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System Architecture and Potential Analysis of Electric Axle Drives

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Abstract

In order to meet future CO2 requirements, the entire automotive industry is increasingly focusing on the electrification of the powertrain. The whole powertrain layout changes with the implementation of an electric drive system and furthermore this electrification provides challenges to the automotive industry in form of package-, weight-, performance-, efficiency- and cost targets. To overcome these challenges one solution is the principle of integration through electric axles. These combine the main components, which are reduction gearing, differential, electric motor and power electronics, and sub components like actuators, control units and wiring harness, in one compact unit. This thesis describes the application field of electric axle drives, which ranges from mild hybrids over full hybrids to plug-in hybrid vehicles. Not only hybrid vehicles, but also battery electric vehicles and range extended vehicles were taken into account. The different options in terms of system architecture of electric axles were elaborated and discussed. Next the focus was set on the major components and their improvement potential. Because thermal management and the closely related battery technology are critical for efficiency these subjects were also included. Finally, an e-axle design guideline was created to point out possible options during the development phase of electric axles.

Kurzfassung

Um die zukünftigen CO_2 Grenzwerte einhalten zu können, konzentriert sich die gesamte Automobilindustrie zunehmend auf die Elektrifizierung des Antriebsstranges. Die gesamte Architektur des Antriebsstranges ändert sich durch die Implementierung elektrischer Traktionsantriebe und weiters wird die Automobilindustrie vor Herausforderungen in Form von Package-, Gewichts-, Leistungs-, Effizienz- und Kostenzielen gestellt. Um diese Hürden zu meistern, kann eine Lösung in dem Prinzip der Integration durch elektrische Achsen gefunden werden. Diese kombinieren die Hauptkomponenten Reduktionsgetriebe, Differential, Elektromotor und Leistungselektronik sowie Teilkomponenten wie Aktuatoren, Steuergeräte und Kabelbäume in einer kompakten Einheit. Diese Arbeit beschreibt das Einsatzgebiet der elektrischen Achsen, das von Mild-, über Voll-, bis hin zu Plug-in-Hybridfahrzeugen reicht. Es wurden nicht nur Hybridfahrzeuge, sondern auch batterieelektrische Fahrzeuge und Range Extender Fahrzeuge berücksichtigt. Die verschiedenen Möglichkeiten der Systemarchitektur elektrischer Achsen wurden ausgearbeitet und diskutiert. Folgend wurde der Schwerpunkt auf die Hauptkomponenten und deren Verbesserungspotenzial gelegt. Da das Thermomanagement und die damit eng verbundene Batterietechnologie für die Effizienz entscheidend sind, wurden diese Themen ebenfalls eingebunden. Abschließend wurde ein E-Achsen Design Guideline erstellt, um mögliche Optionen während der Entwicklungsphase von elektrischen Achsen aufzuzeigen.

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1 Introduction

One of the basic needs of mankind is mobility and cars are the main mode of transportation today. But because of the finite availability of fossil fuels and the growing ecological awareness, fuel consumption and pollutant emissions get increasingly in the focus of the society. Not only is the view of the society changing, but also politics force stricter emission standards for motor vehicles of all kinds. Carbon dioxide, which is produced by combustion of fossil fuels, is in reasonable concentration not poisonous, but contributes as greenhouse gas to the ongoing global warming. In response, the European Union has set for the year 2021 a limit of 95 g CO_2/km for fleet consumption (European Parliament, 2009). To reach those ambitious goals, the automotive industry focusses on the electrification of the drivetrain. Battery electric vehicles, which completely remove the combustion engine from the drivetrain, do not release any harmful substances into their immediate environment and are therefore also called zero emission vehicles. Because of lacking charging infrastructure, smaller range and high costs of those vehicles, hybrid vehicles are considered as an interim solution. Hybrid vehicles use a minimum of two power converters and most commonly electric motors and combustion engines are combined. Other concepts are range extended vehicles, which use fuel cells or smaller engines, called auxiliary power units, to charge the traction battery. All those mentioned vehicles have one common feature and this is the electric machine in the drivetrain. Of course, other components like power electronics, reduction gearings and differentials are needed for electric propulsion. To make electric drivetrains more cost efficient, space-saving and lighter OEMs and their tier one suppliers integrate all the mentioned components and even parts like wiring harness, control units and actuators in one unit called electric axle. But not only efficiency is the key to success of electric and hybrid vehicles, also technologies, like torque vectoring, that create additional customer values like performance and safety are gaining importance.

1.1 Problem Statement and Aim of the Work

The range of applications of electric axles is huge and not only covers the different mentioned vehicle types, but also the performance goals vary massively depending on application. The bandwidth ranges from low power 48 V units to powerful high voltage drivetrains. Furthermore, because most electric axles are new to the market there is no “golden standard” and manufacturers have different opinions about the optimal concept. Because electric axles combine many different components in one package the subject area is very broad. With the help of this thesis existing electric axle topologies should be analyzed in terms of system architecture, advantages and disadvantages and future potential. For the evolution of the system all important mechanical and electrical components need to be discussed. Furthermore, the thermal management and the closely related batteries are important for efficiency and robustness of the system. Finally, the elaborated system architectures should be integrated in an electric axle design guideline to show available solution principles during development phase.

2 Hybrid Propulsion Systems

The term “hybrid” has its origin in the Latin language and means in our context “mixed” or “from different breeds”. From this meaning you come to the simple definition, that a vehicle with hybrid drive uses a minimum of two different energy converters and two different energy sources for propulsion. The energy converters can produce mechanical energy for direct propulsion or provide electrical energy for the propulsion. The energy source can contain chemical energy (e.g. fuels), mechanical energy (e.g. flywheel, pneumatic or hydraulic pressure accumulators), electric energy and combinations of these energy forms. Theoretically there are many possible ways to convert one energy form in another, this thesis focusses on systems that convert chemical and electrical energy directly or indirectly in mechanical work. (Tschöke, 2014)

2.1 Hybrid Drives

Hybrid electric vehicles can basically be characterized according to two main criteria. The first division of the vehicles takes place according to their degree of hybridization or electrification, this means that the availability or storage of the two energy forms and the design of the drive motors are at the forefront. A second classification is based on the drive architecture by describing the combination and the use of the drive components. Furthermore, the possible driving modes are important to differentiate diverse types of hybrid drives:

- pure combustion engine driving,
- pure electric driving,
- hybrid driving,
- boosting,
- recuperation,
- generator mode,
- start-stop function.

(Tschöke, 2014)

2.1.1 Classification by Degree of Hybridization or Electrification

Usually hybrid electric vehicles (HEV) are classified by their degree of hybridization in:

- Micro hybrid
- Mild hybrid
- Full hybrid
- Plug-in hybrid

The **micro hybrid** is by the definition, which can be found in chapter 2, not a hybrid system. This is because for propulsion only mechanical energy, which is provided by the combustion engine, is used. The electric energy from the board battery and the standard 14 V generator is only used for a star-stop strategy during standing. If the vehicle comes to rest for example at a traffic light, the drivetrain is moment free (neutral is engaged), the state of charge of the battery is sufficient and the engine is at operating temperature the engine will be shut off. If the clutch is engaged or the brake is disengaged when used with automatic transmissions the engine restarts automatically. These start-stop systems require a stronger gear driven starter motor or use a belt driven starter motor/generator. Downsides are that the battery must withstand the frequent starting processes and sometimes even a small additional battery is needed to balance the electrical system during starting processes. In a coast situation, the motor can be used in generator mode to provide a limited amount of electrical energy to charge the battery. Such a system can be laid out in a way that every auxiliary unit is powered electrically so that the whole power of the combustion engine is available during acceleration and each auxiliary unit works during stand still. The micro hybrid was a very important step on the way to electrification and cuts fuel consumption up to 5 % in the New European Driving Cycle (NEDC), which is a test cycle used to determine fuel consumption and emissions of vehicles, and up to 10 % during pure city driving. The next evolution can be seen in the **mild hybrid** which is equipped with an electrical motor with a power roughly between 5 to 20 kW besides the combustion engine and an additional traction battery. This system uses the electric motor for start-stop function as the micro hybrid does, but additionally provides torque during launch and acceleration and recovers energy during braking. In mild hybrid systems, the electric motor is normally connected directly to the crankshaft of the combustion engine. During assisted acceleration, which is called boost mode, the torque of the electric motor is added to the torque of the combustion engine to enable a more dynamic performance especially in the low rpm range. Pure electric driving is mostly not useful, because the drag torque of the combustion engine also must be compensated. The conventional starter may still be maintained to ensure the cold start of the combustion engine at very low temperatures. Voltages of the traction batteries in these applications range from 42 to 150 V and are above the normal board net voltage. But there is not only a performance gain, but also the load point of the engine can be shifted for better fuel economy. The benefit during NEDC ranges from 15 to 20 %. Component wise mild hybrids need stronger electric motors, more advanced battery technology and more advanced control units when compared to micro hybrids. The **full hybrid** allows a purely electric or purely combustion engine or combined driving operation. The energy flow can be structured in parallel, serial or as a combination thereof (power split) by corresponding arrangement, design and number of drive components. In contrast to the mild hybrid, the internal combustion engine does not need to be dragged with the electric motor. The electric drive power is more than 20 kW and reaches values of approximately 60 kW depending on the energy flow strategy. The high-voltage board net and traction battery operate in a range from 200 to over 400 V. The standard 14 V power system is installed in parallel for the standard consumers. A generator for this is no longer necessary. The low-voltage battery is fed from a DC-DC converter. Depending on the system design, the conventional starter may still be maintained to ensure the cold start of the combustion engine at very low temperatures (see mild hybrid). The potential for reduction in fuel consumption is 20 to 30 % in the NEDC, but is significantly dependent on the energy flow strategy. The distances which can be driven purely electrically are low, without an increased battery capacity and are within the range of 10 km. The **plug-in hybrid** is in principle a full hybrid with the possibility of battery charging from an external power source (e.g. wall power outlet). Vehicles equipped with such a system are called plug-in hybrid electric vehicles (PHEV). Other charging systems (for example contact free charging at vehicle standstill or during slow travel) are also possible and in development. The focus of the plug-in technology is to significantly extend the electrical range. Larger batteries with a higher energy capacity are primarily required for this purpose. The realistic electrical ranges vary from 30 to 100 km and depend very much on the driving profile or test cycle and the ambient conditions (such as temperatures). Plug-in hybrids form the bridge from pure combustion engine powered vehicles to pure electric powered vehicles, which are called battery electric vehicles (BEV). Depending on the installed electrical energy capacity, the electric driving operation can take over an ever-greater share of the total operation, until finally 100 % is driven electrically. Plug-in hybrids are particularly attractive for daily short-haul traffic. For reference in Europe, 70 to 80% of the daily distances traveled are less than 50 km. The main disadvantages of the plug-in hybrids are still the high costs, the large space requirement, the high weight and the unsatisfactory charging situation (availability and duration). After this fundamental definition and division of the hybrid drives according to their degree of electrification, the differences in the energy or power flow of the drivetrain are described based on the different component architectures (arrangement and design). (Tschöke, 2014)

The abilities of each hybrid type are summarized in Table 1.

