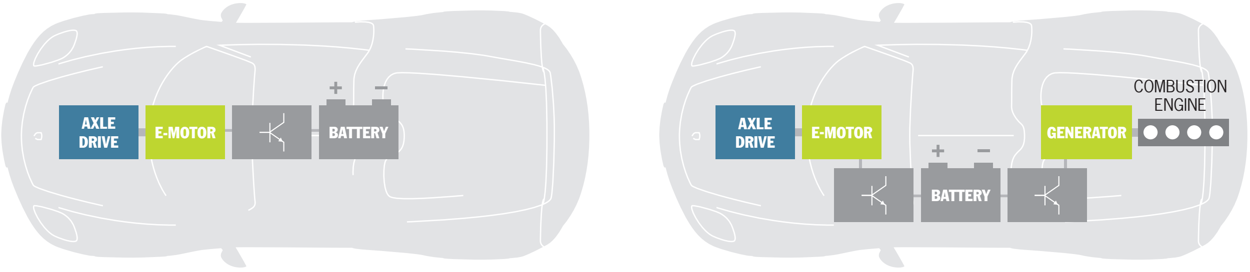
IDENTIFIED

Electric Motors—the Heart and Soul of Tomorrow's Powertrain

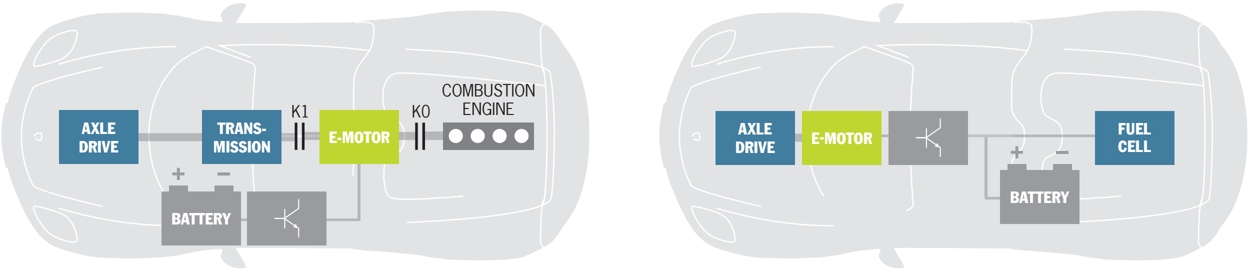
____Electric mobility is playing a key role in future drivetrain technology. Step by step, it is leaving its niche and becoming reality—a serious challenge for vehicle manufacturers used to dealing with gasoline, pistons, and spark plugs. Porsche Engineering is uniquely positioned to benefit from this radical and disruptive shift in technology by providing the type of closely integrated expertise new vehicle architectures demand. In this article we take a first look at the theory and functionality of the device that is central to tomorrow's powertrain.

By Dr. Malte Jaensch



BATTERY ELECTRIC VEHICLE

SERIES HYBRID ELECTRIC VEHICLE



PARALLEL HYBRID ELECTRIC VEHICLE

FUEL CELL ELECTRIC VEHICLE

Topologies of electric powertrain systems

More than 150 years ago, James Clerk Maxwell laid the foundation for the development of the electric motor by devising a set of governing equations commonly known as Maxwell's equations (see below). These equations capture both the beauty and the challenges inherent to electric motors: a machine with only one moving part—the rotor—described by only four short equations seems deceptively simple. Yet, working with electric motors can still be confusingly complex.

