WHITEPAPER

Optimized drivetrain and new semiconductor technologies enable the design of energy-efficient electric vehicles

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The traction inverter is the core component of the drivetrain in all-electric vehicles, making it the most essential system: The device plays a crucial role in enabling efficient and sustainable electromobility since it directly influences the power output and significantly affects the vehicle's dynamics. However, to develop efficient electric vehicles the integration of complementary sub-systems and the utilization of cutting-edge semiconductor technologies are also vital factors that must be considered.

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Mobility and transportation have become integral parts of our daily lives. For this reason, this sector is crucial in achieving climate protection goals, especially when it comes to reducing greenhouse gas emissions such as CO2 and NOx, as well as particulate matter emissions. However, as the market for electric vehicles continues to grow, there is an increasing demand for raw materials and rare earths. So, merely transitioning to all-electric vehicles is not enough. To truly enable a greener future, we need to embrace energy-efficient and sustainable solutions. By electrifying the drivetrain, emissions can be significantly reduced, while the utilization of the latest semiconductor power technologies and complementary chipsets optimizes energy efficiency. So, let's explore how we can turn Infineon's vision of "10 kWh for 100 km" into reality.

The drivetrain system in modern vehicles includes various components, such as the on-board charger (OBC), the battery management system (BMS), inverters, as well as the traction motor (Fig. 01). These applications work together to achieve optimal vehicle efficiency. Factors like battery capacity and electrical efficiency are important for determining the vehicle's range. However, to achieve optimal driving performance, all aspects of the electric drivetrain and the electric vehicle itself must be optimized. These include aspects such as weight reduction, minimization of aerodynamic drag, reduction of rolling resistance and maximization of recuperation performance. When developing the overall concept, it is also important to consider the integration of the vehicle into smart charging infrastructures. At the same time, the vehicle must be appropriately selected and dimensioned for its intended use. To ensure a sustainable life cycle, vehicle production processes and recycling options should also be considered.

