2.1 – Vehicle and component specifications

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EVC1000

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

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Abbreviation

Abbreviation	Long Version
EVC	Electric Vehicle Components
EV	Electric Vehicle
NEDC	New European Driving Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure
SUV	Sports Utility Vehicle
BEV	Battery Electric Vehicle
2WD	Two Wheel Drive
r_{dyn}	Dynamic Rolling Radius
BBW	Brake By Wire

FMVSS	Federal Motor Vehicle Safety Standards
ECE	Economic Commission for Europe
EPB	Electric Parking Brake
GVW	Gross Vehicle Weight
RPM	Revolutions Per Minute
IP	Intellectual Property
EMC	Electro Magentic Compatibility
FEM	Finite Element Method
HEV	Hybrid Electric Vehicle
PHEV	Plug-In Hybrid Electric Vehicle
VMU	Vehicle Management Unit
IGBT	Insulated-Gate Bipolar Transistor
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
GDB	Gate-Driver Board
SVM	Support Vector Machine
BMS	Battery Management System
OEM	Original Equipment Manufacturer
DBI	Driver Braking Interface
VCL	Vehicle Control Logic
NC	Normally Closed
NO	Normally Open
BCU	Brake Control Unit
EM	Electric Motor
EHA	Electro-Hydraulic Actuators
CES	Continuously controlled Electronic Suspension
EMD	Electro Magnetic Damper
DCU	Damper Control Unit
USR	University of Surrey
TUIL	Technical University of Ilmenau
TEN	Tenneco
ABS	Anti-Lock Braking System
PI	Proportional-Integral (controller)

ISMC	Integral Sliding Mode Control
ITAE	Integral Absolute Value of the Error
HIL	Hardware in the Loop
MIL	Model in the Loop
VDC	Vehicle Dynamic Control

History

Version Number	Comment
V01	First version submitted (May 8th)
V02	Second version submitted on July 1st, including the request for change (addition of paragraph in Summary).
V03	Third version submitted on August 9th, including the request for change (explanation of formulas)

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1 EVC1000 project aims

With falling prices and recent technological advances, the **second generation of electric vehicles (EVs) that is now in production** makes electromobility an affordable and viable option for more and more people. With the help of strong governmental support (e.g., see Norway [1]), it appears that electromobility is on the **verge of major expansion in Europe** and the rest of the world.

To maintain this EV momentum, the latest edition of ERTRAC's **European Roadmap for Electrification of Road Transport** [2] defines four big initiatives outlining the research and development needs. Under the initiative of "**user-friendly affordable EV passenger car + infrastructure**" the topics include:

- **Electric motors**, **power electronics and charging systems** with **high impact on powertrain efficiency** as well as **reduced needs for raw materials and rare earths**.
- **Energy efficient control of electric vehicle** (EV) **operation** (vehicle, powertrain, passenger comfort, traffic flow, charging and energy management) with high impact on the integration of the EV in the traffic environment.

The EVC1000 project addresses these 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.

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

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**

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**. For example, "design-for-purpose" vehicles built for dedicated usage models [2] can become reality more easily. 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** (see Section 1) 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**.

To complement the in-wheel motor technology and exploit their full potential, EVC1000 provides **new chassis components and integrated controllers.** In particular, an **efficient brake-by-wire system** and **electro-magnetic suspension** paired with **predictive controllers will be implemented to extend the driving range by up to 10%.** What is more, the systems are selected to ensure **relaxed, comfortable and safe driving on long journeys**.

Despite the high level of integration within EVC1000, full **flexibility in the commercialisation 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. In summary, the main components/systems developed in EVC1000 are:

- **New components for in-wheel powertrains**: **i)** Efficient, scalable, reliable, low-cost and production-ready **in-wheel motors** suitable for a wide range of torque and power levels; and **ii) Compact centralized drive** for in-wheel motor axles, based on Silicon Carbide technology, targeting superior levels of functional integration and failsafe operation – so called, **eWD^2**. The designs consider **electro-magnetic compatibility aspects**, and include **prognostics and health monitoring techniques** of the electronic components.
- **New components for electrified chassis control with in-wheel motors**: **i) Brake-by-wire system**, consisting of front electro-hydraulic brakes and rear electro-mechanical brakes for seamless brake blending, **high regeneration capability** and enhanced anti-lock braking system performance; and **ii) Electro-magnetic and electro-pneumatic suspension actuators**, targeting increased comfort and EV efficiency, e.g., through the optimal control of the ride height depending on the driving conditions.
- **Controllers for the novel EVC1000 components and new functionalities**, exploiting the benefits of functional integration, vehicle connectivity and driving automation for advanced energy management, based on the results of previous projects and initiatives.

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.

2 AUDI e-tron demonstrator

The Audi e-tron is the first full-electrical model from the brand with the four rings. The sporty SUV combines the space and comfort of a typical luxury class automobile with a range suitable for everyday use, catapulting the driver into a new era with the electrical all-wheel drive. Forward-looking, innovative, and electric – the next step into the future.

Figure 1: AUDI e-tron / AUDI AG

The e-tron model is an excellent base to be used as a vehicle demonstrator for the EVC-1000 project. The intended modifications are presented in **Table 2**.

Table 2: Overview of considered modifications on the AUDI e-tron demonstrator

Modifications
In-wheel motors
eWD²
Brake-by-wire system
Electro-magentic suspension
Predictive energy management
High-Voltage Battery

It can be seen easily that crucial changes to the vehicle architecture will be considered – powertrain, chassis and the energy management will be affected.

2.1 Technical battery specifications

Since the AUDI e-tron is a battery electric vehicle (BEV), it owns a high-capable battery pack. The relevant specification information are introduced in **Table 3**.

Table 3: technical battery specifications

Designation	High-voltage battery
Nominal voltage	396 V
Capacity	240 Ah
Operating temperature	- 28 °C to + 60 °C
Energy content	95 kWh
Usable energy content	83.6 kWh
Charging capacity	150 kW
Weight	699 kg
Dimension [mm]	1630 x 340 x 2280 B x H x L
Cooling	Liquid cooling

Due to its advantageous characteristics in terms of high energy storage capacity and charging capacity, it means an excellent starting point for the research work within the EVC-1000 project. As a consequence, the battery pack is not considered to be replaced by a more powerful one during the project elaboration, which helps to focus the available resources to powertrain, chassis and energy management.

2.2 Requirements

Since during the EVC-1000 project the vehicle architecture is modified to reach the efficiency objectives, also the vehicle requirements have to be adjusted. Only by doing this, the ambitious project objectives are reachable.

Table 4: vehicle requirements for the AUDI e-tron demonstrator

Vehicle Parameter	Value
Type of drivetrain	2WD, rear
Gross Vehicle Weight	3130 kg
Curb Weight	2660 kg
Vehicle dimensions or front surface area	2.65 m^2
Air drag coefficient	0.28
Rotational resistance coefficient	0.006
Rim size in inches	20” rim size (with r_{dyn} = 371 mm)
Outer diameter of the tire	r_{dyn} = 371 mm
Expected acceleration	7 s (0 – 100 km/h)
Expected top speed	180 km/h
Expected cornering ability force	1.1 g
Expected braking torque on powered wheels (in Nm)	3417 Nm (for 3130 kg and 0.3 g deceleration)
Hill-climbing ability (in %)	PEAK: 50% CONTINUOUS: 40 % HILL-START: 40%
Desired driving range and battery capacity estimate (in kWh)	1000 km with charging per day 95 kWh (gross) / 83.4 kWh (net)
Operating conditions	-28°C to 60°C

In **Table 4** the vehicle requirements are presented. It can be concluded, that the vehicle characteristics are adjusted, but still on a very high level in terms of vehicle dynamics, driving safety and use cases. It must be mentioned, that the project consortium intends to develop practical and reasonable solutions, which are fully accepted by the customers without any significant renunciation on safety, performance and comfort.

2.3 Simulation requirements for BBW system

The brake system is a safety-relevant device in every car, its functionality has to be ensured even under harsh conditions. Hence, the innovative Brake-By-System (BBW system) has to be tested for safety critical conditions.

Within the EVC-1000 project, several test scenarios might be considered, the necessary simulation requirements will face various functional safety tests as well as testing of fallback functions.

2.4 Test bench requirements for BBW system

Testing and validation of new and innovative systems can be divided on component and vehicle level. On component level, various tests on test benches have to be considered.

Therefore, particular requirements and protocols have to be addressed. Bench testing includes investigations of performance, safety and comfort for different use cases. Since EVC-1000 project is strongly focused on energy efficiency, investigations on residual brake torque will take place.

Besides already existing protocols (for instance regulatory standards such as FMCSS / ECE-R13 H) also new / adapted testing procedures are used for the research work.

2.5 Vehicle testing requirements for BBW system

As already mentioned in section 2.4, also vehicle testing is a necessary part of the testing and validation work. Similar to bench testing, requirements and protocols have to be defined.

Those vehicle tests will face performance, safety and comfort issues, but also energy efficiency (reduced residual brake torque) requirements.

Test protocols are derived from regulatory standards, AUDI-internal procedures and media-related specifications (so-called “newspaper tests”).

3 JAC demonstrator vehicle

The JAC iEV7 is a production fully electric vehicle by JAC. **Figure 2** shows the front, side and rear views of the vehicle. Its main characteristics are reported in **Table 5**. The iEV7 model is an excellent complementary base with respect to the e-tron, to be used as a vehicle demonstrator for the EVC-1000 project. The intended modifications are presented in **Table 6**.

