Innovative e-Machine and Power Electronics Solutions for e-Axle and e-Corner Vehicle Powertrains

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ABSTRACT: The Horizon Europe EM-TECH and HighScape projects address innovative solutions for automotive electric powertrains, to achieve higher energy efficiency, reduced volume and mass, as well as reduced cost. The two projects are distinct yet complementary and synergic, where the former focuses on electric machines (e-Machines), while the latter on wide bandgap (WBG) based power electronics (PE). This paper outlines the main innovations of EM-TECH and HighScape, targeting a wide range of vehicle applications, including passenger cars and commercial vehicles. Specifically, EM-TECH deals with: i) modular designs of on-board axial flux machines (AFMs) for reducing the implementation costs of scalable centralised powertrains for electric axle (e-Axle) solutions; ii) in-wheel motors (IWMs) integrated with electric gearing, for expanding the high efficiency region of electric corner (e-Corner) powertrains; and iii) the use of permanent magnets deriving from recycling processes to improve sustainability. In parallel, HighScape targets the physical and functional integration of the PE of WBG based traction inverters, onboard chargers, DC/DC converters, and electric drives for auxiliaries and actuators.

KEY WORDS: electric machines, in-wheel machines, on-board axial flux machines, electric gears, wide bandgap-based power electronics

1. Introduction

The Horizon Europe topic CL5-2022-D5-01-09, "Nextgen EV components: High efficiency and low-cost electric motors for circularity and low use of rare resources (2ZERO)", targets the advancement of electric machines (e-Machines) for the core road vehicle market (with powertrains of 50-120 kW continuous power), to achieve high efficiency, power/torque density, and sustainability. In parallel, the complementary Horizon Europe topic CL5-2021-D5-01-02, namely "Nextgen EV components: Integration of advanced power electronics and associated controls (2ZERO)", aims at promoting wide bandgap (WBG) technologies (SiC, GaN, and beyond) for the implementation of vehicular power electronics (PE) solutions. In fact, the recent introduction of WBG semiconductors requires further effort for their integration into new powertrain architectures and systems, targeting the 800V voltage class. Innovative, compact and integrated powertrain solutions will enable economies of scale, increase packaging flexibility, reduce energy consumption, increase user's acceptance, and facilitate the path towards the mass-production of new electric vehicle (EV) architectures with multiple distributed electric drives.

In this context, the project *Innovative e-Motor technologies covering e-Axle and e-Corner vehicle architectures for highly efficient and sustainable e-mobility* (EM-TECH) targets the topic CL5-2022-D5-01-09 with the following objectives: i) increasing the primary efficiency of electric traction machines, namely to achieve 35% energy loss reduction for direct drive in-wheel machines (IWMs) for electric corners (e-Corners), and 25% energy loss reduction for on-board (OB) axial flux machines (AFMs) for electric axles (e-Axles), with respect to (w.r.t.) current state-of-the-art (SoA) e-Machines with the respective topologies, during realistic driving cycles; ii) increasing the torque density and specific torque of IWMs, to achieve >150 Nm/L and >50 Nm/kg; iii) increasing the power density and specific power of on-board AFMs, to obtain >30 kW/L and 10 kW/kg; iv) achieving production costs of <6 Euro/kW for IWMs and 5 Euro/kW for AFMs (assuming >100k yearly units); v) facilitating circularity solutions, resulting in >60% reduction in the use of rare earth resources; vi) implementing a model-based toolchain for digital twinning and X-in-the-loop (XiL) testing; vii) demonstrating novel functionalities at the vehicle level, e.g., electric gearshift layouts and enhanced anti-lock braking system function based on e-Machine torque modulation.

The parallel project *High efficiency, high power density, cost effective, scalable and modular power electronics and control solutions for electric vehicles* (HighScape) contributes to CL5-2021-D5-01-02, by targeting: i) scalable WBG based PE components, with so far unexplored levels of functional integration in IWMs, battery systems, and auxiliaries / chassis actuators; ii) improved power density, resulting in >100 kW/L and >80% reduction of component volume w.r.t. existing Si based solutions; iii) enhanced energy efficiency (up to 99%), and thermal management of the resulting PE components; iv) >35% production cost reduction w.r.t. the available WBG based PE products and prototypes; v) improvements in functional safety, fault-tolerance, predictive maintenance, and electro-magnetic interference (EMI) and electro-magnetic compatibility (EMC) performance; and vi) the implementation of holistic simulation based design and validation approaches.

This paper focuses on a few highlights of the activities that EM-TECH and HighScape, sharing a significant number of consortium participants, will carry out in the next 2.5 years, and outlines the respective innovative solutions for e-Machines and PE. For example, in EM-TECH, the conservativeness in the sizing, rating, and amount of rare earth materials during e-Machine design will be relaxed by direct and active cooling, virtual temperature sensing, and enhanced machine control during operation. Life cycle analysis will be employed for costing evaluation and circularity of e-Machines. An electric gearing system will be realised by reconfiguring the multi-phase stator windings of IWMs for low-speed/high-torque or high-speed/low-torque operation. In HighScape, highly efficient WBG based PE components will be physically integrated in the battery pack and IWMs to achieve zero footprint in the vehicle sprung mass. The number of parts will be reduced through functional integrations. Phase changing materials will be employed as heat buffers, and optimised thermal paths will be designed within the PE. For the drives of critical auxiliaries and chassis actuators, multi-motor inverter topologies will be evaluated, to reduce the count of switches and achieve fault tolerance.