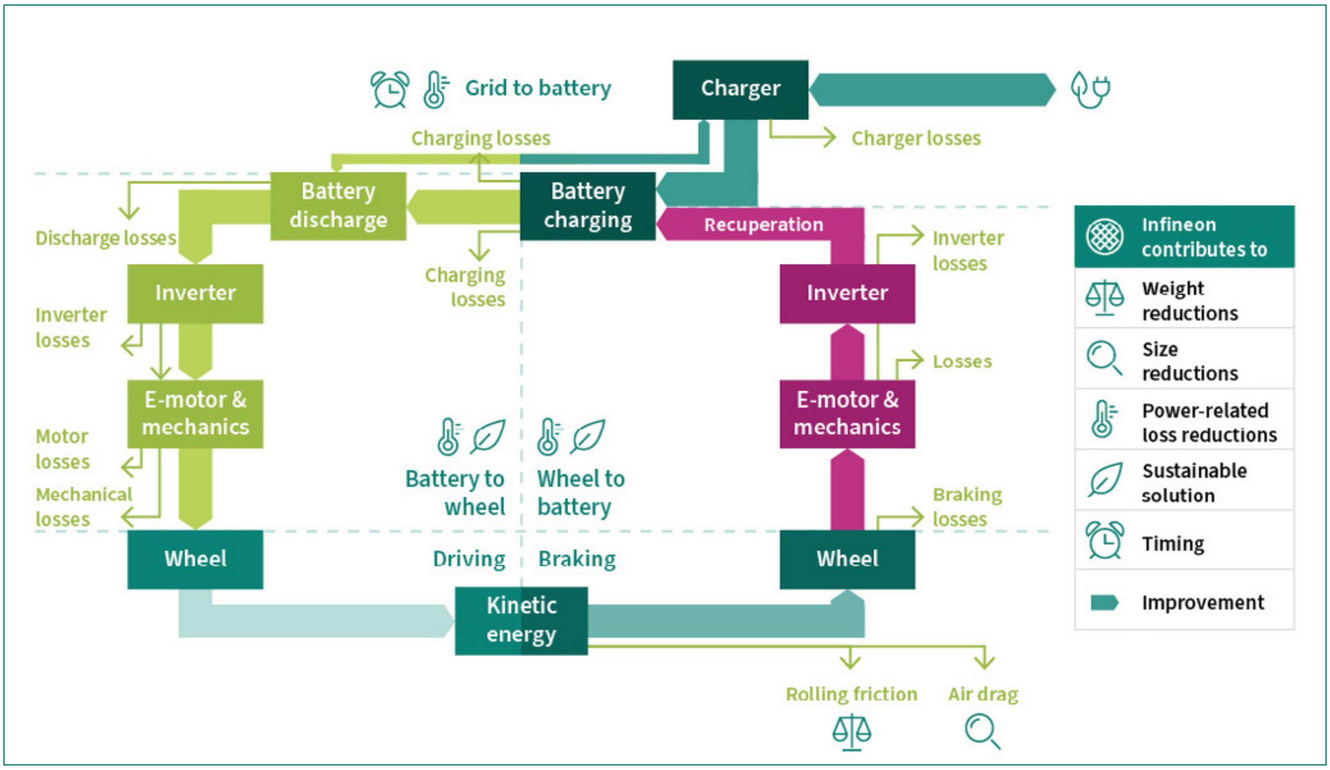


Figure 1 Components of the electric drivetrain © Infineon Technologies

When OEMs discuss efficiency, range is not necessarily the only decisive factor: improvements in vehicle efficiency lead directly to a reduction in vehicle weight. A lighter vehicle requires fewer raw materials and rare earths to produce, while using less energy to travel a given distance. “Efficiency” thus becomes the central aspect for producing a higher number of vehicles at affordable prices.

1 More than just an inverter

The inverter controls the traction motor, converting direct current (DC) into the required alternating current (AC) for engine power. It can also adjust the motor’s speed by modifying the AC frequency. In “generator” mode, the inverter acts as a brake, capturing the vehicle’s dynamic energy and closing the energy loop (Fig. 02). The efficiency of recuperation plays a crucial role in the amount of energy retained within the system. This is where silicon carbide (SiC) based power semiconductors offer an advantage, as they enable bidirectional currents within the switch. Additionally, the more energy that is recuperated, the less energy needs to be dissipated as heat by the mechanical brakes, resulting in a reduction in brake dust.