Table 1: Operation modes of different hybrid types. (cf. "Hybrid vehicle drivetrain - Wikipedia," n.d.)

Type	Start-stop	Recuperation Boost	Pure electric driving	Rechargeable
Micro hybrid	Yes	No	No	No
Mild hybrid	Yes	Yes	No	No
Full hybrid	Yes	Yes	Yes	No
Plug-in hybrid	Yes	Yes	Yes	Yes

2.1.2 Classification by Energy Flow

Depending on the arrangement and combination of the components internal combustion engine, electric machine, battery, gearbox and clutch hybrid drivetrains can be categorized by their power flow in:

- Series hybrid
- Parallel hybrid
- Power-split hybrid or combined hybrid

(Tschöke, 2014)

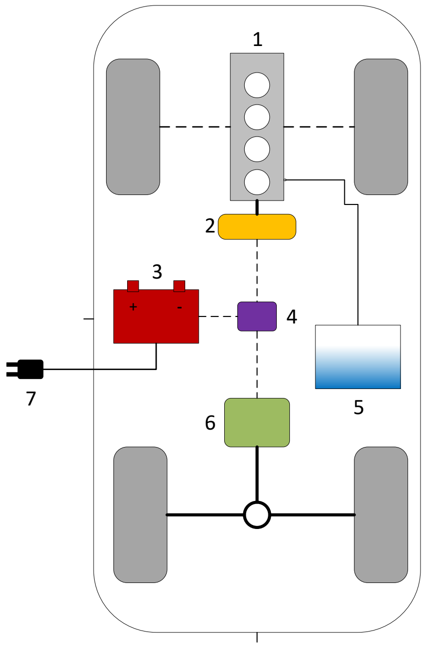

Figure 1: Series Hybrid. 1 combustion engine, 2 generator, 3 traction battery, 4 power electronics, 5 tank, 6 electric machine, 7 power plug. (cf. Tschöke, 2014)

In case of the **series hybrid**, Figure 1, the energy converters, which are combustion engine and electric machine, are arranged serially. This means that the mechanical connection between combustion engine and tires is completely removed and only the electric machine propels the vehicle. Instead the combustion engine and the generator are mechanically coupled. The generator provides the electric energy for the second electric machine, which can be used as motor or as generator for recuperation and propels the vehicle. The drive is therefore always electrically and the internal combustion engine operates dependent from the operational strategy. In the simplest, but most inefficient case, the internal combustion engine produces just the required electrical energy. This means that the efficiency must be lower compared with a mechanical drive from combustion engine to the wheels, because of electrical losses for the double energy conversion (mechanical/electrical and electrical/mechanical). The advantage of this layout lies in the possible recuperation during braking. When a high capacity traction battery is used the combustion engine and the generator can be downsized and an optimized operating point for the combustion engine is possible. The fuel consumption or the emissions can be optimized. The combustion engine provides than only a mean power and excess power is used to charge the traction battery, which provides additional energy for acceleration and short high-speed phases when needed. This can partially compensate the mentioned energy conversion losses. An additional downsizing is possible when a plug-in system is used and the combustion engine is only used as a range extender. (Tschöke, 2014)

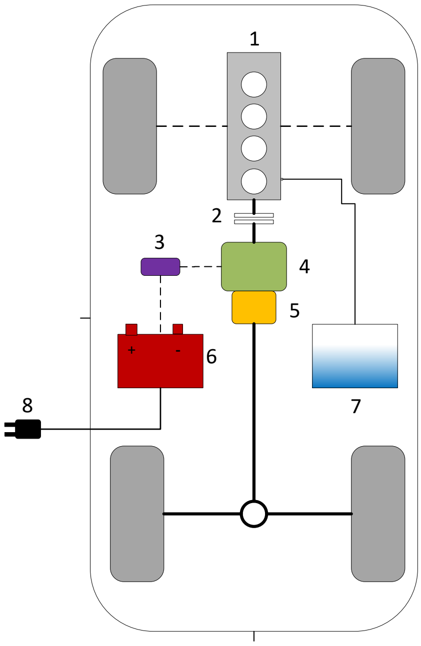

Figure 2: Parallel Hybrid. 1 combustion engine, 2 coupling, 3 power electronics, 4 electric machine, 5 generator, 6 traction battery, 7 tank, 8 power plug. (cf. Tschöke, 2014)

In contrast to the serial hybrid drive, in the case of the **parallel hybrid** drive, Figure 2, only one electric machine (both motor and generator) and a clutch are required. When the clutch is open, it can be driven purely electrically or in the closed state purely mechanically or mechanically / electrically. Depending on the type of connection of the electric machine to the internal combustion engine (directly or via a transmission), the desired driving performance can be achieved via a torque addition (rotational speeds in a fixed ratio to one another) or by means of planetary gear units via speed addition. A simple parallel hybrid is the mild hybrid with a crankshaft mounted starter-generator, in which the clutch is arranged after the electrical machine. In the case of the pure electric drive, however, as already mentioned, the drag torque of the internal combustion engine has to be overcome. Depending on the design of the electrical components, it is usually only possible to boost, to short-term drive electrically, or to "sail", which means maintaining a constant low speed. The series hybrid drive can also be upgraded to a parallel hybrid by using a disengageable mechanical torque connection between the two electrical machines (2 and 6 in Figure 1). The electrical machines could be designed smaller, if at low power scenarios the series drive is used, and if the power demand is high, only the internal combustion engine or both energy converters are used via a direct drive. (Tschöke, 2014)

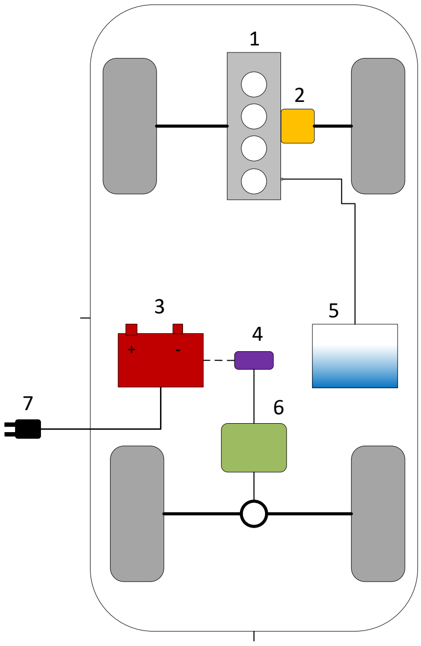

Figure 3: Axle-Split Hybrid. 1 combustion engine, 2 conventional gearbox, 3 traction battery, 4 power electronics, 5 tank, 6 electric machine, 7 power plug. (cf. Tschöke, 2014)

Another type of a parallel hybrid is the **axle-split hybrid**, Figure 3, where the combustion engine and the electric machine operate on different axles (typically the combustion engine on the front axle and the electric machine on the rear axle). There is no mechanical connection between the two energy converters, so a tractive force addition through the road takes place. The advantage of this configuration is that it is only necessary to have one electric machine which is both motor and generator. The dimensioning of the drive components can be better designed, as the design of the combustion engine can be based on the maximum speed and that of the electric machine on city driving (large ICE, small electric machine). Furthermore, the direct mechanical connection from the combustion engine to the wheel, especially at higher speeds has the best efficiency, because there are no electric conversion losses. Therefore, this hybrid has a very good potential to achieve low fuel consumption. A little disadvantage for exhaust emissions and energy consumption can be, depending on the design, that the combustion engine can no longer operate stationary and independently of the wheel drive. The operating point optimization of the combustion engine, mentioned for the serial hybrid, is also not possible. (Hofmann, 2010)

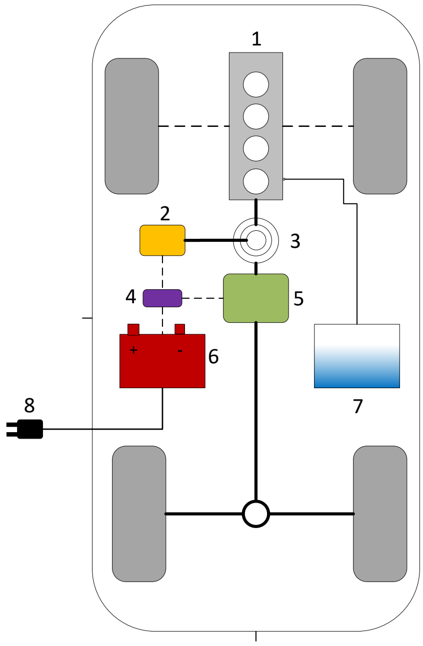

Figure 4: Power-Split or Combined Hybrid. 1 combustion engine, 2 generator, 3 planetary gearbox, 4 power electronics, 5 electric motor, 6 traction battery, 7 tank, 8 power plug. (cf. Tschöke, 2014)

The **power-split or combined hybrid**, Figure 4, has a planetary gearbox as a characteristic component, which adds the power of the electric and the mechanical path of the drive train via speed addition. The planetary gearbox acts as a continuous transmission. In case of the so-called output-coupled form the internal combustion engine is connected to the planet carrier, the generator is connected to the sun gear, while the drive axle and the electric machine are coupled to the ring gear. Such a system requires two electric machines in form of a generator and an electric motor, since electricity must be generated from a portion of the combustion engines power to charge the battery and provide power to the electric motor. That’s why the combustion engine in a power-split system is usually bigger than in a parallel hybrid. (Wallentowitz and Freialdenhoven, 2011).