By the end of the projects, representative solutions will be prototyped and tested on component rigs and/or vehicle demonstrators, and their scalability to wider vehicle segments will be validated through hardware-in-the-loop (HiL) or model-in-the-loop (MiL) simulations.

2. Innovative e-Machine solutions

Car makers are racing to convert electrical power into mechanical power through more and more efficient, compact and lightweight e-Machines, e.g., see the examples of motors of production vehicles – and their characteristics – in the recent review paper [1]. The EM-TECH consortium is willing to contribute to such a challenge, as its members are convinced that there is still a relevant innovation potential to be unleashed, by proposing the design optimisation of two motor topologies, namely in-wheel direct drive radial flux and on-board axial flux permanent magnet machines. EM-TECH brings together 10 participants from industry and academia to develop novel solutions to push the boundaries of electric machine technology for automotive traction.

2.1. Workflow

A model-based design routine will be followed. To this purpose, initial multi-domain representations of the e-Machine will be implemented. The electrical and thermal physics will be coupled through finite element and computational fluid dynamics approaches. The models will serve as a workbench for: i) performance evaluation in the mechanical and electrical domains; ii) accurate representation of the power loss distribution; iii) realistic representation of the coolant flow; and iv) reliable reproduction of the temperature behaviour. A workflow diagram of the modelling approach is presented in Figure 1. The coupled multi-physics models will yield reliable output in terms of electromagnetic, thermal, structural and NVH (noise, vibration, and harshness) performance. The models will be used for the initial design of the electric gear systems, thermal cooling solutions, as well as for the virtual sensing algorithm setup and tuning. The models will have increasing complexity, starting from a 2-dimensional approach that can be enhanced into 3-dimensional representations to account for specific aspects, such as end turns, cooling, and fault behaviour. The e-Machine models will also be interfaced with vehicle models, for the assessment of the machine energy loss along realistic driving cycles, and to tailor the motor design to the operating characteristics of the specific EV application.

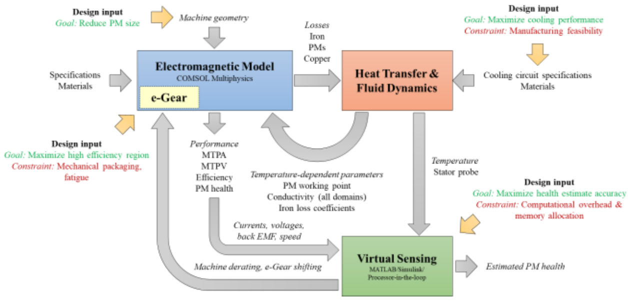

Figure 1. Multi-physics modelling workflow.

2.2. In-wheel machines

EM-TECH will carry out a simulation-based optimisation of the baseline L1500 e-Machine unit by Elaphe, one of the EM-TECH participants, characterised by 1500 Nm peak torque, 1670 rpm maximum speed, 45 Nm/kg specific torque, 114 kW peak power, and 3.4 kW/kg specific power.

Moreover, the consortium will design an innovative system with two electric gears. This will significantly contribute to the efficiency improvement of the e-Machine, by extending its high-efficiency operating region, see Figure 2, through winding reconfiguration. Previous work by Oak Ridge National Laboratory [2]-[3] suggested a solution based on five antiparallel thyristors (1600V/120A at ~20 € each, or 1600V/240A at ~40€ each). However, this type of semiconductor-based switching system would be difficult to realise for less than 200€, in terms of power electronics alone, without considering control circuitry or cooling.

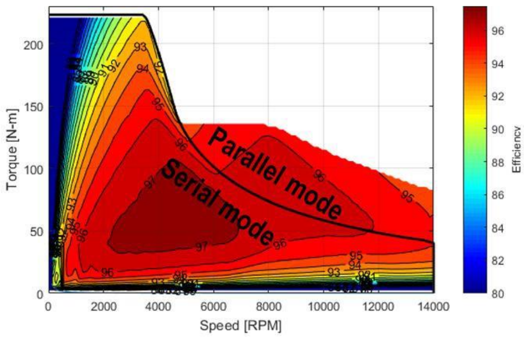

Figure 2. Combined efficiency map of an e-Machine with electric gear system, from Oak Ridge National Laboratory [3].

The EM-TECH 2-speed electric gear concept exploits a mechanical switching system as working principle. This offers a feasible route to achieve the cost requirement and extend this technology through the mainstream market of automotive applications. One of the key challenges in the mechanical design will be to achieve low electrical resistance between the switch contacts, without excessive mechanical clamping force. As well as traditional flat contacts, a variety of alternative solutions will be investigated, including conical contacts and lamellar contacts. The electric gearshift will unavoidably add cost to the system if all other parts remain unchanged. However, by developing and demonstrating a mechanical solution with a single actuator, it is expected that the cost will be considerably less than that of alternative solutions, such as solid-state semiconductor implementations or mechanical transmissions. In contrast, the mechanical switching setup uses widely available materials and inexpensive manufacturing techniques. Thus, it poses excellent potential for cost optimisation, either by downsizing the machine, which reduces usage of high-value magnetic materials, or by downgrading the PE in the inverter to lower current ratings.