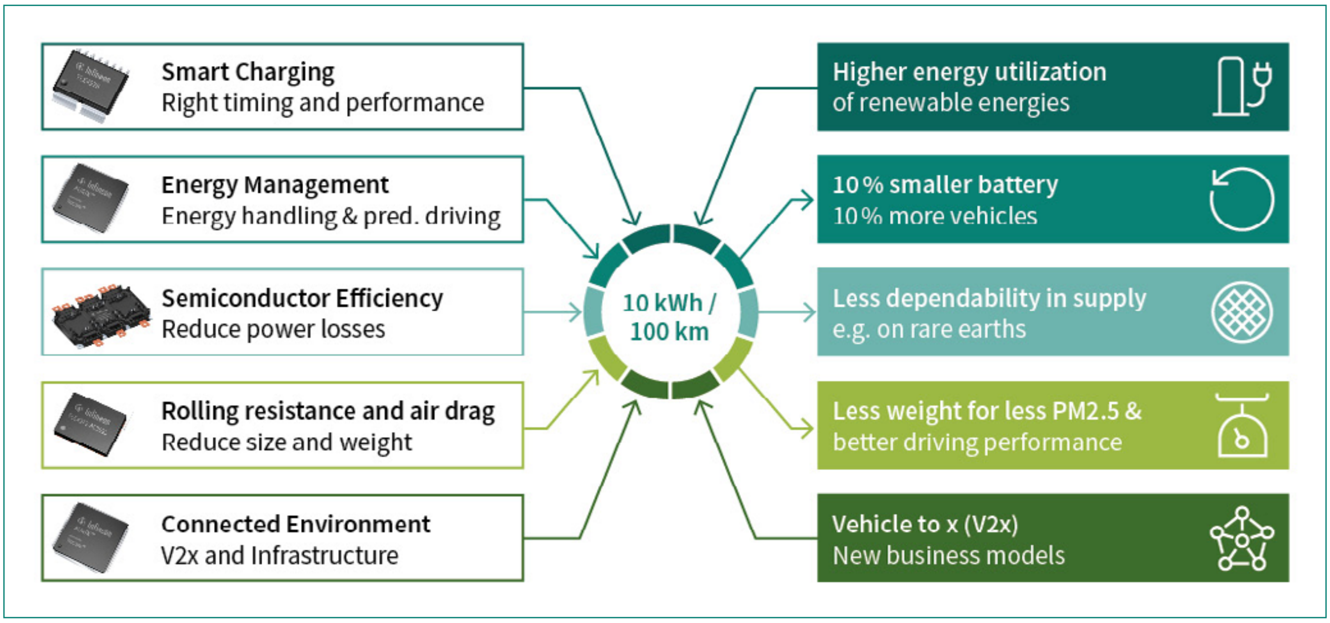
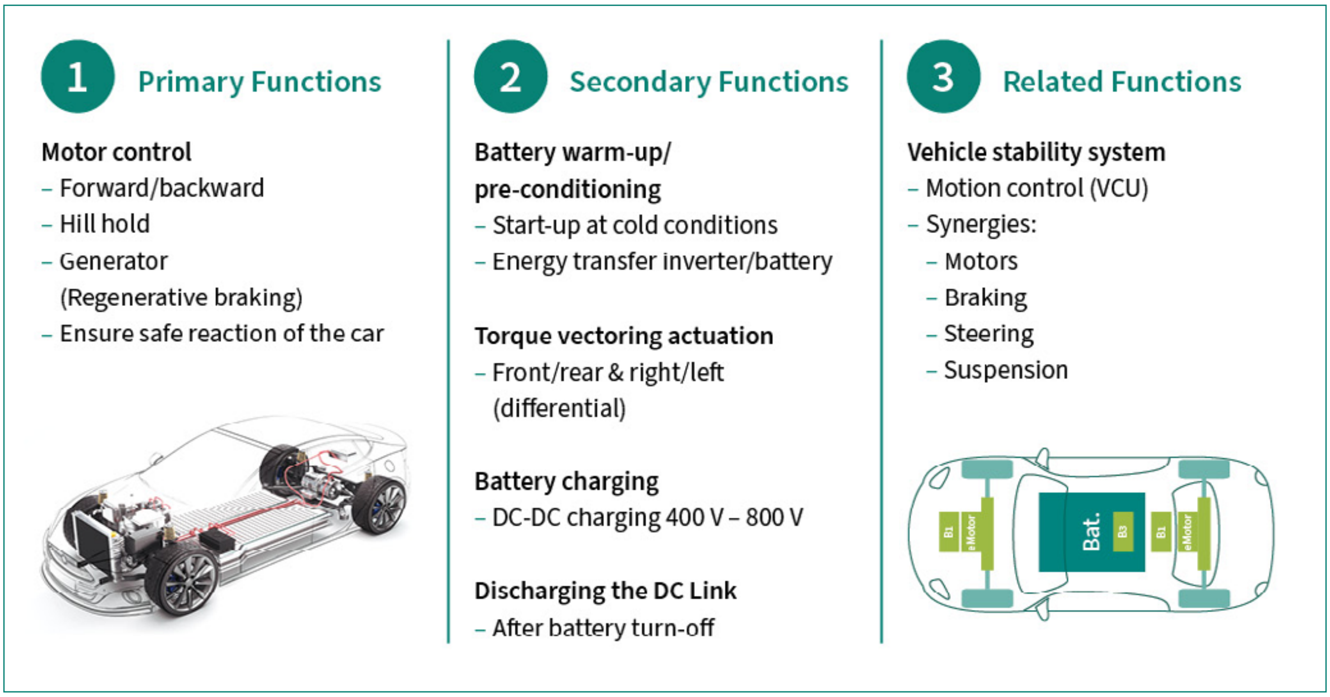


Figure 2 For a greener future, it is critical to consider all aspects of the vehicle’s architecture to achieve the best efficiency. © Infineon Technologies

The introduction of the all-electric drivetrain presents new challenges, as there is a greater integration of applications that rely on one another. These interdependencies require a more holistic approach from OEMs, which, in turn, opens new possibilities for optimization. One example is utilizing the traction inverter as a braking system, which can reduce the reliance on a complete mechanical braking system. The traction inverter can generate torque that is more precise and efficient compared to a mechanical system. It supports functions such as hill hold, braking, and ABS. Additionally, a four-motor system with torque management has the potential to replace a standard ESC (Electronic Stability Control) system. It is important to note that the traction converter serves multiple other functions beyond just being a motor drive for the vehicle (Fig. 03).



