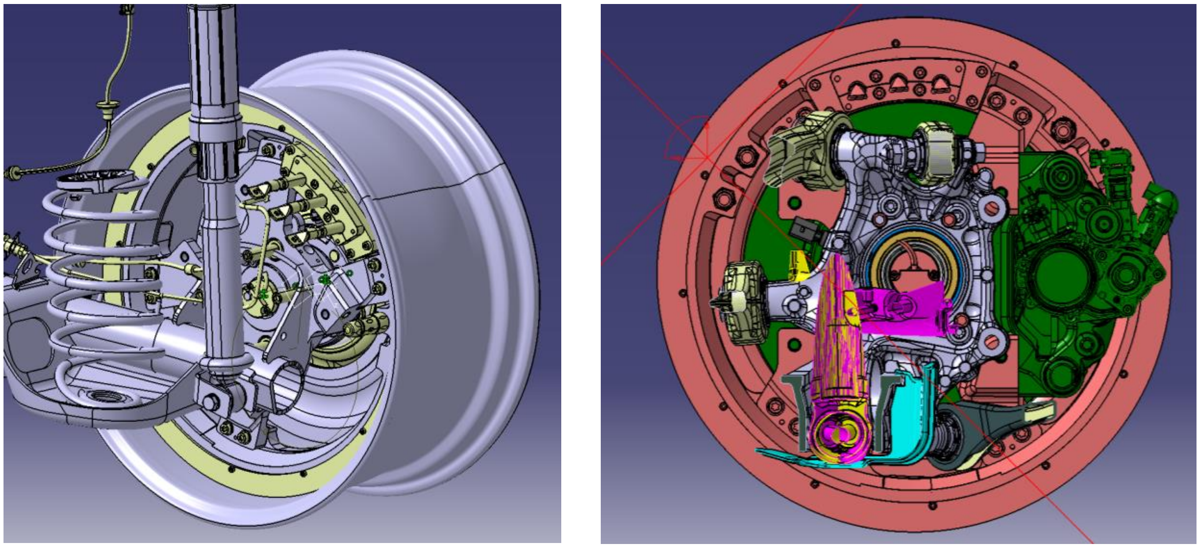


Figure 8: Left: Motor positioning to the JAC vehicle torsion beam suspension. Right: Motor integration on the Audi demonstration vehicle rear corner.

3.3.1 Electromagnetic compatibility (EMC)

The Elaphe L-type standard in-wheel system including off-the-shelf Elaphe inverters and PCU (control unit) was tested for EMC according to ECE Regulation No. 10, Revision 5. The system will be referred to as DUT (device under test).

The following tests were performed:

- Radiated emission (broad and narrow-band) for electronic subassembly (ESA);
- Immunity to bulk current injection (BCI);
- Immunity to radio-frequency electromagnetic fields.

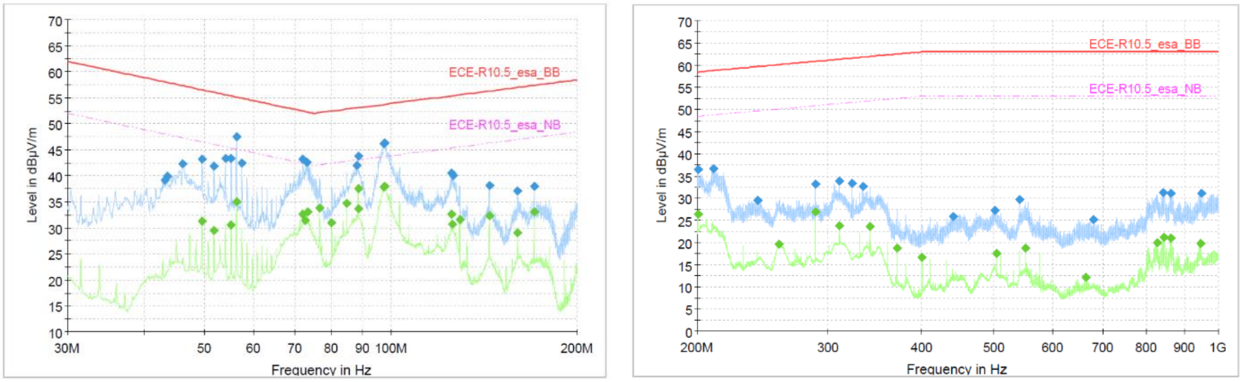


Figure 9: The images show the radiated power of the L-type powertrain (L1500 motor, H300 inverter, PCU)

The blue line in Figure 9 represents max. peak measurements, the green line represents average measurements. Upper red allowable limit corresponds to the limitation for max. peak values, the lower pink line to the limitation for average values.

The device under test (DUT) passed all tests (Certificate: C251-0007/18; notified body: SIQ). Radiated emission test result examples are given in charts above.

Length of the wiring harness will also influence the EM emissions. For both Audi and JAC demonstrators the position if the eWD² was chosen to be on the rear axle between the motors (see Figure 10). In this configuration the wiring is the shortest. Best practices of the standard L1500 system integration on vehicles will be used also on the EVC1000 vehicles.

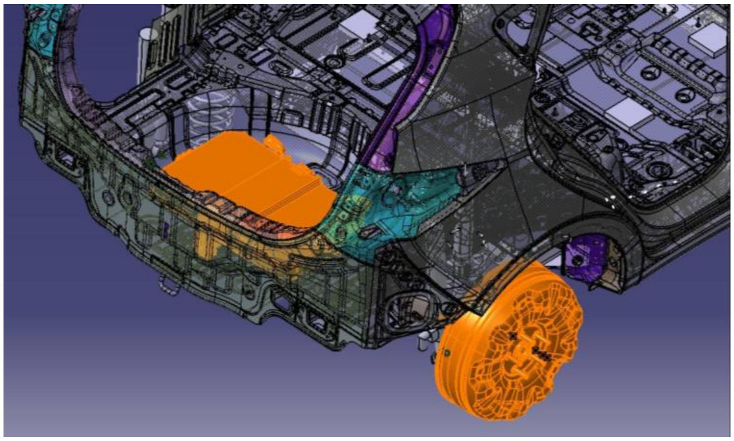


Figure 10: Positioning of the in-wheel motor and the eWD² within the JAC vehicle.

3.4 Optimization of motor electromagnetic part

Within motor design, electromagnetic part of the motor is developed through an extensive optimization process, which is focused to deliver efficient and high torque direct drive, with minimal mass and volume footprint within the wheel integration space.

In the first step electromagnetic design is optimized through genetic algorithms based on semi-analytical approach, which enable extensive number of motor design evaluations and rapid convergence of motor design to within few percent of final performance. Within this phase not only electromagnetic but also NVH, including airborne noise, and thermal motor characteristics are taken into consideration. Also coupling to inverter for system wide performance is accounted for.

In the second step, performance of promising designs from the first step is confirmed by more extensive numerical simulations, also fine tuning of the models is done within this phase.

In the final step the selected design is fully characterised by detailed numerical simulations. Also coupling to mechanical models for detailed NVH, thermal and structural analysis is performed.

Within this project several design modifications are evaluated for maximum drive efficiency, also taking into the consideration new generation of high frequency SiC inverters. We have assessed possibilities of several design adaptations to maximize to powertrain efficiency while also retaining or even improving other motor characteristics. These include evaluation of new generation of windings, especially in terms of reducing high frequency losses. New materials, manufacturing procedures and geometry optimizations for magnets and bladestack were evaluated.

Motor design with new materials and technologies in combination with high frequency inverters offer space for improvement over current propulsion systems.

Motor designs exploiting high frequency inverter, show possibility of significant system efficiency increase to current designs in WLTP cycle evaluations. These evaluations are based on 350V, 450A inverter with 40kHz switching frequency, and usage of new component materials and technologies, for which manufacturability is currently still being under evaluation.

Motor design based on these assumptions is expected to reach maximum motor efficiencies up to 94% with motor WLTP cycle energy drainage (including available regeneration) below 4 kWh, based on estimated mechanical energy of 4.9 kWh needed for the Audi E-tron WLTP cycle.

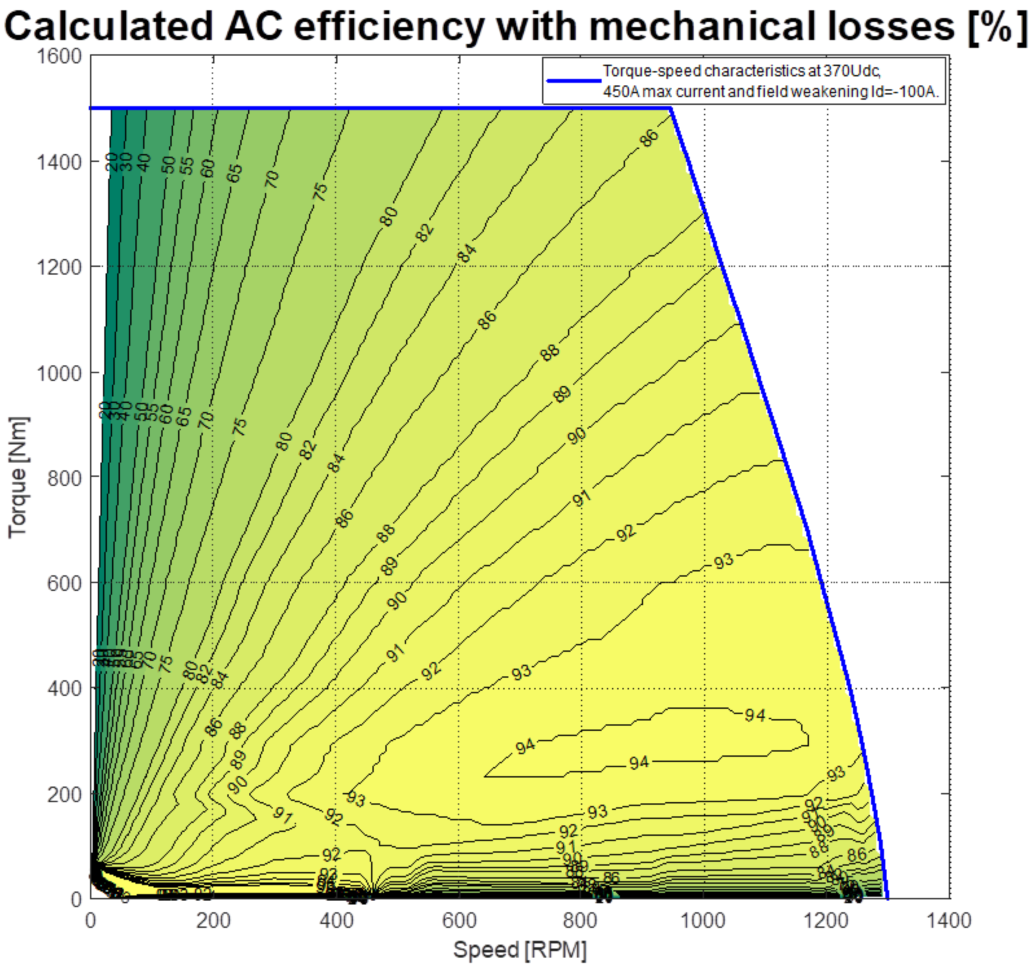


Figure 11: Motor design for EVC1000. Blue line is the motor natural characteristics with field weakening.

The expected performance of the demonstration vehicle equipped with two L-type in-wheel motor is listed in Table 5 below. Referring to Table 3 on page 13 we can see that the demonstration vehicles will be able to meet the OEM expectations. In Table 5 we also list expected performance in case of integration of four L-type motors for reference.

	AUDI e-tron		JAC iEVS7	
	2 x L-type	4 x L-type	2 x L-type	4 x L-type
Maximum speed [km/h]	165	165	165	165
Accelerate time from 0 to 30 km/h [s]	3,4	2	2,5	1
Accelerate time from 0 to 100 km/h [s]	11	5,5	7	3,3

Table 5: Maximum speed and expected acceleration of demonstration vehicles.

4 The DIDIMO dual inverter

4.1 The name

DIDIMO is the acronym for **D**ual **I**nverter **D**eveloped at **I**deas & **MO**tion.

DIDIMO is an Italian male name deriving from Greek, *didymos* (*δίδυμος*), meaning twin.