2.3. Modular axial flux machines

Table 1 reports examples of SoA e-Machines for EVs. Axial flux configurations (Yasa, Magnax) can bring significantly higher performance in comparison to the established radial flux motor implementations currently available on the market (e.g., those of the Volkswagen ID.3, BMW i3, and Tesla Model 3). Recent advances in AFMs have been presented in the literature [4]-[5], and further improvements have been demonstrated by the EM-TECH participants (in particular, by Vaionic Technologies) prior to the project kick-off, thanks to the proof-of-concept introduction of ground-breaking innovations, namely:

- Iron-less stators, leading to: i) the absence of iron losses, which are typically dominant in driving cycles, such as the WLTP (Worldwide Harmonised Light Vehicle Test Procedure); ii) reduced bearing losses, because of the minimal axial forces; and iii) NVH improvements, due to the decreased torque ripple and acoustic noise.
- Internal water direct cooling, which is expected to be highly effective in avoiding derating effects, and thus improving efficiency (>97%, see Figure 3) and specific power (10.4 kW/kg).

To make the baseline Vaionic AFM solution mature for many use cases across vehicle types and segments, the EM-TECH project will pursue four crucial improvements: i) the development of a scalable design methodology; ii) the introduction of a Halbach array permanent magnet (PM) configuration to improve the flux density; iii) the use of PMs deriving from recycling processes, and implementation of the corresponding life cycle assessment (LCA); and iv) virtual sensing of PM temperature. iii) and iv) are being carried out with a methodological approach that is applicable also to the EM-TECH IWMs.

Table 1. Characteristics of state-of-the-art on-board e-Machines for EVs, and the proposed EM-TECH solution by Vaionic.

	VW ID.3	BMW i3	Tesla Model 3	YASA R400 P	MAGNAX AXF 250	Vaionic
Topology	Radial flux	Radial flux	Radial flux	Axial flux	Axial flux	Axial flux
Iron-less stator	No	No	No	No	No	Yes
Mass (kg)	40	46 (w/o housing)	47	28	25 (w/o housing)	24
Cont. power (kW)	60	75	100	100	n.d.	250
Cont. specific power (kW/kg)	1.5	1.6	2.1	3.5	n.d.	10.4
Maximum speed (rpm)	16,000	12,000	18,000	8,000	12,00(	20,000

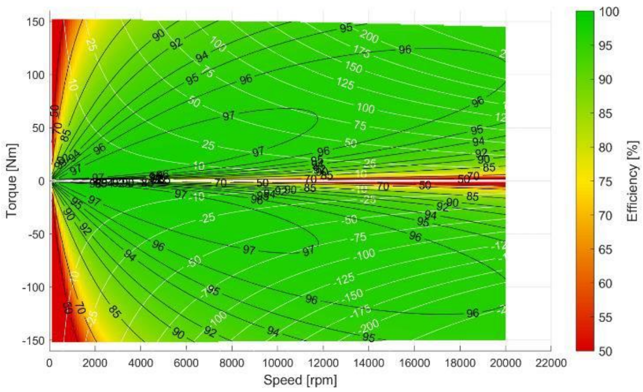

Figure 3. Example of efficiency map of an AFM unit by Vaionic Technologies.

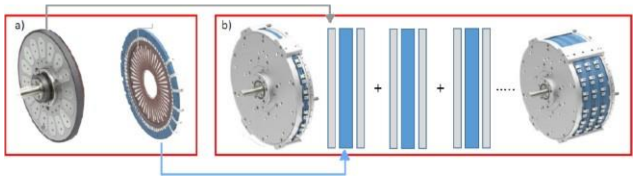

Figure 4. Modular approach of the EM-TECH AFMs: a) rotor and stator; and b) single-module and multiple-module (up to 5) arrangements.

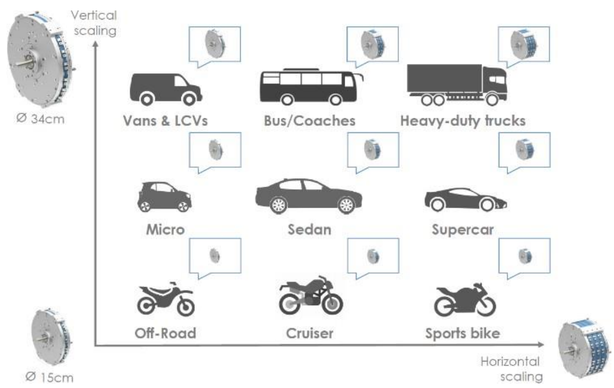

Figure 5. Vertical and horizontal scalability of the EM-TECH AFMs to comply with the market needs.

The EM-TECH AFM concept is based on a single stator and double rotor configuration (Figure 4), which opens the route to the development of a scalable design methodology (from 1 to 5 modules) able to comply with high performance requirements (continuous specific power of 10.4 kW/kg) and low-cost expectations, since the bill of materials and number of individual parts are reduced. Preliminary investigations show that the e-Machine combinations resulting from 3 sets of diameters and up to 5 modules allow covering the zero emission powertrain requirements of a very wide range of road vehicles (Figure 5).