1 Primary Functions

Motor control
- Forward/backward
- Hill hold
- Generator (Regenerative braking)
- Ensure safe reaction of the car

2 Secondary Functions

Battery warm-up/ pre-conditioning
- Start-up at cold conditions
- Energy transfer inverter/battery

Torque vectoring actuation
- Front/rear & right/left (differential)

Battery charging
- DC-DC charging 400 V – 800 V

Discharging the DC Link
- After battery turn-off

3 Related Functions

Vehicle stability system
- Motion control (VCU)
- Synergies:
  - Motors
  - Braking
  - Steering
  - Suspension

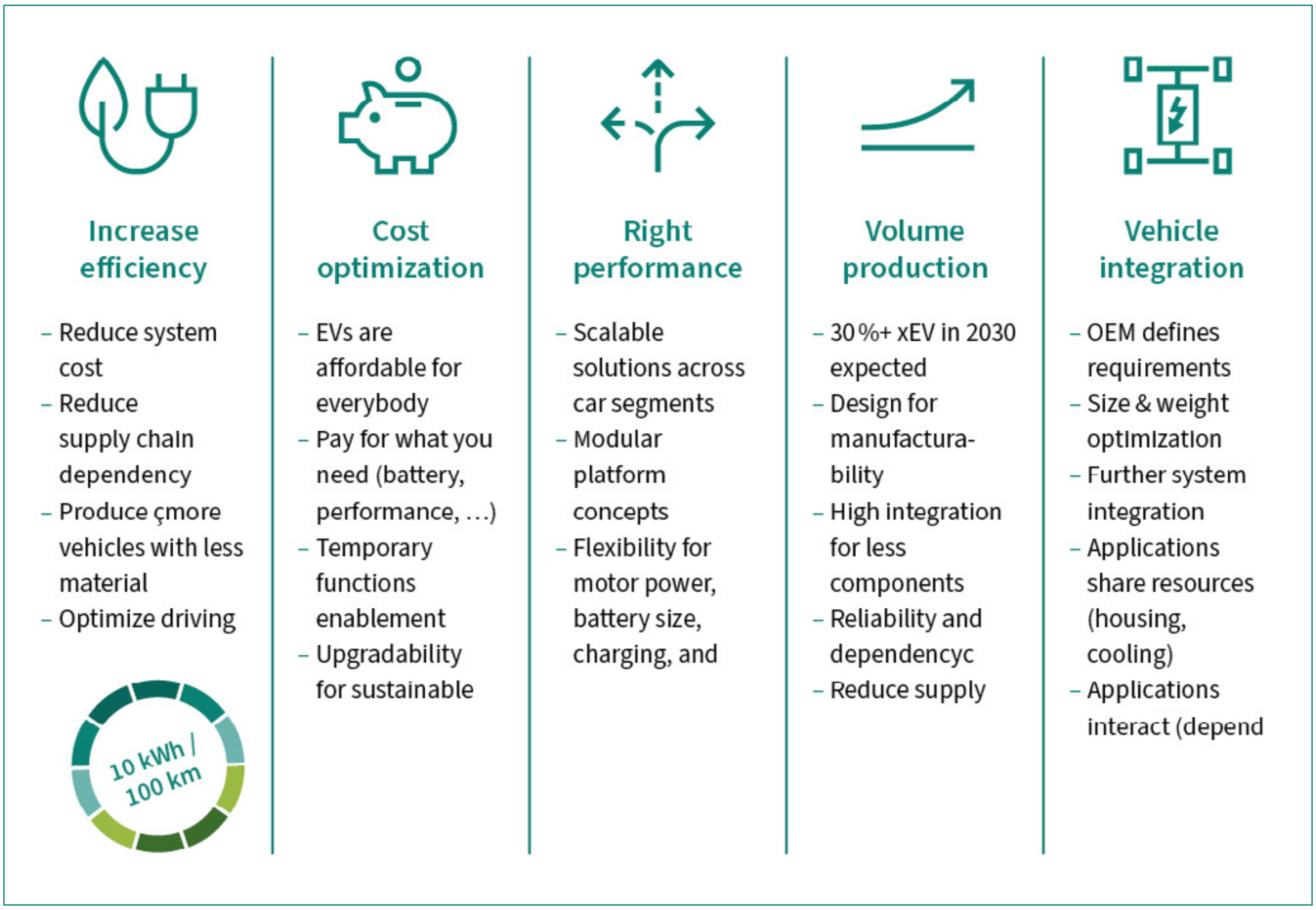
Figure 3 The many different functions of a modern traction converter/motor in an electric vehicle © Infineon Technologies.