Operating principles

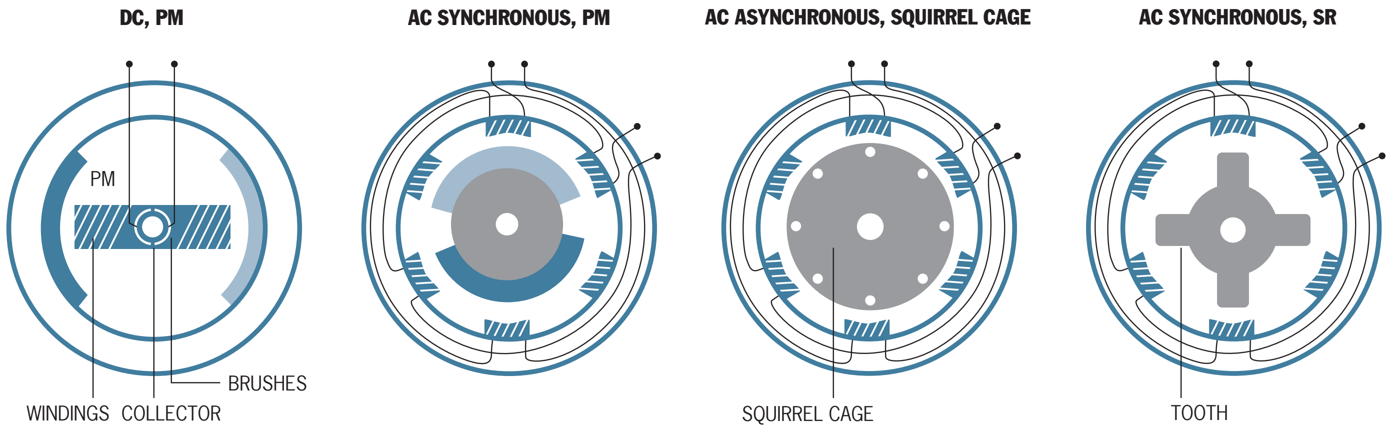
Within a vehicle environment, electric motors are part of a larger system: the electric powertrain. Battery electric vehicles have the simplest type of electric powertrain: a high-voltage battery pack provides direct current power (DC), which is converted by a frequency inverter into three-phase alternating current power (AC) of variable frequency. The electric motor finally converts the electric power into mechanical power, which is then used to propel the vehicle. Other types of electric vehicles, such as fuel cell electric vehicles or hybrid electric vehicles, exhibit more complex topologies. (see left-hand page).

Most electric motors rely on the interaction of two distinct electromagnetic fields—the rotor field and the stator field—to produce torque. At least one of these fields is established by current injected in the machine by the inverter. ›

E	ELECTRIC FIELD
ρ	CHARGE DENSITY
ε_0	PERMITTIVITY OF FREE SPACE
B	FLUX DENSITY
μ_0	PERMEABILITY OF FREE SPACE
t	TIME
J	CURRENT DENSITY

Gauss's Law	$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$	Describes the relationship between the electric field and the charge that causes it
Gauss's Law for Magnetism	$\nabla \cdot B = 0$	Magnetic field lines have no start or end; there are no magnetic monopoles
Faraday's Law of Induction	$\nabla \times E = \frac{\partial B}{\partial t}$	Changing magnetic fields can induce voltages, as in an electric generator
Ampere's Circuital Law	$\nabla \times B = \mu_0 J$	Electric currents create magnetic fields, as in an electric motor

Maxwell's equations



Functional principle of an electric motor

The second field might be produced by permanent magnets, (PMs) through induction or by current fed from a second external power source (see above).

It is one of the great advantages of the electric motor that energy conversion is reversible. An electric motor used as a motor turns electric power into mechanical power. The same machine—employed as a generator—converts mechanical power back into electrical power. This characteristic is used, for example, during recuperative breaking, whereby the vehicle's kinetic energy is transferred back into the battery.