The considered ironless solution requires 1.3 kg of NdFeB PMs per module (for the largest diameter case) to achieve the targeted specific power value. To satisfy the Horizon 2020 call requirements in terms of rare resources reduction, EM-TECH will – among several other improvements – implement the Halbach array magnet configuration [6] to create a stronger magnetic field on one side of the array (in the axial direction for the AFM), while nearly cancelling the field on the other side. The use of Halbach array PMs obtained from a recycling process will further reduce the environmental impact.

2.4. Direct cooling and virtual sensing

Accurate thermal management is essential during critical operating/driving conditions, to avoid failures that are usually caused by local hotspot formation, and material degradation. In this respect, magnetic losses and heat generation govern the electromagnetic efficiency performance, and determine life expectancy. In fact: i) excessively high temperatures can cause accelerated insulation aging and deterioration within essential components, such as the winding conductors; ii) the electrical resistivity of the winding conductors is directly proportional to temperature; iii) the remanence and coercivity of PMs are inversely proportional to temperature; and iv) partial or full demagnetization may occur at high temperatures. In case of recycled PMs, lower rotor temperatures may significantly boost the torque density and efficiency of the e-Machine, as the remanence sensitivity of these PMs to the temperature is 200%-to-300% higher than for conventional rare earth PMs.

In EM-TECH, disruptive improvements will be achieved through multiple solutions based on direct liquid cooling slots in the stator lamination, cooling slot channels, and wet stator cooling. Each of them has a strong impact on the mechanical layout, packaging, and manufacturing process of the motor. In the case of the EM-TECH IWMs equipped with the mechanically actuated electric gear system, coupled interactions are stronger, and a multidisciplinary approach based on systematic optimisation will be used for exploring slot- and iron-embedded technologies. Manufacturing aspects will also be accounted for, which are identified as an important challenge for effective practical implementation (insulation, packaging, connectors, etc.).

Concurrently with the hardware optimisation, real-time measurements and estimates of key electrical and mechanical quantities, i.e., voltage commands, phase currents and DC-link voltage signals, back EMF (electromotive force), torque and speed, together with the temperatures in key stator locations, will be used for the real-time prediction and monitoring of the temperature distribution within the PMs. The impacts are significant as: i) the accurate estimation of PM temperature allows for a more effective use of the material in limit conditions; and ii) timely derating can be applied, and safety factors will be limited to a minimum, thus enabling the possibility of using lower-grade, lower-performance, or recycled PMs.

In this area, past research efforts have been focusing on state observers. To overcome the drawbacks of model based techniques, in EM-TECH novel artificial-intelligence (AI) based approaches will be developed and implemented, to guarantee fast execution times and adaptability to multiple input signal combinations. Unsupervised and supervised learning will be compared to yield robust solutions able to respond to variable working conditions, including transients of the electrical, mechanical and thermal variables. At the same time, EM-TECH will address the efficient integration of these algorithms onto conventional digital signal processors for motor control.

In EM-TECH, virtual sensing will enable a more compact footprint of the e-Machine, and its power capability to be exploited to its limits. A PM mass reduction will be possible by means of more effective exploitation of the rotor PM materials. In particular, dysprosium, which defines the coercivity level and temperature grade of NdFeB magnets, can be drastically reduced if the thermal conditions are monitored in real-time and stabilised via direct cooling through the EM-TECH methodologies. Thereby, materials with lower coercivity and higher remanence will be evaluated and used for the e-Machine prototypes.

2.5. Sustainability

The EM-TECH e-Machine innovations will be strongly supported by an in-depth environmental impact assessment to demonstrate ecological advances. Recyclability will address PMs [7]-[8] (dysprosium and neodymium), copper windings (copper), stator lamination (silicon), terminals (copper), and electronic controller (copper, rare earths). A procedure addressing collection, disassembly, dismantling, recycling and recovery will be designed, to avoid sub-optima in the overall recycling chain. The resulting workflow will combine reuse, mechanical recycling, and element recovery technologies, to achieve an economic process and overall sufficient recycling rate. A mass and energy balance starting from the collected materials down to recovered valuables and including reuse and recycling will be set up, to illustrate the effort and estimated costs. This also includes process models for individual stages. The outcome of the mentioned methods and procedures will be used to provide data for an LCA. The LCA concept will consider the assessment from the cradle, through manufacturing and assembly, transport, use and maintenance, to the grave.

3. Innovative power electronics solutions

3.1. Physical and functional integration

The main concept of HighScape is to demonstrate a high level of physical and functional integration of the WBG based PE parts and components, in EV architectures with IWMs. In the conventional approach to PE for EVs, the following independent components, implemented in the form of separate physical devices, are present: i) the e-Machine/s; ii) the traction inverter/s; iii) the on-board-charger (OBC); iv) the DC/DC converter (e.g., 800V-12V) for the auxiliaries; v) the high-voltage (HV) battery; and vi) the low-voltage (e.g., 12V) battery.

