

State of the Art and Future Trends of Electric Drives and Power Electronics for Automotive Engineering

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ABSTRACT

Discussions about the optimal technology of propulsion systems for future ground vehicles have been raising over the last few years. Several options include different types of technologies. However, those who are advocating conventional internal combustion engines are faced with the fact that fossil fuels are limited. Others favor hydrogen fuel as the solution for the future, either in combination with combustion engines or as an energy carrier for fuel cells. In any case, the production and storage of hydrogen is an ongoing challenge of numerous research works. Finally, there are battery-electric or hybrid propulsion systems in use, gaining more and more popularity worldwide.

Ongoing advances in power electronics help to improve control systems within automotive applications. New developed or designed components enable more efficient system architectures and control. This paper includes a detailed comparison of different electric drive technologies, e.g. a DC motor, an asynchronous and synchronous motor in battery-electric or hybrid drivetrain configurations. Parameters for future drive architectures, such as high torque and power output, high system efficiency, low mass, low energy consumption, very low exhaust gas emissions, and low costs are introduced and discussed. Advantages and disadvantages of different drivetrain configurations are specified, evaluated, and discussed. Additionally, a selection of advances in power electronics is listed and described in detail. Practical examples of electric drive systems are given explicitly and conclusions for future development are made. The publication closes with an overview of current components in use and presents an outlook to future trends.

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INTRODUCTION

The tradition of electrical machines within automotive applications is more than 180 years old, as they have already been invented in about 1830. Combined with the invention of the lead accumulator in 1859, electric drives represent a concept for propulsion systems older than conventional internal combustion engines. At that time, three different propulsion systems were in use: steam drives, electrical drives, and gasoline engines. Because of the higher energy density of mineral oil, the cheaper raw material and its seemingly infinite availability, the combustion engine became the dominant propulsion system. However, boundary conditions are changing nowadays. An increasing shortage of mineral oil, the problematic of CO₂-emissions, and noise exposure, as well as an increasing demand for mobility, especially in urban areas, makes the conventional internal combustion engine questionable as propulsion system for future mobility concepts, illustrated in [Figure 1](#). Therefore, a changeover to environmentally friendly propulsion technologies is needed. The change to electric technologies does not only include a modification of drive train components, it requires a

fundamental technology turnaround by implementation of a complex system with different characteristics [1][2][3][4][5], as shown in [Table 1](#) and [Figure 2](#).

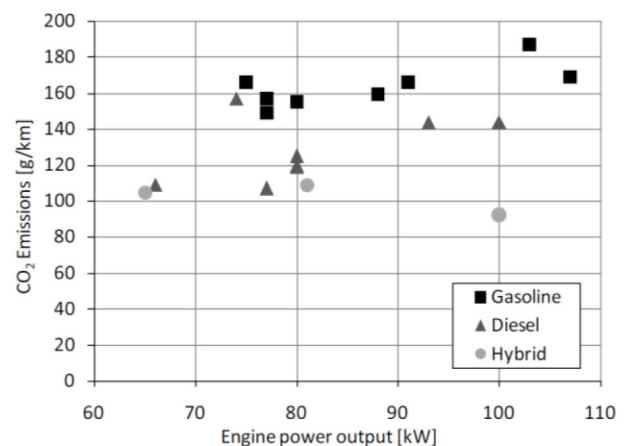


Figure 1. CO₂-emission comparison of different propulsion systems for compact cars [4].

Table 1. Changes in the drive train of electric vehicles compared to vehicles with conventional internal combustion engines [1].

components not needed	adapted components	additional components
combustion engine	transmission	electric machine
fuel-injection system	wheel suspension	power electronics
tank	drive line	battery system
clutch	air conditioning	
exhaust-gas system	water pump	
auxiliary equipment (e.g. gear oil pump)	thermal insulation	



Figure 2. Components of battery electric vehicles (Hybrid4All i-BSG 48V) [6].