2.1.3 Conclusion

The described hybrid systems have, as described, their specific advantages and disadvantages. Depending on the application (length of the route, topography), the size of the vehicle, the legal framework, but also the social requirements and the emotional needs of the customer, the decision must be made as to which system is used. Nevertheless, there is still a great need for improvements in component and system function, cost (biggest downside), weight and service life. Additionally, hybrid vehicles are often only considered as a temporary solution till the maturity of battery electric vehicles. Irrespective of this, the electrification of the powertrain by the hybrid technology has already achieved a high technical level, which makes it possible to make a significant contribution to the fulfillment of emission regulations. Start-stop systems (micro hybrids) are today present in nearly all vehicle classes and will be evolved to mild hybrids in the future. In the case of full hybrids, the trend towards parallel systems is taking place, whereas series hybrids are used in electric vehicles with range extender. The plug-in function is a huge benefit and can be implemented in all hybrid systems. Finally a very big improvement potential lies in battery technology. (Tschöke, 2014)

2.2 Range Extender

Because of the limited capacity and longer charging time of today's battery technologies, BEVs can typically not reach the driving range of conventional and hybrid vehicles. This makes it hard to use BEVs outside of urban and other short driving environments. Range-extended electric vehicles (REEV) incorporate an auxiliary electrical power source to the propulsion system to increase the driving range. The range extender can be either a small internal combustion engine with a generator (thermal REEV) or a fuel cell (chemical REEV). The capacity of the battery is designed for a customer's average daily usage and the range extender allows the vehicle to maintain a long driving range when needed. Carbon dioxide emission and fuel consumption are significantly reduced by this technology, when compared to traditional vehicles powered by ICEs. (Emadi, 2014)

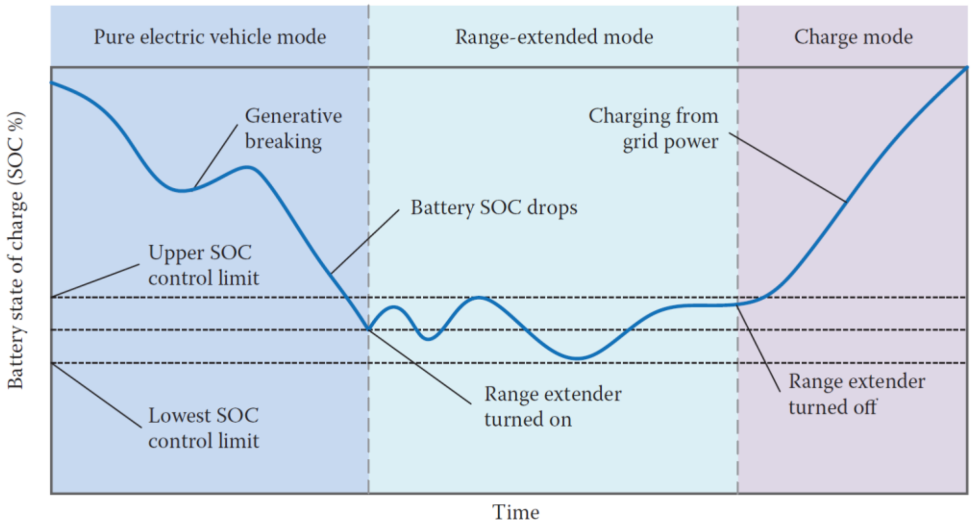

Figure 5: Range-extended electric vehicle operating modes. (Emadi, 2014)

Figure 5 shows the basic operating modes of a REEV. In the pure electric driving mode energy is consumed from the traction battery and only regenerative braking helps to lengthen the electric range. When the batteries state of charge (SOC) drops below the upper control limit the range extender is started and keeps the SOC of the battery between upper and lower control limit. Finally, when the travel destination is reached, the vehicle is charged from the power grid. This mode is called charge mode and is used to provide a fully charged battery at the start of the next drive.

2.2.1 Thermal Range Extender

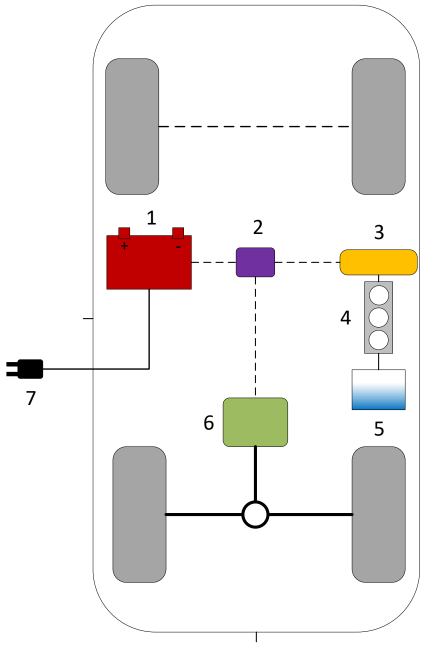

Figure 6: Thermal Range Extender. 1 traction battery, 2 power electronics, 3 generator, 4 combustion engine, 5 tank, 6 electric motor, 7 power plug. (cf. Tschöke, 2014)

If the series hybrid concept, which was discussed before, is used in a plug-in hybrid vehicle, the charging group, which consists of combustion engine and generator, can also be dimensioned considerably smaller than the electric motor because it is only used for increasing the range. This design is called Range Extender or Auxiliary Power Unit (APU) and can be seen in Figure 6. In this case, the charging group cannot generate the electrical energy which would be necessary for a continuous maximum speed. Rather, it provides an average power required during city driving, while power peaks are covered by the battery. The main energy for movement is provided by externally charged batteries (plug-in hybrid vehicle). This design avoids the partial load operation of the charging group, it operates instead at a fuel consumption and emission optimized load point (mostly at full load). (Hofmann, 2010)

There are many types of internal combustion engines (ICE) that are conceivable as APU in a range extender application like petrol and diesel engines (both two and four stroke), Wankel engines, Stirling engines and gas turbines. But because of the very high demands in request to NVH behavior, size, weight and start behavior the industry favors petrol two and four stroke engines and in some instances Wankel and diesel four stroke engines are also used.

2.2.2 Chemical Rage Extender (Fuel Cell)

Another way to provide electric energy in range extender applications is the fuel cell. Fuel cells are electrochemical converters that convert the chemical energy contained in hydrogen directly into electrical energy. This gives them a higher efficiency than other electricity generating processes. Hydrogen as an energy source reacts in a cold combustion with the oxygen of the air and a voltage occurs between the electrodes. Fuel cells work without moving parts, without mechanical friction and work efficiently, quietly and without emission of pollutants. In the automotive industry polymer electrolyte membrane (PEM) fuel cells, which can be seen in Figure 7, are mostly used. (Reif, 2010)

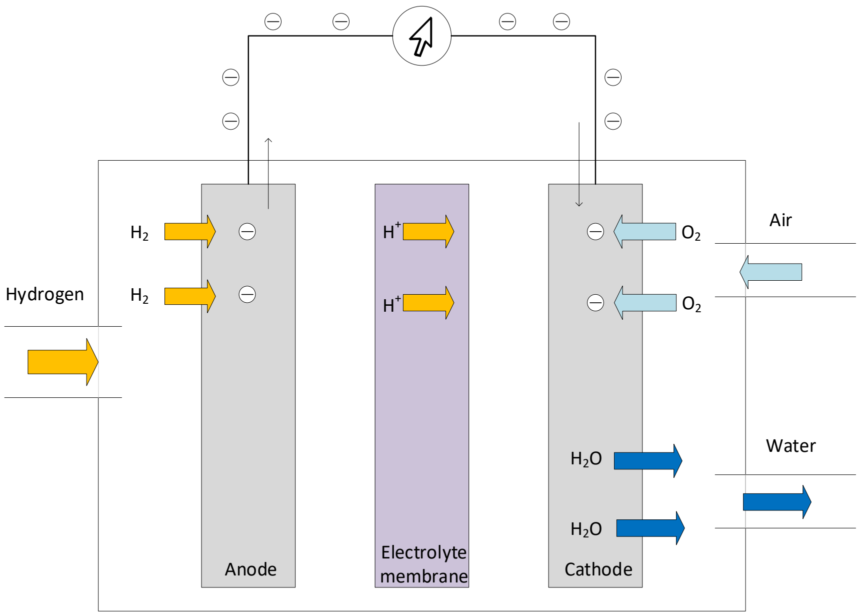

Figure 7: Polymer Electrolyte Membrane (PEM) Fuel Cell

Table 2: Chemical reactions of a PEM fuel cell.