The HighScape solution only includes two or four IWMs (depending on the two- or four-wheel-drive nature of the specific EV) and an integrated HV battery, i.e., all PE components are physically incorporated into these two major building blocks, with the potential exception of the filter towards the grid, at a level never seen in any previous EV implementation. Also, from a functional perspective, the PE parts are used for multiple purposes whenever possible, across the IWMs and HV battery, with major benefits in

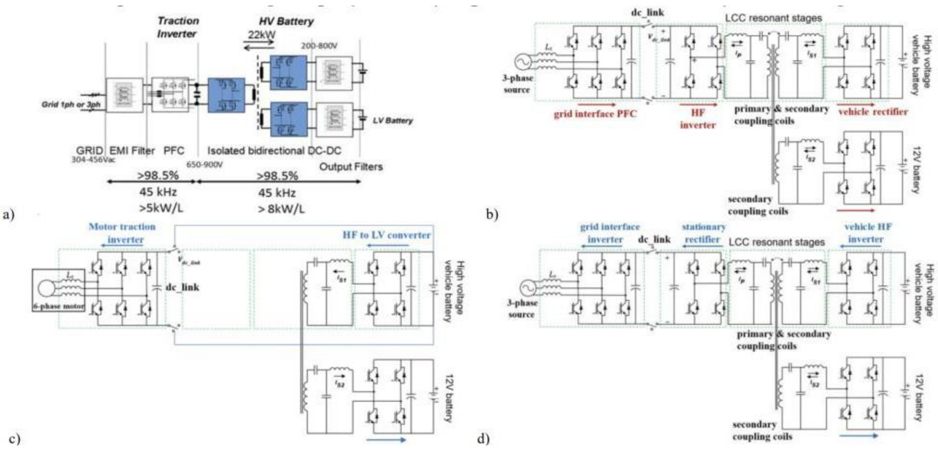

Figure 6. The HighScape integrated PE architecture concept (a), and its three operating modes (b-d).

terms of cost as well as power density and specific power, since the “overhead” parts disappear. Major simplifications will be implemented in terms of physical connection between the components, as the HighScape system only requires 2 wires from the battery to each integrated IWM. Figure 6a) is the schematic of the HighScape PE concept; more specifically:

- The OBC, traction inverter and accessory DC/DC converter will be functionally integrated, with significant cost reduction and major power density increase, thanks to a substantial reduction of the number of components, and the replacement of the Si-based power modules with the WBG equivalents (SiC and/or GaN), enabling higher switching frequencies and temperatures.
- The galvanically isolated integrated OBC will be implemented by using the SiC power MOSFETs of one of the traction drives, with the coils of one of the IWMs that are “re-used” as boost inductors. The dual-active full-bridge converter is placed within the battery, as this is the converter that adapts the voltage and current needed to charge the battery from the DC voltage created by the PFC (power factor conversion) circuit, which consists of the traction drive components. The transformer of the high voltage converter will be designed to also enable a conversion to a much lower voltage, and create the charger function for the 12V battery and accessory circuits. For vehicles with a 48V structure, a separate 48V DC outlet will be added. This system can also be used in vehicle-to-grid implementations, e.g., the battery can be deployed in a smart grid energy storage device supplying power to the grid during peak hours.
- The EMI filters for the grid inlet, 3-phase or 1-phase, will be placed close together to enhance the system packaging.
- The traction motor will have the inverter as well as the PFC circuit of the on-board-charger incorporated in some of the existing cavities in the IWM housing, while all the other PE components will be incorporated in the battery pack. Such integration technology will be developed with focus on IWMs, which will allow a significant volume saving in terms of PE components on the sprung mass of the vehicle. This will result in enhanced flexibility of the volume utilisation within the EV, including additional space for passengers and luggage, as well as reduced turning radius.
- The DC/DC converter from the DC-link to the HV battery and the DC/DC converter from the HV battery to the 48V–12V system for the auxiliaries will be using the same transformer with 3 outlets, which will be fully isolated from each other.

The integration of OBC, DC/DC, motor unit and battery will enable sharing of: i) housing, wires, and connectors; ii) passive and active components; iii) sensors, processors, gate drivers, voltage supply, and transceivers; and iv) cooling system. The result of the integration of the DC/DC part of the OBC with the battery system will bring cost savings, system size reduction, efficiency improvement, and power density increase (by ~2 kW/L).

Table 2. Main characteristics of a sample of traction inverters in current use, the expected performance levels according to US and UK roadmaps, and the HighScape project ambition.

Model/roadmap	Vehicle or motor type	DC-link (V)	Power (kW)	Power density (kW/L)	Specific power (kW/kg)
Nissan Leaf (2012)	EV	345	80	7.1	4.7
Tesla Model S (2015)	EV	375	193	30.1	33.3
Chevy Volt (2016)	PHEV	430	180	17.3	21.7
Toyota Prius (2016)	HEV	600	162	23.7	13.6
Audi A3 e-Tron (2016)	PHEV	396	75	9.4	7.4
Tesla Model 3 (2017)	EV	375/400	200	n.d.	n.d.
Yasa (Si400)	OBM[1]	400	n.d.	17	14
EDRIVE H300	OBM[1]	450	n.d.	14	14
XPT	OBM[1]	425	n.d.	8	6.4
US DRIVE (2025)[2]	EV	n.d.	100	100	n.d.
UK Auto Council (2025)	EV, PHEV	400	100	25	20
HighScape ambition	IWM	800[3]	40-120 x2 or x4	≥100[4]	≥60[4]