Different arrangements of electric machines are possible, as can be seen in Figure 3. Because of its simple and cost-effective configuration, central electrical machines are widespread, although this category needs most constructional space of all three types. On the one hand, in view of the vehicle packaging, the required space of the propulsion system can be reduced by placing the electric motor near the wheels. If the electric propulsion system is realized as a wheel hub motor, the optimum space within the package is provided [1]. On the other hand, wheel hub motors have disadvantages regarding the unsprung masses and state a challenge for thermal layout of the drive unit. In any case, electric propulsion systems show an advantageous behavior in view of their space requirements and the vehicle packaging in comparison with conventional drive train technologies.

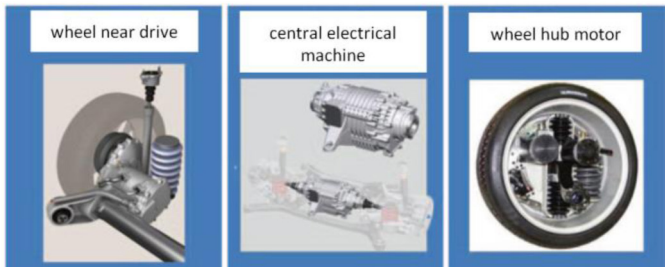


Figure 3. Examples of different integration of electrical machines, adapted from [1], [7][8][9].

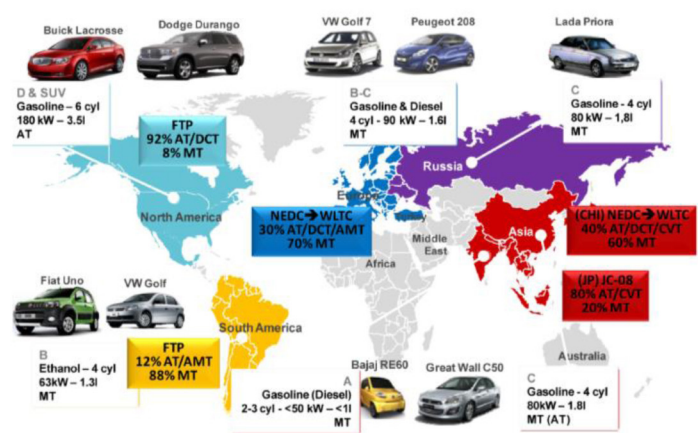


Figure 4. International vehicle specifications: vehicle segments, powertrain type, transmission type, driving cycle [6].

Alternative Powertrain Concepts

Although OEMs are currently able to offer and deliver green technologies, future market predictions still remain uncertain. As a long-term commitment for clean mobility beyond internal combustion engines, the hybrid electrical vehicle shows the highest market share for alternative powertrains due to its wide driving range and high flexibility [3]. Therefore, different hybrid configurations are given. Figure 5 shows a selection of configurations.

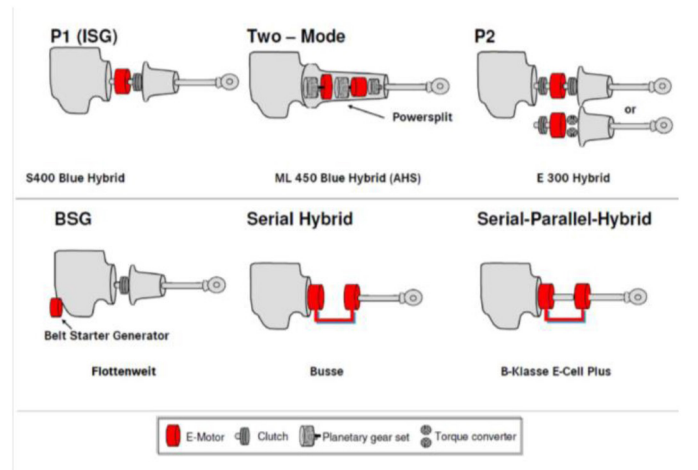


Figure 5. Different hybrid configurations [10].

Practical examples of different electric and hybrid modular systems are shown in Figure 6.

With focus on so called ultra clean powertrain technologies, the hydrogen powered fuel cell provides a high potential to become independent from fossil energy sources. Its advantages are long driving range, high efficiency, and a relatively short refilling time. For example, the refilling process (under various temperature conditions, even down to -25°C) takes less than three minutes, allowing a driving range of more than 500 km. Furthermore, the Li-Po battery technology with its integrated power electronics is used as key power source for many electric vehicle technologies [3].