2 SiC and GaN enhance performance

Wide bandgap (WBG) semiconductor devices offer substantial power efficiency gains across various applications, including electric vehicles. They are particularly advantageous for traction inverters, on-board chargers, and high-voltage DC-DC converters (HV-DCDC).

When considering efficiency, it is important to take a holistic approach, encompassing a complementary and optimized chipset comprising microcontrollers, sensors, gate drivers, and power switches, as well as vehicle integration and peripheral functions. Present-day traction inverters already exhibit high efficiency levels, surpassing 98 percent. As a result, innovations are currently directed towards advancements in motors, gearboxes, and cooling systems as key areas of focus.

The primary focus of ongoing developments is the optimization of efficiency, with the next generation of traction inverters relying on new power switching technologies and advanced microcontroller capabilities as key enablers. While cost remains a central concern, considerations such as performance, manufacturability, and integration also hold significant importance.



Increase efficiency

- Reduce system cost
- Reduce supply chain dependency
- Produce çmore vehicles with less material
- Optimize driving

Cost optimization

- EVs are affordable for everybody
- Pay for what you need (battery, performance, …)
- Temporary functions enablement
- Upgradability for sustainable

Right performance

- Scalable solutions across car segments
- Modular platform concepts
- Flexibility for motor power, battery size, charging, and

Volume production

- 30 %+ xEV in 2030 expected
- Design for manufactura-bility
- High integration for less components
- Reliability and dependencyc
- Reduce supply

Vehicle integration

- OEM defines requirements
- Size & weight optimization
- Further system integration
- Applications share resources (housing, cooling)
- Applications interact (depend

Figure 4 The most important market drivers for traction inverter applications © Infineon Technologies

For a moment, let's explore the world of WBG semiconductors: When it comes to defining and improving the efficiency of traction inverters, switching devices such as MOSFETs and IGBTs, along with their associated diodes, have the greatest impact. Two materials, namely silicon carbide (SiC) and gallium nitride (GaN), known as wide bandgap materials due to their higher electron mobility, offer the necessary performance improvements. Many engineers consider these materials as the key to achieving the performance requirements of future power systems, especially in challenging environments like drive converters. SiC-based switching devices enhance performance by addressing the two primary areas responsible for power losses in designs. The first area being conduction losses, where the lower resistance between drain and source (RDS(ON)) reduces losses and minimizes heat generation. Given that SiC and GaN switches allow current to flow through the channel instead of the diode during motoring and generator mode, which is a crucial parameter.

The second type of loss is known as switching losses, which are of comparable magnitude to conduction losses and hence equally significant. With the growing trend of higher switching frequencies, targeting up to 40 kHz, it becomes crucial to minimize losses during each individual switching event. The utilization of SiC or GaN technology enables increased switching speeds of up to 40 V/ns, thereby reducing losses. Currently, the state-of-the-art stands at approximately 10 V/ns, but further advancements, particularly with GaN, are possible. However, the application itself, such as traction motors and EMC constraints, imposes certain limitations, and therefore requires a compromise.

