SCALABLE PLATFORM FOR AN EFFICIENT 400-VOLT AXLE DRIVE

Dr. Gerd Rösel
Head of Innovation Department

Nico Daun
Team Leader
Innovation e-Machines & Axle Drives

Petra Mönius
Head of Innovation Power Electronics

Gunter Mühlberg
Head of Product Management
Axle Drives

Alexander Reich
Head of Product Management
High Voltage Electronics

SCALABLE PLATFORM FOR AN EFFICIENT 400-VOLT AXLE DRIVE

ABSTRACT

As the market success of electric vehicles accelerates significantly, the momentum and variance in the brands, segments and models on offer is continuously increasing This increases the importance of the greatest possible scalability of electric drives. Electric axle drives, such as the EMR3 (Electronics Motor Reducer 3rd generation) in volume production and the EMR4 currently in development and presented here, can optimally meet these requirements in a highly integrated unit design with multi-criteria optimization at system level. Compared with the predecessor generation, the EMR4 delivers up to 5% increased efficiency, significantly freer power scaling, and substantial cost reductions. The enhanced efficiency and performance of the drive in particular contribute to attractive handling and vehicle characteristics. To facilitate progress with the EMR4, numerous effect chains in the axle drive have been further optimized down to the smallest detail. In the interests of scalability, many internal and external interfaces have also been standardized to ensure that the three main components – power electronics, electric motor, and reducer – can be combined as freely as possible in line with the tailored-off-the-shelf principle. With regard to the drive's acoustic comfort, another focus was and remains the simulation, testing and optimization of the drive's noise characteristics (noise vibration harshness) throughout the entire operating map. Comprehensive industrialization expertise from the previous generations of axle drive systems has been incorporated in the development of the EMR4 right from the outset.

1

REQUIREMENTS OF A RAPIDLY GROWING MARKET

Highly integrated electric axle drives, such as the EMR3, which is in volume production, make a significant contribution to the success of electrification in terms of unit volumes. With their advantages over the integration of individual components (electric motor, power electronics, reducer), complete axle drives facilitate the structural integration of the unit into different vehicles. Compared with electric drives made up of individual components, integrated axle drives save costs, weight, complexity in the interfaces and connections, as well as space, and offer a high power density. They thus contribute to good handling and attractive overall vehicle characteristics. In this context, it is also important that the properties of the powertrain – particularly with regard to its efficiency – influence the size of the battery which remains the largest cost factor of an electric vehicle.

Compact vehicles featuring the EMR3, for example, have already received numerous awards in the first year of volume production: the Opel Corsa-e for its handling characteristics (Golden Steering Wheel 2020), the Peugeot e-208 for its overall package of handling characteristics, price/performance ratio and range (Britain’s Best Electric Car 2020) and, once again, the Opel Corsa-e for its energy efficiency (first place in the FIA E-Rally Regularity Cup 2020) [1].

The number of vehicle manufacturers, brands and models offering electrification as a drive option is now increasing – particularly in Asia and Europe. This means that the requirements placed on the design of integrated axle drives are increasing significantly. The higher the unit volumes and the broader the range of applications for electric axle drives become, the more important it is to master the complexity of these drives and industrialize them smoothly. At the same time, the assessment of the total cost of ownership (TCO) of an axle drive is becoming even more important for vehicle manufacturers due to high unit volumes. Only with further TCO progress will it be possible to further approximate the purchase costs for electric vehicles to the cost level of vehicles with internal combustion engines. The costs of integrating a drive into a vehicle continue to play a significant role in TCO consideration.

In pioneering applications such as the EMR3, the main aim has been to shift the complexity of an electric powertrain out of the vehicle into a complete module, where it can be better controlled and optimized within the system, in order to simplify integration for the vehicle manufacturer. The module has also been optimized on a system level compared with the design comprising individual components, in such a way that the highest possible efficiency is achieved with the lowest possible weight and compact dimensions. With the EMR3, this has been accomplished highly successfully at a weight of just 76 kg, an output of up to 150 kW and a torque of up to 2,900 Nm at the axle. Despite these performance features, the EMR3 axle drive with its dimensions of around 400 x 550 x 380 mm, is not much larger than a standard aircraft carry-on bag.

In addition to the requirements for high power density and high efficiency, another parameter is now being added. In view of the rapidly increasing application figures and the ever broader range of vehicle models, the possibility of scaling an integrated axle drive is becoming a decisive factor. Only if it is possible to cover as many highly diversified applications as possible within a modular and systematically planned component portfolio can the electric axle drive make the best possible contribution to cost efficiency and therefore rapid electrification in high unit volumes. For this purpose, it is particularly necessary to standardize as many interfaces within the drive unit as possible, as well as the interfaces to the outside. The goal is to enable enumerative combinatorics within the component portfolio without the need to re-adapt mechanical, electrical and software interfaces each time.