Figure 2: JAC iEV7

Table 5: Main vehicle characteristics of the production JAC iEV7

Vehicle Parameter	Value
Curb weight (kg)	1480
Mileage at 60 km/h (km)	300
Mileage (ECE) with energy recovery (km)	200
Maximum motor torque (Nm)	270
Maximum electric motor power (kW)	85
Gear ratio (-)	7.2
Battery capacity (kWh)	33
Battery type	Lithium Ion
Fast charge time (h)	1.5 (10%～80%SOC）
Slow charge time (h)	11.5 (10%～100%SOC)

Table 6: Overview of considered modifications on the JAC iEV7 demonstrator

Modifications
In-wheel motors
eWD²
Electro-magnetic suspension
Predictive energy management
Lithium Sulfur battery pack

4 EVC1000 components and controllers

4.1 In-wheel motors

4.1.1 Applications

The Elaphe™ L-type motors are designed as in-wheel motors intended for direct-drive applications with high torque requirements. Elaphe™ L1500 in-wheel liquid cooled motor is designed to be installed on either front or rear axle in two- or four-wheel drive applications. It is a versatile motor, suitable for different vehicle platforms that can exploit its small footprint, supreme packaging and easy integration. In combination with Elaphe control electronics it presents a new, modular platform for electric vehicles and electric light commercial vehicles and is perfectly suitable for the next-generation of autonomous and connected mobility.

The Elaphe™ L1500-series in-wheel motors are liquid-cooled synchronous motors with an outer rotor and a high number of poles. They are excited by permanent magnets.

MAIN ADVANTAGES ARE:

- Direct-drive
- Market-leading specific torque
- High energy efficiency
- Low weight and compact design
- Regenerative braking
- Compatible with existing mass-produced car parts
- Possibility of integrated disc brake and EPB
- Modular, with minimal number of moving parts and optimized controllability
- Part of Elaphe™ modular platform for optimal packaging

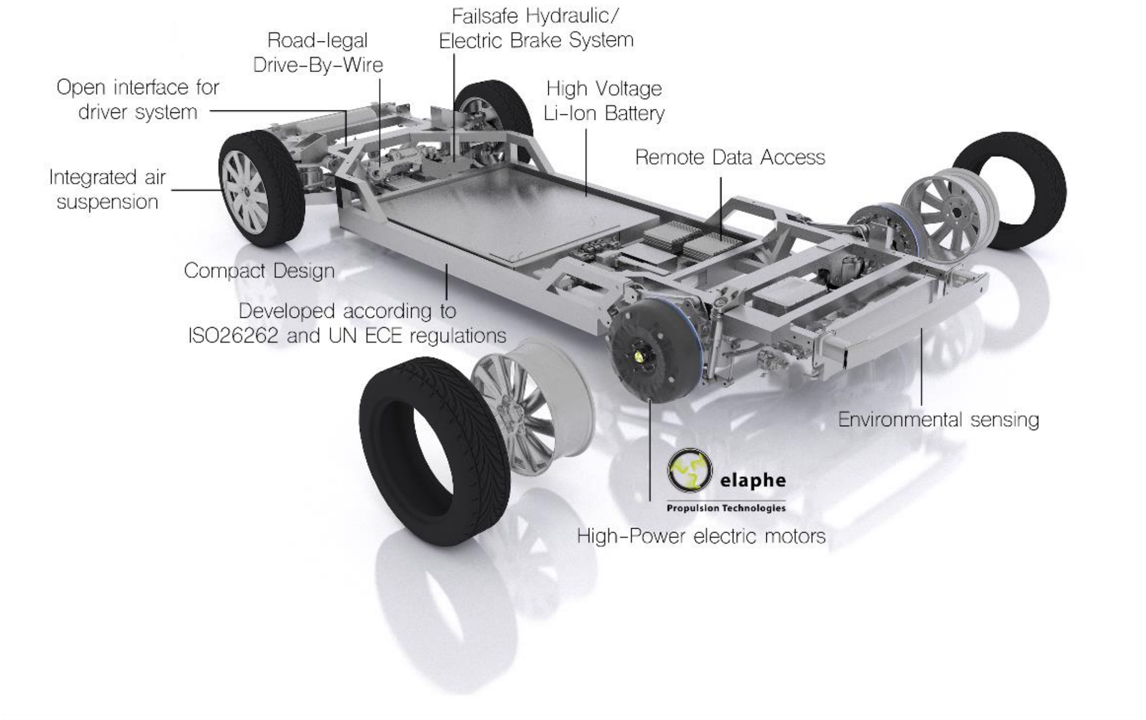


Figure 3: Example of L1500 integration

High specific torque and absence of mechanical gears in direct drive motors allow for distinct advantages in performance and efficiency as compared to central e-motor architecture. Compact integration of either four in-wheel motors in applications where performance is the main objective or for integration of two motors where efficiency is the main goal is possible. In line with project main objective of high drivetrain efficiency the demonstrators will be equipped with two L1500 motors on rear axle. Additional parameter that dictate the choice of in-wheel configuration are mainly connected with:

- Gross Vehicle Weight (GVW) and weight distribution per wheel.
- Vehicle performance requirements (vehicle performance, hill-climbing, driving scenarios and cycles, and maximal generated lateral acceleration - cornering)
- Vehicle braking requirements at point of motor application (rear, front, required braking torque, brake thermal capacity, heat dissipation)

4.1.2 Motor specification

The L1500 in-wheel motor basic characteristics are given below (**Table 7**). The winding is optimized for a wide operating area with respect to efficiency and speed of typical applications. At voltages different than nominal, the operating area is proportionally scaled to the voltage increase or decrease with respect to the nominal voltage of the given winding configuration. At different voltages than nominal, the speed of the motor will increase or decrease accordingly.

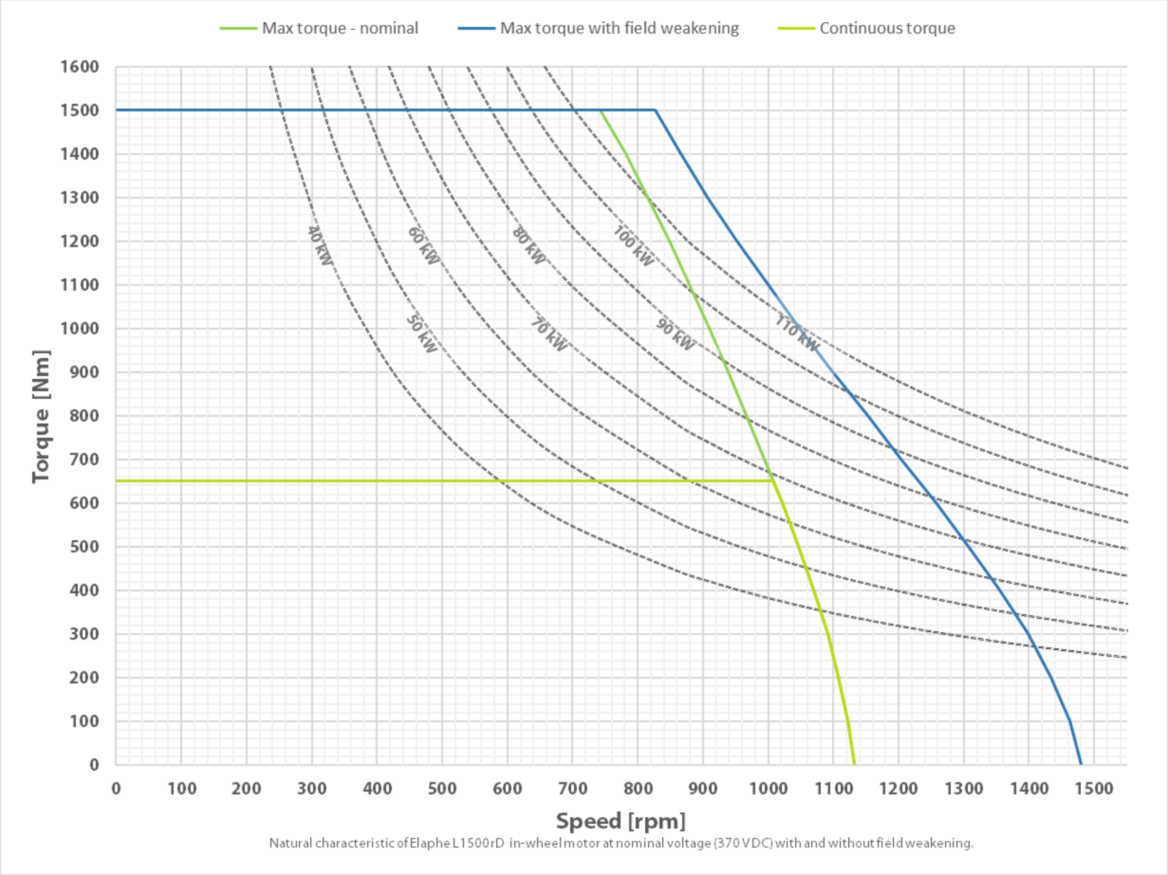
Table 7: ELAPHE motor specification

Parameter	Value (VD2 EM design spec)		Unit
Nominal supply voltage	370		V DC
Supply voltage range for motor	Limited by applicable inverter. Currently to 425 V DC.		V DC
Max. torque (> 20 sec) @ 300 rpm, phase current	1200* | 390*		Nm | Arms
Max torque (< 10 sec) @300 rpm	1500* | 500*		Nm | Arms
Continuous torque @ 800 rpm	650* | 210*		Nm | Arms
Max. speed (no-load) @ nominal supply voltage Max speed is given at harshest environmental temperature of -40 °C.	1132* At room temperature the top speed can be increased by 5%. At +85 °C environmental temperature, the top speed can be increased by 10 %.		rpm
Max. speed (with field weakening) (no-load) @ nominal supply voltage	1480*		rpm
The rated DC voltage of the motor is UDC = 370 V. The voltage constant, torque constant and top speed may vary from +5% to -10 % due to different operating temperatures. If the power supply voltage varies (e.g. voltage variation in battery pack due to different state of charge), the maximum speed changes proportionally with the voltage. Higher rotational speeds than the nominal can be achieved by increasing the input DC voltage of the power supply.			
Max. speed (no-load) @ 425 V DC	1516*		rpm
Max. output power (@370 V DC, without field weakening) [Net Power; ECE R85] (Torque, speed)	110 kW* (1500 Nm, 700 rpm) The full torque-speed characteristic is achieved with a stable DC voltage source, however, in battery powered vehicles, voltage may drop due to high drawn current and consequently the peak available mechanical power could be lower than shown above.		kW
Continuous output power (Id = 0, @370 VDC) (30 min power; ECE R85) (Torque, speed)	65 kW (650 Nm, 955 rpm)		kW
Max. electric motor efficiency e-machine efficiency	94*		%
Max. overall electric actuator wheel efficiency including mechanical losses of seals	92,5*		%
Coolant type, typical flow	Water/Glycol 50/50; 8 l/min		/
IP rating	IP67 and IPX9K		
Operating conditions for full motor performance (intended)	ambient temperature: - 40 °C to + 85 °C	Coolant inlet temperature: -40 °C to 65 °C	°C
Operating conditions for limited motor performance (intended)	ambient temperature: - 50 °C to + 85 °C	coolant inlet temperature: -30 °C to 85 °C	°C
Typical vehicle mass limitation with respect to cornering (lateral acceleration)	Passenger car 2300 @1,35g lateral acceleration 3000 @1,1g lateral acceleration	Slow cornering vehicles 8000 @ 0,4g lateral acceleration	kg

*Preliminary information based on simulation and/or preliminary tests, approximate value based on 40 °C magnet temperature.