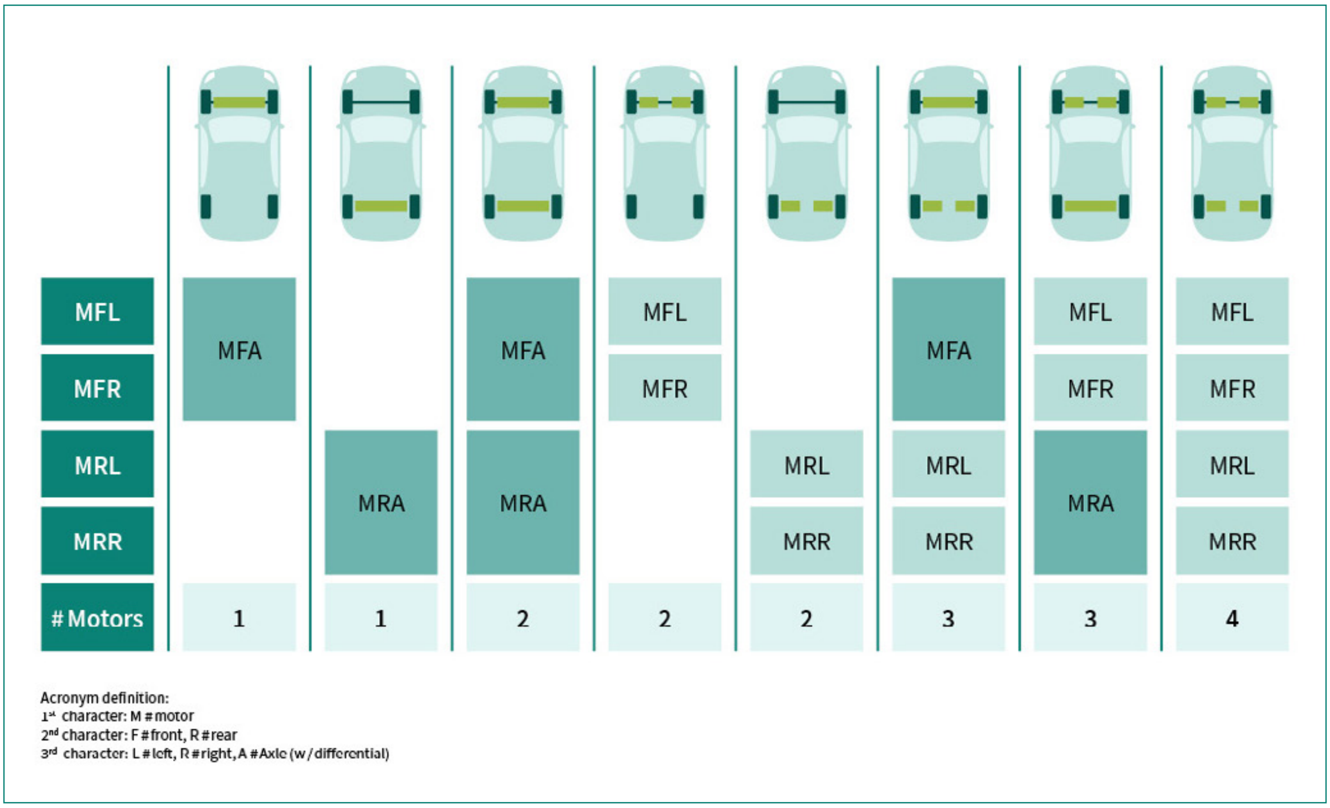
GaN and SiC offer distinct strengths in terms of application solutions, with their advantages dependent on the specific use case. The advantages of SiC technology stem from its material band gap. SiC offers not only high electron mobility but also a high critical breakdown voltage compared to silicon. As a result, SiC devices can be designed to be smaller with shorter channel lengths, resulting in reduced on-resistance at a given nominal voltage. The smaller chip size also reduces device capacitance, thereby minimizes switching losses as the capacitance is charged and discharged during each cycle.

GaN surpasses SiC in terms of its larger band gap (3.4 eV) and significantly higher electron mobility. GaN devices have a gate charge that is only one-tenth that of silicon devices, and their recovery charge is negligible. This characteristic enables GaN to switch with significantly lower losses. As a result, GaN-based solutions can operate at extremely high frequencies, reaching up to approximately 10 MHz. Due to these advantages, GaN is a favored choice for resonant topologies.

3 How to reduce demand for raw materials and rare earths

The introduction of electric vehicles has presented opportunities for diverse drivetrain configurations. Depending on an OEM's specific performance and functional objectives, multiple motors are used in different locations. As the market for all-electric vehicles grows rapidly, the attention is now turning towards enhancing the optimization of drivetrain architectures (Fig. 05). The goal is not only to optimize efficiency but also to maximize the usage of the limited supply of raw materials and rare earth elements (Fig. 01).