Anode:	$2H_2 \rightarrow 4H^+ + 4e^-$
Cathode:	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Overall reaction:	$2H_2 + O_2 \rightarrow 2H_2O$

In the PEM fuel cell, hydrogen is oxidized at the anode and H^+ ions and electrons are produced. The polymer electrolyte membrane is designed to be proton conductive and so it is permeable to protons, which reach the cathode, but not for electrons. At the cathode oxygen is reduced with electrons, which pass from the anode via the external circuit. As an overall reaction of the fuel cell, this results in the conversion of hydrogen with oxygen to water in terms of a cold combustion. The voltage of a single hydrogen-oxygen fuel cell is theoretically 1.23 V at a temperature of 25 °C, but in fuel cell operation due to reaction inhibition or disturbed gas diffusion only about 0.5 to 1.0 V are reached. In order to achieve the higher voltages required for a technical application, stacks are connected in series from single cells. In drivetrains stacks in the power range of 60 to 100 kW are used. These stacks consist of about 300 to 450 cells, so that the maximum operating voltage is 300 to 450 V and power densities of 1500 to 2000 watts/liter stack volume are reached. For commercial use as a vehicle drive, the fuel cell stacks must be improved both technically and economically. Technically the longevity and the temperature sensitivity are problems. In terms of cost, the high price of fuel cell stacks must be significantly reduced. The greatest savings potential lies in the platinum content of the catalytic coating. (Reif, 2010)

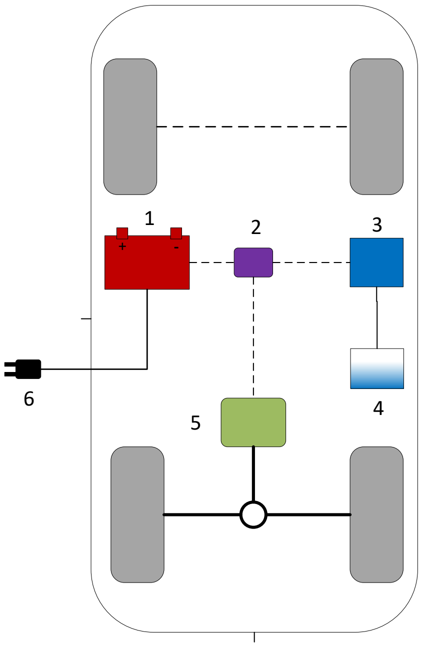

Figure 8: Chemical Range Extender. 1 traction battery, 2 power electronics, 3 fuel cell, 4 hydrogen tank, 5 electric motor, 6 power plug. (cf. Tschöke, 2014)

It can be seen in Figure 8 that the layout of a REEV with fuel cell is pretty similar to one with a combustion engine as an APU. The obvious difference is that no generator is needed, because a direct conversion from chemical to electrical energy takes place. This means that the losses for double energy conversion, which are typical for thermic REEV, are avoided. The hydrogen storage is realized by a tank in either liquid or compressed hydrogen form. Both types have a cylindric or spherical shape to minimize the surface for pression strength and low heat transfer. These shapes make hydrogen tanks inferior in regard to packaging compared to traditional fuel tanks. Again, a big drawback of REEV vehicles compared to ICE powered vehicles are the costs, which increase the vehicle price up to 30 %. Another big problem is the needed energy to liquify (-252 °C) or compress (up to 700 bar) the hydrogen for transport or storage, which reduced the overall efficiency a lot. The specific energy of 33,33 kWh/kg is even higher than that of petrol, but the energy density at 700 bar is with 1,86 kWh/l low compared to petrol (8,2 kWh/l). The specific energy is higher compared to Li-ion batteries (max. 0,73 kWh/l), but electric efficiency factor of PEM fuel cells, which is in best cases 60 %, reduces the achievable range.

3 E/E (Electric and Electronics)

3.1 Electric Motor Technology

Electric motors for battery electric vehicles (BEV) or hybrid electric vehicles (HEV) have to fulfill a lot of complex requirements and therefore the development creates some significant challenges to engineers. The basic requirements for an electric motor in an automotive application are:

- compact dimensions,
- adequate power,
- high specific power,
- highest possible efficiency,
- minimal cost. (Moser et al., 2013)

The expectations change even to a higher level, if the drive is integrated in an electric sports car like the Exagon Furtive-eGT. The four-seater is able to accelerate with the help of two electric motors from 0 to 100 km/h in just 3.5 seconds and the top speed is electronically limited to 250 km/h. It is obvious that such high performance figures can only be reached with motors that offer outstanding absolute and specific power levels. Efficiency and achievable range are also hugely important in an electric vehicle because of the high weight and costs of the battery systems. The wide variety of motor concepts include DC motors, induction motors, synchronous motors with electrical and permanent-magnet excitation, as well as switched and synchronous reluctant motors. But not all electric machine designs are suitable for an application as traction motor. DC motors for example require a commutator, which is a rotary electric switch used to reverse the current every half turn to make a steady motion possible. Because of the relative movement in these sliding contacts, which are called brushes, wear occurs. Because of this wear of the mechanical commutator, DC motor concepts require intensive maintenance and are therefore only of secondary importance for automotive applications. Another motor concept that is not ideal as a vehicle traction motor is the switched reluctance motor. This electric machine is basically a stepper motor and has a typical periodic increase and decrease of output torque called torque ripple. Also, the axial forces between stator and rotor fluctuate and due to that the noise level under operation is high. Therefore, the focus of the industry and this thesis is on synchronous motors and induction motors. (Moser et al., 2013)

3.1.1 Permanent Magnet Synchronous Machines (PMSM)

The Permanent Magnet Synchronous Machine is a design that is widely used as automotive traction motor and therefore in electric axle drives. Figure 9 shows the two main parts of a PM machine which are the stator and the rotor. The mechanically fixed stator doesn't rotate and is connected to the external circuitry. The stator has in most applications a three-phase star connected design and can be broken down in a magnetically conductive iron part and winding slots, which contain copper windings to generate the magnetic flux. On the other hand, the rotor is not mechanically fixed and is mounted to the rotor shaft with the help of bearings. The rotor can again be broken down into two parts, which are first the iron which conducts the magnetic flux and second the PMs that produce the rotor magnetic flux. (Emadi, 2014)

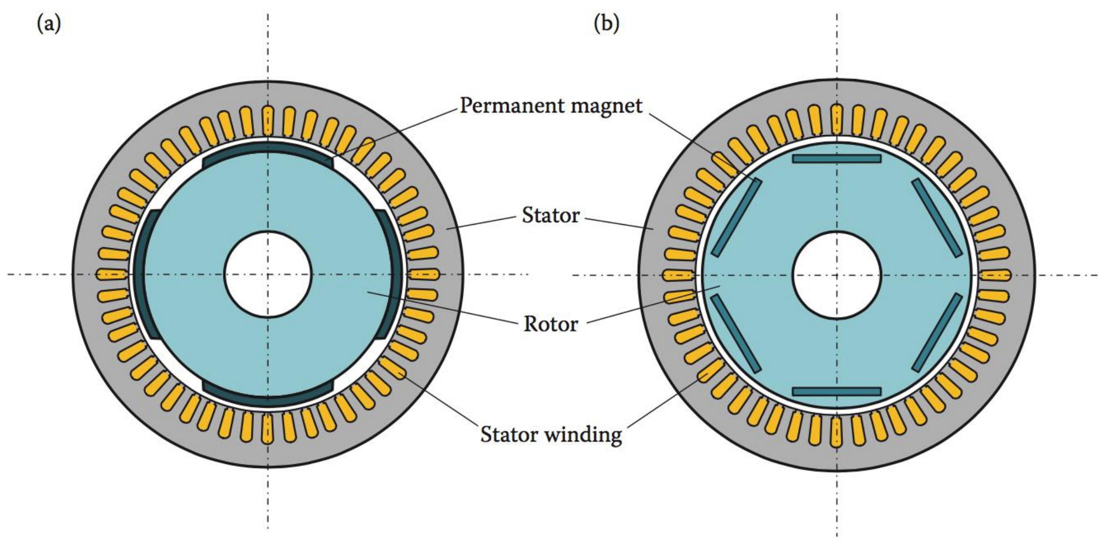

Figure 9: Cross section view of PM machines (a) surface permanent magnet machine (SPM), (b) interior permanent magnet machine (IPM). (Emadi, 2014)

The rotor magnets are placed in an alternating north and south order and generate flux in radial direction to flow through the air gap. The magnetomotive force (MMF) generated by the stator currents interacts with the PM flux and causes the rotor to spin. When the rotor moves, the flux linkage varies and induces back an electromotive force (EMF) in the windings of the stator. Finally, the electromagnetic torque is produced by the interaction between the stator phase currents and the corresponding back EMFs. PMSM need no mechanical connection between the rotor and the stator, but to operate such a motor properly the rotor position has to be known. This data can be submitted either by a position senor or can be calculated by a position estimation algorithm. The PMSM basically operates in four quadrants as shown in Figure 10. Each quadrant consists of a constant torque and constant power region. The torque T stays constant from $\omega = 0$ to nominal speed $\pm\omega_b$. In the constant power region, the torque decreases inversely with the speed from ω_b to ω_{max}. (Emadi, 2014)

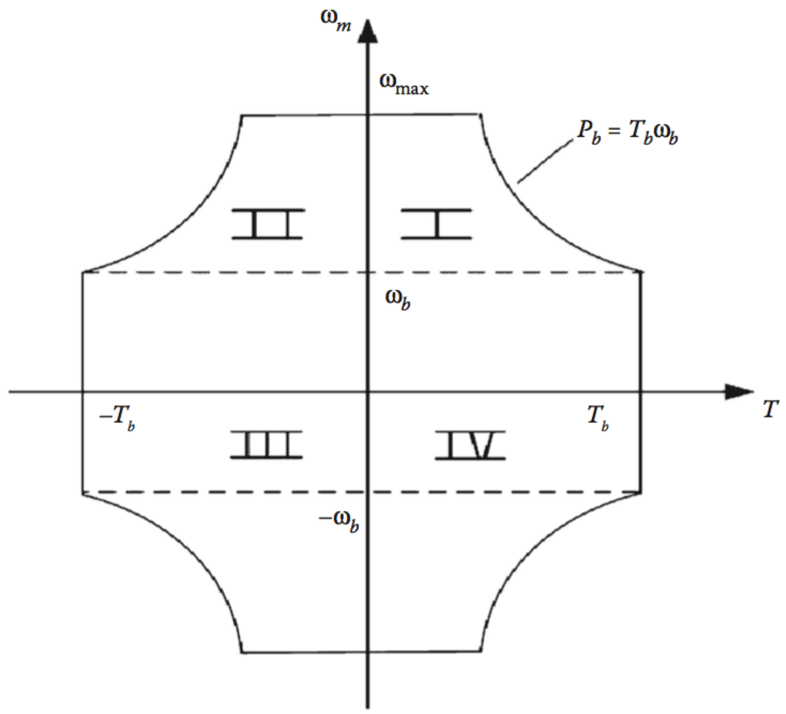

Figure 10: Four-quadrant operation of a PMSM. (Emadi, 2014)

Of course, the PMSM can act as a motor or as a generator, which is important to recharge the batteries during braking when used in electric axles. The relation of torque and speed in either motoring or regeneration mode for all four quadrants can be seen in Table 3.