DIDIMO internal architecture, based on two equivalent inverters, make both origins perfectly fitting the device.

4.2 Product description

DIDIMO is a dual inverter developed by Ideas & Motion aimed at integrating functionalities available on two separate inverters into a single unit. Integrating two inverters in the same box helps in sharing hardware resources, facilitating also software development and system control.

The idea is to target those applications where a pair of inverters is required and the two devices need to communicate to synchronize their activity (e.g., in-wheel motors; engine and turbo compound electrification; benches for driveline testing; six-phase motors...).

DIDIMO has a symmetric structure and the two parts composing it are equivalent: this helps optimizing size and room thanks to the sharing of some hardware components. Moreover coordination of the two motors is much easier than having two separate inverters, making this device more suitable for applications where reaction time between the two electric machines is important and safety has to be taken into account.

Total achievable power is 300kW (peak for 10s). Wide-bandgap power devices will be evaluated to provide high efficiency, a crucial point for e-mobility requirements. Its control unit is shared between the two inverters and it is able to coordinate the two electric machines connected with a high time resolution.

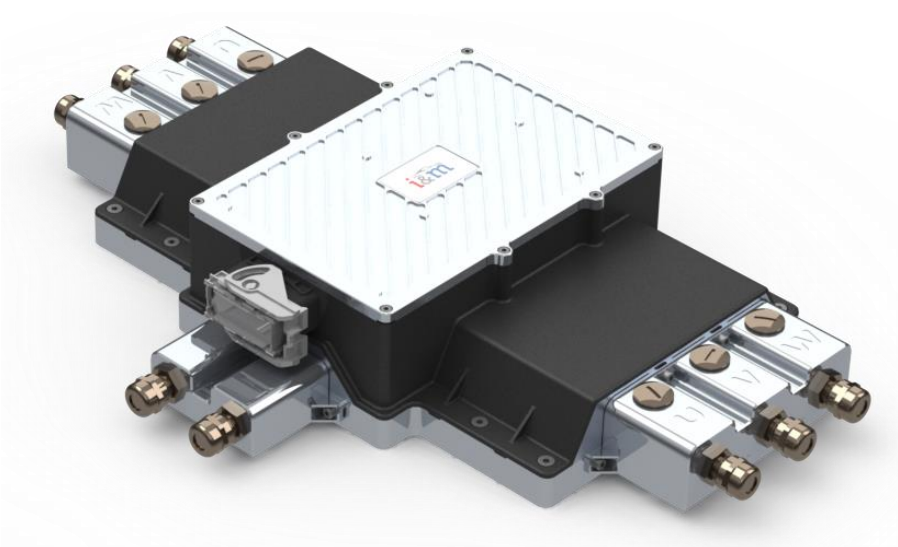


Figure 12: DIDIMO 3D model.

4.3 System architecture

The main target applications of DIDIMO dual inverter are Electric Vehicles (EV), but it may be adopted as well in Hybrid Electric Vehicle (HEV) or in Plug-in Hybrid Electric Vehicle (PHEV).

The drive and management of the two in-wheels motors of an electrified axle has very strict requirements in terms of safety. Indeed a failure might cause an abrupt change of torque delivered by a single wheel or, in the worst case, a change of its direction. This could lead to a momentum on the yaw angle of the vehicle, making the vehicle instable and hard be controlled for the driver. To overcome similar situation I&M developed the idea of a dual inverter.

A high-level block diagram of the DIDIMO dual inverter is shown in Figure 13. It is composed of:

- Two separate three-phase full bridges, able to deliver the requested power, each of them is fully independent.
- Two separate gate-driver boards, to convert logic signals into commands suitable for driving the full bridges. These boards are playing a crucial role for inverter control, since they carry on circuitry for the reading of motor important physical parameters (i.e., AC voltages and currents).
- A control board, able to command and coordinate the two separate power stages, to read all sensors required for motor control, and to communicate with the external environment. In particular, DIDIMO is able to acquire the rotor angular position by means of different types of position sensors, as well as to drive the 3 motor phases.

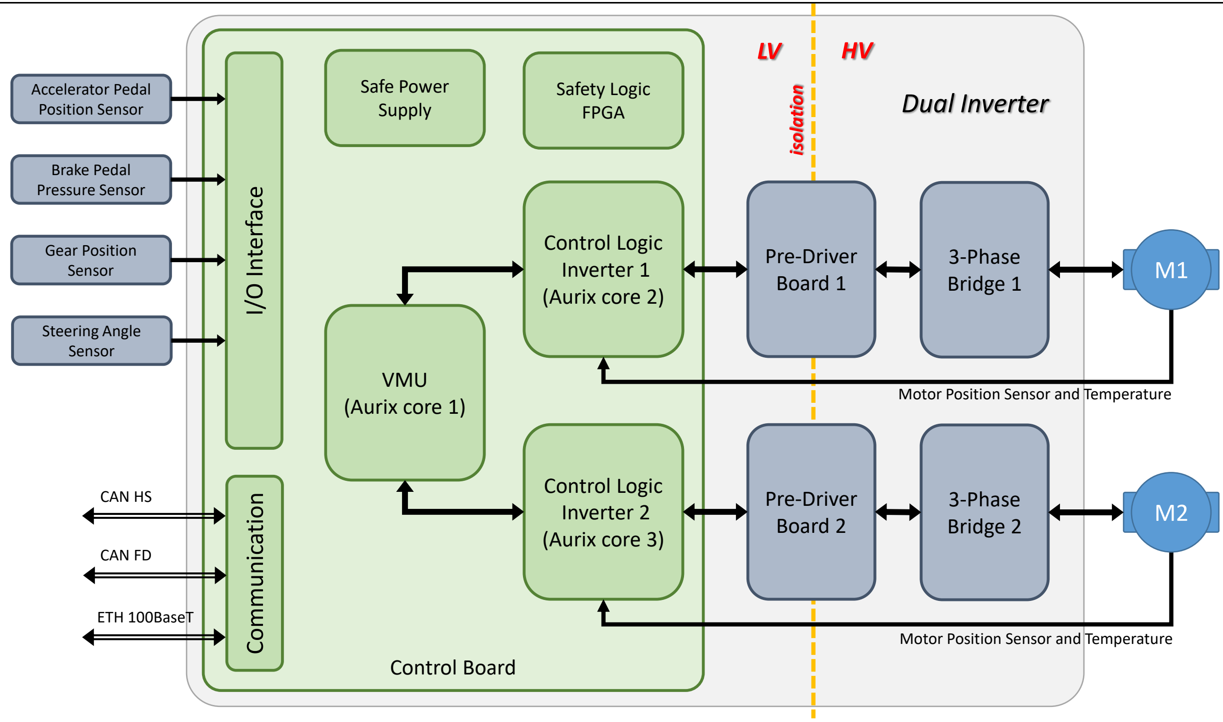


Figure 13: High-level block diagram of the eWD².

Thanks to its architecture, DIDIMO is also capable of performing vehicle management unit (VMU) functionality, acquiring different sensors providing inputs from the driver (such as key and start/stop management, accelerator pedal, brake pedal, steering angle, drive mode selection).

4.3.1 Three-phase bridges

The three-phase bridge is one of the crucial parts of an inverter:

- It is exposed to high voltage during operation;
- it handles the current required by the loads;
- it generates most of the inverter losses, hence it has to be designed with good thermal properties.

Both demo cars used in EVC1000 project will be equipped with a 400V battery. The power expected for this application requires the bridge to withstand to high currents (up to 400 A, peak).

Due to the current and the voltage range, both silicon and silicon-carbide devices are under investigation. Indeed, even if SiC MOSFET are generally more efficient, silicon IGBT could be more suited for high current operation (Figure 15 and Figure 15). The main objective of EVC1000 project is to realize the most efficient inverter, given operating voltage, load currents, switching frequency, and environmental conditions. For this reason our design targets both technologies and enables the possibility to choose the best solution after the characterization of real inverter losses.

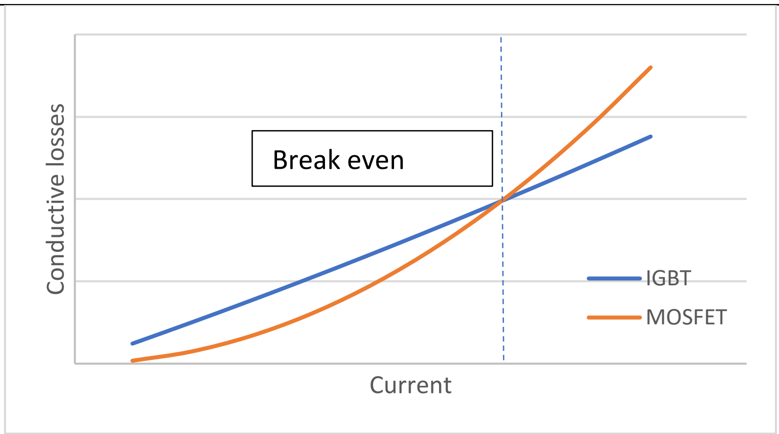


Figure 14: Comparisons of IGBTs and MOSFETs conduction losses with respect to current. Break-even point is highly dependent on chosen devices, on switching strategy, and operating conditions.

The evaluated power modules are fully qualified for automotive application, but chosen among commercial-off-the-shelf products available on the market. DIDIMO is equipped with Hybrid-Pack-Drive compatible power modules (Figure 16), as it is a package widely used by many PM manufacturers. This allows the inverter to be updated easily in case of new power devices being presented on the market, without needing to redesign completely mechanic and hydraulic sub-systems.

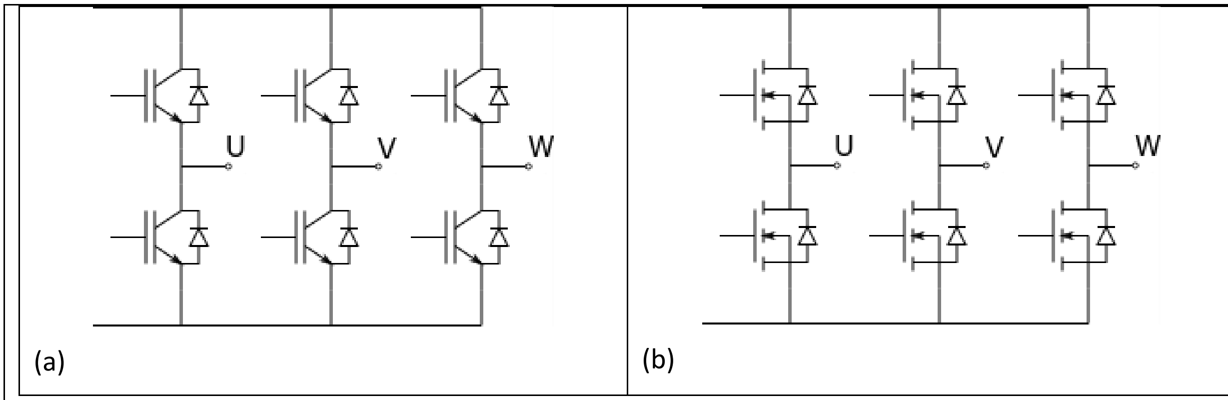


Figure 15: An IGBT-based three-phase bridge (a) and a MOSFET-based one (b). Which one will be used on DIDIMO will be decided after efficiency considerations.

The evaluated silicon carbide chips are from well-known manufacturers, designed to operate at 1200 V and able to withstand up to 550 A. This might be a non-optimal choice with respect to inverter efficiency (losses are proportional to breakdown voltage). Indeed several manufacturers are announcing chips with lower breakdown voltage (i.e., 600 and 900 V), but at present there is no viable solution in the package chosen. For this reason maintaining mechanical compatibility with different manufacturers was preferred, in order to have the possibility to change power modules in case new devices with lower breakdown level will be available.