Given the already high efficiency of electrical components, integration has become a crucial progression. Microcontrollers, in particular, have advanced to the point where their capabilities enable the handling of multiple dedicated tasks, facilitating enhanced function integration.



MFL	MFA		MFA	MFL		MFA	MFL	MFL
MFR				MFR			MFR	MFR
MRL		MRA	MRA		MRL	MRL	MRA	MRL
MRR					MRR	MRR		MRR
# Motors	1	1	2	2	2	3	3	4

Acronym definition:
1st character: M = motor
2nd character: F = front, R = rear
3rd character: L = left, R = right, A = Axle (w/differential)

Figure 5 Freedom of design: different engine configurations in the car © Infineon Technologies

Electric motors are increasingly becoming the focus of innovation, along with the associated transmissions and cooling systems. They also hold a key role in reducing the dependence on raw materials in vehicles and promoting sustainable production processes. Moreover, there is an economic aspect to consider: the utilization of less expensive and more easily accessible materials serves as the foundation for affordable electric vehicles with shorter production timelines.

As an example, externally excited synchronous machines (EESMs) can serve as traction motors and have been employed in various industries, such as power generation in power plants. One key advantage lies in the rotor design, which incorporates electrically fed field windings instead of magnets. Magnets are expensive, and rare materials are often needed to achieve optimal performance. However, to generate the magnetic field in the rotor, an additional field exciter circuit is required. By having full control over the stator and rotor behavior, the electric motor can be optimized for a broader range of applications with enhanced efficiency. In the automotive sector, three-phase synchronous machines (multi-phase configurations are possible as well) are commonly used for traction applications.

The choice of motor design depends on the specific application, and it is even possible to combine different types of motors within a single vehicle. For instance, an EESM can efficiently and powerfully drive the main axis, while a cost-optimized permanent magnet synchronous machine (PMSM) or an asynchronous machine (ASM) can be employed for the optional second axis. This approach allows for a tailored and optimal motor configuration based on the requirements of each axis in terms of efficiency and cost-effectiveness.

When considering the aspect of recycling, it is worth noting the significance of EESMs and PMSMs. In a PMSM, the magnets are typically embedded within metal sheets and firmly attached, making it challenging to recycle these magnets effectively. On the other hand, in an EESM, where the rotor is wound solely with copper wires, the recovery of materials is much more efficient. This characteristic of the EESM design, thus, enables a more effective and sustainable recycling process.

It is important to acknowledge that there are challenges to overcome in the adoption of certain technologies.
For instance, implementing an ASIL-D torque path requires additional hardware components and software functions. The inclusion of extra circuits and control loops contributes to the increased complexity of the system. As torque control involves both stator currents and field winding currents, more current sensors become necessary.

Ensuring safety requires different actions for different safe states, resulting in updates to the vehicle's functional safety concepts. Moreover, certain effects specific to EESMs, such as Ross (series resistance) coupling effects between the rotor and stator, need to be thoroughly investigated. Currently, the maximum efficiency of an EESM is lower than that of a PMSM. However, considering the WLTP (Worldwide harmonized Light vehicles Test Procedure) and the higher efficiencies observed at commonly used operating points, the effective efficiency of an EESM is either slightly higher or at least on par with that of a PMSM. When evaluating efficiency, it is essential to consider the power consumption of EESM excitation. The excitation current, approximately 30 Arms, is generated using a partially wired H-bridge and draws current from the high voltage side.

Conclusion

In our pursuit of a greener future, the electrification of vehicles plays a vital role in saving energy and reducing emissions of NOx, CO2, and particles. To achieve optimal efficiency in electric vehicles, a holistic and comprehensive approach is necessary, considering the entire powertrain and the complete life cycle. GaN and SiC semiconductors offer distinct strengths, with their ad vantages varying depending on the specific application. SiC and GaN technology excel in high switching frequency applications such as on-board chargers and HV-DCDC systems, making them the preferred choice for wide band gap technology. Among these applications, the traction inverter holds significant importance as it influences vehicle dynamics and range. SiC semiconductors, coupled with complementary chipsets and advanced microcontrollers, facilitate innovations in motors and system integration, resulting in improved efficiency.

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