For this reason, in parallel with the market success of the EMR3, Vitesco Technologies is already developing the EMR4 electric axle drive, which will support much wider scaling and power spread while also attaining very high efficiency.

2

THE ARCHITECTURE OF THE EMR4

In the interests of greater scalability, the basic structure of the EMR4 electric axle drive has been changed compared to the current EMR3. All three basic components (power electronics/inverter, electric motor, reducer) are arranged in-line in the EMR4, **Figure 1**.

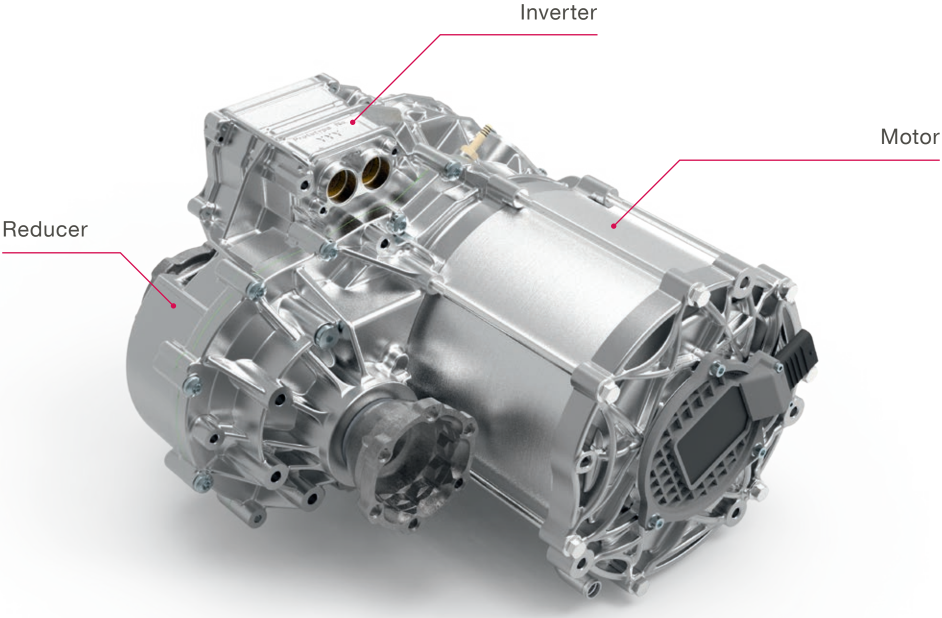

Figure 1: Basic structure of the EMR4 axle drive

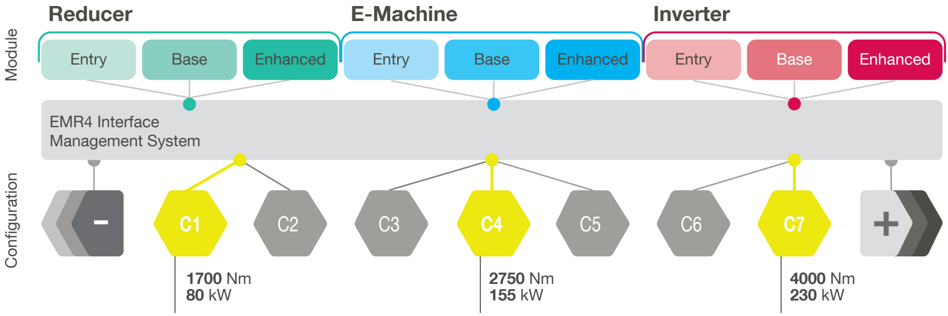

Figure 2: Standard configurations of the EMR4 platform

With this basic principle, it is possible to connect the two components with the greatest need for variability in different designs, while the modification requirements for the reducer gearbox can be implemented within the housing dimensions. This in-line arrangement forms the basis for key architecture features of the EMR4.

The standard configurations (for vehicles in segments A to J2, i.e., vehicle weight classes from 1,800 kg to 2,800 kg) planned during development can be covered purely by scaling the motor length in three steps of 60 mm (Entry), 90 mm (Base) or 105 mm (Enhanced), **Figure 2**.