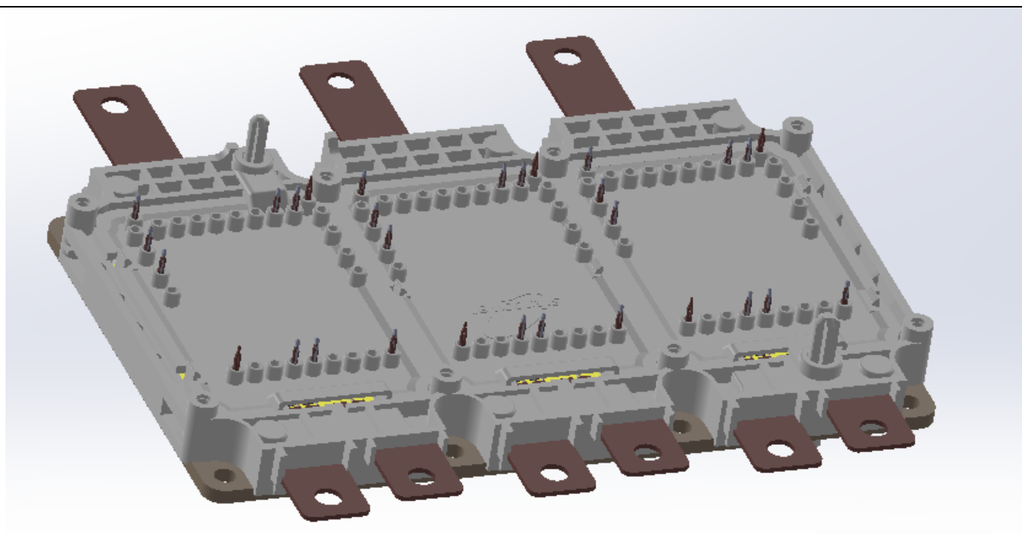


Figure 16: Power module package compatible with HybridPack Drive.

4.3.2 Gate-driver board architecture

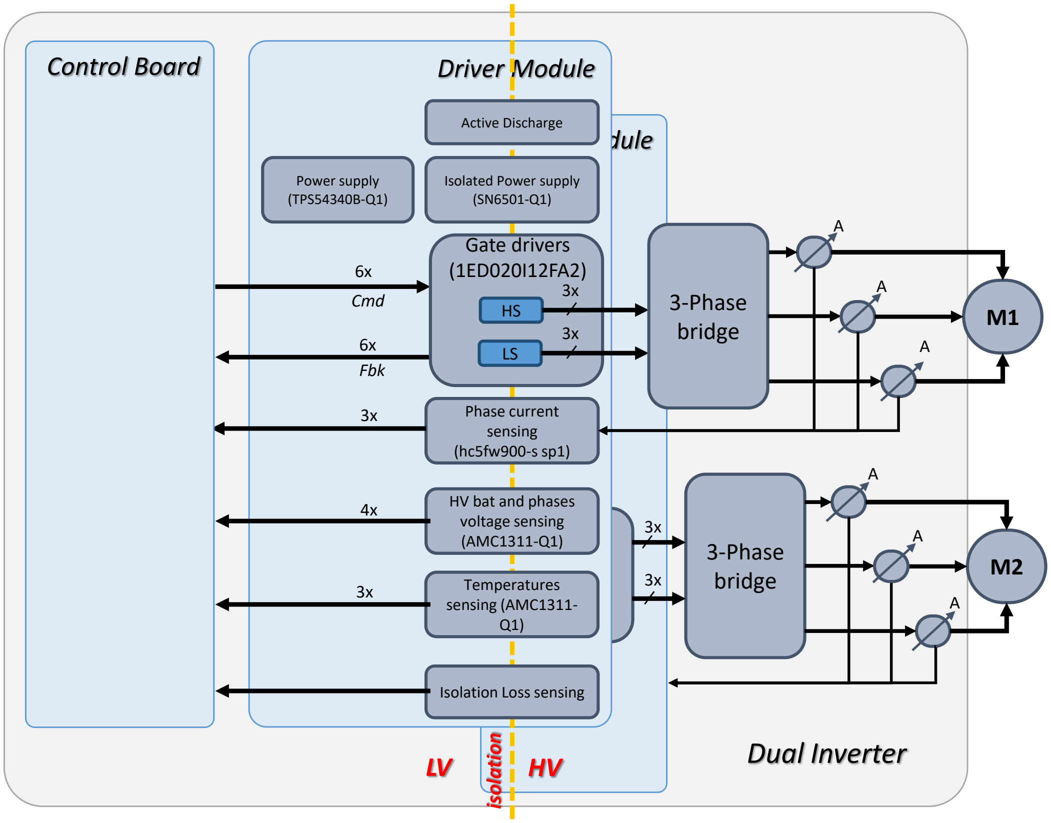


Figure 17: Gate-Driver Board Block Diagram

The gate-driver board (GDB) contains the electronic circuitry that is able to drive the three-phase bridge in the best way to guarantee both high efficiency and high reliability. To allow the three-phase bridge to switch at high switching frequency (i.e., > 30kHz) the GDB will contain high power gate drivers characterized by high current and high slew-rate. Since the board is placed between high voltage (the three-phase bridge) and low voltage systems (control board), the GDB will implement galvanic insulation to guarantee safety for the rest of the system. In addition, this board will generate high losses and hence it will have to dissipate a lot of heat. Air and liquid cooling will be considered for guaranteeing the board the proper environment. This board is also enrolled of reading AC and DC voltages for motor control purpose.

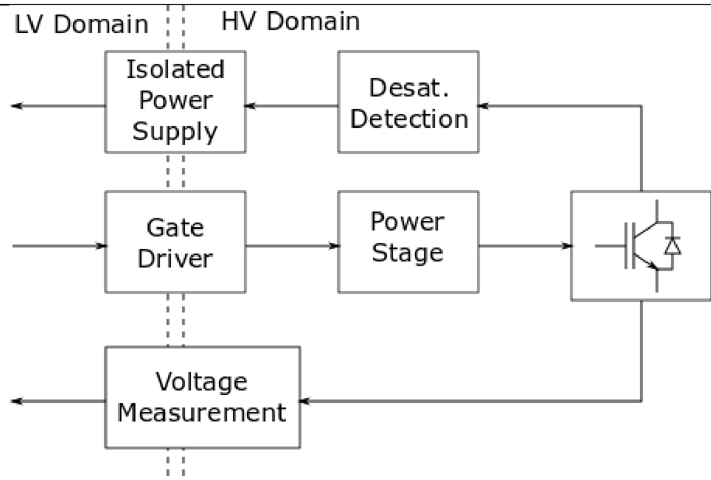


Figure 18: Block diagram for gate-driver board used on DIDIMO.

4.3.2.1 Gate driver

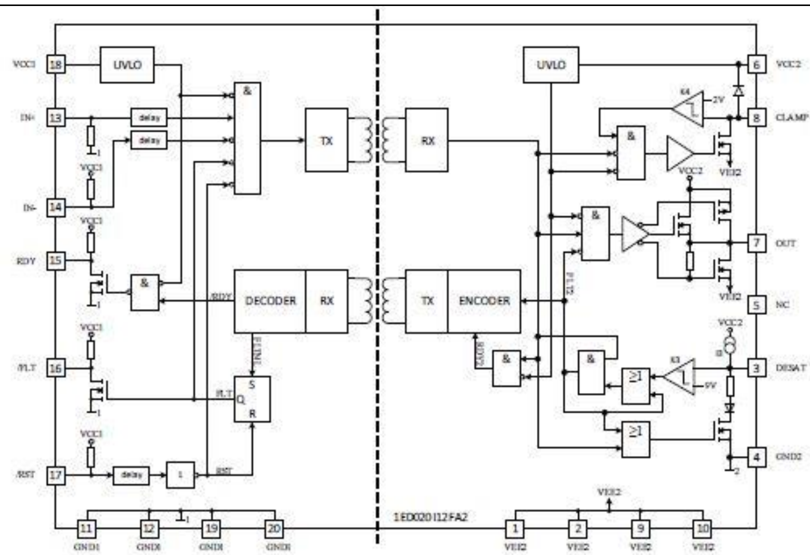


Figure 19: 1ED020I12FA2 DS Block Diagram

The IFX 1ED020I12FA2 DS device is an advanced isolated IGBT gate driver with state-of-art protection features and can be also used for driving power MOS devices. The device can support up 1200V SiC MOSFETs and IGBTs, targeting larger than 10kW applications such as HEV/EV traction inverter, motor drive, on-board and off-board battery charger, solar inverter etc. The galvanic isolation is realized by the integrated Coreless Transformer Technology, which can realize a reliable reinforced isolation between the low voltage DSP/MCU and high voltage side. The device can support up to 1.420 kV as a maximum repetitive insulation voltage. The minimum 50V/ns CMTI guarantees the reliability of the strong drive strength. The small propagation delay and part-to-part skew can minimize the dead time setting, so the conduction loss can be reduced. The device includes extensive protection and monitor features to increase the reliability and robustness of the MOSFET and IGBT based systems. The 12V output side power supply UVLO is suitable for switches with gate voltage ≥ 15V. The active miller clamp feature prevents the false turn on causing by miller capacitance. The device has IGBT desaturation protection and fault reporting function to the low voltage side. All digital pins are 5V CMOS compatible and could be directly connected to a microcontroller pins, the PWM signal can be fed directly to DSP/MCU or through a low-pass-filter as an analogue signal.

Each Gate Driver device has its own power supply and is capable to feed an overall voltage between gate and source of the power switch equal to 20V (up to 16V for turn-on phase and up to -4.5V for the turn-off phase).

An external booster circuit is required at the driver output. A complementary pair of transistors is used to amplify the driver ICs current. This allows driving IGBTs and MOSFET that need more current than the driver IC can deliver. The NPN transistor is used for switching the power switch on and the PNP transistor for switching the power switching off.

4.3.2.2 Isolated power supply

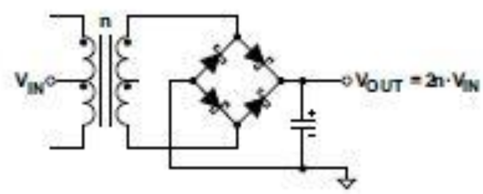


Figure 20: Isolated power supply topology

The SN6501-Q1 is a push-pull driver for transformers with centre taps to transfer power from the primary to the secondary. The SN6501-Q1 consists of an oscillator that feeds a gate drive circuit. The gate drive provides two complementary output signals that alternately turn the two output transistors on and off. The output frequency of the oscillator is divided down by an asynchronous divider that provides two complementary output signals with a 50% duty cycle. A dead time is required to avoid shorting out both ends of the primary.

When the LS switch conducts, it creates a ground path for lower primary end of the centre tap, the supply drives a current through the lower half of the primary to ground. Current flowing in the primary winding of transformer will create a magnetic flux which will cut the secondary winding. The secondary current flows through diodes, and charges the capacitor. A similar scenario takes place when HS is ON, resulting in the current flowing in opposite diode. Based on the turns ratio and frequency of the SN6501-Q1, unregulated power is transferred across the isolation barrier.

4.3.2.3 Voltage measurements

The voltage measurement is realized by mean of the isolation amplifier AMC1311-Q1 of TI. The AMC1311-Q1 is a precision, isolated amplifier with an output separated from the input circuitry by an isolation barrier that is highly resistant to magnetic interference. Used in conjunction with an isolated power supplies, this isolated amplifier separates parts of the system that operate on different common-mode voltage levels and protects lower-voltage parts from damage.

4.3.3 Control board architecture

DIDIMO features a modular and scalable architecture in order to cover a wide range of different applications such as:

- Control two in-wheel motors in a fully decoupled way (e.g. three phases with one driver and power module and three phases with another driver and power module).
- Control a single six-phases electric motor (i.e., synchronizing the two three-phase bridges with the control board).

The selected architecture enables a coherent drive of the two in-wheel motors, to implement an enhanced driving experience and prevent any safety issue even in case of faults.

The Control Board, in the 12V supply domain, is based on a high performance Infineon AURIX Plus multi-core microcontroller. Its power supply is provided by an Infineon TLF35584 System Base Chips (SBC), supplying both the microcontroller and the external sensors.

Two of the AURIX Plus cores are dedicated to motor control, performing both PWM command generation and acquisition of motor signals (phase-current/voltage, fault information).