Vehicles	Power Electronics	Onboard Charger (AC)	Battery	E-Motors
E-Cell Sprinter AMG SLS	80/100kW	22kW	6 Modules a 33 Z	TEM
PI-Hybrid S-Class		3.3 kW	6 Modules a 20 Z	GEM 80kW 20kW
Hybrid E-Class S-Class	35/55kW	Not necessary	4 Modules a 20 Z	
E-Cell Smart Electric drive		optional 22kW standard 3.3kW	3 Modules a 33 Z	

Figure 6. A modular system as precondition for economic efficiency [10].

Table 2 gives a comparison of the current development status of hybrid propulsion system technologies.

Table 2. Hybrid development status [3].

Powertrain System	2.0 Gasoline	2.0 Gasoline + Hybrid	1.7 Diesel MT
Power kW	121	110 Gasoline 30 e-Motor	100
Battery	-	Li-Polymer	-
CO ₂ g/km	177	- 30% → 125	128
Driving Range km	920	- 30% → 1200	1400

OVERVIEW OF DIFFERENT TYPES OF ELECTRICAL MACHINES

In general, all types of electrical machines can be used as drive unit for electric vehicles. Which type of machine is preferred, depends on the operational profile, costs, constructability of the selected electric machine, maintainability, recyclability, durability, power density, efficiency, and the used materials. The maximum rotation speed of electrical machines in passenger cars lies between 5,000 and 15,000 rpm, and at commercial vehicles between 2,000 and 8,000 rpm. On the one hand, there is an ongoing tendency to higher rotational speed, which leads to a reduced torque demand. In general, the machines building volume and their mass are proportional to the torque, machines with lower torque output can be built smaller and lighter. On the other hand, a higher speed level of the motor makes the implementation of multi-stage transmission necessary, which are often designed as planetary gears. The total efficiency is a main factor of influence and has a big effect on the driving range of electric vehicles (besides the capacity of the battery system). Therefore, the total efficiency of an electric vehicle represents a key factor for selecting and dimensioning an electric machine [1], [2].

Figure 7 depicts different types of electrical machines, which are described in the following chapters shortly. A more detailed description can be found in [1].

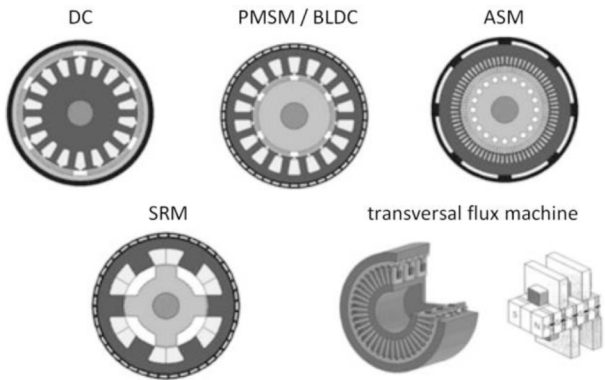


Figure 7. Different types of electrical machines for application in electrical vehicles [1].

DC Machine

Nowadays the DC machine is not used anymore for passenger cars due to its lower torque density and increased need of maintenance, but it is found particularly in mobile work machines of lower power output [1].

Permanent Magnet Electric Machine

In permanent magnet synchronous machines (PMSM), the rotor winding is replaced by permanent magnets, in general ferrite, neodymium-iron-boron, or cobalt-samarium. This type of electrical machine has the highest efficiency due to elimination of the rotor losses and allows highest power density. Because of up-to-date materials, such as NdFeB (high energy

permanent magnet), compact constructions are possible. Although material prizes are recently high, there are no other equivalent materials, if a high power density is the main criteria. Typically power values are below 100 kW, but have been increasing recently [1], [5], [11].