4.1.3 Natural characteristic (torque, speed)

The natural characteristic in terms of torque and speed is shown in **Figure 4**.



Natural characteristic of Elaphe L1500rD in-wheel motor at nominal voltage (370 VDC) with and without field weakening.

Figure 4: Torque – speed (natural) characteristic at 40 °C magnet temperature

In case of continuous drive at high speed, the magnets will heat up and the maximum achievable speed can be up to 1300 RPM without field weakening.

4.1.4 Standard Conformity

Relevant procedures for standard conformity are presented in **Figure 5**.

Figure 5: Overview of relevant standards

APPLICABLE STANDARDS:

ISO 6469-3: Electrical safety

IEC 60034-1: Performance rating

IEC 60349-4: Motor characteristics

ISO 20653: IP rating

ECE R10: Electromagnetic compatibility

ISO 16750-3: Mechanical loads

ISO 16750-4: Environmental loads

4.1.5 Electromagnetic compatibility (EMC)

The Elaphe L-type in-wheel motor prototype Ver C. was tested for EMC according to ECE Regulation No. 10, Revision 5.

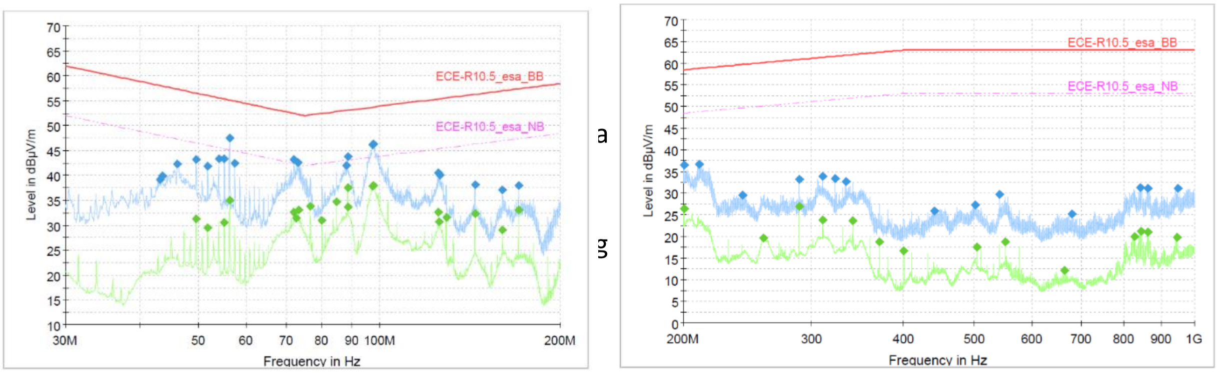


Figure 6: The images show the radiated power of the L-type powertrain (L1500 motor, H300 inverter, PCU)

The blue line in **Figure 6** 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.

4.1.6 Motor parts and dimensions

The L1500 disc brake version with caliper configuration and electronic parking brake (EPB) is shown in **Figure 7**, the correlating legend can be seen in **Table 8**.

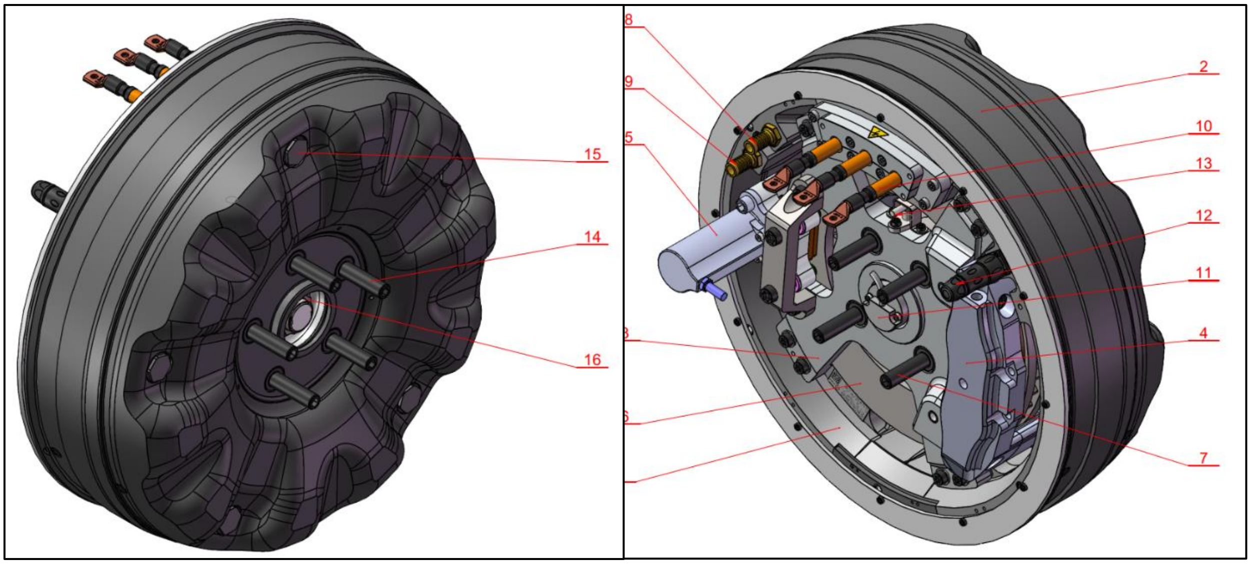


Figure 7: Front view (left) and rear view (right) of the *L1500*

Table 8: Legend related to Figure 7

No.	Part name/installation detail	No.	Part name/installation detail
1	Stator	10	Phase Cable
2	Rotor	11	Position Sensor
3	Stator Plate	12	Temperature Sensor Connector
4	Main Caliper	13	ABS Sensor
5	EPB	14	Stud Bolts for Rim mounting
6	Brake Disc	15	Sealing Plug
7	Stud Bolts for vehicle mounting	16	Bearing Nut
8	Coolant - Inlet	17	
9	Coolant - Outlet	18	

4.1.7 Motor Dimensions

The motor dimensions can be found in **Figure 8** and **Figure 9**.

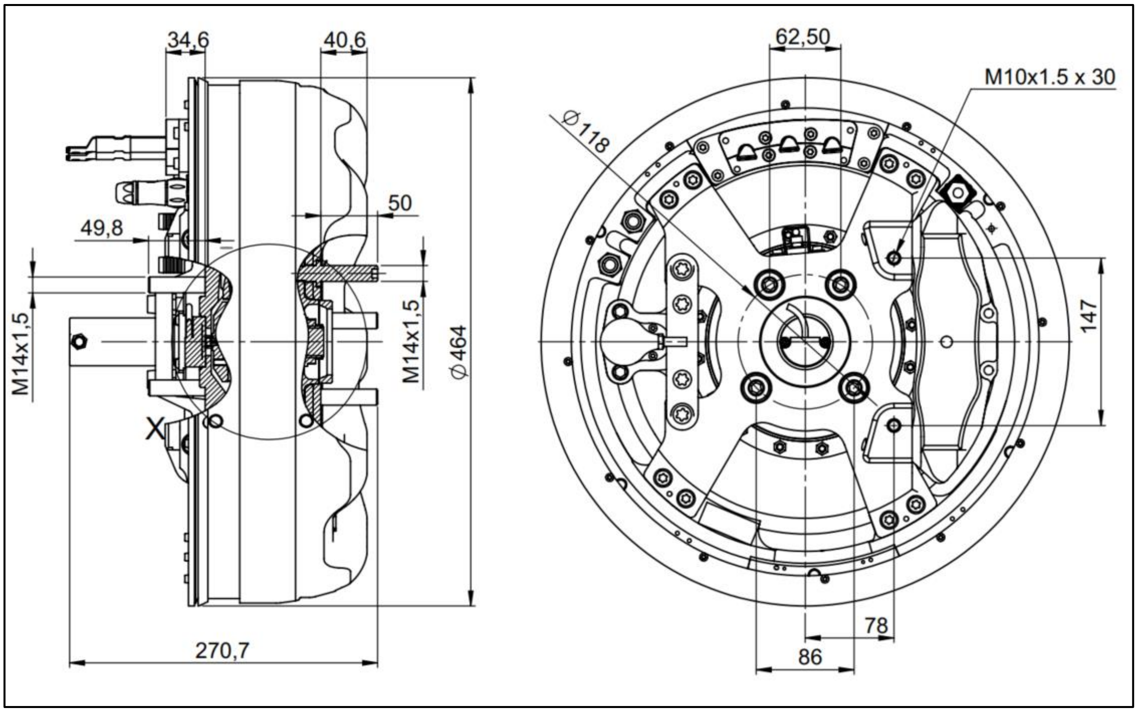


Figure 8: Outer dimensions and mounting feature

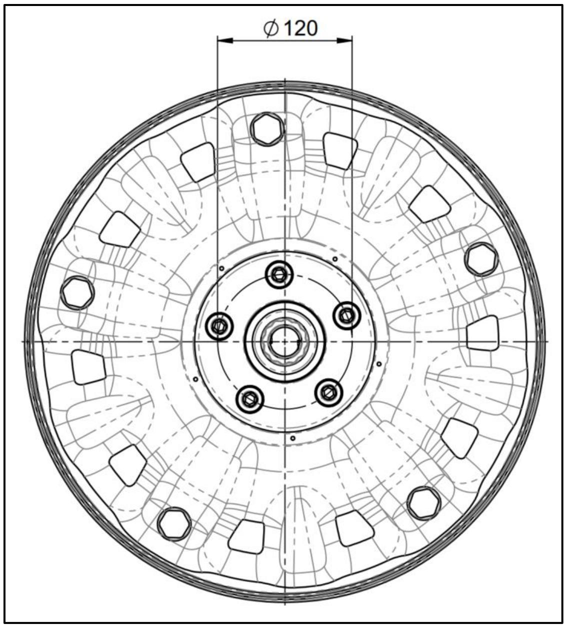


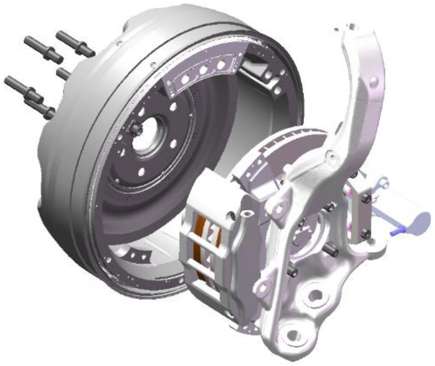
Figure 9: Rim mounting feature; Bearing PCD = 5x120