Depending on the design, the newly developed EMR4 axle drive delivers between 80 kW and max. 230 kW of power (10 s). The torque range at the axle extends from 1,700 Nm up to a maximum of 4,000 Nm (10 s). The scalability achieved is also clearly apparent in the weight of the module. Depending on the power requirements for the drive, its mass can be between only about 45 kg and approximately 80 kg. According to previous findings, the EMR4 axle drive will be able to achieve a 5.6% efficiency advantage in the WLTP compared with the EMR3, which will have a tangible effect on the vehicle range.

These values were achieved through the systematic optimization of many central effect chains in the drive system. Potential for improvement was realized here with numerous detailed measures. Despite considerable efficiency gains and a power density increase of over 20% compared with the already optimized EMR3, the EMR4 has achieved further cost reductions. Although higher-quality materials are used in many places in the EMR4, the technical advantages of the materials result in greater savings in other areas, allowing the cost to be optimized.

2.1 ARCHITECTURE AND ELECTRIC MOTOR

The diameter of the PSM motor (and therefore its housing diameter) has been fixed for the integrated EMR4. With an unchanging stator outer diameter of 208 mm, the EMR4 platform motor has a diameter just under 20 mm more than the EMR3 electric motor. Nevertheless, performance-enhancing design measures in the motor have made it possible to almost halve the axial length of the EMR4 motor compared with the current axle drive (90 mm instead of 175 mm).

The stator now has at least four layers per groove (instead of two in the EMR3). The number of layers (e.g., 4–8) to be selected according to the individual case in the future continues to be strictly determined based on the desired cost level and performance class or voltage. A balance between cost minimization and maximum utilization of the potential of the active parts serves as a yardstick.

2.2 ARCHITECTURE AND POWER ELECTRONICS

The inverter of the EMR4 platform is based on the fourth generation high-voltage power electronics from Vitesco Technologies (EPF4). For the power range of the EMR4 platform, the highly integrated EPF4 inverter is available in three power levels with 290 amps (“Entry”), 550 amps (“Base”) and 820 amps (“Enhanced”). The Entry version provides a cost-effective solution for a power output of up to 80 kW (10 s) and an axle torque of up to 1,700 Nm (10 s). The Base version is suitable for a wide range of applications with electrical power outputs up to 135/165 kW (10 s) and up to a torque of 2,500/3,000 Nm (10 s) at the axle. The Enhanced variant is designed for a power output of up to 230 kW at a mass of 2,800 kg and up to 4,000 Nm.

In principle, however, all inverter variants can be combined with every motor power variant and every required reducer. This allows special requirements (e.g., for delivery vehicles) deviating from those for standard high-volume passenger cars to be met. With dimensions of only 270 x 221 x 126 mm, the EPF4 inverter is very compact.

2.3 ARCHITECTURE AND REDUCER

Depending on the torque of the electric motor, the platform includes three versions of the reducer, which are configured for either < 2,000 Nm (“Entry”), < 3,000 Nm (“Base”) or < 4,000 Nm (“Enhanced”). Reduction ratios between i = 9.3 and i = 11.64 are envisaged. This reduction ratio, which has been expanded compared with the previous generation, makes optimum use of the higher peak speed of the electric motor possible. In the reducer, this measure can be implemented very economically and results in significant savings in the motor, offering scope in terms of the costs for higher-quality materials.

Regardless of the design, the air-cooled reducer is designed for up to 16,000 rpm input speed and a maximum of 255 Nm of motor torque. The reducer provides up to 3,000 Nm of axle torque on the output. The maximum permissible axle speed is 1,720 rpm. An electric parking brake can optionally be integrated into the reducer.

3

EFFICIENCY GAINS AS A RESULT OF EFFECT CHAIN OPTIMIZATION

Worldwide, a clear trend toward further increasing the efficiency of electric drives at the vehicle level is evident. Range and battery size/battery cost considerations as well as legal requirements with the aim of air pollution control and climate change mitigation contribute to this. In addition, further improvement of the efficiency of electric drives increases the attractiveness of vehicles thanks to the resulting system cost reduction. The Wh/km in the WLTP is used as a measurand for energy consumption.