Overloading

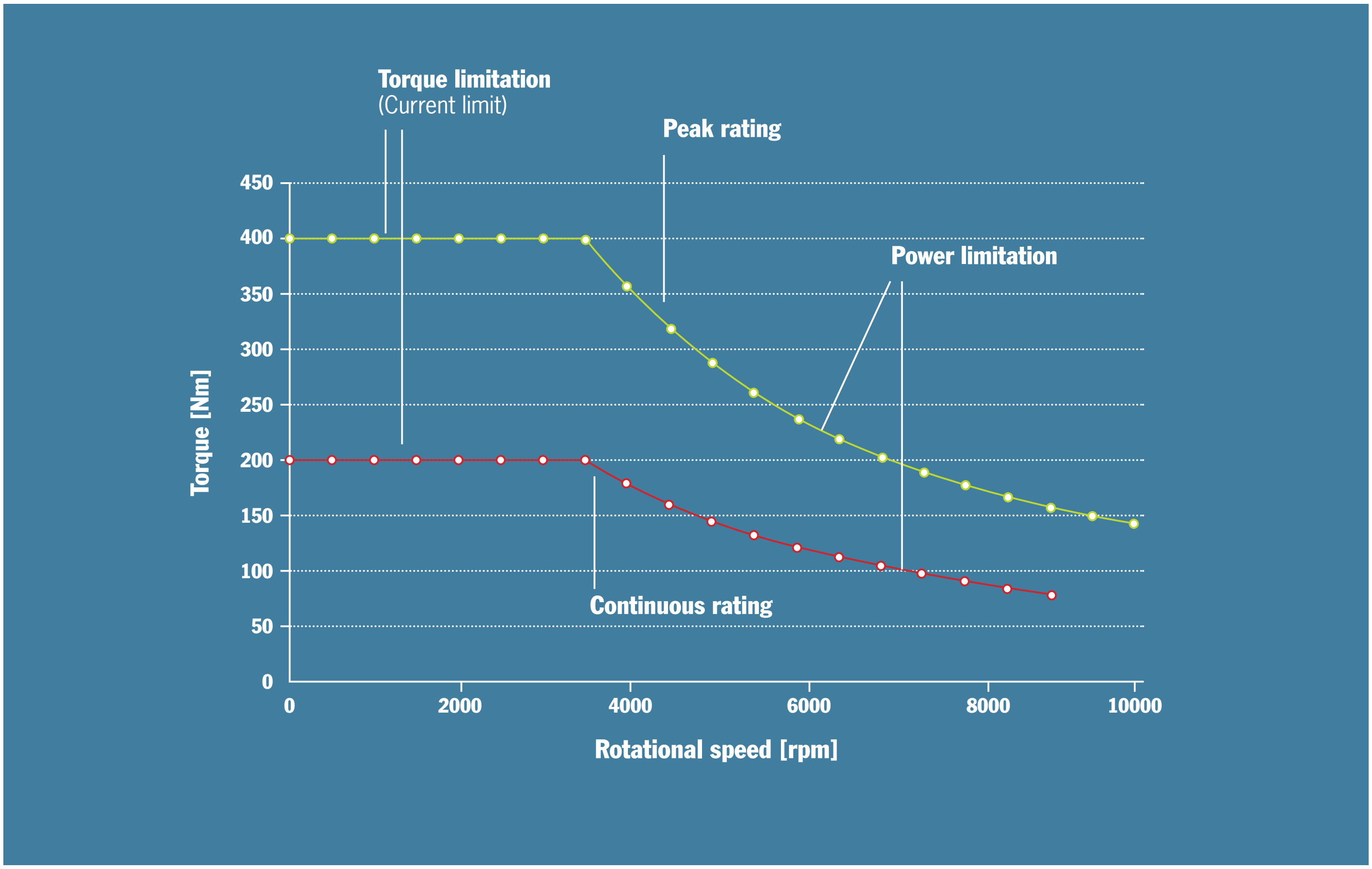
Whereas the performance and power output of combustion engines is generally fixed, an electric motor can deliver short bursts of power at very high levels. Thus, a distinction needs to be made between continuous or "S1" power rating, and the short-term peak power rating of the electric motor.

In some driving scenarios such as sustained uphill driving or driving at high speeds, continuous power is critical. In other scenarios, like overtaking slower vehicles or climbing over a curb when parking, peak power is required. In modern electric motors, peak power ratings can be up to 5 times higher than nominal power ratings, thus inevitably changing the driving characteristics of electric vehicles compared with conventional vehicles.

During a peak power event, the temperature of the copper wires carrying the current rises quickly, eventually reaching the copper wire's temperature limit. At this point, power needs to be reduced to prevent damage to the machine. However, the peak performance depends not only on time but also on other parameters, such as the DC voltage applied to the inverter and the coolant temperature. This gives the electric motor a multidimensional performance characteristic, which is virtually impossible to capture in a single data sheet.

Torque/Speed curves

As is the case with combustion engines, torque/speed curves, plots of torque and power over rotational speed, are useful tools for characterising a given machine (see right-hand page: Torque/speed curve). Torque/speed curves of all electric motors exhibit a certain characteristic: up to a certain speed, the corner speed, torque is constant and power increases.



Torque/speed curve

Beyond the corner speed, torque drops while power stays constant.