The related mass is indicated by **Table 9**.

Table 9: Overview of the mass

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

4.1.8 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).

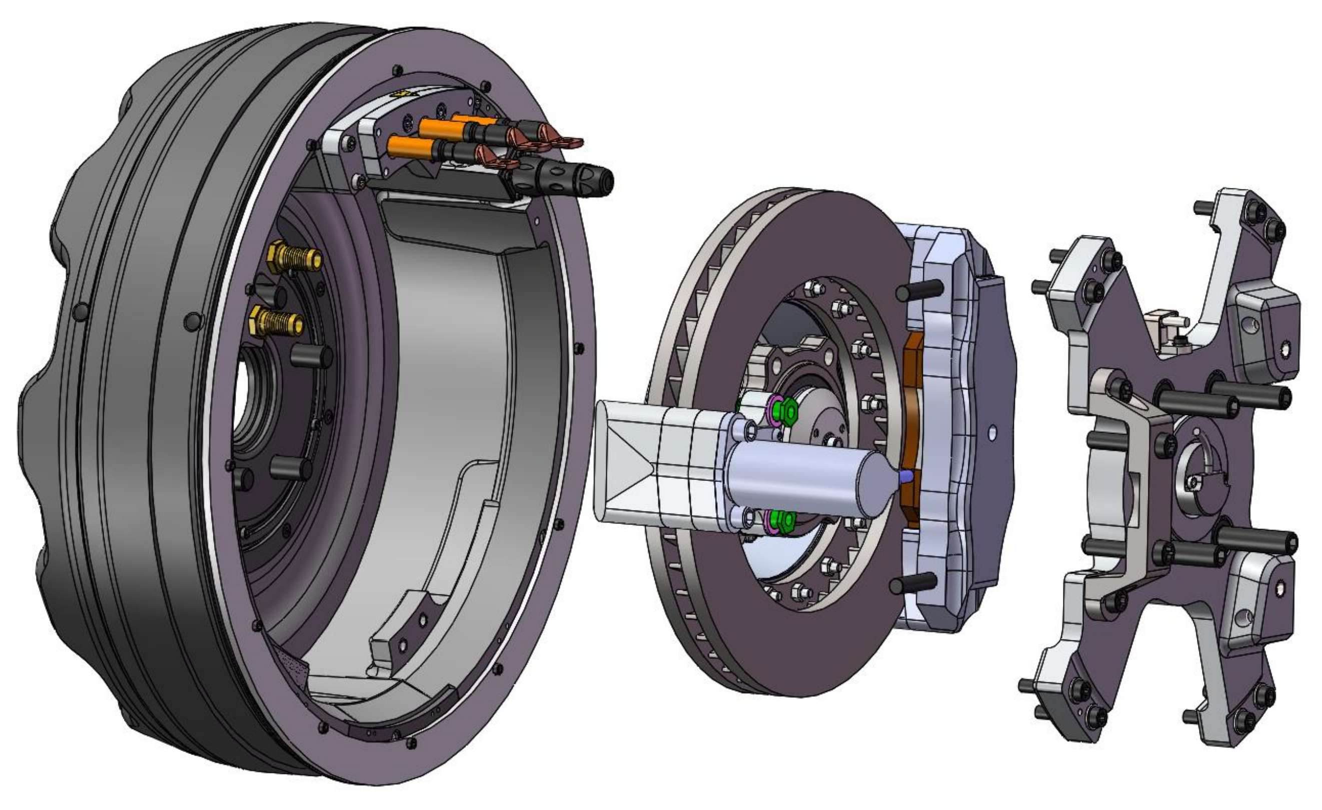


Figure 10: Motor assembly including brake components

Details of the assembly are shown in Figure 10. The motor assembly is comprised of the motor, the brake subassembly including the main caliper and EPB and the vehicle knuckle or stator plate adapter, to which the braking systems are attached (main caliper, EPB caliper).

4.2 Dual inverter

4.2.1 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.

4.2.2 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 (**Figure 11**).

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 rooms 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 300 kW (peak for 10 s). Wide-bandgap power devices will be evaluated to provide high efficiency, 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.

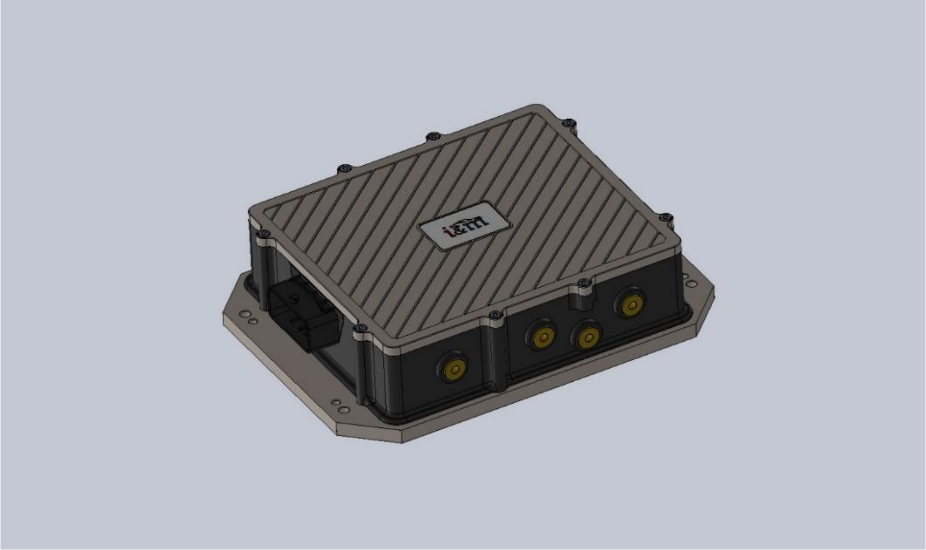


Figure 11: 3D model sketch concept for one of the two inverters of DIDIMO

4.2.3 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 12. 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.

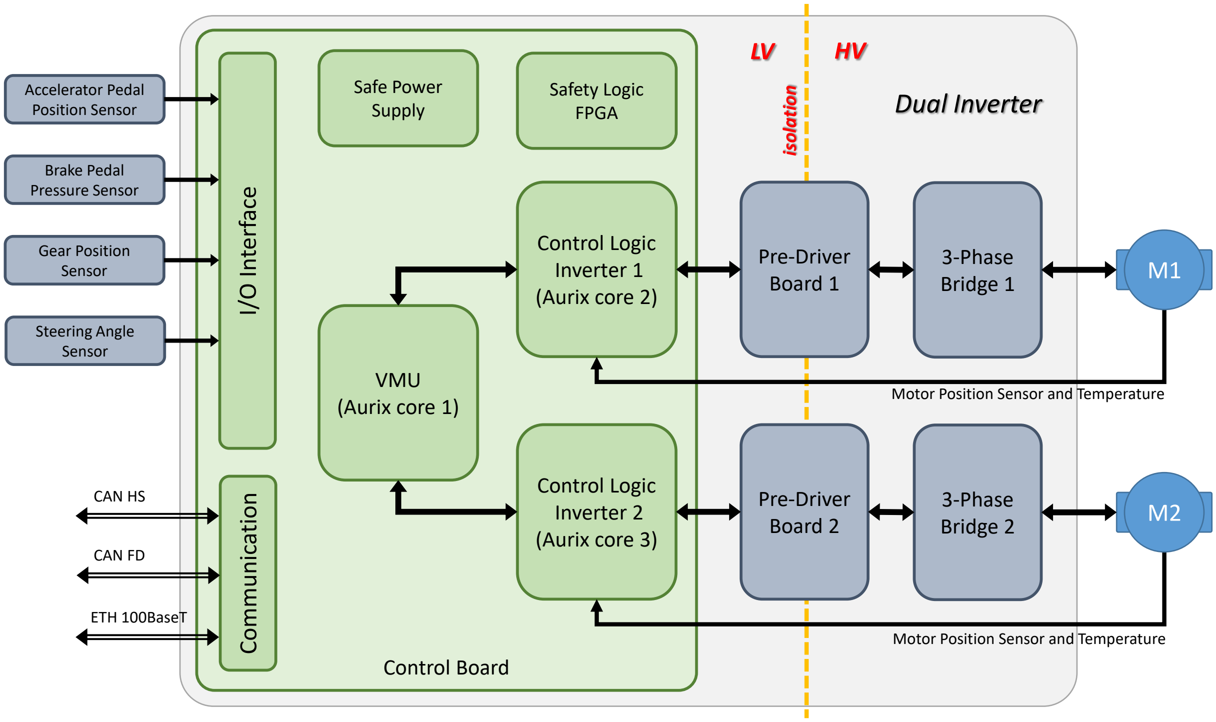


Figure 12: High-level block diagram of the Dual Inverter

Thanks to its architecture, DIDIMO is also capable to perform 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).