Numerous individual factors define the efficiency of a vehicle. Although most of these are attributable to the entire vehicle, the powertrain has a considerable influence. **Figure 3** illustrates the extent to which the powertrain, with its specific losses, influences efficiency at the vehicle level in the

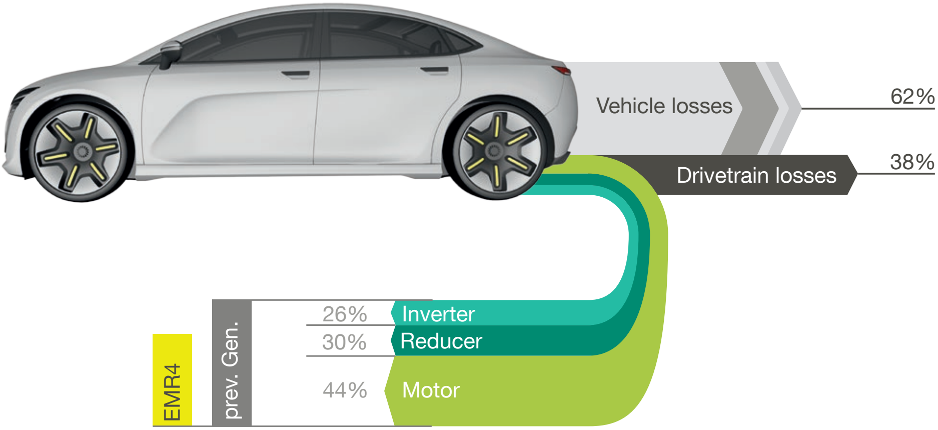

Figure 3: Breakdown of WLTP losses in the electric vehicle

example of integrated axle drives. In general terms, around a third of the losses are caused by the drive, and around two-thirds by the overall vehicle.

In terms of the power electronics, motor and reducer, further progress has been made in the EMR4 to the benefit of overall vehicle efficiency: Compared with the previous generation, the EMR4 is much more efficient, reducing the total energy consumption for an average D-segment vehicle in the WLTP up to 5.6%.

3.1 EFFECT OF THE EXAMPLE MEASURES ON THE MOTOR AND INVERTER

In the electrically active components of the EMR4 platform, laminated cores made of very thin, high-strength sheets are used that enable higher motor speeds with lower material use. The maximum speed is now 16,000 rpm (EMR3, by way of comparison: 14,000 rpm). With these speed characteristics, a higher gear reduction can be used with the same vehicle end speed.

A major step forward was made in the continuous power of the EMR4 motor. Thanks to significantly reduced losses and optimized cooling geometry, the motor can permanently deliver between 40 kW and 80 kW at a maximum speed. Thanks to the short motor length and compact design, heat dissipation is also more effective because the heat flows from the hot spot in the center of the motor have a short distance to travel to its edges.

The increased gear reduction (see section 2.3) means that lower motor torque is required for the same axle torque. In combination with a new rotor sheet metal cutting and a resulting increase in reluctance, the magnetic mass has been significantly reduced, the power kept constant, and efficiency increased.

The EPF4 inverter is designed for operating voltages between 210 V and 470 V, and works with PWM switching frequencies between 2 and 12 kHz. Depending on the operating point, the field-oriented control (FOC) process is used to switch between the modulation methods of Space Vector Pulse Width Modulation (= SVPWM at low speeds to enable higher currents), Synchronized PWM (= SynchPWM in the medium speed range), Generalized Discontinuous PWM (= GDPWM in the medium speed range) and Flux-Bidirectional Modulation (= FBM at high speeds). A rotor position sensor on the front end of the motor housing provides the geometric information for the rotor position signal which is required for electronic commutation of the rotor and stator field. **Figure 4** shows the reference operating points used to evaluate the motor and inverter losses during the simulation. The large efficiency gains, especially at high rotation speeds, can be used to see the effect of the higher number of layers in the motor and the massively reduced iron losses.

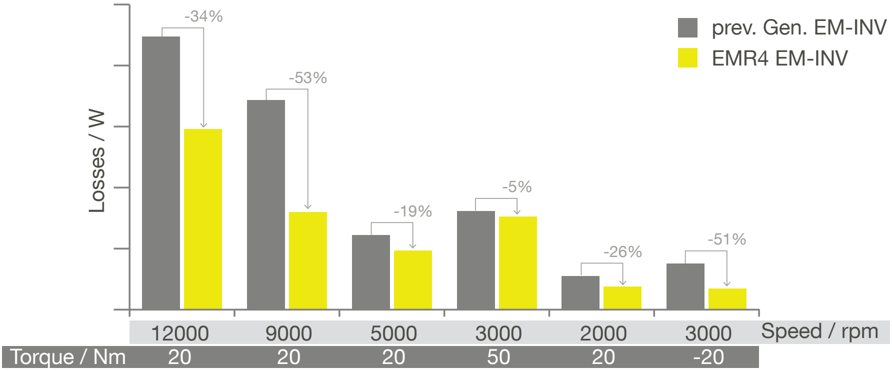

Figure 4: WLTP operating points for the motor/inverter efficiency assessment

Compared to the previous generation, the EPF4 inverter for the EMR4 platform has succeeded in reducing the losses in the inverter significantly. The EPF4 inverter was designed for efficiency from the outset. Thanks to this stringent objective, the design demonstrates an extremely optimized commutation inductivity. The interaction of the power module produced in-house with the intelligent control modules means that a minimum amount of switching losses can be achieved. This progress in efficiency benefits the overall efficiency of the axle drive. According to the current state of development, a further efficiency boost can be achieved by using silicon carbide (SiC) in the inverter [2]. The high power density of the inverter is made possible by the 1-PCB design with a low design height.