The third AURIX Plus core implements a Vehicle Management Unit (VMU), acquiring all inputs from the driver (such as accelerator pedal, brake pedal, steering angle, drive mode selection) and coordinating the two motors adopting a torque vectoring strategies. Since the management of the two in-wheel motors and the vehicle dynamics reside in different cores of the same microcontroller, a very close interaction between the various modules can be achieved, enabling the implementation of complex torque vectoring strategies and a very fast and coordinated reaction to failures.

The VMU manages vehicle communication as well. DIDIMO integrates a redundant internal inertial platform (3-axis accelerometer plus 3-axis gyroscope), which will allow the safe integration of advanced vehicle dynamic functions.

A detailed block diagram of the control board is shown in Figure 21.

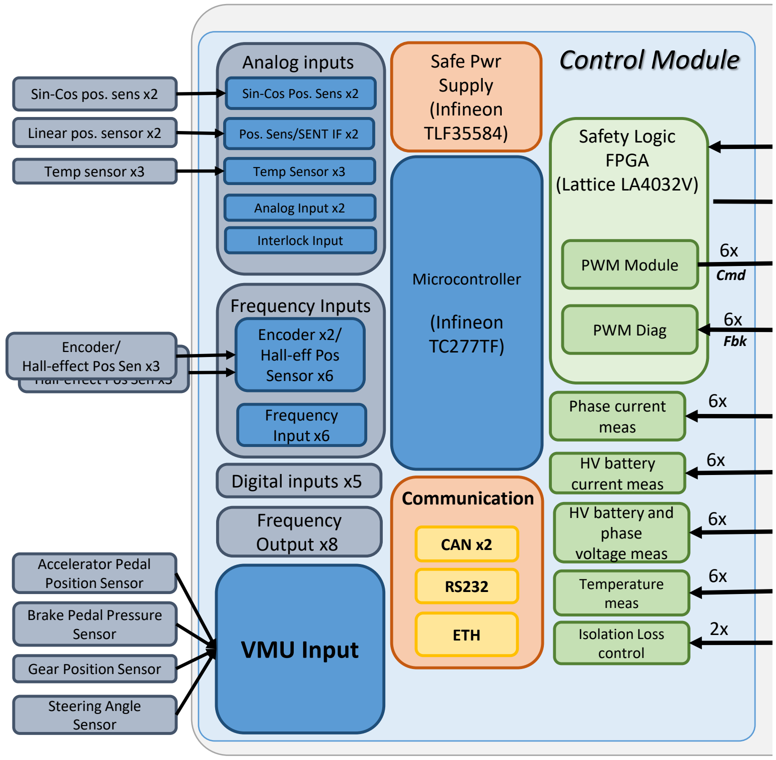


Figure 21: Detailed Dual Inverter block diagram.

4.4 Dual inverter functions

The main functions of DIDIMO are summarized below:

- A dual 3-phase motor controller, able to drive two PMSM, BLDC or induction motors;
- Continuous input power in excess of 75kW per motor (150kW per motor for 10s)
- High efficiency
- Four quadrant motor control - forward or backward with regeneration;
- SVM current control to minimize the torque ripple, vibrations and noise of the motors;
- SVM control feasible with inexpensive Hall-effect position;
- Trapezoidal motor current control;
- Support for several types of rotor angular position sensors (e.g. encoder, Hall-effect, analogue sin/cos, analogue with linear output,);
- Phase current and voltage sensing;
- DC-link capacitor voltage sensing;
- Internal temperature sensing in critical points;
- Motor temperature sensing and protection;
- Full diagnosis and protection from external short circuits of the 3-Phase Bridge outputs
- Over-current, over-voltage, under-voltage, over-temperature protection
- Motor stall protection
- Dedicated digital outputs, one of which features a diode in series for reverse battery polarity protection, for external relay command;

- Dedicated peak & hold output to drive the contactor and pre-charge relay of the HV battery (in case which they are not correctly managed by the BMS);
- Support of vehicle management functions (VMU), including key and start/stop management, multiple interfaces with different accelerator pedal sensors, brake pedal sensors, gear position sensors and steering angle sensor;
- Integrated redundant inertial platform (6 axis);
- 5V supply output for external sensors;
- Two CAN line for communications, one of which supporting CAN-FD protocol, the second one features high voltage isolation;
- 100-BaseT Ethernet Interface;
- High voltage interlock function;
- High voltage insulation check.

4.5 Electrical specification

4.5.1 Three-phase bridge specification

DIDIMO is composed of two equivalent inverters. Table 6 details HV characteristics of the three-phase bridge of any of them.

Parameter	Value	Unit
Maximum peak phase current (10s), RMS	400	A
Continuous phase current, RMS	200	A
Input DC link voltage range	350÷450	V
Maximum peak output power (10s)	150	kW
Continuous output power	75	kW
Switching frequency	50	kHz

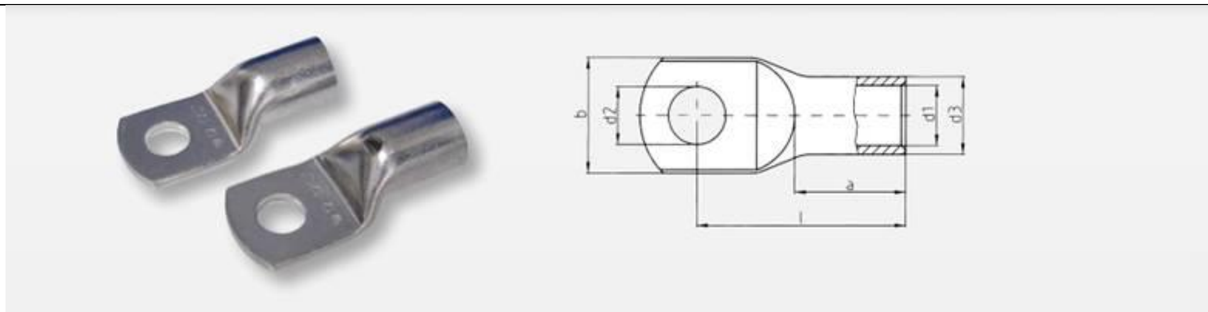
Table 6: Power stage electrical characteristics.

Power devices used will be either standard silicon or newer silicon-carbide devices, depending on results obtained on system efficiency.

The 3-Phase power stage integrates a DC-link capacitor bank for reducing harmonic current on battery supply line. The 3-Phase Bridge and the DC-link capacitors are cooled by means of a liquid cooled heatsink.

4.5.1.1 Connectors

DIDIMO will be equipped for AC and DC connections with screw terminals suitable for properly connecting 35-mm^2-wide lugs through M6 bolt/nut pairs (see Figure 222).



cross section mm^2	flat hole M	art.-no. without inspecting hole	dimensions in mm d1	d3	d2	b	l	a	weight 100 pcs./kg	packing unit (pcs.)	art.-no. with inspecting hole
35	6	16220	8,5	12	6,4	17	33	17	2,07	100	15241

Figure 22: Characteristics for WEITKOWITZ Cable Lug 35-6 EURO.

Safety of these connections will be empowered by interlock functionality.

Cable size has been decided to be compatible with the one requested by in-wheel motors we target [1]. Cables might be shielded or not depending on EMC requirements and qualification requested.

4.5.1.2 Pinout

Pin.	Pin Name	Interface	Description
DC+	Positive Voltage	DC	Positive terminal for DC bus
DC-	Negative Voltage	DC	Negative terminal for DC bus
LU	Left U	AC (Left)	Left Inverter, Phase U terminal for motor drive
LV	Left V	AC (Left)	Left Inverter, Phase V terminal for motor drive
LW	Left W	AC (Left)	Left Inverter, Phase W terminal for motor drive
RU	Right U	AC (Right)	Right Inverter, Phase U terminal for motor drive
RV	Right V	AC (Right)	Right Inverter, Phase V terminal for motor drive
RW	Right W	AC (Right)	Right Inverter, Phase W terminal for motor drive

Table 7: Logic pinout for HV-domain connector.

4.5.2 12V-Domain specification

4.5.2.1 Connector

DIDIMO uses a standard automotive 64-ways connector, FCI F015300, for all interconnections in the 12V domain, both to the vehicle and the motor sensors. Figure 23 shows a picture of this connector.

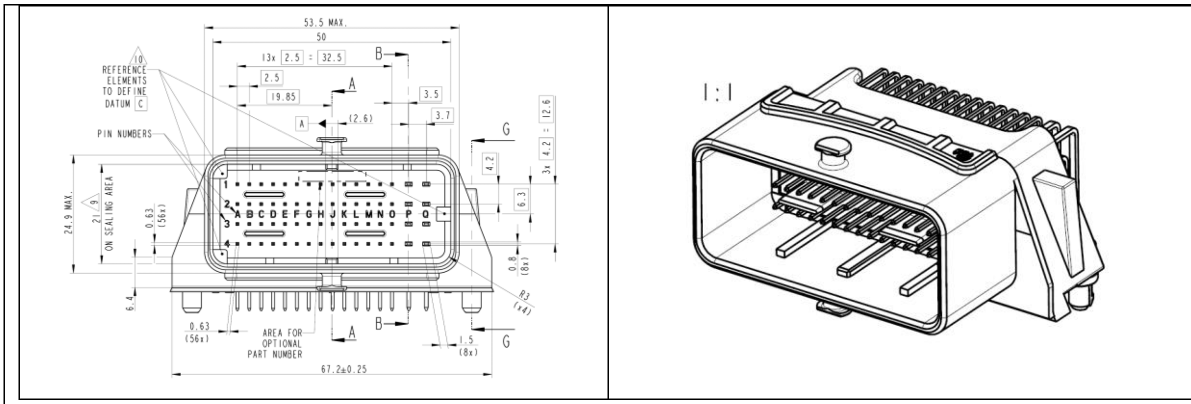


Figure 23: FCI F015300 connector header (64-ways).

4.5.2.2 Pinout

DIDIMO's 12V connector pinout is described in Table 8. Pins are grouped by interface type, i.e., either Motor Position Sensor IF, or Vehicle IF, or Communication IF.

Pin no	Pin Name	Interfaces	Description
1A	cmdRelay1_OD	Vehicle IF	HS Relay driver + feedback
2A	cmdRelay0_OD	Vehicle IF	LS Relay driver (LV battery)
3A	CANisoL_BC	Communication IF	Isolated High Speed CAN bus (Terminate) - L Line
4A	GND_iso	Communication IF	Isolated CAN Ground
1B	CAN-H_BC	Communication IF	High Speed CAN bus (Terminate) - H Line
2B	SpareLS_OF	-	Spare Digital/Frequency LS output
3B	-	-	-
4B	CANisoH_BC	Communication IF	Isolated High Speed CAN bus (Terminate) - H Line
1C	SSIData2N-PosSensB-EncB2_IF	Motor Position Sensor IF	digital on/off Hall sensors (block commutation): B
			digital incremental encoder with single-ended output: B
			digital absolute position sensor (Hall/encoder): PWM signal
			SSI Interface: Data channel - L Line
2C	CAN-L_BC	Vehicle IF	High Speed CAN bus (Terminate) - L Line

3C	GearPosSens1_IF-ID	Vehicle IF	Gear/Driving lever position sensor: PWM input
			Gear/Driving lever position switch: forward/reverse gear
4C	-	-	-
1D	cmdCoolPumpHs_OPH	Vehicle IF	Coolant pump Relay Half-Bridge driver - HS Switch
2D	IntLock_IA	Vehicle IF	Interlock analog input
3D	SSIClk2N_OF-DigitalSpare2_IF	-	Spare Digital/Frequency input 1
		Motor Position Sensor IF	SSI Interface: Clock channel - L Line
4D	AccPedPos1_IA-IF-ID	Vehicle IF	Accelerator pedal position: potentiometer track
			Accelerator pedal position: PWM input
			Accelerator pedal switch: (throttle switch or boost switch)
1E	cmdRelay2Ls_OPH	Vehicle IF	LS Peak and Hold Driver 3 (HV battery Contactor)
2E	SSIData2P-PosSensA-EncA2_IF	Motor Position Sensor IF	digital on/off Hall sensors (block commutation): A
			digital incremental encoder with single-ended output: A
			digital absolute position sensor (Hall/encoder): PWM signal
			SSI Interface: Data channel - H Line
3E	IntLock_OD	Vehicle IF	Interlock Digital output
4E	SSIClk2P_OF-DigitalSpare1_IF	-	Spare Digital/Frequency input 2
		Motor Position Sensor IF	SSI Interface: Clock channel - H Line
1F	cmdCoolPumpLs_OPH	Vehicle IF	Coolant pump Relay Half-Bridge driver - LS Switch
2F	SSIData1N-PosSensC-EncIdx2_IF	Motor Position Sensor IF	digital on/off Hall sensors (block commutation): C
			digital incremental encoder with single-ended output: Index
			digital absolute position sensor (Hall/encoder): PWM signal
			SSI Interface: Data channel - L Line
3F	AccPedPosSw_ID	Vehicle IF	Accelerator pedal switch: (throttle switch or boost switch)
4F	StartSw_ID	Vehicle IF	Start/stop switch
1G	cmdRelay2Hs_OPH	Vehicle IF	HS Peak and Hold Driver 3 (HV battery Contactor)