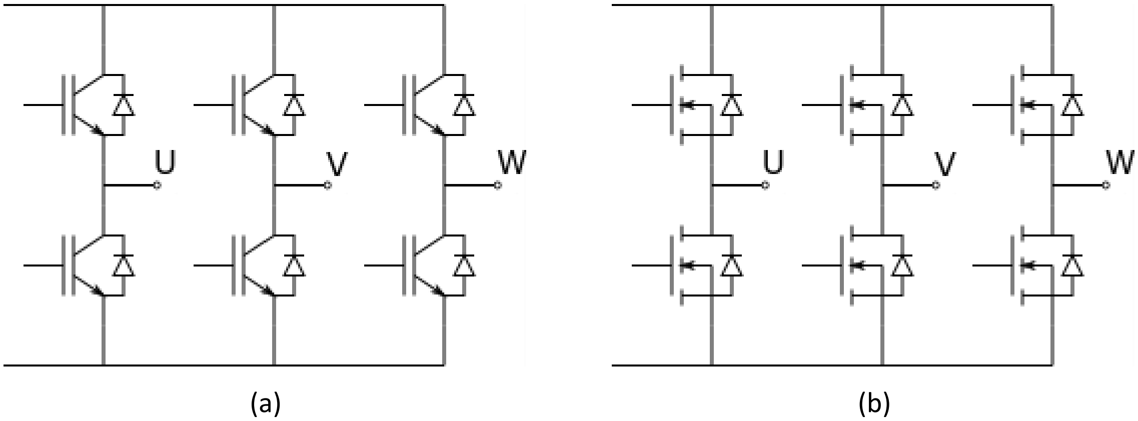
4.2.4 Three-Phase Bridges

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

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

Both demo cars used in EVC-1000 project will be equipped with a 400 V battery. The power expected for this application requires the bridge to withstand to high currents (up to 400 A, peak).

Switches used will be the most suitable for our application, i.e., given the voltage and the current ranges, given the switching frequency, the technology that will provide the inverter with highest efficiency levels will be used. At present, we are evaluating silicon IGBTs and silicon carbide MOSFET (see **Figure 13**).



(a) (b)

Figure 13: IGBT-based three-phase bridge (a) and a MOSFET-based one (b)

4.2.5 Gate-Driver Board Architecture

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., > 30 kHz) the GDB will contain high power gate drivers characterized by high current and high slew-rate.

Since the board is in between high voltage (the three-phase bridge) and low voltage system (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 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.

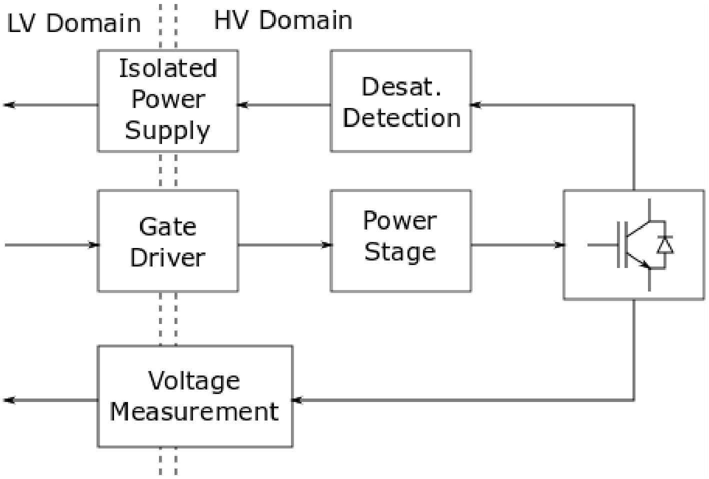


Figure 14: Block diagram for gate-driver board used on DIDIMO

4.2.6 Control Board Architecture

The Dual Inverter 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. The Dual Inverter 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 15.

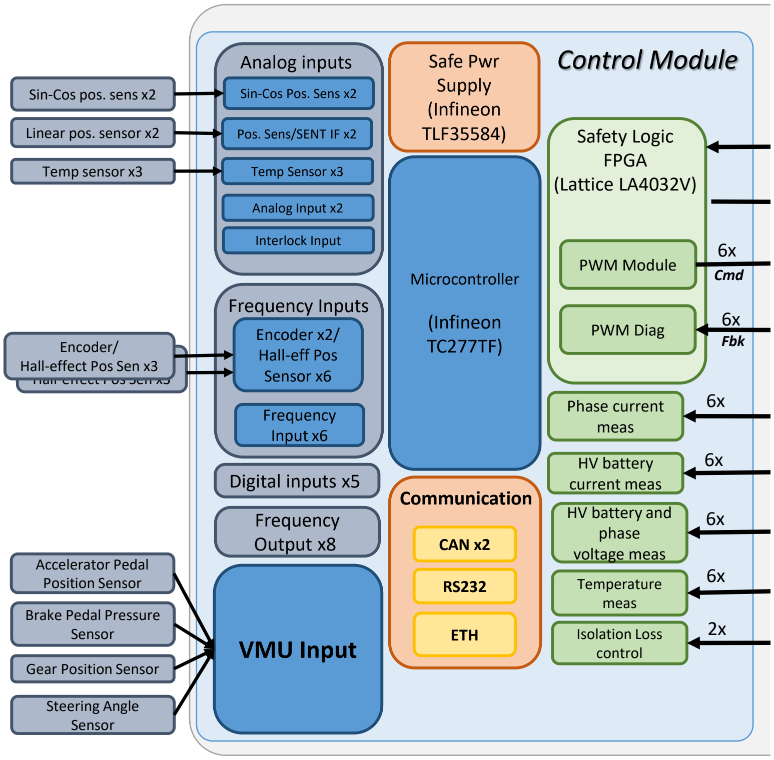


Figure 15: Detailed Dual Inverter block diagram

4.2.7 Dual Inverter functions

The main functions of the Dual Inverter are summarized below:

- A dual 3-phase motor controller, able to drive two PMSM, BLDC or induction motors;
- Continuous input power in excess of 75 kW per motor (150 kW per motor for 10 s)
- 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, analog sin/cos, analog 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 (option);
- high voltage interlock function;
- high voltage insulation check.

4.3 Brake-by-wire system

4.3.1 BbW system definition

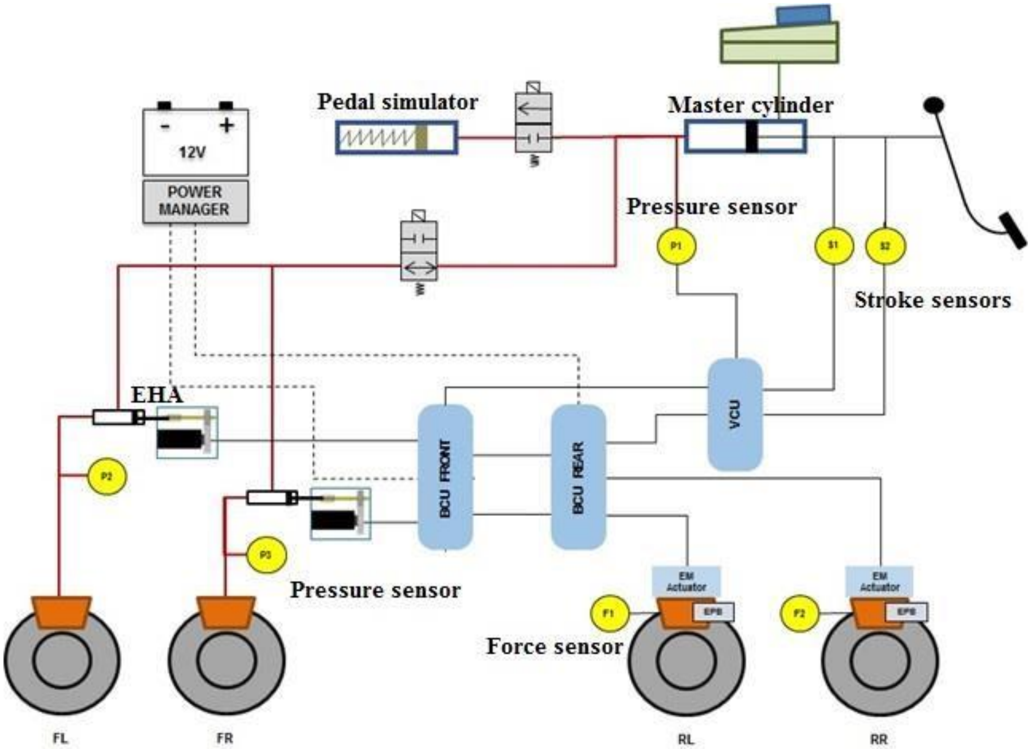


Figure 16: Scheme of Brembo Brake-by-Wire system for EVC-1000 application

The scheme of Brembo Brake-by-Wire system for EVC-1000 application with its NO and NC valves to switch from BbW mode to hydraulic backup mode is shown in **Figure 16**.

The brake system described in this document is a Brake by Wire system composed by:

4.3.2 Driver Braking Interface (DBI)

The brake pedal, supplied by the OEM, is connected to the push-rod which moves the master cylinder.

The fluid displaced by the master cylinder can either flow:

a) To the pedal simulator, which provides the desired pedal feel to the driver through elastic elements, during
BbW mode (normal operating mode), or

b) Directly to the hydraulic calipers (passing through the actuators which are open in the rest position), during the hydraulic back-up mode (safe state).

Two valves, one normally closed (NC) and the other normally open (NO), ensure the switch between BbW and hydraulic backup mode if a failure is detected and even during lack of electrical power.

Integrated in the DBI, which can be seen in **Figure 17**, there are pressure and stroke sensors responsible to acquire the driver braking request and provide it to the vehicle control logic (VCU).