3.2 EFFECT OF THE MEASURES ON THE REDUCER

Although the mechanical reducer component was already highly optimized in the previous generation, further efficiency advances were made here, which are of great importance because the reducer also has a significant influence on the overall efficiency of the drive **(Figure 3)**. In the 2-stage reducer gearbox with differential, minor design measures such as lubrication and shaft topology further increased the efficiency, **Figure 5**.

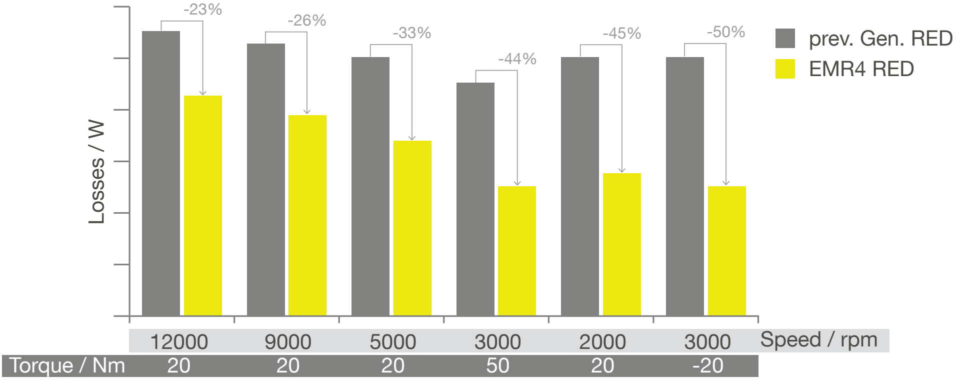

Figure 5: WLTP operating points for the efficiency evaluation of the reducer

4

PLATFORM APPROACH FOR THE EMR4

The ever-increasing range of applications required by the market for integrated electric axle drives can only be achieved with a high degree of scalability of the drive in terms of performance, efficiency, costs, size and weight. Scalability ultimately means that it must be possible to put together an optimal combination of main components for the relevant application without intervening in the production sequence. In view of the large number of parameters and their complex interaction defining the desired performance features of a drive, this goal is highly challenging in design terms – if it is thoroughly implemented down to detail.

During the development of the EMR4 platform, extensive sensitivity analyses, for example, were conducted to determine the effects of individual parameters on the efficiency of an electric drive axle in the WLTP, for example, **Figure 6**.

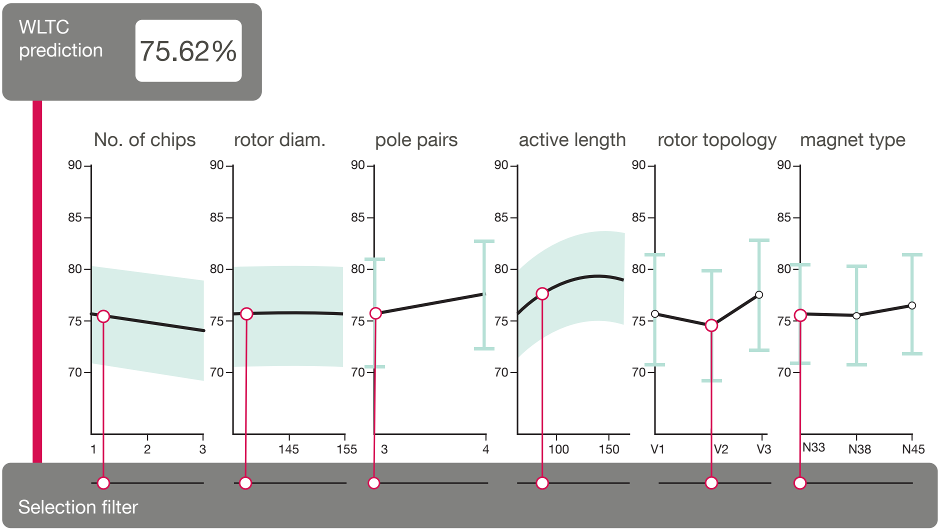

Figure 6: Examples of the influence of individual parameters on the efficiency of an electric drive in the WLTP

To achieve optimum weighting of the desired performance features and the associated costs, the proprietary tool iMCO was used by the developers during this multi-criterial phase of development, **Figure 7** [3].