[1]OBM: on-board e-Machine; [2]This level of performance is expected from prototypes in laboratory testing conditions; [3]Value of the experimental HighScape implementations, which will be focused on 800V, and scalable to 400V and 1200V; [4]To be verified on the HighScape EV demonstrators

The integrated system operates in three modes:

Mode 1: charging the HV battery from a 3-phase or 1-phase grid, see Figure 6b). The grid voltage is converted (boosted) in an interleaved way by using the SiC MOSFETs and coils integrated in one of the IWM units towards the DC-link (at ≥800V). The DC-link voltage is then isolated and converted into the battery voltage through a line level control (LLC) resonant converter. Also, the battery or DC-link voltage is converted towards the 12V battery for the EV auxiliaries.

Mode 2: battery-to/from-motor operation, i.e., with power flow from/to the HV battery to/from the 6-phase IWM units. In this mode the battery is supplying or receiving power to/from the traction inverters while the HV system is also charging the 12V battery and supplying power to the accessory units, see Figure 6c). This is the operating mode during vehicle driving.

Mode 3: battery-to-grid, i.e., from the HV battery to a 3-phase grid. In this mode the HV battery is supplying power to the grid while it is charging the 12V battery and supplying power to the accessory units (12V and/or 48V), see Figure 6d). This is the standard operating mode for vehicle-to-grid connection.

As a summary, Table 2, adapted from [9], reports the main characteristics of examples of SoA production traction inverters used in recent EVs, hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs), or to be coupled with generic electric machines for automotive traction, together with the 2025 expectations of recent PE development roadmaps (by US DRIVE and the UK Automotive Council), as well as the HighScape ambition.

3.2. In-wheel machines with electric gearshift based on semiconductor switches

Whilst the EM-TECH electric gearshift solutions will adopt mechanical switches because of cost-related reasons, in HighScape, thanks to the significant integration and reuse of PE for multiple purposes, the overall cost reduction could justify an electric gear system with semiconductor switches.

HighScape will adopt and optimise one of the possible reconfiguration architectures, and will incorporate it within the IWM units, with focus on the optimisation of the number and size of PE modules, the number of motor coil groups, the torque/speed range, and the cost and weight/size of the system. The reconfigurable HighScape in-wheel PE concept will combine the electric gearshift capability during motoring with the OBC functionality of the baseline HighScape PE architecture, and include at least three operating modes: i) electric gear 1, for low-speed and high-torque operation; ii) electric gear 2, for high-speed and low-torque operation; and iii) battery charging. A potential suitable architecture is suggested in Figure 7. HighScape will also evaluate solutions with more than two electric gears.

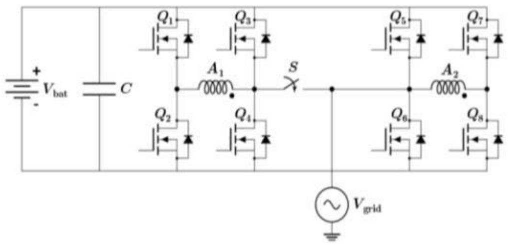

Figure 7. Example of PE architecture for reconfigurable winding arrangement.

3.3. Power electronics for auxiliaries and chassis actuators

Despite their relatively low power rating w.r.t. the traction inverter, auxiliaries (e.g., cooling pumps) and electrified chassis actuators, e.g., suspension ride height actuators and electro-mechanical brake actuators, are associated with a non-negligible power use and impact on mileage in real EV use, with peak power ratings that can reach 10 kW in modern EVs, e.g., for active suspensions, which can also include energy harvesting capability. Some of these systems include multiple identical actuators within the same axle, which is the case of electro-mechanical braking or ride height systems, and faults of individual drives can give origin to safety-critical conditions. For the PE of auxiliaries and chassis actuation systems, a distributed approach is conventionally used, where each drive is embedded in the respective motor, separately from the other motors and drives.

In this area, HighScape will replicate the high level of system integration achieved in the PE of the traction inverter, OBC and DC/DC, and will make generalised use of GaN MOSFET based PE, with gate drivers integration on the same silicon as the switches. The resulting 48V PE components will be installed on the HighScape demonstrator vehicles, e.g., to actuate existing ride height actuators, and their efficiency implications will be experimentally measured. Depending on the actuation system and its specific requirements, three levels of integration will be evaluated:

- Inverter modules spatially integrated, i.e., with shared DC-link, cooling system, sensors, micro-controller, package, etc., but with separate switches. This reduces cost and volume, and slightly improves reliability while keeping performance, without any new limitation.
- Multi-motor inverter topologies with reduced switch-count, i.e., including integration of the switches, see the shared leg (SL) and shared arm (SA) topologies in [10] and Figure 8, which can be applied to any number of motors, potentially increasing power density and reliability, while reducing cost, despite having some drawbacks – to be carefully assessed in HighScape – in terms of respective switch currents, frequencies, or resulting voltages.
- Multi-motor inverter topologies with reduced switch-count and fault-tolerance. Realising a fault-tolerant multi-motor system in the conventional way is costly, as redundant PE parts are needed for each of the drives, see Figure 9a). With a multi-motor drive some of the components may be shared. For example, the SL topology can be made fault-tolerant through a single redundant leg, which, for two-motor systems, can give origin to the conventional-combined to single leg topology (CCtoSL) in Figure 9b), or the leg-redundant conventional-combined (LR-CC) topology in Figure 9c), see the detailed assessment in [11].