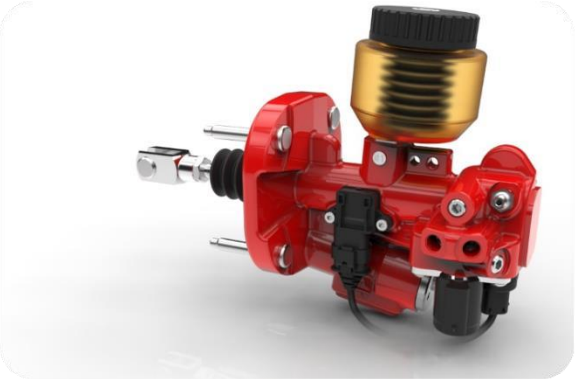


Figure 17: The Driver-Brake Interface (DBI) with integrated sensors, valves and reservoir

4.3.3 Brake control units (BCU)

Two BCUs process an external braking request and request a braking action on the corners. The Rear BCU controls the rear corners and the front BCU controls the front corners. They are responsible for the low-level actuator control.

They shall thus be connected to the actuators to:

- Supply them the power
- Read the feedback signals by the force (for the rear EM) and pressure (for the front EHA) sensors

They shall be also connected to the vehicle bus and/or the Vehicle Control Unit bus to exchange the signals required by both the BCU and the VCU (e.g. to receive the torque targets for the corners and send back the feedback forces/pressures acquired by the sensors).

Figure 18: The brake control unit

Each of these BCUs (**Figure 18**) can control two corners (one axle). For EVC1000 project they will be configured as “smart actuator”; this means they won’t have vehicle dynamics software on them, which will instead be on a central vehicle control unit (VCU). The BCUs will actuate and control the braking torque level required by the VCU on each of the four corners (being Brembo BbW a distributed system, four different braking torque values on the corners can be achieved, enabling advanced vehicle dynamics control functions).

4.3.4 Corners

Four corners which are responsible for generating the braking pressure/force in the calipers when requested by the system. In particular:

- Each front corner is composed by Electro-Hydraulic actuators with hydraulic calipers
- Each rear corner is composed by an Electro-Mechanical actuator integrated into a sliding caliper together with a EPB (electrical parking brake) device

4.3.5 Electro-Hydraulic actuators

EHAs are responsible to apply the braking pressure on the front hydraulic calipers. The pressure is applied through an electric motor coupled to a mechanical system which translates the rotational movement into a linear displacement of a piston which in turn displaces the fluid through the hydraulic calipers.

The actuated pressure is monitored by a pressure sensor and the information is used by the BCU as a feedback to actuate the control.

Figure 19: The Electro-Hydraulic Actuator (EHA) integrating electric motor, pressure sensor and the brake cylinder

The Electro-Hydraulic Actuator (EHA) integrating electric motor, pressure sensor and the brake cylinder will actuate and control the pressure on the front Brembo aluminum monobloc fixed calipers. One actuator for each front caliper will be installed (**Figure 19**).

4.3.6 Electro-Mechanical actuator

Together with a caliper it is responsible for the application of the clamping force on the rear brake discs.

The braking force is applied through an electric motor which transmits the torque to a floating caliper which applies the force to the discs.

The actuated force is monitored by a force sensor and the information is used by the BCU as a feedback to actuate the control.

Figure 20: The dry electro-mechanical sliding caliper

The dry electro-mechanical sliding caliper (shown in **Figure 20**) with integrated force sensor and parking brake mechanism will be used for the rear axle. This caliper is a dry caliper with built-in motor and transmission, so there will be no use of brake fluid for the rear axle in EVC1000 application.

4.3.7 Locking mechanism (EPB Device)

After the target clamping force is reached by the service brake, the EPB Device (integrated in the rear calipers) locks the clamping force and allows to maintain it even without power supply.

Below, system and braking functionalities are discussed.

4.3.8 Safe state

"Safe State" state represents the operating mode reached by the BbW System when a safety critical failure is detected, in order to avoid an unreasonable level of risk.

4.3.9 Hydraulic backup

In hydraulic backup mode the DBI is directly connected to the electro-hydraulic actuators and thus decoupled from the pedal simulator. BCUs are shut down in this configuration.

This state is assured even if the power is off due to the two NO and NC valves.

The legal requirement of minim deceleration 2.44 m/s^2 with pedal force lower than 500 N is always met during this operating mode.

4.3.10 Pedal feeling

The pedal feel is defined by means of a passive pedal simulator that consists of a series of elastic elements compressed by the fluid displaced by the master cylinder.

The relationship between pedal force and pedal stroke can be tuned during design phase by changing the stiffness of the elastic elements.

The relationship between vehicle deceleration and pedal stroke (or force) is decided entirely through the software VCU, thus the pedal feeling and the stroke-deceleration curves are independent. The dead stroke of the pedal can be tuned by software as well.

4.3.11 Base brake (smart actuator)

The Base brake function shall acquire brake pedal stroke and pressure through the DBI and it shall send the raw sensor signals to the VCU in the form of stroke and pressure. The stroke signal shall be redundant.

The Base brake function shall acquire an external braking request for each corner coming from the VCU and it shall generate the braking torque to each wheel accordingly.

The Base brake function shall send the actual force/pressure developed by the actuators to the VCU as feedback.

4.3.12 Parking brake

The Parking brake function shall apply the parking brake when requested and maintain the vehicle standstill.

The Parking brake function shall release the parking brake when requested.

The parking brake function shall send the status of the parking brake to the VCU.

4.4 Active suspension actuators

The suspension system will consist of a hybrid solution of a cross linked hydraulic shock absorbers and, in parallel, electro magnetic dampers. The result is a system, capable of efficiently controlling the low frequency body movement (<6 Hz), including roll stiffness control, while at the same time delivering the elevated high frequency control requirements (up to 24 Hz) that a vehicle with in-wheel motors poses, countering the classical compromise for high and low frequency vibration control. The four quadrant controller of the Electro Magnetic damper enables energy harvesting when the road condition are suited for this. The combination of the 2 separate damper systems results in an extended level of fail safe operation

4.4.1 The hydraulically interlinked dampers

Figure 21: Schematic overview

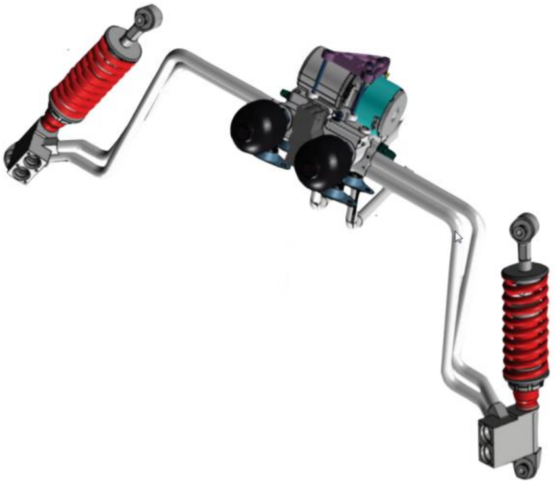


Figure 22: CAD render

- Passively allows simultaneous high roll stiffness (for better handling), reduced articulation stiffness (better traction) and reduced single wheel stiffness (better comfort)

- Reactively allows high roll damping (for reduced roll rate), high pitch damping (for better braking and acceleration) with reduced bounce and single wheel damping (for improved comfort and traction) and independent wheel hop control
- Passive operation allows instant stiffness response, minimal weight, simplicity
- Uses standard damper components and standard CES valves, while incorporating proven CES control algorithms
- Roll stiffness can be adjusted by adjusting pressure and a comfort valves allows for additional comfort and less head toss.

4.4.2 Electromagnetic damper

The EMD's will be installed in parallel with the hydraulic suspension system. These linear actuators consist of an inner magnet stack and an outer 3 phase stator stack. The damper controller transforms a force request into a 3 phase current that drives the stator. An inverter enables 4 quadrant control necessary for the energy harvesting. The damper controller combination will allow for 2000 N control forces with a frequency content of 20 Hz.

4.4.3 Damper Control Module DCU

Per axle there will be 1 DCU handling the force requests from the integrated controller over the CAN bus, providing the 3 phase current for the EMD, providing the control currents for the CES valves, and reading the sensors, such as temperature and position sensors, necessary for control and state detection (**Figure 23**).

Figure 23: Ride height control

On the Audi, the existing air spring ride height control feature will be kept. On the front, this necessitates the integration of the CVSA2 damper in the air spring module. The original damper will be replaced with a CVSA2 damper. The ARB will be replaced with steel and flexible hydraulic lines. The magnetic damper will interface with the wheel arch structure and ARB attachment point on the control arm (**Figure 24**).

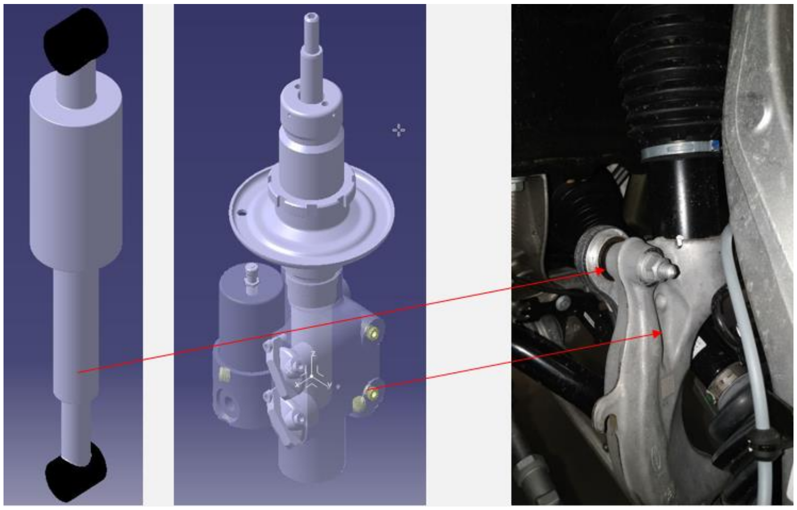


Figure 24: EMD and CVSA2 package Front

On the rear, a similar approach is made, although a bit more simple, since it does not require the integration of the damper in the air spring. Also, here, the EMD will be placed in parallel (**Figure 25**).