Table 3: PMSM Four quadrant operation (Chau, 2015)

	Quadrant	Torque	Speed
Forward motoring	I	Positive	Positive
Backward regeneration	II	Positive	Negative
Backward motoring	III	Negative	Negative
Forward regeneration	IV	Negative	Positive

The above mentioned three-phase induced back EMF waveforms can be calculated by

$$e_a = E_m \sin(\omega t)$$

$$e_b = E_m \sin(\omega t - 120°)$$

$$e_c = E_m \sin(\omega t - 240°)$$

where E_m expresses the amplitude of the back EMF and ω is the angular frequency. The machine is also supplied with the balanced three-phase sinusoidal currents

$$i_a = I_m \sin(\omega t - \phi)$$

$$i_b = I_m \sin(\omega t - 120° - \phi)$$

$$i_c = I_m \sin(\omega t - 240° - \phi)$$

where I_m is the current amplitude and ϕ is the phase difference between current and back EMF. With the help of the waveforms above the converted electrical power results in

$$P_e = e_a i_a + e_b i_b + e_c i_c = \frac{3E_m I_m}{2} cos\phi$$

and the torque of the PMSM is further calculated by

$$T_e = \frac{P_e}{\omega_r} = \frac{3E_m I_m}{2\omega_r} cos\phi$$

and is constant at a given speed ω_r. The torque reaches a maximum when the phase difference ϕ is zero. (Chau, 2015)

The PMSM is a type of synchronous motor where the field circuit is replaced with permanent magnets. This design eliminates the need for maintenance of the field excitation circuit and also minimizes rotor copper losses. Therefore, a PMSM is highly efficient compared to other synchronous machines and makes the cooling system less complex. Other important benefits are the high power density and torque-to-inertia ratio, which result from the increased flux density in the air gap by use of rare-earth magnet materials. That's why the PMSM can provide fast response, compact motor structure and high efficiency in traction motor applications. (Emadi, 2014)

The advantages of the PMSM can be summarized as:

- Higher power factor compared to the induction motor because no magnetizing current is needed.
- No brush maintenance is required.
- Rotor losses are very low.
- Lower noise and vibrations compared to switched reluctance and induction machines.
- Fast response due to lower rotor inertia.
- Compact structure and higher power density.

(Emadi, 2014)

But there are also disadvantages in the PMSM design which are mainly the high costs of PM materials and their sensitivity to temperature.

3.1.2 Induction Machines (IM)

Due to their simple and robust structure, induction machines have been the workhorse in industrial electric drive applications for many years. There are basically two different types of induction machines: Wound-rotor induction machines, where the rotor circuit consists of three-phase windings similar to that of the stator and these rotor windings are then short circuited with the help of slip rings. The second type are squirrel-cage induction machines where the rotor bars are inserted by die casting, where melted aluminum is molded in the rotor slots. End rings then short circuit the bars. Figure 11 shows a cross-section view of a squirrel cage induction machine. (Emadi, 2014)

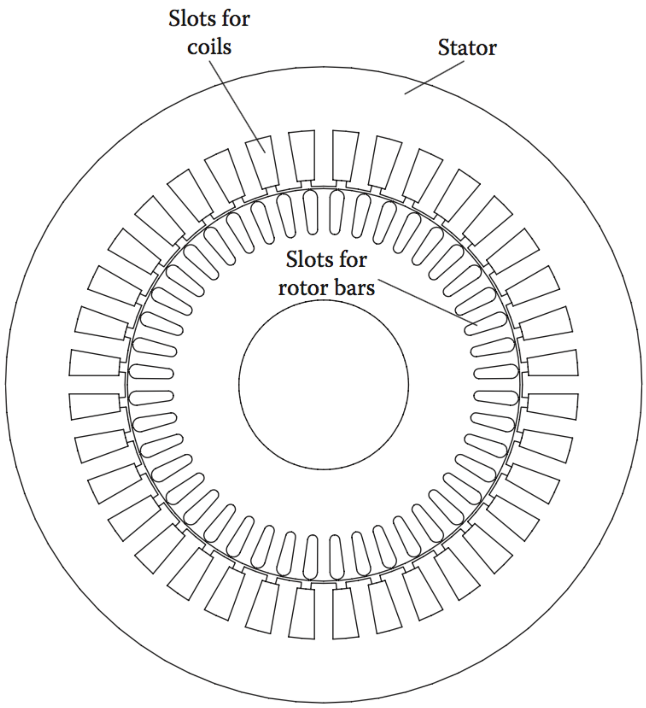

Figure 11: Cross-section view of a squirrel-cage induction machine. (Emadi, 2014)

The squirrel-cage induction motor is the preferred type for electric propulsion in electric vehicles (EVs), because high costs, need for maintenance and lack of sturdiness are serious drawbacks of wound-rotor induction machines. The wound-rotor type will therefore not be further discussed and all future discussions are based on the squirrel cage induction machine. In addition to the common advantages of commutatorless motor drives, the induction motor drives possess the advantages of low cost, because of the absence of PM materials, and ruggedness. The main disadvantage in form of control complexity can be easily outweighed by the above-mentioned advantages and make induction machines suitable for EVs. (Chau, 2015)

Induction machines generate torque based on the force created by rotor currents, which are induced by the rotating airgap field from the stator currents. When the three-phase stator windings are excited by their currents a rotating magnetic field is created in the airgap. This time-changing magnetic field induces voltages in the rotor conductors, which can be explained with Faraday’s law. Because of Lorentz’s force law the induced currents create a force on the rotor, when the rotor conductors are short circuited. This force generates the motion in induction machines. Rotor currents are only induced when the rotor is not turning synchronous with the stator magnetic field and therefore an induction machine only creates torque, when the rotational speed of the rotor is lower than synchronous speed. This speed difference is called slip (s) and is given by

$$s = \frac{\omega_s - \omega_r}{\omega_s}$$

with rotor speed (ω_r) and rotating airgap magnetic field (ω_s). The frequency of the EMFs and induced currents of the rotor are given by

$$f_r = s f_s$$

and it can be seen in this formula, that when s is zero the rotor frequency is zero and no currents are induced. When the induction machine is used as a motor the slip varies between zero and one and when used as a generator the slip is smaller than zero. In practice induction machines are designed to operate at a slip smaller than 5% at full load. (Emadi, 2014)

The total airgap power of the induction machine can be written as

$$P_a = m I_2'^2 \frac{R_2'}{s}$$

with the help of the number of stator phases (m). This airgap power includes the rotor copper loss $m I_2'^2 R_2'$. If the copper loss is subtracted from the airgap power the result is

$$P_{conv} = m I_2'^2 R_2' \frac{1-s}{s}$$

which represents power used in the electromechanical energy conversion. It can be seen, that the airgap power increases with smaller slip, but the rotor copper losses decrease. That's why induction machines are designed to operate with a small amount of slip. The torque T is simply defined as

$$T = \frac{P_{conv}}{\omega_r}$$

or

$$T = \frac{P_a}{\omega_s}$$

with the above mentioned relation $\omega_r = (1-s)\omega_s$. (Emadi, 2014)

Figure 12 shows a typical torque-speed characteristic of an induction machine. As discussed earlier the torque drops to zero at synchronous speed n_{sync} and the maximum torque (pullout torque) is reached at the maximum slip s_{max}. If the load is increased any further the torque drops drastically and the motor stalls. If n_{sync} is surpassed the induction machine simply acts as generator.

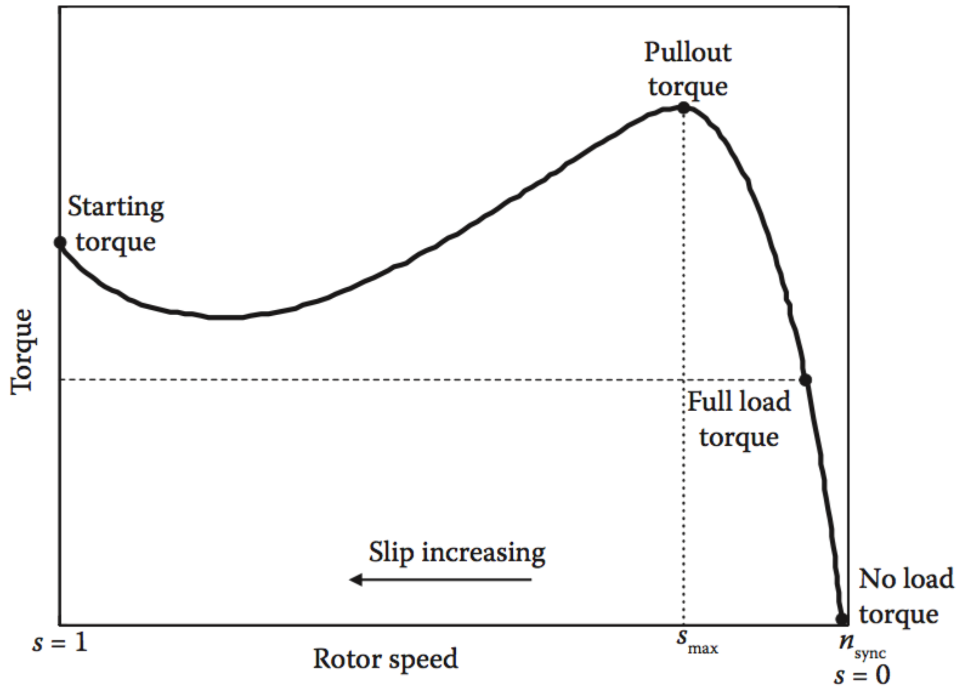

Figure 12: Torque-speed characteristic of an IM. (Emadi, 2014)

3.2 Power Electronics

The task of power electronics is to adapt the electrical energy from the energy storage to the requirements of the electric machine. The voltage of the energy storage is usually present as a DC voltage and the level of the voltage determines the state of charge. In automotive applications the electric machines are usually supplied via three-phase alternating voltage with variable frequency, amplitude and phase position in order to set the desired speed and the desired torque. During reversing the direction of rotation is changed by swapping the phase sequence. In contrast to conventional vehicles with internal combustion engines this is realized electronically. Because in addition to the electric drive other electric loads, usually powered by a separate 12 V circuit, are present, DC-DC converters are required. This DC-DC converters scale down the voltage of high voltage (HV) batteries. (Hofmann, 2014)

In principle, the transformation of the electric current can be done in four different ways:

- AC voltage to DC voltage: Rectifiers form a DC voltage from a single or multi-phase AC voltage.
- DC voltage to DC voltage: DC-DC converters change the level of the DC voltage. Depending on the level of the input and output voltage, it is referred to as a step-up or step-down converter.
- DC voltage to AC voltage: Inverters generate from a DC voltage an AC voltage with a given amplitude and frequency.
- AC voltage to AC voltage: Inverters convert from a given AC voltage an AC voltage of different amplitude and frequency.