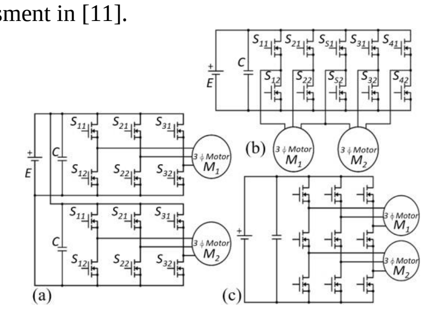

Figure 8. Multi-motor inverter topologies: (a) Conventional; (b) SL; and (c) SA.

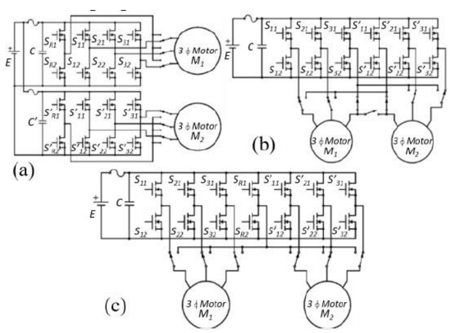

Figure 9. Fault-tolerant multi-motor inverter topologies: (a) Conventional; (b) CCtoSL; and (c) LR-CC.

4. Vehicle level control functions

Given the absence of the drivetrain torsional dynamics and mechanical plays, direct drive IWMs can provide significantly higher wheel torque responsiveness and bandwidth than typical on-board powertrains, as well as more accurate wheel torque actuation. It is estimated that the new EM-TECH and HighScape IWM drives will have a rise time of less than 10 ms for a step torque demand. The achievable IWM responsiveness in terms of electro-magnetic torque, together with the torque-to-mass-moment-of-inertia ratio and torque ripple of the e-Machine, will be carefully assessed and tuned during the projects, and will be exploited to explore new functionalities at the EV level.

For example, the new IWMs will provide faster dynamic response than conventional friction brake actuators, and therefore could be adopted for anti-lock braking system (ABS) torque modulation. During ABS events, the friction brakes would provide only the low-frequency component of the braking torque, differently from the current ABS implementation practice. This idea has been mentioned and preliminarily assessed in the past in a proof-of-concept analysis by Toyota [12], see the qualitative schematic in Figure 10, but it has never been systematically implemented, also for the lack of IWMs meeting the industrialisation requirements for passenger cars, which will be covered by EM-TECH and HighScape. During ABS actuation, the bottom plot of Figure 10 shows that, for vehicles equipped with IWMs, the braking torque fluctuations could be mostly generated through the powertrains. On the contrary, the conventional ABS actuation method, in the top plot of Figure 10, deactivates or significantly reduces the regenerative braking torque component during ABS modulation. The result of the IWM-based ABS function is a potentially significant reduction of the stopping distance (7% in very low tyre-road friction conditions according to [12]). Similar benefits could be achieved during traction control operation. In parallel, tire-road friction preview for wheel slip control, which could be achieved through future vehicle-to-everything (V2X) implementations, will be evaluated, according to the initial promising study in [13], focused on sudden variations of the friction coefficient during longitudinal acceleration tests.

Also other innovative functionalities will be implemented. For example, these will include pitch control through front-to-rear motor torque distribution, comfort- and energy-efficiency-oriented electric gearshift control, and innovative drivability control. W.r.t. the last function, in the simulations of Figure 11, the modulation of the IWM torque is used to dampen the longitudinal vehicle body acceleration oscillations caused by the road irregularities. The control action is computed by an online optimisation based on a complex nonlinear prediction model (i.e., implicit nonlinear model predictive control). The information of the vertical road profile ahead, gathered by a road scanner, is used in the preview version of the controller, and allows to almost cancel the acceleration oscillations, compared to the controller without preview and the passive vehicle. In this respect, a preliminary simulation study has been presented in [14]. Within HighScape and EM-TECH, a first proof-of-concept experimental implementation will be assessed.

Another technique that will be further developed and experimentally evaluated on the HighScape vehicle demonstrators with the considered IWM drives is the so-called Pulse-and-Glide (PnG, Figure 12). The desired vehicle speed, e.g., during the operation of the cruise controller, is realised by modulating the machine torque between an approximately zero level and an optimal torque derived from the analysis of the powertrain efficiency characteristics at each motor speed, see the preliminary study in [15]. By exploiting this technique, up to 5-7% power use reduction was achievable with negligible disturbance of the occupants' comfort, for the electric quadricycle prototypes of the Horizon 2020 project STEVE.