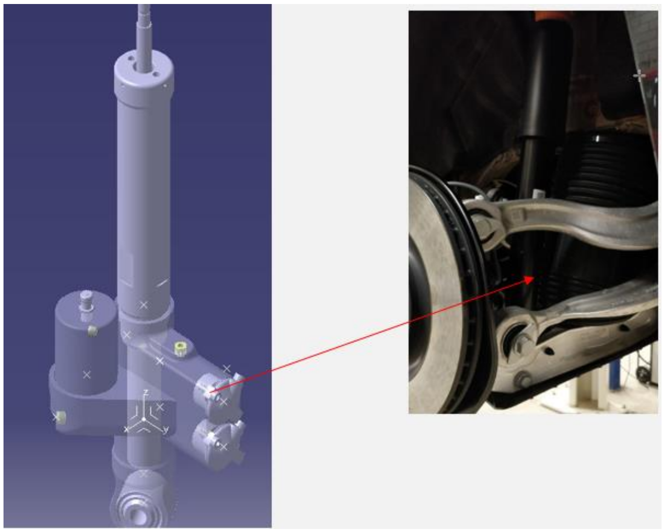


Figure 25: Integration of CVSA2 damper in the rear

4.5 Torque-vectoring and active suspension control

Within EVC1000 USR will provide a torque-vectoring controller with the following features:

- Multi-layer control structure for ease of integration with other controllers, such as: i) the wheel slip controllers for traction and braking developed by TUIL, based on the actuation of the in-wheel motors and friction brakes; and ii) advanced drivability controllers, using the in-wheel motors for the compensation of the longitudinal jerk induced by road irregularities

- Generation of a reference yaw rate that allows a safe vehicle cornering response while reducing the power losses in cornering. The off-line reference yaw rate generation process will account for the electric motor power losses as well as the longitudinal and lateral tyre slip power losses
- Variation of the reference yaw rate as a function of the estimated sideslip angle to keep stable cornering response
- Capability of varying the understeer characteristic, i.e., the graph of steering wheel angle as a function of lateral acceleration, depending on the driving mode selected by the user
- Increased yaw and sideslip angle damping in transient conditions, with respect to the same vehicle with even wheel torque distribution
- Seamless integration of torque-vectoring with the stability control function based on the actuation of the friction brakes (e.g., commercially known as Electronic Stability Program or Electronic Stability Control)
- Ease of integration with the active suspension system by TEN, through a multi-variable control structure to be developed in EVC1000. The suspension controller will vary the front-to-rear anti-roll moment distribution to facilitate the yaw rate tracking control action of the torque-vectoring system

Figure 26 shows a simplified block diagram of the torque-vectoring control structure, including its integration with the active suspension controller. The ‘handling yaw rate generator’ outputs a reference yaw rate suitable for the operation of the vehicle in high tyre-road friction conditions. The ‘sideslip based correction’ modifies the handling yaw rate as a function of the estimated sideslip angle, to account for variable tyre-road friction conditions. The ‘high-level controller’ is based on a multi-variable structure that outputs the total wheel torque demand, reference direct yaw moment and front-to-rear anti-roll moment distribution. Appropriate allocation blocks calculate the reference wheel torque and suspension force levels for the four corners.

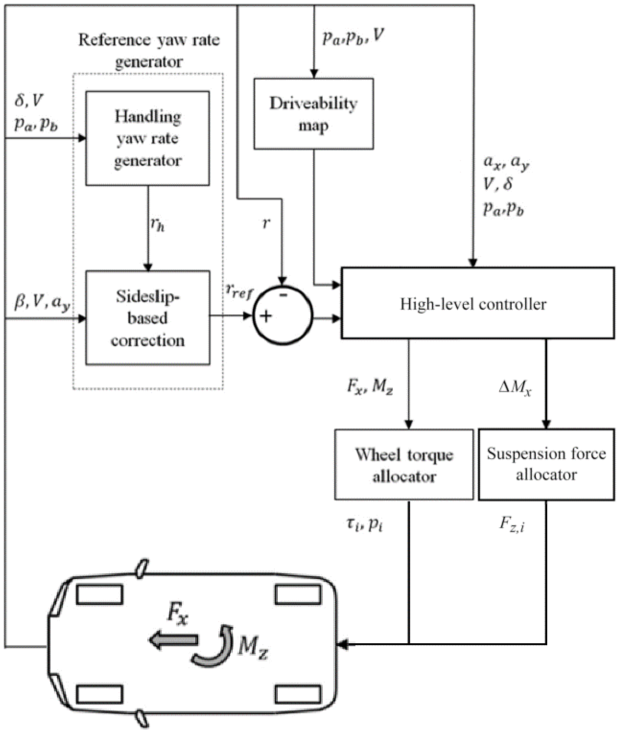


Figure 26: First approximation block diagram of the EVC1000 torque-vectoring and suspension control structure

δ - steering wheel angle; V – vehicle velocity; p_a, p_b – displacements of acceleration and brake pedals correspondingly; r_h – handling yaw rate value; β - sideslip angle; a_x, a_y – longitudinal and lateral acceleration correspondingly; r – actual yaw rate value; r_{ref} – reference yaw rate value; F_x – longitudinal force; F_z – vertical tyre force; M_z - yaw moment; ΔM_X – torque difference.

In EVC1000 energy-efficient understeer characteristics will be designed and implemented, based on the experimentally validated theory developed by the Centre for Automotive Engineering of USR. The preliminary experimental results from the FP7 project iCOMPOSE (see

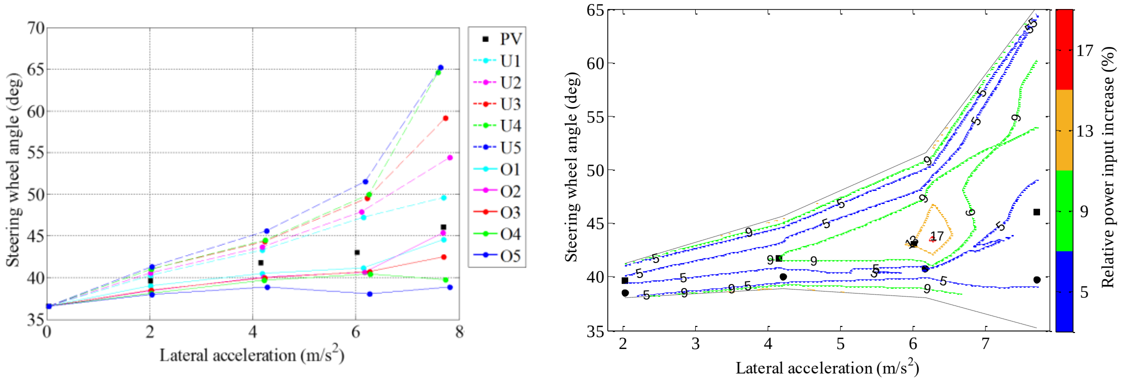


Figure 27) show several percentage points of energy consumption reduction of the optimal configuration (corresponding to the rhomboidal markers in

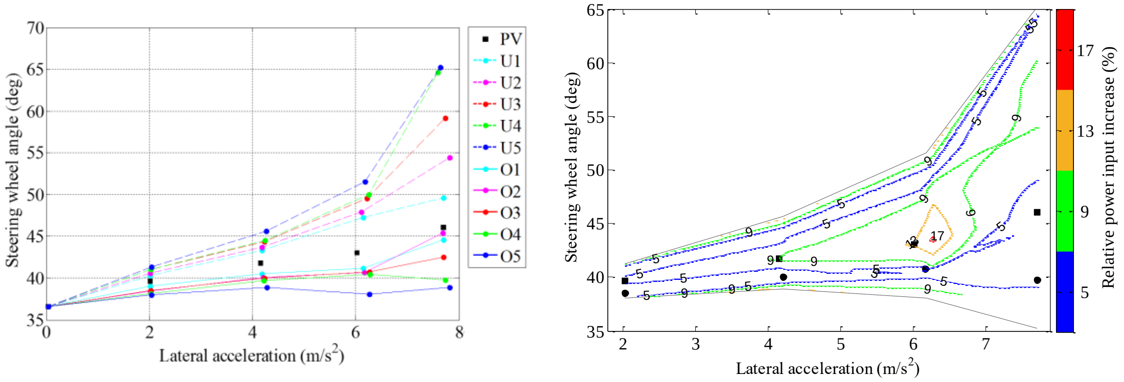


Figure 27, right) with respect to the same electric vehicle with even left-to-right wheel torque distribution (see the squares in

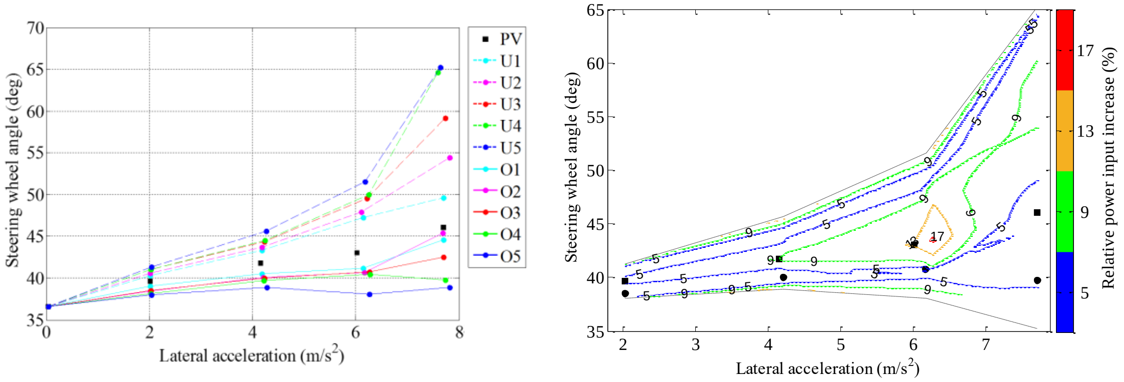


Figure 27, right).