(Hofmann, 2014)

Figure 13 shows the above mentioned possible transformation types of electrical energy in a schematic manner. The AC circuit can be realized via a three-phase wiring, as illustrated in Figure 13, or via a one phase wiring (charging port for standard wall outlet). Also, the name of an AC-DC converter, dependent on the conversion direction, is either rectifier or inverter. Both AC-DC and DC-DC converters can be capable to transform in both directions (bidirectional), or when not needed only in one direction.

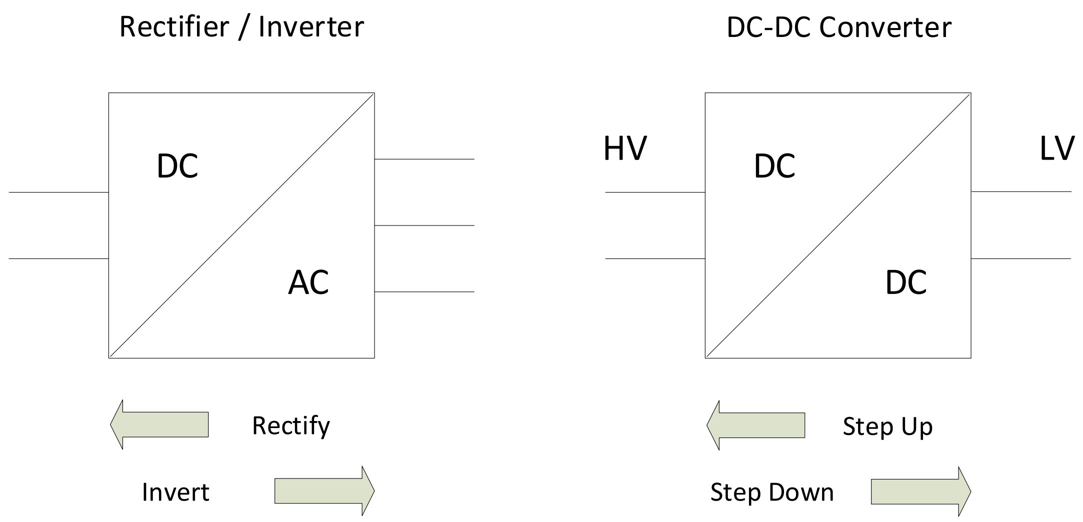

Figure 13: Transformation types of electrical energy. (cf. Hofmann, 2014)

A possible setup of the above shown power electronic components in a BEV or PHEV can be seen in Figure 14 in a simplified way.

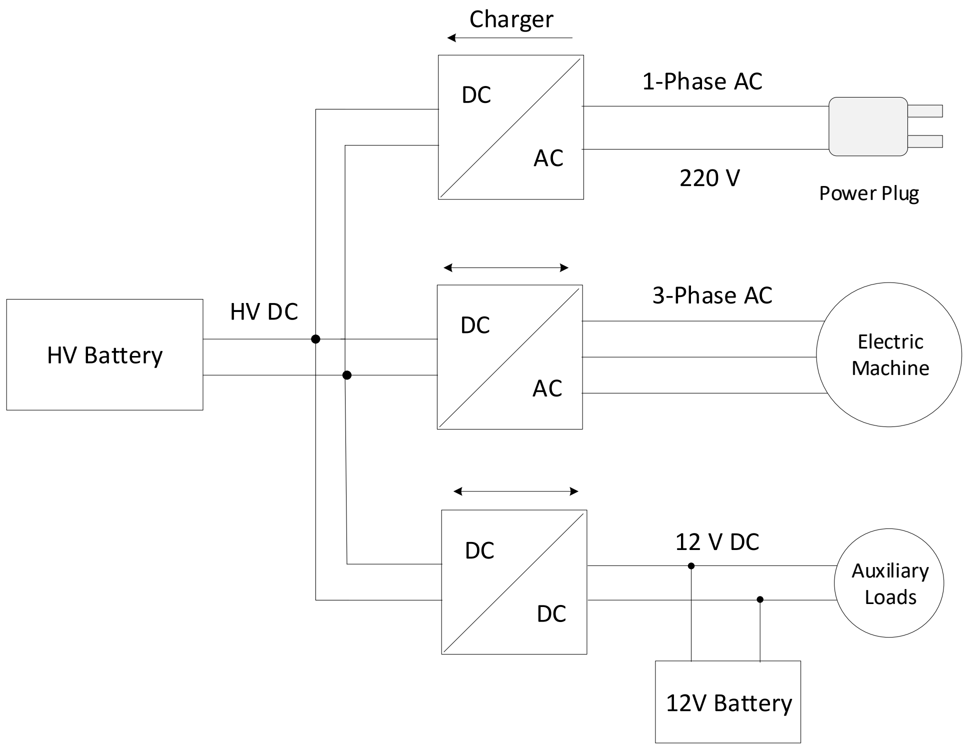

Figure 14: Power electronics in a BEV or PHEV. (cf. Hofmann, 2014)

A rectifier is used to charge the HV battery from a lower voltage home or public electric network. A bidirectional converter is usually not needed, because back feeding of electric energy in the network makes barely sense in private transportation scenarios. Because the

HV battery supplies DC current and commonly AC motors are used in hybrid or battery electric vehicles, a DC-AC converter is needed. It is important to mention that this unit must be designed bidirectional, because recuperation during braking is mandatory to reach a high electric range or to minimize emissions of hybrid vehicles. The last shown component is a DC-DC converter, which is used to scale down the current from the HV circuit to 12 V. This low voltage circuit is needed to power a large number of auxiliary users from lights to sound systems. This converter generally can also be realized unidirectional, but because it is an advantage for HEVs to make for example jump-starting possible, a bidirectional layout makes sense.

3.2.1 Semiconductor Components

The functions of the above-mentioned converters are realized by fast switching electronic components, which are called transistors. These are essentially power semiconductors, which have the task of either conduct or insulate the power. This is needed for example to invert from DC to AC to run the electric machine. The DC is switched on and off very quickly by the transistor switches to create a sine wave AC current for the motor via pulse width modulation (PWM). The switching frequency must be considerably faster than the output frequency, which dictates the motor speed, in order to get a good sine wave approximation. For electric drive systems in hybrid or battery electric vehicles switchable semiconductors, which can switch high currents, are particularly interesting. Possible types of semiconductors, to realize these functions, are bipolar transistors, field-effect transistors and insulated gate bipolar transistors (IGBT). In case of the **bipolar transistor**, the main current is switched via a control current. Large currents can be switched with low passage losses. Disadvantages are the relatively large switching losses in the component, which must be dissipated as heat, and the complex control by a control current. Today the bipolar transistor has been replaced by the MOS-FET and IGBT in almost all applications. The most used type of **field-effect transistors** is the metal-oxide-semiconductor field-effect transistor (MOS-FET), which is switched by a control voltage in the conductive state. Because of the simple control and the low switching losses very high switching frequencies can be achieved. However, the resistance becomes very large with increasing blocking voltage. The area of application is therefore at medium voltages (<200 V). The **IGBT** combines the advantages of the bipolar and field effect transistor, which are low control complexity, high voltage rating and high current rating. It is controlled via voltage, whose field effect controls internally a bipolar structure, which allows a large current capacity. The circuits of the IGBTs are designed so that they can safely switch off even at very high currents during the event of a short circuit. This has the advantage that in case of a fault in the circuit, the power supply can be stopped controlled. The IGBT is today the most important transistor in power electronics. For the electric vehicle drive mostly IGBTs are used because of the advantages already mentioned. For low power scenarios or small battery voltages also MOS-FETs are used. In the low voltage 12 V electrical system almost exclusively MOS-FETs are implemented. (Hofmann, 2014)

Table 4: Comparison of Transistor Types

	Bipolar Transistor	MOS-FET	IGBT
Control type	Current	Voltage	Voltage
Control power	Large	Minimal	Minimal
Control complexity	High	Low	Low
Switching frequency	Medium	Very High	High
Switching losses	High	Medium	Low
Voltage rating	High	Medium	Very High
Current rating	High	Low	High
Cost	Low	Medium	High

3.2.2 Losses in Power Electronics

Losses occur in both states of a semiconductor. In the conductive state a voltage drop occurs, and in the insulated state, a leakage current flows. In general losses consist of conductive, insulating and switching losses and are converted into heat. The power loss is the product of the voltage drop across the component and the flowing current. The conductive losses are much greater than the insulating losses. In addition to these stationary losses, the so-called switching losses, which are dynamic losses occur. These occur during the transition from the conducting to the insulating state and vice versa. To minimize these losses the shortest possible switching times are sought. The switching losses are furthermore directly proportional to the switching frequency. In order to prevent thermal damage to the components, the resulting heat must be dissipated, because the temperature must never exceed the junction temperature of about 150 -1 75 °C for silicon, which limits the coolant temperature to about 65 °C. (Hofmann, 2014)

3.2.3 Development Potential in Power Electronics

Due to the high requirements, there is currently a relatively high proportion of costs for power electronics in electric vehicles, which would even increase in the future due to falling battery and vehicle costs. The mass proportion of power electronics in vehicles is only very small, but nevertheless there is also a potential for weight reduction. Because weight has significant impact on the range of electric vehicles, it is important to use this potential. Current development in power electronic is basically aimed at reducing costs, weight and increasing efficiency. However, these three points are incompatible in their respective optimum. Most of the weight of power electronic components is distributed over magnetic components and current-carrying copper. The installed semiconductors hardly contribute to the total weight. The cost distribution is exact the opposite. Here, the semiconductors are the biggest cost drivers in the system. When targeting a weight-loss the focus should be on the magnetic components and the current-carrying parts in the system, because the weights of both components is directly dependent on the current. Half the current leads, because of the quadratic relationship with the stored energy, to a theoretical volume and weight reduction of the magnetic components by a factor of four. The reduction of the current can be done by increasing the voltage, or by dividing the current into several parallel power paths. For example, doubling the voltage in power electronic components allows a realistic weight reduction of 15 to 30 %. (Hohmann et al., 2017)

Another way to reduce losses and an option for increasing switching frequencies are so-called wide-bandgap semiconductors. These consist of silicon carbide (SiC) or gallium nitride (GaN) from the group of so-called compound semiconductors and have a band structure with extended band gap, about 3 eV versus 1 eV, compared to silicon. These new semiconductors can endure significantly higher voltages, so that high voltage transistors and diodes with low losses can be designed. Another important aspect for electric traction applications is the temperature resistance of the components, so that a high degree of robustness is achieved at short-term extreme loads. These short-term loads can be used to improve the acceleration performance of electric vehicles. (Lohner et al., 2015)

3.3 Energy Storage Systems

Energy storage systems are not exactly part of an electric axle drive, but because their demands in respect to operation conditions make them a critical part of the whole thermal management system, this thesis includes basic knowledge about battery technology. Furthermore, the high price and weight of energy storage systems are the primary reason for the high effort, which is used to make the other components in the drivetrain more efficient.