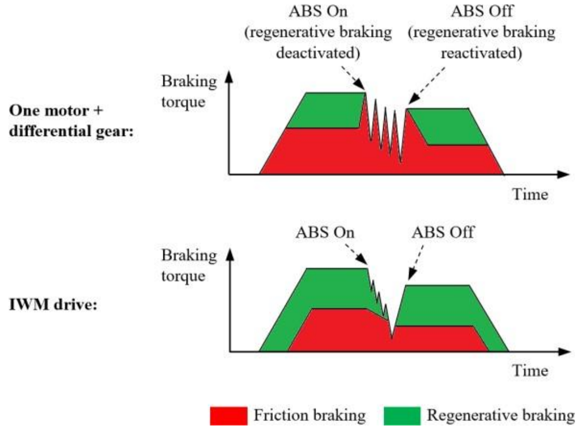

Figure 10. Conventional ABS actuation concepts in EVs with centralised on-board powertrains (top), and EVs with IWMs (bottom).

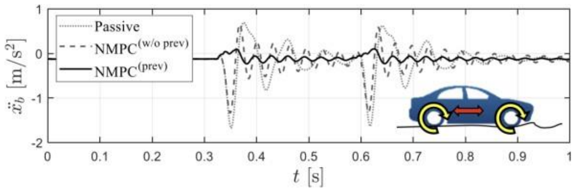

Figure 11. Simulated longitudinal acceleration ($\ddot{x}_b$) profiles of the vehicle body for the passive EV, and the same EV with nonlinear model predictive IWM torque control with (NMPC$^{(prev)}$) and without (NMPC$^{(w/o\ prev)}$) preview of the road profile.

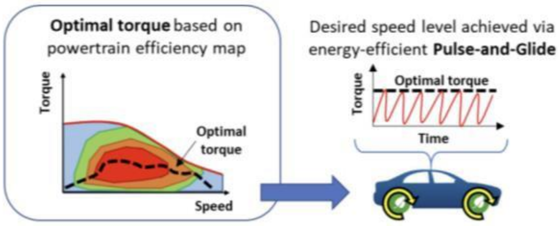

Figure 12. Working principle of the Pulse-and-Glide longitudinal dynamics controller for energy efficiency.

From a methodological viewpoint, nonlinear model predictive control (MPC) solutions will be adapted to the control of the new electric drives, and expanded to include neural network (NN) prediction models, which will result into neural network model predictive control. For example, the NNs will be used for capturing the nonlinear dynamics that are difficult to model analytically, e.g., the effect of the uncertain tyre-road friction coefficient. The activity will focus on: i) exploring the achievable vehicle performance impact of IWM settings with different levels of responsiveness; and ii) providing robust and real-time implementable controllers that will be further developed and industrialised at the project completion.

5. Virtual and experimental testing

EM-TECH and HighScape propose an extended multi-level digital-twin approach for designing and testing IWMs and AFMs, PE solutions, and relevant EV systems. The methodology will be characterised by: i) agile model based XiL methods integrated into the standard V-model of the system development lifecycle; ii) adaptive interfaces for coupling virtual and physical systems from different domains and process holders; iii) extension of the XiL concept by real-time networking complex testing facilities in different geographical locations, which enables co-verification and co-validation involving multiple partners. The approach is an advancement of established procedures [16] through the integration of network- and internet-based complex testing facilities for real-time cooperative experiments.

The EM-TECH and HighScape verification and validation environment will consist of: i) a set of models of e-Machines, powertrains and full vehicles, including real-time reduced-order models, together with a functional mock-up interface (FMI) for co-simulation; ii) connected HiL platforms for propulsion control units, motor/inverter controllers, vehicle CAN, private CAN, and other relevant controllable hardware components, including EV systems that require a joint operation with the e-Machine, e.g., for regenerative braking; and iii) dynamometrical test setups to emulate the operation of electric propulsion units in laboratory conditions under real load and speed cycles. This constellation of tools enables flexible testing as part of a digital twin development process to perform functional and life cycle analyses of the new IWMs, AFMs, and PE components.

The XiL verification approach of the components and systems will be complemented by testing on the project EV demonstrators, which will be represented by modified versions of production vehicles of the involved car makers (AUDI and TOFAŞ). Moreover, to maximise impact, the new e-Corner and e-Axle drive solutions will target applications for a much wider range of passenger car segments (A-D and M segments) and vehicle categories (e.g., quadricycles and heavy goods vehicles) than those considered in the experimental demonstration. Therefore, the consortia have selected examples of production vehicles, including front-wheel drive, rear-wheel drive, and all-wheel drive configurations, for which the benefits of the EM-TECH and HighScape technologies will be evaluated through simulations and XiL.

6. Conclusions

This paper has outlined the planned developments of the Horizon Europe EM-TECH and HighScape projects, dealing with next-generation electric machines and power electronics for vehicular applications. The innovations will result in new in-wheel machines (IWMs) with so far unexplored levels of torque density and specific torque (>150 Nm/L, >50 Nm/kg), and on-board axial flux machines (AFMs) with high power density and specific power (>30 kW/litre, >10 kW/kg). Both machine technologies will be characterised by significant reductions of the energy losses during driving cycles, and their rare earth content. As a result, it will be possible to reach the competitive production costs of <6 Euro/kW for IWMs and 5 Euro/kW for AFMs, for yearly volumes in excess of 100k units/year. For the new WBG based traction inverter solutions, >80% size reduction and >60% average power loss decrease w.r.t. Si-based solutions are expected, while the WBG based power electronics for chassis actuators will more than halve the average power losses w.r.t. the corresponding available components.

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