In this constant power region, the voltage applied to the machine no longer rises with speed but is kept constant. Keeping voltage constant despite increasing speeds requires an artificial weakening of the electromagnetic fields inside the machine. This can be achieved, for example, by changing the timing of the AC current injected in the machine. However, part of the current is then no longer available for torque production, which is why torque drops beyond the corner speed.

Considering the described complex behavior of electric motors, real-life evaluation on test benches is of paramount importance for identifying the properties of a given machine. Porsche Engineering's electric motor test bench (see article "Electrified," p. 22) thus provides customers with an essential tool for verifying the actual performance of an electric motor.

Performance limits

Electric motor performance is limited by a number of factors. One is the maximum temperature of the copper windings carrying the electric current. Covered with multiple layers of electrically insulating plastic coating, the permissible temperature typically ranges between 140 and 200°C. Since current running through a wire creates losses, the windings heat up, thereby limiting the current applicable.

Permanent magnets, if present, have a temperature threshold as well. Modern neodymium–iron–boron (NdFeB) magnets can withstand temperatures of up to 220°C. If the limit is exceeded, however, the magnets will de-magnetise, irreversibly reducing performance. Magnetic heating is a complex phenomenon, influenced by machine speed, DC voltage, and the magnitude and harmonic content of the AC current waveform. Sophisticated "motor models" are needed to calculate magnetic temperature in situ, since it can be measured only with great difficulty. Predicting the response of an electric powertrain system within a vehicle system therefore requires highly integrated simulation (see article "Optimized").

In addition to the thermal limitations discussed, electric motors face the same constraints as other pieces of rotating machinery: the maximum speed is limited by the rigidity of the rotor and the bearings, while the level of power › supplied by the inverter and/or the battery naturally limits what the machine can deliver.

(A)Synchronous

A large variety of different machine topologies exist in the market, only a few of which are utilised by vehicle manufacturers. Synchronous machines are so named because the electromagnetic field set up by the injected current rotates synchronously with the machine rotor. Most relevant for automotive applications are permanent magnet synchronous machines (PSMs). These machines deliver high torque and power, have a high efficiency and run at high speeds.

The rotor of an PSM can be located either inside or outside the stator. A typical example of an internal rotor PSM is the traction motor powering the front wheels of the Porsche 918 Spyder (see p. 28). External rotor PSMs have an increased torque capability and short axial length. These machines are therefore often used as integrated motor/generators that sit between the combustion engine and the gearbox of hybrid vehicles such as the Panamera S E-Hybrid.

Unlike PSMs, asynchronous machines (ASMs) do not utilise permanent magnets. Torque is produced by the reaction between the stator electromagnetic field created directly by the injected current and a reaction field induced indirectly in the machine's rotor. In these machines, the stator field and the rotor turn asynchronously, i.e. at different speeds. The establishment of the reaction field—as described by Faraday's law of induction—can only happen when there is relative movement or "slip" between the stator field and the rotor.

ASMs are very robust and generally cheaper than PSMs because they don't employ permanent magnets, which are by far the most expensive components of a PSM. However, ASMs are also comparatively inefficient and heavy.

Conclusions

High-power electric motors and generators such as those used in modern electric vehicles are highly complex devices despite their seemingly simple design and elegant physical description. Understanding their true characteristics is therefore essential for integrating them optimally within a complex vehicle system.

A wide range of different types of machines with idiosyncratic and non-obvious advantages and disadvantages populates the market. Choosing the machine most suited for a given vehicle concept therefore necessitates extensive evaluation on an electric motor test bench coupled with advanced simulation of machine and surrounding vehicle system.