2G	SSIData1P-PosSensC-EncIdx1_IF	Motor Position Sensor IF	digital on/off Hall sensors (block commutation): C
			digital incremental encoder with single-ended output: Index
			digital absolute position sensor (Hall/encoder): PWM signal
			SSI Interface: Data channel - H Line
3G	*_EmgStopSw_ID*	*Vehicle IF*	*Emergency Stop Switch (development only)*
4G	BrakePedSw_ID	Vehicle IF	Brake pedal switch
1H	SSIClk1P_OF-PosSensA-EncA1_IF	Motor Position Sensor IF	digital on/off Hall sensors (block commutation): A
			digital incremental encoder with single-ended output: A
			digital absolute position sensor (Hall/encoder): PWM signal
			SSI Interface: Clock channel - H Line
2H	SSIClk1N_OF-PosSensB-EncB1_IF	Motor Position Sensor IF	digital on/off Hall sensors (block commutation): B
			digital incremental encoder with single-ended output: B
			digital absolute position sensor (Hall/encoder): PWM signal
			SSI Interface: Clock channel - L Line
3H	*Rs232Rx_IC*	*Communication IF*	*Rs232 Rx input (development only)*
4H	*Rs232Tx_OC*	*Communication IF*	*Rs232 Tx output (development only)*
1J	GearPosSens0_IA-ID	Vehicle IF	Gear/Driving lever position sensor: Analog input
			Gear/Driving lever position switch: forward/reverse gear
2J	AccPedPos0_IA-IC-ID	Vehicle IF	Accelerator pedal position: potentiometer track
			Accelerator pedal position: SENT interface
			Accelerator pedal switch: (throttle switch or boost switch)
3J	Sens1_IC-IA	Motor Position Sensor IF	analog absolute position sensor (Hall/encoder): linear analog signal
			absolute position sensor: SENT interface
			analog absolute position sensor (Hall/encoder): sin/cos single-ended signals
4J	KeySw_BS	Vehicle IF	Battery power supply via Key Switch

1K	PosSensCosP1_IA	Motor Position Sensor IF	analog absolute sin/cos position sensor: Cos P-line
2K	BrakePedPres_IA-ID	Vehicle IF	Brake pedal pressure: analog input
			Redundant brake pedal switch
3K	SteeringSens_IA	Vehicle IF	Steering Angle Sensor
4K	PosSensCosP2_IA	Motor Position Sensor IF	analog absolute sin/cos position sensor: Cos P-line
1L	cmdRelay1Hs_OPH	Vehicle IF	HS Peak and Hold Driver 2 (HV battery Contactor)
2L	PosSensCosN1_IA	Motor Position Sensor IF	analog absolute sin/cos position sensor: Cos N-line
3L	PosSensCosN2_IA	Motor Position Sensor IF	analog absolute sin/cos position sensor: Cos N-line
4L	PosSensSinN1_IA	Motor Position Sensor IF	analog absolute sin/cos position sensor: Sin N-line
1M	cmdRelay0Ls_OPH	Vehicle IF	LS Peak and Hold Driver 1 (HV battery Contactor)
2M	PosSensSinN2_IA	Motor Position Sensor IF	analog absolute sin/cos position sensor: Sin N-line
3M	PosSensSinP1_IA	Motor Position Sensor IF	analog absolute sin/cos position sensor: Sin P-line
4M	Temp2_IA	Vehicle IF	Temperature sensor 2
1N	cmdRelay1Ls_OPH	Vehicle IF	LS Peak and Hold Driver 2 (HV battery Contactor)
2N	PosSensSinP2_IA	Motor Position Sensor IF	analog absolute sin/cos position sensor: Sin P-line
3N	Temp1_IA	Vehicle IF	Temperature sensor 1
4N	Sens2_IC-IA	Motor Position Sensor IF	analog absolute position sensor (Hall/encoder): linear analog signal
			absolute position sensor: SENT interface
			analog absolute position sensor (Hall/encoder): sin/cos single-ended signals
1O	cmdRelay0Hs_OPH	Vehicle IF	HS Peak and Hold Driver 1 (HV battery Contactor)
2O	Temp3_IA	Vehicle IF	Temperature sensor 3
3O	Analog1_IA	-	Spare Analog input 1
4O	Analog0_IA	-	Spare Analog input 0
1P	SensGnd2_SG	Vehicle IF	Sensor ground 2
2P	SensSply2_SS	Vehicle IF	Sensor supply 2
3P	DGND	Vehicle IF	Battery power supply ground
4P	DGND	Vehicle IF	Battery power supply ground

1Q	SensGnd1_SG	Vehicle IF	Sensor ground 1
2Q	SensSply1_SS	Vehicle IF	Sensor supply 1
3Q	DirPwrSply_BS	Vehicle IF	Direct LV battery supply
4Q	EmgPwrSply_BS	Vehicle IF	Backup LV battery supply

Table 8: Logic pinout for 12V-domain connector.

4.5.3 Operating voltage

Battery voltage requirements of a standard 12V automotive application have been targeted, to take into account both hybrid and electric vehicles. Following sections are detailing nominal voltages for both 12V-domain and HV-connectors

4.5.3.1 Nominal battery low voltage: 12V system

- Operating battery voltage range (full performance): $9V \leq V_{BATT} \leq 16V$;
- Limited performances: $6V \leq V_{BATT} < 9V$;
- Overvoltage (broken alternator): $16V < V_{BATT} \leq 18V$, 1 hour max operation;
- Start jump: $V_{BATT} \leq 24V$, 2min operation @ ambient temperature.

4.5.3.2 Nominal traction battery voltage: HV system

- Operating battery voltage range (full performance): $350V \leq V_{BATT} \leq 450V$;
- Limited performances : $300V \leq V_{BATT} < 500V$;
- Voltage range: $250V < V_{BATT} \leq 550V$.

4.6 Environmental conditions

4.6.1 Operating temperature range

- Minimum ECU ambient temperature: -40°C;
- Maximum operating ECU heatsink temperature[1]: 75°C;
- Maximum operating ECU air ambient temperature[2]: 105°C;
- Maximum operating ECU internal temperature[3]: 125°C;
- Average operating ECU air ambient temperature during lifetime: 65°C.

Please, note that DIDIMO's heatsink can be liquid or air-cooled. In the first case, the nominal operating parameters above can be easily granted by a proper design of the cooling circuit, while in the second case the heatsink temperature may vary according to air speed and temperature. Proper functionality may be achieved only in case the heatsink is cooled by a proper flow of fresh air from the external of the vehicle.

[1] In case of both air cooling and liquid cooling.

[2] In case of hybrid vehicle, liquid cooling required.

[3] Air temperature inside the housing.

4.6.2 Vibration

DIDIMO housing system is designed to withstand mechanical shocks and vibration for a chassis installation, according to, ISO 16750-3 [2], Test IV — Passenger car, sprung masses (vehicle body). Figure 2422 and Table 9 detail PSD shape and values for this test.

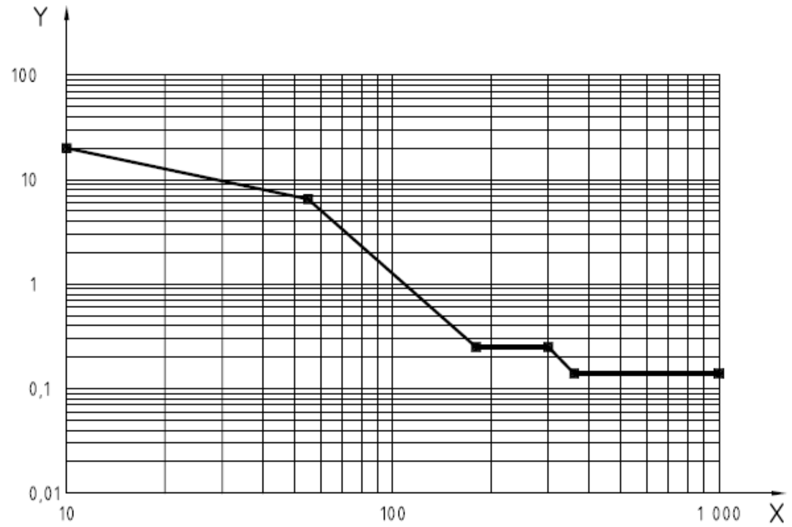


Figure 24: Power spectral density (PSD) requested by ISO 16750-3.

Frequency, Hz	PSD, $(m/s^2)^2/Hz$
10	20
55	6.5
180	0.25
300	0.25
360	0.14
1000	0.14

Table 9: Values for frequency and power spectral density.

4.7 Mechanical specification

4.7.1 Dimensions

DIDIMO mechanical housing is show in Figure 25. The two power sections are included in a custom mix aluminium/plastic housing where we can install connectors, hoses, and junctions.

For weight saving, a plastic cover will be considered; to improve EMC, we might consider the application of metallic painting or specific shielding.

The mechanical housing has the following characteristics:

- Weight: ~10 kg (Cad estimation);
- Physical dimensions max (L x W x H): 530 x 330 x 90 mm;
- Dust protection: IP6K;
- Water protection: IP9K.

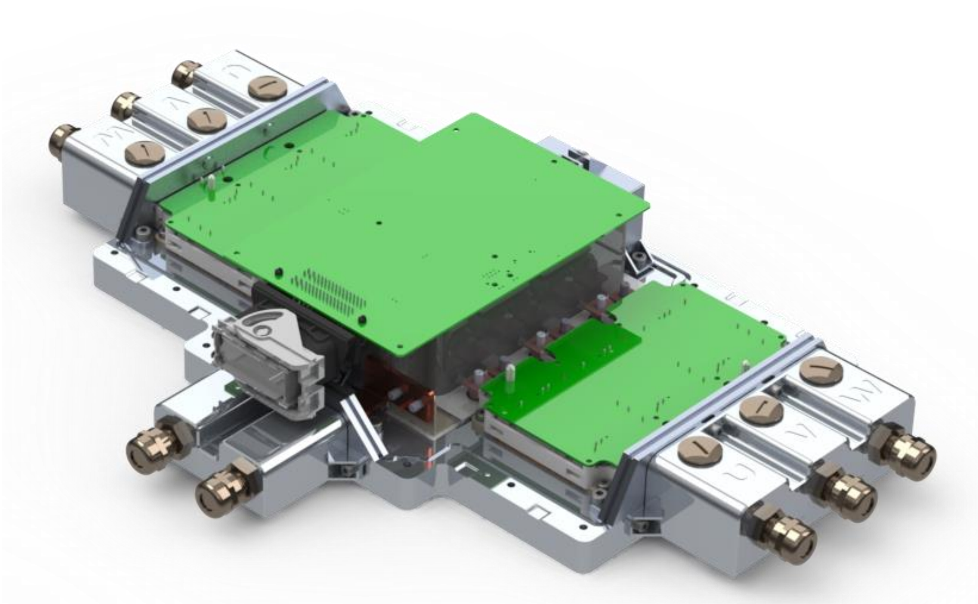


Figure 25: DIDIMO's mechanical housing.

4.7.2 Cooling system

DIDIMO is liquid cooled. The liquid will be water in solution with glycol (max 50%). The unit has two water hoses, one inlet and one outlet. Hose fitting are not defined yet: they can be adapted in accordance with partners. Some refinement are ongoing on the liquid plate itself too in order to match cooling performances with allowed pressure drop.