The applied technology of power supply gives the machine its name, whereas the construction of the machine is same in both cases (Figure 8). In case of power supply in form of rectangular voltage shape, it is called brushless DC motor and in case of sinusoidal voltage shape it is called permanent magnet synchronous motor (some authors also refer to this type as brushless AC machine). Mainly the sinusoidal power supply is used at lower rotational speed, whereas the rectangular shaped voltage is used at higher speed. This has the advantages of a smooth driveaway at low speed and a high efficiency of power electronics at higher speed. In some cases, both operational modes are applied.

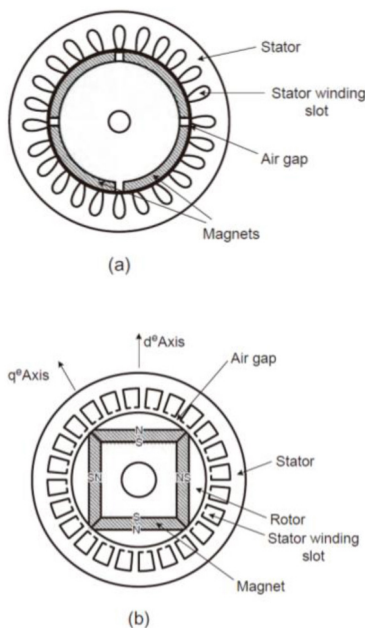


Figure 8. Schematic cross section of sinusoidal permanent magnet synchronous machine: (a) surface permanent magnet (SPM) and (b) interior permanent magnet (IPM) [11].

Permanent magnet synchronous machines can be designed for a high speed range at high torque output. Because of its good efficiency and high power density, this type of electrical machine is used with an increasing tendency as automotive drive unit. However, if an unexpected failure within the power electronics system occurs, safety measures have to be taken. Therefore, propulsion concepts with synchronous machines are equipped with an additional mechanical transmission.

In general, the permanent magnets are applied inside the rotor system. Mainly with wheel hub motor applications, this could be a constructive advantage, for space-performance-ratio reasons [1], [4], [11].

Induction Machine

The induction or asynchronous machine represents a mechanical and thermal robust as well as cost efficient drive technology. Disadvantageous is a lower efficiency compared to synchronous machines due to the fact that induction machines do have a demand on reactive power. For this reason, a larger constructive volume and a lower power density has to be considered. At higher speed, a good efficiency can be reached. To achieve higher rotational speed, in general, flux weakening is used easily. In this case, the torque demand is low [1].

Switched Reluctance Machine

This type of electric machine has a simple and robust assembly without permanent magnets or a rotor winding, as shown in Figure 9. Both, stator and rotor do have distinctive teeth, where a torque results from the different reluctance (magnetic resistance).

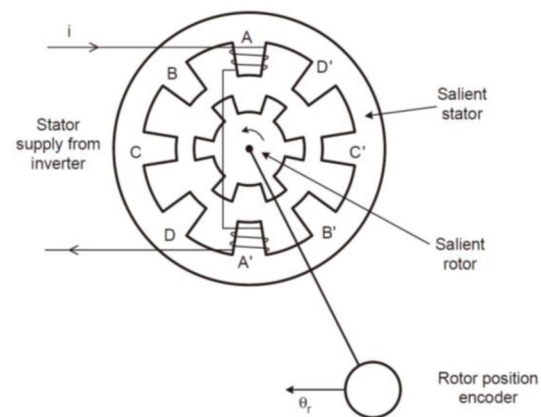


Figure 9. Schematic cross section of a switched reluctance machine (SRM) [11].

Reluctance machines cause relatively high noise, which needs to be minimized by a proper geometrical machine design, whereas a compromise has to be found in a noise-performance-ratio. This type of propulsion system is an upcoming technology with potential for future applications for electric road vehicles, because of its cheap and robust production as well as its high power density at high speed ranges [1].

Transversal Flux Machine

The transversal flux machine is a special type of electrical machine with a very high number of pole pairs, which leads to very high torque densities. Typically, they are used within electric vehicles with direct drive. Advantageous is the short axial length of the machine. Applications can be found mainly at wheel hub drives of minibuses.

Comparison of Different Machine Types

Table 3 gives an overview of design and construction relevant parameters of different electrical machines.