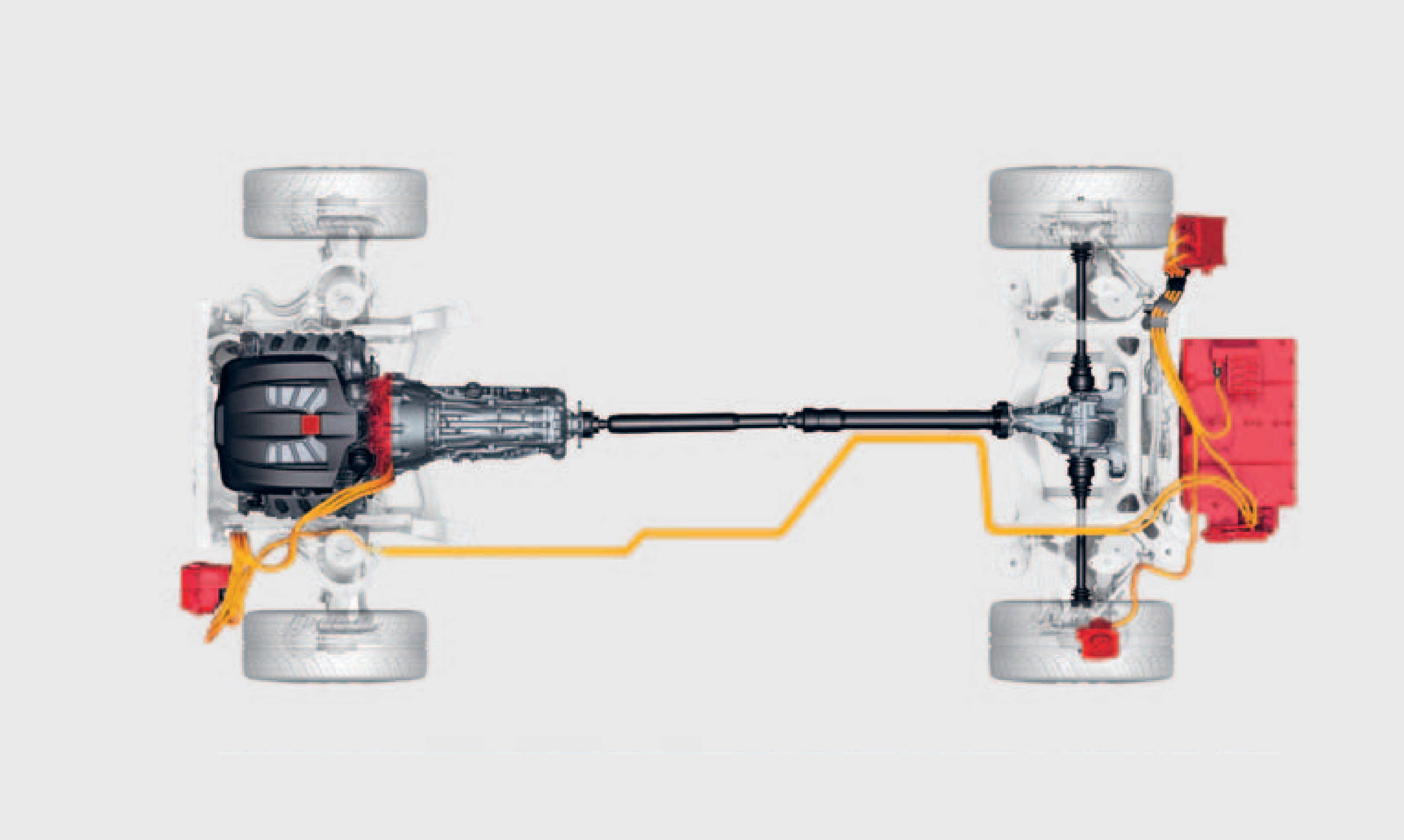
Hybrid Powertrain of the Panamera S E-Hybrid

The seamless interplay between the combustion engine and electric motor forms a drive concept that unites high performance and high efficiency. The new lithium-ion battery can be charged via the vehicle charging connection. The powerful and high-torque electric drive ensures adequate electric performance. The engines are still mechanically connected to the axles, so typical Porsche performance can be called up at any time: via the combustion engine or with extra punch using both drives–also known as boosting.

The increasing prominence of electric mobility is creating considerable pressure on established vehicle manufacturers to develop new products quickly. Porsche Engineering stands ready to accept the challenge and drive new vehicle technologies into the future. ■

PANAMERA S E-HYBRID Fuel consumption (combined): 3.1 l/100 km; CO_2 emissions: 71 g/km; energy consumption: 16.2 kWh/100 km; efficiency class: DE/CH A+/A

The Panamera S E-Hybrid: forward-looking



Hybrid Powertrain of the Panamera S E-Hybrid