4.7.3 System Integration and Mechanical Fixing

External shape and thus physical dimensions of the eWD² housing have been defined taking into account mounting constraints of the unit on the vehicles. As often happens in electric axle systems, both EVC1000 donor cars will have eWD² in between the motors, at the centre of the rear axle.

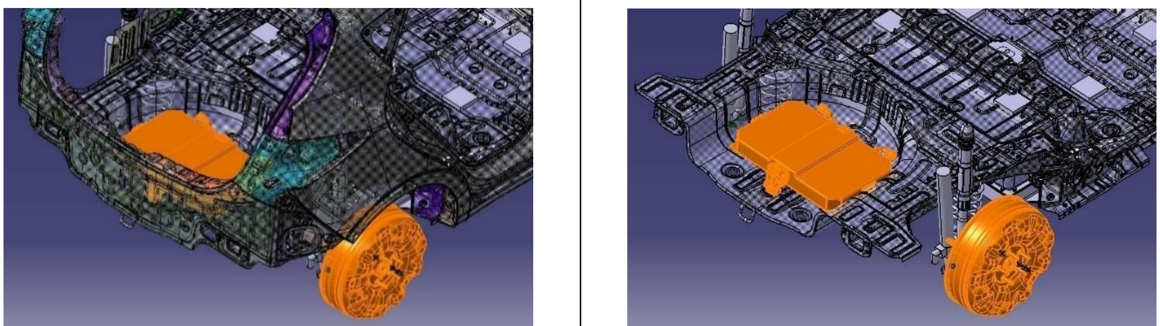


Figure 26 - DIDIMO integration on JAC vehicle

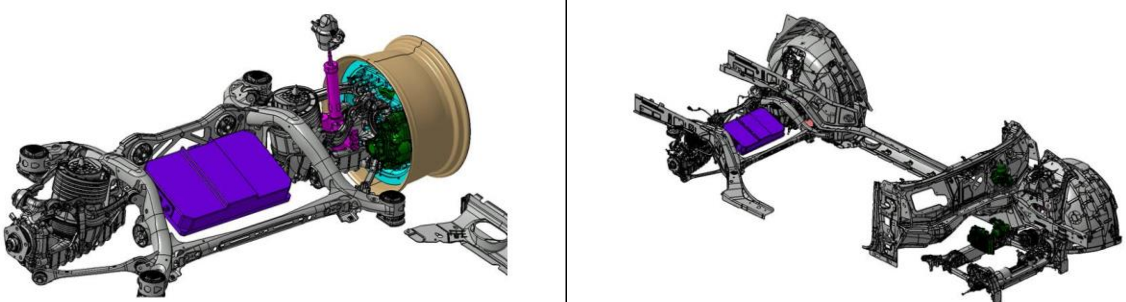


Figure 27 - DIDIMO integration on AUDI vehicle

As shown in Figure 26 and Figure 27, the eWD² housing has been designed as flat as possible in order to have a smaller impact on trunk volume. Mechanical fixing points are not defined yet: specific brackets for each vehicle are under evaluation.

4.8 Tests for DIDIMO dual inverter

This chapter describes the tests required to characterize DIDIMO dual inverter and verify its behaviour is conformal to expectances. Each section recalls the aim of the test and lists some requirements, either technical or logistical, to perform the test properly. These tests will be carried out as preliminary steps of D3.3 which is related to the verification and validation of subcomponents at test-beds.

4.8.1 Switching characterization

4.8.1.1 Aims of the test

Switching characterization is the first test to be performed on a new power stage. It aims at understanding switching behaviour of the power devices in the real environment and allows the designers to estimate several important parameters of the power modules, as stray parameters and energy lost during commutations.

4.8.1.2 Requirements

This activity is based on double-pulse test (DPT) [3], a standard de facto in power electronics for this kind of characterizations. The idea is to monitor current and voltage at each power device terminals when switched on and off. This operation is repeated for several current and voltage values, in order to build a map that describes power switches behaviour in all operating conditions.

DPT can be done in a standard electronic lab with oscilloscopes and power suppliers.

4.8.2 Thermal characterization

4.8.2.1 Aims of the test

Characterizing thermal interface of the power modules is necessary to make the inverter always operate in the correct temperature range, independently of the load.

4.8.2.2 Requirements

The activity aims to map thermal behaviour of power modules at different loads (i.e., currents) and at different cooling conditions (i.e., varying flow rates and varying temperature).

This characterization will be made in a standard electronic lab, monitoring temperature increase on specific points of the unit with temperature sensors and thermal cameras. Thermal impedance of the power modules will be derived by repeating this mapping at different conditions.

4.8.3 Functional testing

4.8.3.1 Aims of the test

Functional testing is required to guarantee correct operation of the inverter, when exposed to different torque requests.

4.8.3.2 Requirements

The test verifies the ability of the inverter to deliver the appropriate torque level by driving a static load, hence it can be done in an electronic lab, without special requirements. The test is repeated at different DC voltages and torque levels, to check inverter behaviour in these conditions.

The test can be integrated by another session performed at a dynamic bench, where the inverter drives an electric motor used as a variable load. To perform this test we need a bench equipped with a wheel-motor and another electric motor used as variable load for the system. This second part of the test is optional and can be substituted by a test on board of the target vehicle.

4.8.4 Communication check

4.8.4.1 Aims of the test

The inverter is an electronic control unit (ECU) integrated with other ECUs in the same vehicle. Correct communication among the units is crucial to avoid malfunctioning.

4.8.4.2 Requirements

This test is composed of two parts: The first one is performed on a bench with the inverter alone and a PC aimed at emulating use case we will have on the vehicle. The second one will be performed interfacing the other ECUs and verifying the communication is correctly handled in case of realistic inputs. The second part could require specific hardware emulator circuits to emulate inputs coming from a standard vehicle.

Each actor on the network has to share with other partners the communication protocol.

4.8.5 Inverter endurance

4.8.5.1 Aims of the test

This test is to guarantee the inverter is able to operate for the whole amount of hours requested by the application.

4.8.5.2 Requirements

The test has to be accelerated to be completed in a reasonable amount of time. To accelerate the test we can either reduce cooling capabilities of the system, or increase electric loads; in both cases, we are forcing the inverter to operate at more severe conditions.

To perform a realistic test, we request a mission profile for the inverter; more specifically, we need usage, external temperature, and cooling profiles.

This test can be performed in an electronic lab.

4.8.6 Inverter efficiency

4.8.6.1 Aims of the test

The inverter converts DC power into AC power and vice versa. Each power conversion cannot operate without a certain amount of losses in the system. Mapping inverter efficiency is intended to find how the efficiency varies depending on operating conditions.

4.8.6.2 Requirements

The inverter has an efficiency that changes depending on the operating point given by AC current, DC voltage, and electric speed. We have to map its efficiency varying these conditions. An initial test can be done in an electronic lab, using a stator as load, but to be more precise we have to use a bench where motor is connected to a mechanical load/driver able to simulate realistic usage conditions. (Mainly the dyno bench is requested to make the electric motor generating a realistic back EMF, hence moving working point for the inverter.)

This mapping activity is necessary to provide the global power conversion efficiency. For a specific case the global efficiency results from the weighted mean between usage and efficiency at the given operating conditions.

4.8.7 EMC test

4.8.7.1 Aims of the test

Characterization of the inverter for emissivity and susceptibility to electro-magnetic fields. This activity has a characterization purpose only; we do not target the tests for a qualification.

4.8.7.2 Requirements

These tests require an EMC laboratory with an anechoic room and specific equipment to stimulate disturbances. To test the inverter when switching the laboratory has to be equipped with high voltage supplier and a cooling system for controlling temperature.

Test are normed in CISPR-25 international rule [4].

5 Functional safety analysis

1.0 Conventions

In this document, for the requirements definition, the following specific semantics is used.

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as:

SHALL: This word means that the definition is an absolute requirement of the specification.

SHALL NOT: This phrase means that the definition is an absolute prohibition of the specification.

MUST: This word means that the definition is an absolute requirement of the specification due to legal issues.

MUST NOT: This phrase means that the definition is an absolute prohibition of the specification due to legal or end-customer standard constraints.

SHOULD: This word, or the adjective "RECOMMENDED", mean that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighed before choosing a different course.

SHOULD NOT: This phrase, or the phrase "NOT RECOMMENDED" mean that there may exist valid reasons in particular circumstances when the particular Behaviour is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any Behaviour described with this label.

MAY: This word, or the adjective "OPTIONAL", means that an item is truly optional. The implementation must be compatible or prepared to accept or interface with the optional item (i.e. for optional components the hardware shall be prepared to be populated with such components).

5.1 Definition of the system

As shown on Figure 1 and Figure 4, the in-wheel propulsion system, marked as item, consists of in-wheel motors, position sensors and eWD². Quantity of these elements in a system depends on 2-wheel or 4-wheel drive configuration. All related elements inside and outside item's boundary are summarized on Table 10. A short description is also provided.

Element ID	Description	Comment
IWM	In-wheel electric motor is integrated in two or four wheels.	
INV	The eWD² drives the electric motors. Depends on the motor quadrant operations, It provides power from the battery to the motors, or vice versa during regenerative breaking.	
BATT	Battery powers electric vehicle and stores energy.	Outside item boundary
PSEN	The sensor measures motor angular position.	
BMS	Battery management system.	Outside item boundary
VMU	Vehicle control unit processes driver requests and sends powertrain related information to the eWD², such as key start, accelerator and/or brake pedal position, selected driving direction etc. The VMU functions are integrated in the dual-inverter unit (INV). In this document, we will consider the VMU as a separated item.	Outside item boundary

Table 10 – Elements in the context of in-wheel propulsion system.

All elements that are outside the item boundary are connected to the eWD². The list of external interfaces is provided in Table 10.

5.2 Assumptions

It is assumed that direct drive synchronous in-wheel electric motors (IWM) are used, where torque and speed are the same as the motor shaft and the wheel. Synchronous operation of the motors is achieved by the dual-inverter (eWD²) with the help of position sensors (PSEN), which are integrated in the motors. It is also assumed that the eWD² has two 3-phase bridges to drive independently the two electric motors of the same e-axle. It can switch to the regenerative braking mode for additional deceleration when brake pedal is pressed and for providing drag torque when both accelerator and brake pedals are released. Mechanical brakes are integrated into electric motors; however, this braking system is independent and is not part of the propulsion system in terms of functionality.

The VMU, integrated in the eWD² unit, is able to process the driver inputs (Start/Stop switch, the direction of movement selector, position of accelerator and brake pedals, steering angle). In case the vehicle is equipped with ABS and ESP, the VMU must work in close cooperation with those units.

The battery management system (BMS) gives information about the charge and discharge currents that are available. These currents limit the maximum traction and regeneration torque. The inertial measurement unit (IMU) provides linear acceleration and gyroscope information for torque vectoring control.

Assumption ID	Description
ASSM-1	Permanent magnet synchronous (PMSM) in-wheel motors are integrated in the wheels.
ASSM-2	Dedicated position sensor measures the angle between the stator and rotor of the electric motor.
ASSM-3	The eWD² drives each motor of the same e-axle independently (no transmission, differential...).
ASSM-4	Activation/Deactivation of powertrain is enabled by the system.
ASSM-5	Powertrain Activation/Deactivation request is provided by an external interface.
ASSM-6	BATT and BMS are outside item boundary.
ASSM-7	Mechanical brakes are integrated inside the electric motors and are not directly controlled by the in-wheel propulsion system.
ASSM-8	Regenerative braking is activated to provide drag torque and additional braking force in addition to the mechanical brake.
ASSM-9	ABS is outside item boundary but shall provide a signal when it is engaged/disengaged.
ASSM-10	Cooling of powertrain is monitored by the system.
ASSM-11	Regenerative braking torque is lower than the braking regulations for passenger cars.
ASSM-12	BMS provides maximum discharge and charge battery currents.
ASSM-13	External deactivation of the powertrain shall turn off the propulsion system.
ASSM-14	The speed position sensor is integrated in the in-wheel motor.