For the operation of electric motors energy is required, which needs to be carried in energy storage devices in the vehicle. This electric energy storage devices are characterized by the fact that they store the energy in the form of chemical or electrostatic energy and that the conversion into electrical energy takes place without the intermediate step via mechanical energy or heat energy. Two of the key performance indicators are energy density and power density, which are related to the volume. In contrast specific energy and specific power refer to the mass. There are significant differences between the different types of storage devices in regard to this performance indicators. While with rechargeable batteries, also called accumulators, a comparatively high specific energy can be achieved, the strength of electrostatic storage (capacitors) is the specific power. However, at about 150 Wh/kg (Li-ion battery), these systems do not nearly reach the specific energy of petrol fuels. Their lower specific energy is 11,14 kWh/kg. Even the much higher efficiency of the electric machine, compared to combustion engines, changes little on this fact. Essentially, energy storage systems used in a vehicle must meet the following requirements:

- high specific energy,
- high specific performance,
- good discharge and charging efficiency,
- high number of charge and discharge cycles,
- high security,
- temperature resistant in the field of use of automobiles,
- low costs.

(Basshuysen and Schäfer, 2017)

3.3.1 Comparison of Energy Storage Systems

The lead-acid (Pb) battery was for a long time the primary battery system used in vehicles, but with the electrification of the powertrain the requirements have changed. While for a battery that is only used to start the combustion engine specific energy and energy density are of secondary importance, these parameters get hugely important when electric traction motors are used. A lead-acid traction battery would simply be too big and heavy and so the automotive industry implemented new energy storage systems. The main innovation on the way from the lead-acid (Pb) battery, which has a watery electrolyte, to the modern battery systems such as the lithium-ion battery with organic electrolytes, is the principle of the storing ions in the electrodes. In the case of the Pb battery the electrodes, due to chemical reactions, shrink and build up disordered and enter into an interaction with the electrolyte. In lithium-ion cells lithium is taken in and out of solid-state lattices and this process is called intercalation. The mentioned lattice structure is also the reason for the significantly increased number of charge and discharge cycles, which leads to an improved lifetime of the battery. As shown in Figure 15, both nickel-metal-hydride (NiMH) and lithium-ion (Li-Ion) batteries work with intercalation electrodes, whereas the lead-acid (Pb) battery functions with the described process of conversion. For the use in electric traction applications NiMH systems are well proven and established, but the Li-Ion technology clearly takes over. Due to the significantly higher energy densities of the Li-ion batteries, the large-volume market entry of electric vehicles is made possible and this battery technology will almost exclusively be used in the electrification of future powertrains. (Keller et al., 2009)

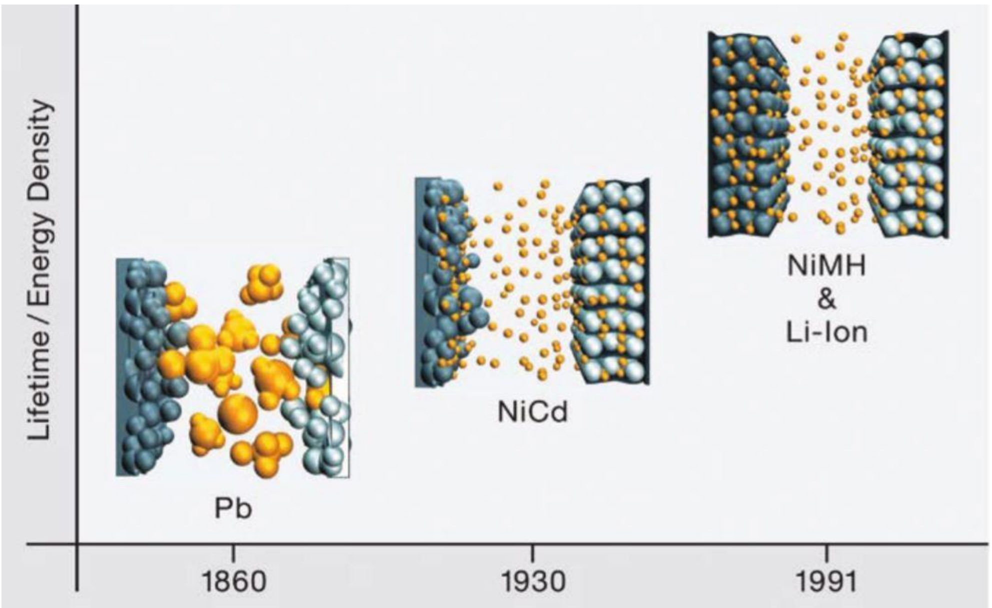

Figure 15: The way from conversion to intercalation electrodes. (Keller et al., 2009)

The available energy storage devices, which are batteries and double-layer capacitors (DLC), are very different in their advantages and disadvantages and hence their respective operation purpose differs. Figure 16 evaluates the most important characteristics of the mentioned energy storage technologies in regard to an automotive application. The low price of the Pb battery, which is their main advantage, comes at the expense of the life-time. The DLC shines with best power density and lifetime, but suffers from highest price and lowest energy density. Especially the low energy density would make the energy storage system of a BEV with acceptable range too big, heavy and expensive. A mixed use with Li-Ion batteries is possible, but power density optimized Li-Ion cells are too close in performance to justify such applications. NiMH batteries have a solid overall performance, without major drawbacks, but the higher power density, energy density and lifetime of Li-Ion cells explains why the focus the industry lies on Li-Ion batteries. (Keller et al., 2009)

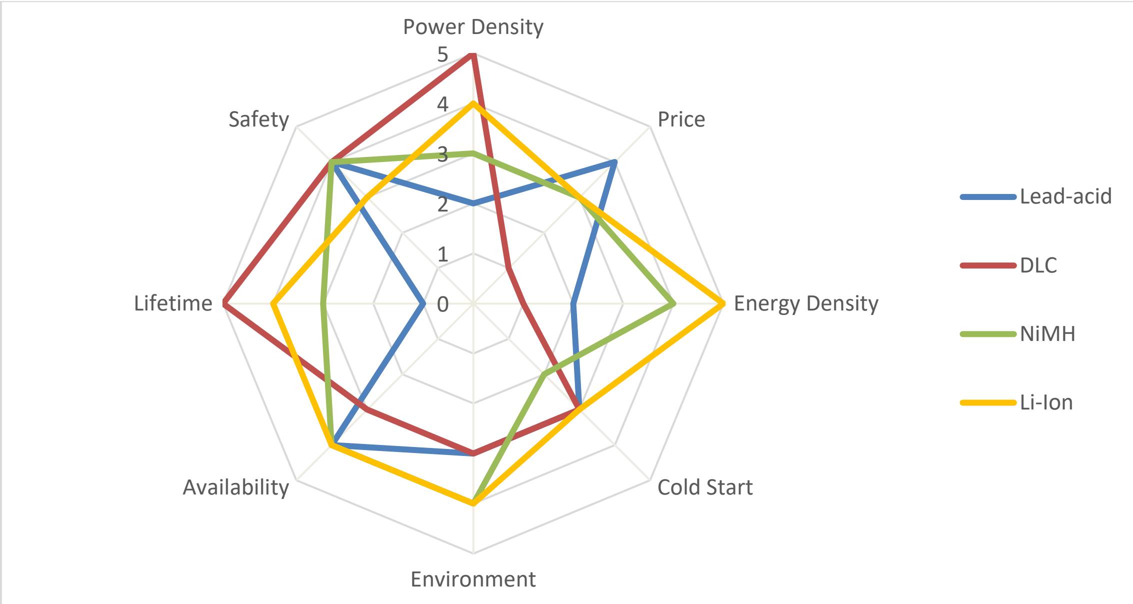

Figure 16: Evaluation of different energy storage systems for automotive application from bad (1) to good (5).(cf. Keller et al., 2009)

For reference the performance parameters of each battery technology can be seen in detail in Table 5. It must be mentioned that the values of each cell type spread significantly, because some batteries allow specific designs for special applications.