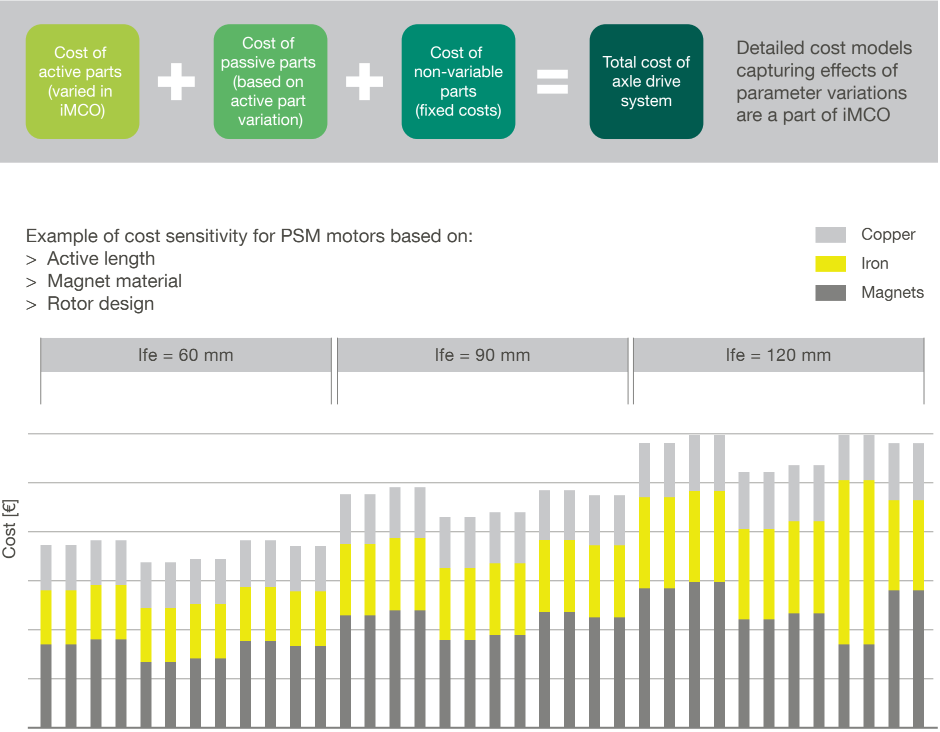

Figure 7: Detailed cost models as part of multi-criteria evaluation and optimization make the correlation between parameter changes and the resulting costs transparent

5

INTERNAL AND EXTERNAL INTERFACES

It has already been mentioned that when designing an integrated axle drive, the complexities of a discretely designed electric drive have been removed from the vehicle and relocated **in to** the drive instead. How much of the complexity has been shifted here is also demonstrated by the numerous interfaces within the axle drive and externally, which must be solved in design terms during integration of this kind. **Figure 8** shows the internal drive interfaces between the individual functions highlighted in gray and, in the green circles, the outward interfaces to the vehicle environment.