Table 11: Item assumption

5.3 Requirements of in-wheel propulsion system

5.3.1 Functional requirements

The key vehicle level functions of the in-wheel propulsion system are shown in Table 12. The listed functions may all be affected by malfunctioning of the item, and thus must be kept in mind while considering possible hazards.

Function ID	Vehicle level system function	Inputs	Outputs	Comment
F1	Provide powertrain start/stop operation	Powertrain start/stop request	Activation/Deactivation of powertrain	This information can be obtained from key start or from external vehicle ECU.
F2	Provide requested drive torque	Requested traction torque	Total requested drive torque	Total torque request is also limited by the battery discharge current and vehicle dynamic control.
F3	Provide braking torque (regenerative)	Requested braking torque	Total braking torque	Total torque request is also limited by the battery charge current and vehicle dynamic control.

Table 12: Item functions

5.3.2 Hazard and operability study

In the HAZard and OPerability study, the system is examined and evaluated in order to identify the possible issues in the design.

ID	Function	Incorrect Function Activation				Unintended Function Activation	Output Stuck at a Value (Failure of function to update as intended)
		Loss of Function	More than Requested	Less than Requested	Opposite direction than Requested		
F1	**Provide powertrain start/stop operation**						
F1-1	Activate powertrain	Loss of powertrain activation				Unintended powertrain activation	
F1-2	Deactivate powertrain	Loss of powertrain deactivation				Unintended powertrain deactivation	
F2	**Provide requested drive torque**						
F2-1	Provide requested drive torque	No torque	Excessive drive torque	Reduced drive torque	Wrong torque direction	Unintended drive torque	Drive torque stuck at a value
F3	**Provide braking torque (regenerative)**						
F3-1	Provide regenerative braking torque	No braking torque	Excessive braking torque	Reduced braking torque	Traction torque applied	Unintended braking torque	Braking torque stuck at a value

Table 13: HAZOP

5.4 Functional safety

5.4.1 Hazard and risk analysis (HARA)

The Hazard Analysis and Risk Assessment is a procedure to identify the potential hazards that the item may cause in case of malfunctioning. Each hazard is associated with an operational situation about the vehicle (e.g. driving on a highway, suddenly braking, driving in snowy conditions etc.): associating the operational situation with the malfunctioning of the item will provide the hazardous situation. This must be analysed, assessing the ASIL (Automotive Safety Integrity Level) by determining the Severity (S) of the possible consequences, the Exposure (E) that indicates the probability of being in the mentioned situation, and the Controllability (C) of the vehicle in said scenario. Table 14 illustrates the determination of the corresponding ASIL.

		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

Table 14: ASIL determination

In the following table, the HARA of the item is shown. As it can be seen, the table is divided in different sections that correspond to the sections in the HAZOP table.

ID	Function	Malfunctioning Behaviour(s)	Vehicle Level Hazard	Hazard Detailed Description	Potential accident scenario(s)- considering worst case mishap potential	ASIL Assessment							Comments or Considerations (if applicable)	Causes
						S	Rationale	E	Rationale	C	Rationale	ASIL		
H1	Activation/deactivation of powertrain													
H1-1	Provide Torque Requests to driving wheels	Loss of Torque Request to one or more wheels	Unintended vehicle lateral motion / Unintended yaw	Driving on secondary road with a speed of >50 km/h. Oncoming traffic present. Torque is lost on one or more wheels, leading to torque distribution imbalance, causing vehicle to depart intended path.	Frontal collision with roadside objects or oncoming traffic	S2 to S3	dV likely to be in the range of 50-90 km/h for this kind of roads. Or even higher in case of frontal collision with oncoming traffic. Table B-1 in SAE Recommended Practice is used for severity estimation	E4	Table B.2 in ISO 26262-3:2011 is used for class of probability of exposure estimation. This kind of roads present >10 % of average operating time	C2	Systems like Torque vectoring and ESC can reduce this effect. Weaker torque imbalances can be corrected by the steering wheel and by releasing accelerator pedal, which is intuitive reaction (C2)	B to C	ASIL is strongly vehicle and system property dependent	Power Switches control HW fault. Power Switch HW fault.
H2	Provide requested drive torque													
H2-1	Provide requested drive torque	Excessive drive torque	Unintended acceleration (without destabilization)	The actual torque is higher than the requested torque by the driver.	Frontal collision with oncoming traffic	S2 to S3	Most likely to be in the range of 50-90 km/h for this kind of roads. Or even higher in case of frontal collision with oncoming traffic. Table B-1 in SAE Recommended Practice is used for severity estimation	E4	Table B.2 in ISO 26262-3:2011 is used for class of probability of exposure estimation. This kind of roads present >10 % of average operating time	C2	Excess of torque can be managed by releasing accelerator pedal and engaging brake pedal, which is intuitive reaction.	B to C		Power Switches control HW fault. Power Switch HW fault.
H2-2	Provide requested drive torque	Reduced drive torque	Unintended deceleration (without destabilization)	The actual torque is lower than requested by the driver and the fault has the influence on both e-axle motors.	Rear collision	S2 to S3	Most likely to be in the range of 50-90 km/h for this kind of roads. Or even higher in case of frontal collision with oncoming traffic. Table B-1 in SAE Recommended Practice is used for severity estimation	E4	Table B.2 in ISO 26262-3:2011 is used for class of probability of exposure estimation. This kind of roads present >10 % of average operating time	C2	Loss of torque can be managed by coasting the vehicle using the steering wheel, which is intuitive reaction	B to C		In case of DC bus fault (open circuit).
H2-3	Provide requested drive torque	Wrong drive torque (unbalanced)	Unintended vehicle lateral motion / Unintended yaw	e-axle motors torque are not balanced.	Frontal collision with oncoming traffic	S3	Most likely to be in the range of 50-90 km/h for this kind of roads. Or even higher in case of frontal collision with oncoming traffic. Table B-1 in SAE Recommended Practice is used for severity estimation	E4	Table B.2 in ISO 26262-3:2011 is used for class of probability of exposure estimation. This kind of roads present >10 % of average operating time	C3	The unintended yaw moment leads to unmanageable vehicle dynamic behaviour.	D		Power Switches control HW fault. Power Switch HW fault.
H3	Provide requested braking torque													

H3-1	Provide regenerative braking torque	Excessive regenerative braking torque	Unintended deceleration (without destabilization)	The actual braking torque is higher than requested by the driver and the fault has the influence on both e-axle motors.	Rear collision	S2 to S3	Most likely to be in the range of 50-90 km/h for this kind of roads. Or even higher in case of frontal collision with oncoming traffic. Table B-1 in SAE Recommended Practice is used for severity estimation	E4	Table B.2 in ISO 26262-3:2011 is used for class of probability of exposure estimation. This kind of roads present >10% of average operating time	C2	Excess of braking torque can be managed by coasting the vehicle using the steering wheel, which is intuitive reaction.	B to C		In case of DC bus fault (short circuit).
H3-2	Provide regenerative braking torque	Reduced regenerative braking torque	Unintended acceleration (without destabilization)	The actual braking torque is lower than requested by the driver and the fault has the influence on both e-axle motors.	Frontal collision with oncoming traffic	S2 to S3	Most likely to be in the range of 50-90 km/h for this kind of roads. Or even higher in case of frontal collision with oncoming traffic. Table B-1 in SAE Recommended Practice is used for severity estimation	E4	Table B.2 in ISO 26262-3:2011 is used for class of probability of exposure estimation. This kind of roads present >10% of average operating time	C2	Loss of braking torque can be managed by increasing brake force on pedal, which is intuitive reaction.	B to C		Power Switches control HW fault. Power Switch HW fault.
H3-3	Provide regenerative braking torque	Wrong brake torque (unbalanced)	Unintended vehicle lateral motion / Unintended yaw	e-axle motors brake torque are not balanced.	Frontal collision with oncoming traffic	S3	Most likely to be in the range of 50-90 km/h for this kind of roads. Or even higher in case of frontal collision with oncoming traffic. Table B-1 in SAE Recommended Practice is used for severity estimation	E4	Table B.2 in ISO 26262-3:2011 is used for class of probability of exposure estimation. This kind of roads present >10% of average operating time	C3	The unintended yaw moment leads to unmanageable vehicle dynamic behaviour.	D		Power Switches control HW fault. Power Switch HW fault

Table 7: HARA

5.4.2 Safety Goals

As a result of the HARA, the safety goals can be obtained. The safety goal is a top-level safety requirement that assess what are the effects of the malfunctioning that are unwanted.

ID	Hazard	Exceptions and Boundary conditions	ASIL rating	Safety Goal	Safe state	Fault tolerance time [ms]
SG-01	Unintended vehicle lateral motion/Unintended yaw	Yaw rate motion for vehicle speed lower than 30km/h are not assumed as critical.	ASIL D	The item shall prevent unintended vehicle lateral (yaw) motion	Balanced torque to both motors.	100

Table 7: Safety goals

5.5 Functional safety concept

The safety critical items are described in this chapter. For each item failure modes are analysed and at least one functional safety solution is proposed.

5.5.1 Phase current sensors

FSR - 01-01: The item shall verify the validity of the current sensor signals.

Phase currents are strictly related to motor torque: for a proper motor torque control an accurate phase currents measurement is essential. The Failure modes of current sensors are derived from ISO26262:

- Out of range (output of sensor goes out of range);
- Offset (output of sensor has a fixed offset in relation to the true value);
- Stuck in range (sensor output is stuck inside range);
- Oscillations (oscillations on sensor output).

Sum of three sensors – detect current asymmetry

In any three phase motor control the sum of phase currents should be close to zero, so two measurements are theoretically enough (third current computed as difference). Nonetheless, adopted solution is to use three current sensors – one current sensor for each phase. In this way, every phase current can be measured in two ways (directly and indirectly) and thus redundancy/voting 1oo2 (1 out of 2) is achieved. A single point of fault in any sensors or in the SUM circuit will be detected by the threshold monitor so the ASIL rating can be lower for them. The threshold monitor should have some kind of start-up check to verify the correct operation preventing any latent faults.

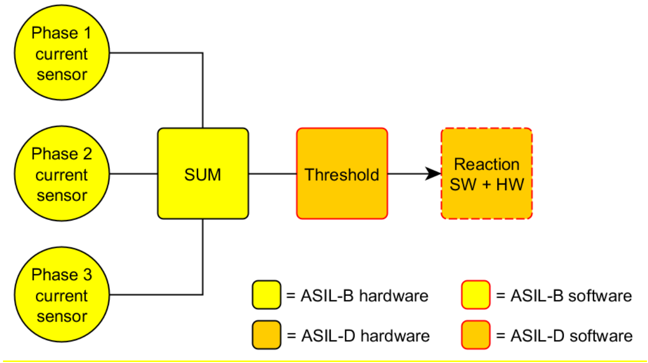


Diagram 1: Phase current sensors

***Note**: The proposed concept can **also detect some motor faults**, which can be classified as a violation to the relationship Ia + Ib + Ic = 0 (motor leakage to chassis, short to chassis ...), but this depends on the whole system.*

5.5.2 DC link capacitor

FSR - 01-02: The item shall be designed to manage faulty state of the DC link capacitor.

A DC link capacitor short circuit failure can cause a very high braking torque (same braking torque as for 3 phase motor short circuit!) on the motor and can result in additional damage on the battery, if the DC line isn't properly fused.

The Failure modes of the DC link capacitor are:

- Fail open (capacitor fails open, resulting in no capacitance in the circuit);
- Fail short (capacitor leads short together);
- Value change (capacitance change).

Fail-open technology

On EVC1000, both left and right-wheel motors of the axle are connected to the eWD². Both 3-Phase Bridges of DIDIMO are tied to the same DC link capacitor, so a failure on the DC link capacitor will result on the same braking torque on both sides. This will not cause vehicle yaw rate, but just a vehicle deceleration, so the requirement for the capacitor might be ASIL-C.

Given that, certain technologies are able to guarantee that the capacitor always fails in open circuit. eWD² EVC1000 is equipped with a film capacitor: that technology is able to fail safely.

5.5.3 Power switches

FSR - 01-03: The item shall detect any faulty condition at power switch level and disable gate driver.

If a fault occurs to a single power switch the whole functioning of the phase, and thus of the inverter, is compromised. This may lead to an unpredictable torque delivery on the connected motor.