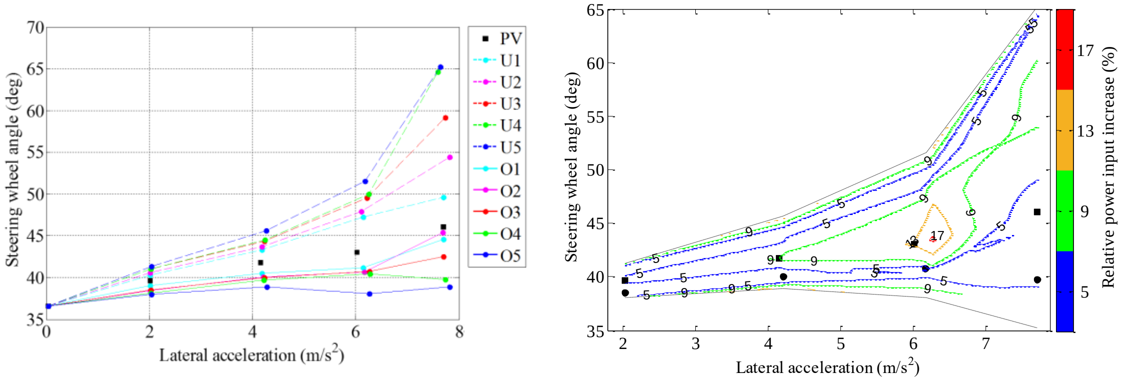


Figure 27: Understeer characteristics of a demonstrator vehicle (left), experimental map of iso-lines corresponding to different relative power input increases (right)

4.6 Wheel slip control

Within the EVC1000 project, a controller is being developed which enables the implementation of safety sub-systems such as antilock braking system (ABS) by BREMBO's Break-by-wire-system and traction control (TC) by ELAPHE's in-wheel motors. Both are concerned with the regulation of the wheel slip, which describes the deviation of the total vehicle speed from the wheel hub speed.

$$\lambda^{ij} = \begin{cases} \dfrac{\omega^{ij} \cdot r_{dyn} - v_{Veh}}{\omega^{ij} \cdot r_{dyn}} \cdot 100\%, & \text{accelerating} \\ \dfrac{v_{Veh} - \omega^{ij} \cdot r_{dyn}}{v_{Veh}} \cdot 100\%, & \text{braking} \end{cases} ,$$

where *i,j* are the wheel indices (front / rear, left / right); ω is the wheel rotational velocity; r_{dyn} is the tyre dynamic radius; V_{veh} is the vehicle velocity; λ is the wheel slip.

This parameter describes the friction between tire and road. On dry asphalt roads, the maximum is reached at 10...15 %. Too high or too low slip leads to a highly decreased tire force transmission and as consequence to this to an unstable behavior of the vehicle. Within the required controller, slip also need to be controlled therefore. The basic structure of the controller is given in Figure 28.

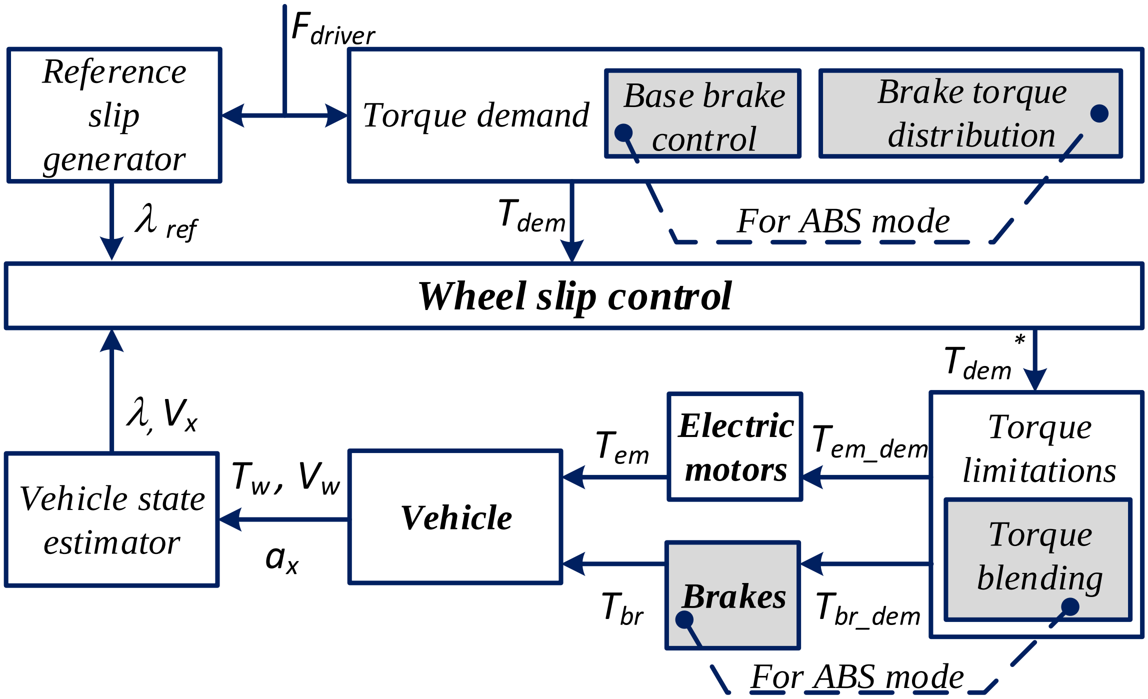


Figure 28 – Block scheme of the integrated controller structure

V_x – vehicle longitudinal velocity; a_x – longitudinal acceleration; λ – actual wheel slip; λ_{ref} – reference wheel slip; F_{driver} – brake pedal force ; T_{dem} – overall brake torque demand; T_{dem} – brake torque demand corrected by the wheel slip controller; T_w – wheel torque*; T_{em_dem} – brake torque demand to be realized by electric motors; ; T_{br_dem} – brake torque demand to be realized by brake system; T_{em} – brake torque from electric motors; ; T_{br_dem} – brake torque demand from brake system.*

As a first approach, a Proportional-Integral controller (PI) will be developed. It serves as reference for the later validation process. By using a linear structure, the control formula equals to:

$$T^{ij}(\lambda^{ij}\ \lambda_{ref}) = K_p \left((\lambda^{ij} - \lambda_{ref}) + \frac{1}{T_I} \int (\lambda^{ij}(\tau) - \lambda_{ref}(\tau))\, d\tau \right) = K_p \left(\lambda_e + \frac{1}{T_I} \int \lambda_e(\tau)\, d\tau \right),$$

where λ_e is the wheel slip error; K_p is the proportional gain; τ is the time variable; T_i is the time component of integral gain.

For better dynamical behavior, the variable structure approach is used, so the controller can switch between different gains in dependency if the reference slip is higher or lower than the real one. Because the slip isn't measurable directly, an additional vehicle state estimator must be implemented.

Secondly, a continuous approach is going to be used. This means an adaption to Integral Sliding Mode control (ISMC).

For ongoing validation activities, chosen performance tests (see **Table 10**) will be done within the project and evaluated in regard of the following indicators:

- **Brake distance**
- **Average brake deceleration** during the braking maneuver
- **ABS performance index** as ratio between the deceleration of the vehicle with and without ABS
- **Average wheel slip** during the braking maneuver
- **Average ABS frequency** during the braking maneuver
- **Peak-to-peak value** - assessment of the peak value of the wheel velocity on the first ABS cycle that can be numerically expressed as
- **Integral absolute value of the error (ITAE) of vehicle jerk** with reference jerk value set to zero

Table 10: Exemplary test scenarios for braking performance with and without brake safety assistance

No.	Description	Tests on MIL/HIL	Tests on car
Straight-line braking			
1.	Braking on dry road (μ = 0.8…1.0) from 60 and 90 km/h. [1] Brake actuation by the driver. With and without ABS.		x
2.	Braking on dry road (μ = 0.8…1.0) from 60, 90 and 160 km/h [2] Brake actuation by the brake robot. With and without ABS. Brake pedal velocity 50, 100, 200 and 500 mm/sec. c)	x	
3.	Braking on low friction road (μ = 0.2…0.4) from 40 and 60 km/h. Brake actuation by the driver. With and without ABS.		x
4.	Braking on low friction road (μ = 0.2…0.4) from 40 and 60 km/h. Brake actuation by the brake robot. With and without ABS.	x	

---

[1] v = 60 km/h and 90 km/h in accordance with ECE 13; v = 30 km/h - for additional estimation of brake pedal feel.

[2] v = 160 km/h (80% from vmax of Range Rover Evoque) only during MIL/HIL tests.

	Brake pedal velocity 50, 100, 200 and 500 mm/sec. [3]		
Split-µ braking			
5.	Braking on split-µ road (µ = 0.8…1.0 on the left side and µ = 0.2…0.4 on the right side)[4] from 40, 60, and 90 km/h. Brake actuation by the driver. With and without ABS/VDC.		x
6.	Braking on split-µ road (µ = 0.8…1.0 on the left side and µ = 0.2…0.4 on the right side)[4] from 40, 60, and 90 km/h. Brake actuation by the brake robot. With and without ABS/VDC. Brake pedal velocity 50, 100 and 200 mm/sec.	x	
Dynamic testing of brake pedal feel			
7.	Pulsating actuation of the brake pedal by the brake robot. Operating points [5]: 15, 40, and 120 bar. Frequencies: 0.1, 0.5, 1, 2, 5, 10 and 15 Hz	x	x

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[3] Brake pedal velocities are chosen in accordance with typical test procedures using the brake robot.

[4] Variation of µ is possible depending on available test facilities.

[5] Operating points and frequencies can be corrected after the preliminary testing of brake pedal feel functions.

Bibliography

[1] https://www.theguardian.com/environment/2017/dec/25/norway-leads-way-electric-cars-green-taxation-shift

[2] ERTRAC, EPoSS and ETIP SNET, European Roadmap Electrification of Road Transport, 2017.

[3] De Filippis, G., Lenzo, B., Sorniotti, A., Sannen, K., De Smet, J., Gruber, P., On the energy efficiency of electric vehicles with multiple motors, *Vehicle Power and Propulsion Conference (VPPC)*, 2016.