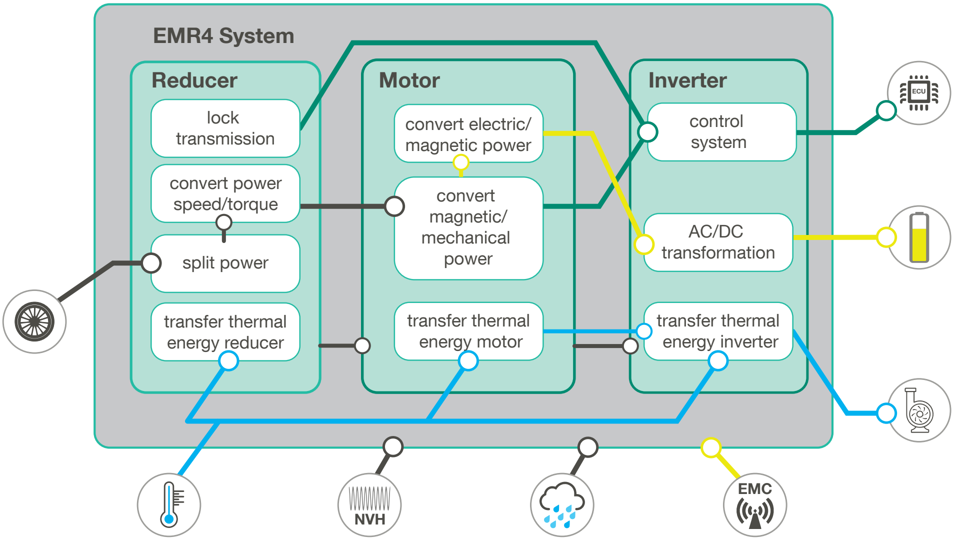

Figure 8: Overview of standardized EMR4 platform interfaces

To enable comprehensive scaling of the pre-validated EMR4 platform components, all of the main components, i.e., inverters (in three versions), reducers (in three variants) rotor and stator (in three lengths each) as well as motor housing (in three lengths) and bearing plate (“cover” in two versions) are clearly defined with respect to the internal and external interfaces. This makes it possible to combine different component designs with uniform interfaces.

Structure-borne noise and electromagnetic radiation play a key role among the external interfaces. To minimize the excitation of body vibrations through structure-borne noise in the electric drive, a great deal of optimization work has been carried out on the acoustic quality (noise, vibration, harshness, NVH) of the drive in all operating situations, **Figures 9, 10**. On the EMR4 platform, tests to confirm the simulation results have already been successfully carried out on an A-sample basis.

This simulation expertise can also be used to optimize the bracket shapes, which could otherwise also lead to design-related excitations in the vehicle.

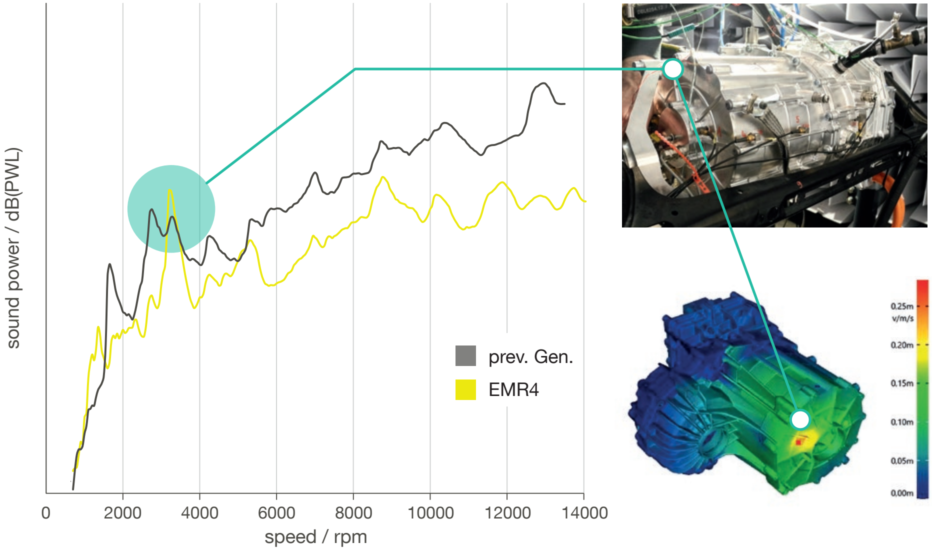

Figure 9: Example of an NVH simulation from the development of the EMR4 platform

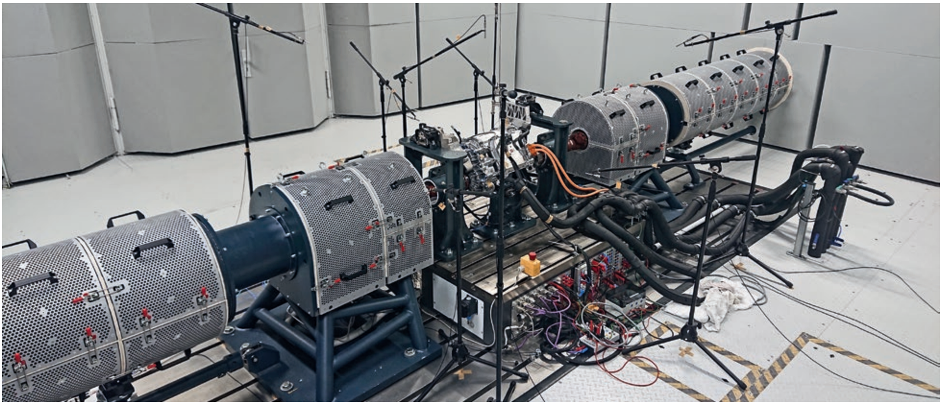

Figure 10: NVH measurement

These brackets play a major role in the mounting of the axle drive in the vehicle, because they may be required to ensure attachment even if vehicle-specific attachment points would lead to geometric conflicts with the technical interfaces of the axle drive.