Failure modes of the power transistor are as follows:

- Switch in open-circuit;
- Switch short.

Desaturation monitoring

Desaturation monitor works by monitoring the switch command versus voltage across the switching terminal. The desaturation monitoring is usually present as built-in function in more advanced gate drivers. An example of a basic desaturation detection circuit is given below (shown as outside of gate drivers). A gate driver will trigger a fault by some digital output and the reaction circuit can be implemented without the need of software intervention. However, the failure has to be relayed to other 3-phase bridge so they disable the power switches as well.

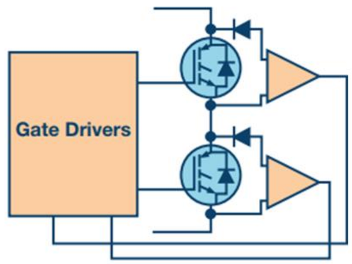


Diagram 2: Gate drivers desaturation concept

Desaturation monitor allows to detect and identify the fault. A suitable reaction, in order to achieve a safe condition, is to force all other working power switches to a state dependent on system boundaries. EVC1000 eWD² is able to ensure the same reaction on both motors.

5.5.4 Power switches control

FSR - 01-04: The item shall verify the validity of the PWM outputs.

Power switches control includes the gate drivers and connections to power switches, as well as the digital outputs of the microcontroller. Some faults in this circuit will behave in the same way as power switch faults and won't be additionally analysed in this chapter, since they are covered in 5.5.3.

Faults of the power switch control circuit are as follows:

- **Gate driver path break** (ex. gate resistor open failure – same as power transistor open fault);
- **Gate driver stuck-at active** (gate driver fails in active state – same as power transistor short fault);
- **Gate driver stuck-at idle** (gate driver fails in idle state – same as power transistor open fault);
- **Wrong PWM signal** (wrong frequency or duty cycle);
- **Gate driver supply failure** (insufficient gate driver supply voltage).

First three faults are already covered in chapter 5.5.3. The proposed safety mechanisms for the last two faults are given separately in the following sub-chapters.

Output signal monitoring (fault: wrong PWM outputs)

Wrong PWM output fault can happen either due to some hardware issue in the microcontroller PWM periphery, digital output periphery or a failure on board (line break).

Note: *"Gate driver path break" means a failure between the gate driver and the power transistor, while the fault described in this sub-chapter means a failure inside of microcontroller periphery or between the microcontroller and gate drivers.*

EVC1000 eWD², by monitoring the PWM outputs with a separate microcontroller periphery, can detect any mismatch between the requested and the measured digital outputs and will trigger an error taking the proper countermeasures on both motors.

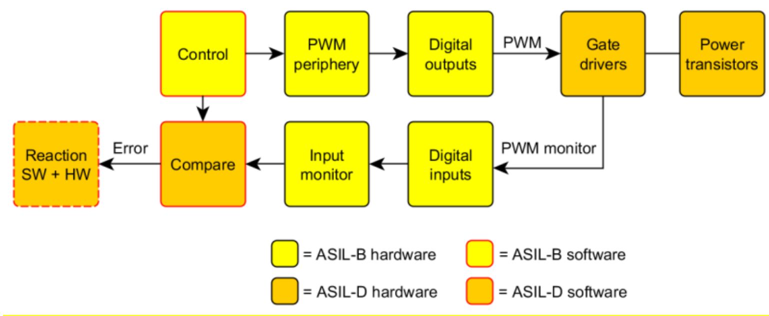


Diagram 3: PWM

Under voltage lock-out (fault: gate driver supply failure)

Low supply voltage on gate driver circuitry leads to unpredictable power switches behaviour and this results in unpredictable torque on the connected motor.

Most of gate drivers available on the market already include supply voltage monitoring, called UVLO (under voltage lock-out). EVC1000 eWD² driver board monitors the supply voltage and disables the driver output if the supply voltage falls below the threshold ensuring the same reaction on both motors.

Logic board general architecture

A hardware fault on the logic core of the main microcontroller or on any peripheral may result in unpredictable PWM command generation in terms of frequency and/or duty cycle. In this condition the torques applied to both motors are not predictable.

EVC1000 eWD² Control board relies on latest Infineon 32-bit TriCore™ AURIX™ family. The selected microcontroller paired with TLF power supply companion chip ensures an ASIL-D level performance. That means that in case the TLF built-in safe machine detects a fault in the monitoring mechanisms, the proper counter measures are taken in order to avoid the worst consequences. EVC1000 control board is equipped with a safety logic circuit, supplied by a separated source, able to override microcontroller outputs and to drive both motors to a safe condition.

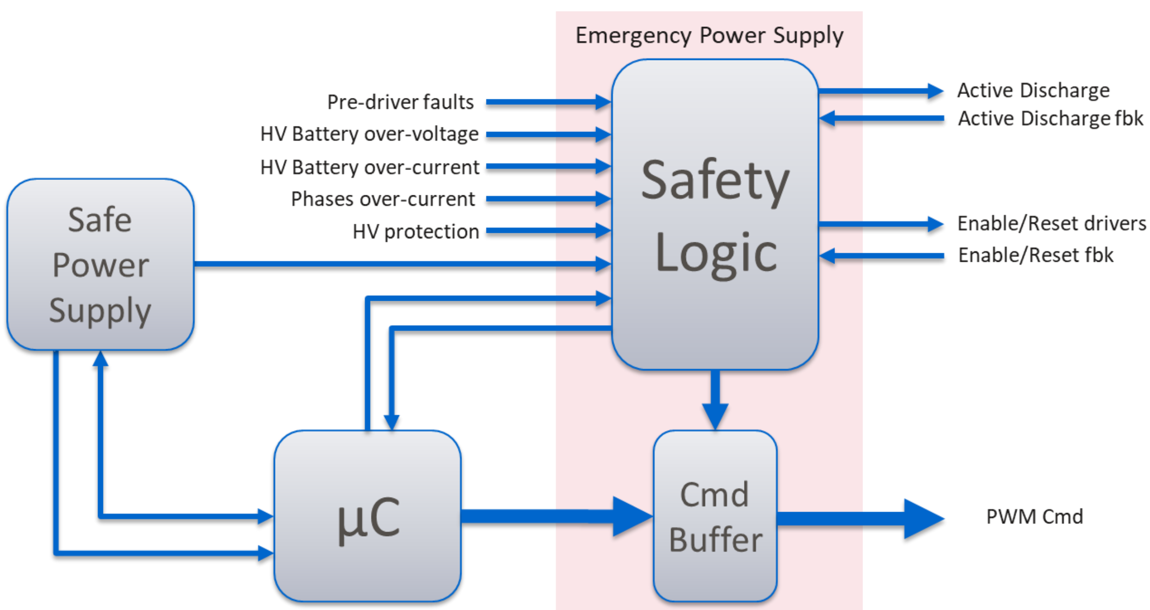


Figure 28: EVC1000 Safety logic concept

5.5.5 Early warning and implementation of PHM features

PoF (physics of failure) investigations are statistically based and do not allow estimates for a specific individual sample. Failure onset and degradation, crack initiation and propagation inside components, in the solder joints, at board and system level are not in the scope of this approach. The statistical evaluation provides information only about the typical behaviour and its scatter for the total set, from which the samples were taken randomly. Prognostic health management (PHM) upgrades reliability methodology by allowing to quantify the remaining useful life (RUL) of the individual sample under its specific use conditions instead of just determining the ultimate lifetime on statistical average.

The objective of PHM is the detection of onset and development of anomalies and defects well before substantial degradation of the functional performance and to estimate the remaining useful life of the system. This early detection shall be used for triggering dedicated maintenance activities so that the anticipated failure can effectively be prevented.

Within EVC1000, focus of the PHM activities will be set on control board and on the driver module, because redundant layout of the both shall be avoided and is not possible, respectively.

In order to implement the PHM features, the following sub-tasks will be performed:

- Investigating PHM structures;
- Warpage analysis of control board and driver module;
- FE analysis.

Investigating PHM structures

Canaries are prognostic devices that are integrated into electronic assemblies to monitor the degradation of electronic components and predict their failure. A canary is designed to degrade by the same mechanism that leads to failure in the target device and fail before the target device. The time to failure difference between a canary and the target device represents the prognostic distance (PD), defined as a measure of how long before system failure the prognostic structures or prognostic cell is expected to indicate failure [5]. The failure times of the canary can be correlated with those of the target device using PD. A simple solder interconnect canary can be implemented with relatively low effort using ceramic chip resistors on a printed circuit board (FR4) as they are common surface mount technology components with a high coefficient of thermal expansion mismatch with the substrate. The reliability of solder interconnects in such components is a concern for devices used in environments with high temperature swings where thermal fatigue is one of the primary failure mechanisms of solder interconnect. Since the thermal cycling reliability of the solder interconnects depends on the solder interconnect area, a canary can be developed by reducing the solder interconnect area.

For this reason, different canary structures in terms of SMD devices with partially reduced solder pad widths will be investigated in the project. Goal of these activities is to realize an early failure indication. Results of these investigations shall then be used to place such canary structures within the next generation control boards and driver modules.

Warpage analysis

The warpage analysis is based on the measurement of the surface deformation of a PCB board for at least two different temperatures. It thereby allows an investigation of thermo-mechanical stresses within the PCB boarded caused by the applied temperatures and in particular caused by the fixation of the PCBs.

The applied methodology was developed by Fraunhofer ENAS to identify critical locations (where local stresses would lead to an early failure of the component) based on an apparatus build in collaboration with FRT (for the frame and the out-off-plane sensors), CWM (for the in-plane deformations analysis software by image correlation) and Berliner Nanotest GmbH for the thermal chamber. This machine combine two different sensors and a temperature chamber to quantify the deformations induced by temperature changes from the component level (First level reliability) up to the overall system (third level reliability) including the influence of its boundary in its housing and its cooling apparatus.

The warpage analysis will be performed for different temperature profiles and different frame conditions. This include measurements on:

I. Bare devices (optional, if required) = first level reliability;
II. Bare PCB board = first level reliability;
III. PCB board with soldered components = second level reliability;
IV. PCB board with soldered components and fixed within the inverter) = third level reliability.

The goal of these investigations is to analyse the interaction of the different system levels (component, PCB, fixation) on the thermo-mechanical stress and hence on the reliability. The results of these investigations will also be used to calibrate and validate the FE simulation models.

FE analysis

3D finite element analysis has to be conducted to compare the strain produced in the canary and standard resistors. The obtained strain range is then used as a damage accumulation metric for solder interconnects and correlates with the solder interconnect fatigue life. The solder will be modelled as a visco-plastic material with creep (generalized Garofalo model). Test conditions will be simulated to prove that the solder interconnects on the resistors with reduced pad area show higher strains than the interconnects on the resistors with standard pad area. Results will also by confirmed by those obtained from testing.

With the results of the warpage analyses as well as of the canary structure investigations it will finally be possible to correlate the (pre-defined) lifetime of the canary structures (=failure indicator) with the lifetime of the whole PCB boards.

6 Conclusions

A detailed design requirements definition for the e-traction axle system, which is the combination of in-wheel motors and eWD², has been developed. The design of the e-traction axle system has taken into account mass production aspects of the components design to guarantee a cost-effective technology transfer into final products. The system has been designed to be flexible and modular enough to be adapted on different vehicles. The mechanical installation of the systems has been analysed in detail as well as its integration into the E/E architecture of the vehicles. Hence, the design goals in terms of performances, dimensions and weight, mechanical, electrical and other specific requirements, have been defined. Special attention has been devoted to the manufacturability of the e-traction axle system, since it affects several important factors of the final product (e.g. quality, cost, maintenance). As a matter of fact, the design flows of both the in-wheel motors and the eWD² are closely coupled with the manufacturing constraints of the assembly line. The relevant safety lifecycle steps, pertaining to the e-traction axle system, has been identified and executed. Special attention has been devoted to eWD² functional safety analysis: this has led to the definition of further technical requirements and recommendations closely related to safe hazard conditions management and safety mechanisms to be implemented in the eWD². Components prototypes will be now manufactured and verified on specific test benches, thus providing a validated system for WP5 and WP6.

7 Bibliography

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