Electromagnetic compatibility (EMC) of the EMR4 platform is ensured through compliance with the standard, CISPR25-2016 Class 3, **Figure 11**.

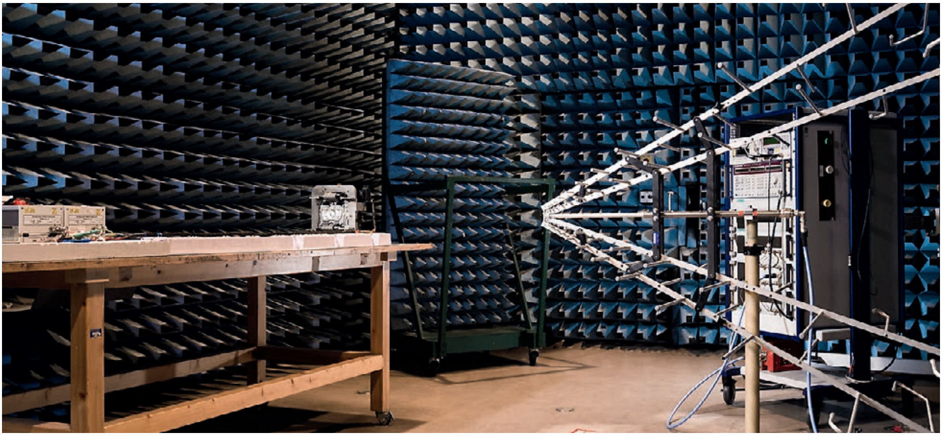

Figure 11: EMC measuring chamber

6

SUMMARY

Industrialization expertise from three generations of electric high-voltage drives has been incorporated into the development of the EMR4 platform: Until beginning of 2021, more than 150,000 units of the EMR3 alone have already been shipped to customers. Thanks to numerous detailed optimizations along influential effect chains, efficiency and performance of the EMR4 have been significantly increased at a reduced cost level, even compared with the EMR3 axle drive that has already been optimized. In particular, the high scalability of the new platform enables highly cost-effective use of EMR4 axle drives in a wide range of different vehicle segments with individual requirement profiles.

With a scalable output of currently between 80 kW and up to 230 kW with a mass of only around 45 kg up to approximately 80 kg, the EMR4 platform supports the transition to electrification in high unit volumes and in a large number of vehicle models. To cover performance requirements above and below the specified current performance range, development for portfolio expansions will start in 2021.

Through systematic cost-side optimization, the EMR4 platform helps to bring the purchase costs for electric vehicles ever closer to the yardstick of previous vehicles with internal combustion engines. Thanks to the further increased efficiency of the EMR4 drive, there is also a cost-reducing influence on the size of the battery.

The EMR4 platform stands for tailored-off-the-shelf solutions that consistently focus on standardization and modularization within the product. At the system limits, customer-specific differentiation is shaped via integration and system expertise. This creates a balance between cost optimization and individualization, which is supplemented by many years of production experience and a high level of quality with electric axle drives. With this strategy, Vitesco Technologies is actively working with its customers and suppliers to design the growth in electric mobility.

Sources

[1]
- Opel Corsa-e -
https://de-media.opel.com/de/04-11-goldenes-lenkrad
(downloaded on November 9, 2020)

https://de-media.opel.com/de/11-19-corsa-e-fia
(downloaded on November 19, 2020)

- Peugeot e-208 -
https://www.autocar.co.uk/car-news/new-cars/
britains-best-electric-car-2020-peugeot-e-208?fbclid=I-
wAR1G5Pgt8F4_AKOUMJ0OFRZRVw6Fyt01ptuAIZ05fn-
7NIVik8IeONJjfwAM
(downloaded on October 26, 2020)

[2]
Rösel, G., Mönius, P., Spas, S., Daun, N.
Inverter and motor optimization using SiC technology
MTZ – Motortechnische Zeitschrift, 82 (2021) Springer,
Wiesbaden, January 2021, p. 54–58

[3]
Adler, C., Siedenberg, D., Töns, M.
Multi-criteria optimization of electric drive trains
ATZ – Automobiltechnische Zeitschrift, 122 (2020),
Springer, Wiesbaden, February 2020, p. 44–49

Vitesco Technologies GmbH
Siemensstrasse 12
93055 Regensburg / Germany
+49 (0) 941 790-0
vitesco-technologies@continental-corporation.com

#weareelectrified
#passionate #partnering #pioneering

WWW.VITESCO-TECHNOLOGIES.COM