Table 5: Performance data of battery systems. (cf. Emadi, 2014)

	Lead-acid	DLC	NiMH	Li-ion
Specific energy in Wh/kg	30–50	2,5–15	60–120	100–265
Energy density in Wh/L	50–80	10–30	140–300	250–730
Specific power in W/kg	75–300	500–5000	250–1000	250–340
Power density in W/L	10–400	100.000	80–300	100–210
Cycle lifetime in cycles	100–2000	10.000–100.000	500–1000	400–1200
Self-discharge in %/day	0,033–0,3	20–40	25–30	0,1–0,3
Capacity cost in $/kWh	150–400	300–94.000	150–1500	500–2500

3.3.2 Lithium-Ion Battery

3.3.2.1 Function and Layout of Li-Ion Cells

Lithium-ion battery technology with its multitude of material combinations is today the basis for energy storage of most concepts for the electrification of the powertrains of vehicles of all kinds. Due to its high energy and power density as well as its high cell voltage, it is regarded as a promising technology in hybrid and electric vehicles, but also for vehicle electrical systems with increased performance. The term lithium-ion battery combines many different battery technologies, all based on the same principle of operation. As shown in Figure 17, a Li-ion battery, like all batteries, consists of two electrodes, a separator and the electrolyte. Li-ion batteries, as mentioned before, belong to the class of intercalation batteries in which lithium ions are dissolved from one electrode during charging and discharging, migrate through the electrolyte to the opposite electrode and integrate themselves in the crystal lattice of the other electrode material. Since this is a pure storage and removal of lithium ions in a crystal lattice, the crystal structures are retained. This basically allows a higher cycle life, than lead-acid and NiMH batteries. The cathode in li-ion batteries consists of a metal oxide, while the anode consists of a carbon modification, such as graphite. Both electrodes are composed of individual particles of active materials as well as binding and conducting materials. They have a large surface area to enable a high reaction rate. As binding materials, various forms of polyvinylidene fluoride (PVDF) are used, whereas carbons act as conducting material. The electrode materials are applied to a thin metal foil, which is made from aluminum at the cathode and copper at the anode, and also serve as a current conductor. The electrolyte is a lithium salt dissolved in an organic solvate, which is stable during nominal operation. The separator usually consists of a polymer structure, which, like the electrodes, is impregnated with the electrolyte. Lithium-ion cells are commercially available in various designs. A distinction is made between the so-called pouch-bag cell and prismatic and cylindrical cells. Cells of all of these designs consist of multiple layers of electrode-separator-electrode stacks. Li-ion batteries are available with high energy density for moderate currents, for example for use in electric vehicles, and with very high power density for hybrid vehicles. The internal structure differs essentially by the coating thickness of the electrodes. The thinner the active materials are, the higher is the power density with simultaneously decreasing energy density. (Ecker and Sauer, 2013)

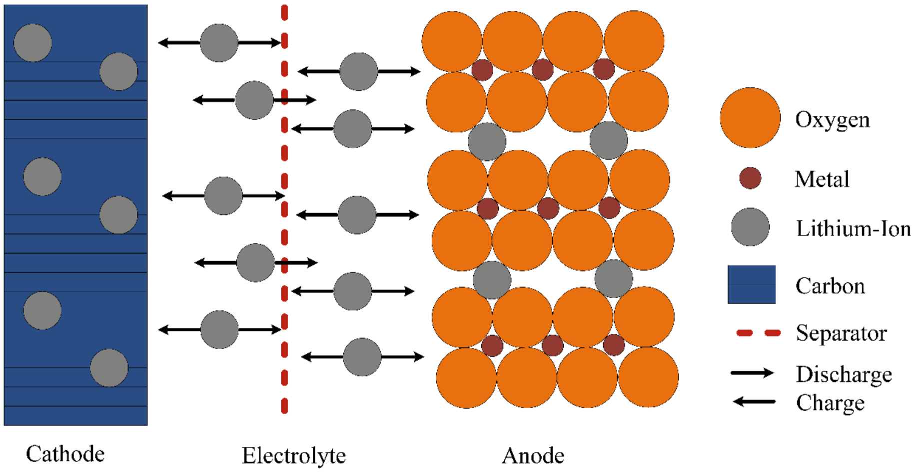

Figure 17: Schematic layout of a li-ion cell. (Ecker and Sauer, 2013)

3.3.2.2 Aging of Li-Ion Batteries

To optimize the operating strategy and to achieve the necessary lifespan of li-ion batteries, it is important to understand the aging behavior of these systems. Aging phenomena such as capacity loss and internal resistance increase occur in particular because lithium or parts of the electrode material are lost or they lose contact with the conductors. Responsible for this are on the one hand chemical reactions, by which layers are formed on the interfaces between electrode and electrolyte, or crystal structures are changed. On the other hand, mechanical loads occur, because the volume of the electrodes changes with storage and removal of lithium. A significant aging effect in lithium-ion batteries is the formation of the so-called solid electrolyte interface (SEI). This layer is formed on a graphite anode by the reaction of lithium with the electrolyte at the interface between the anode and the electrolyte. The SEI is only permeable for lithium ions and prevents further reaction between electrolyte and active material. Forming the SEI is therefore necessary with graphite based li-ion batteries in the first cycles of the cell. However, for the formation of the SEI lithium is irreversibly bound, resulting in a loss of lithium for charging and discharging cycles. In addition, the resistance of the cell increases, as the SEI represents an additional barrier for storage and release of lithium ions. A high internal resistance leads to a significant voltage drop, compared to the no-load voltage, when the battery has to deliver current to the users. The described aging processes lead to internal resistance increase and capacity decrease. Other big influencing factors on cell aging are the voltage level, which is equivalent to the state of charge, and the temperature. For example, the Arrhenius law describes a halving of the lifetime of a cell when the temperature, which is outside of the comfort temperature of the cell, rises by 10 °C. However, because at lower temperatures the performance decreases due to reduced electrochemical reaction rates and increasing electrolyte resistance, an operating temperature range of about 20 to 40 °C should be sought. More about temperature effects on li-ion batteries is covered in the chapter 4. The aging because of the voltage level varies greatly depending on the cell (electrolyte and electrode material) considered, but it is generally true that a high SOC harms the battery. To minimize this effect an intelligent battery management system (BMS) can be installed, which reaches full charge only shortly before the start of the next trip. The discussed effect of the SOC of a li-ion cell on the lifetime can be seen in Figure 18. (Ecker and Sauer, 2013)

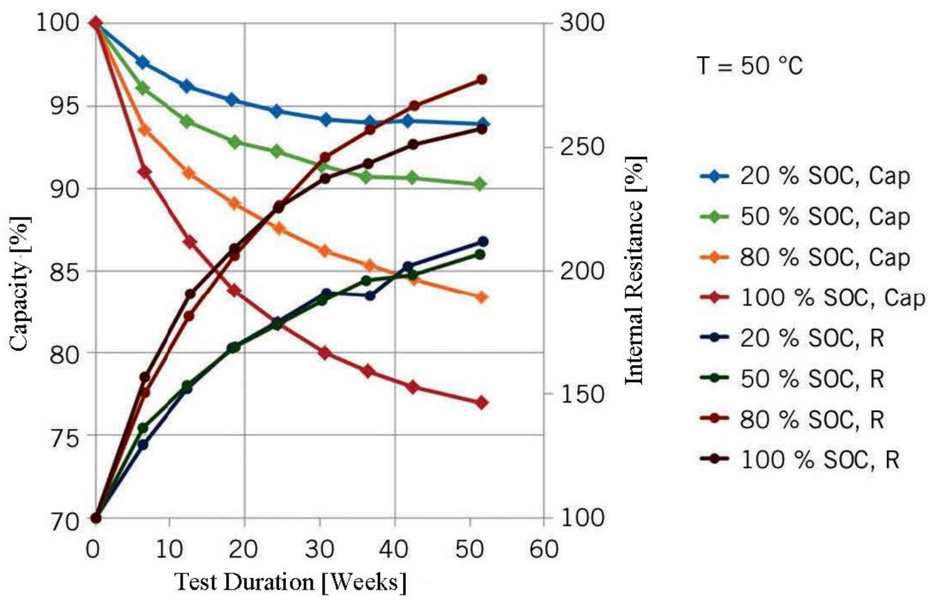

Figure 18: Aging of a Li-Ion cell in regards to capacity and internal resistance depending on SOC. (Ecker and Sauer, 2013)

3.3.2.3 Future Potential of Li-Ion Batteries

Alternative battery chemicals and structures as solid-state li-ion batteries are very promising energy storages for electric traction applications, because they have properties that would solve some of the problems and disadvantages of today's accumulators:

- They are characterized by higher energy density compared to conventional li-ion systems with liquid electrolytes and allow a more compact cell design. This is achieved by serial stacking and bipolar structures. As a result, the so-called dead volume between the individual cells can be significantly reduced, Figure 19.

- Another advantage is the increased safety of solid-state li-ion cells. Because their inorganic solid-state electrolytes are not flammable and thermally stable. There are no risks like leakage and escaping of liquid electrolytes.
- In addition, the exceptionally high cycle stability of the solid-state lithium-ion batteries represents a significant advantage in terms of longevity and therefore efficiency of the technology, because of the better electrochemical stability, the wide electrochemically usable window of the solid electrolyte and the absence of side reactions at the electrode-electrolyte interface.

(Yada and Brasse, 2014)

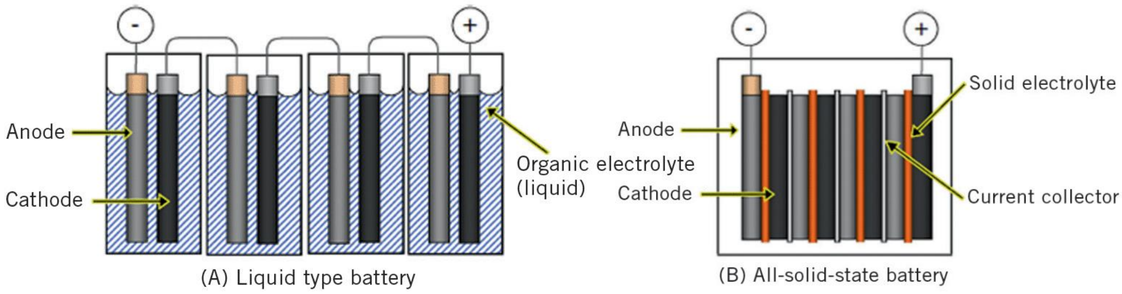

Figure 19: Conventional li-ion battery and stacked solid-state li-ion battery. (Yada and Brasse, 2014)

But besides all mentioned theoretical benefits of solid-state li-ion batteries, until now the required power density could not be achieved. One of the critical hurdles for this is the high lithium-ion transition resistance in the contact surface of the cathode and the solid-state electrolyte. To overcome this limitations the objectives of the research are the development of better lithium-ion-conducting solid-state electrolytes, nano-structural modeling of the electrode-electrolyte contact surface and the improvement of lithium-ion conductivity within the active materials. (Yada and Brasse, 2014)

4 Thermal Management

In the past, the most important task of engine cooling was to protect the engine block from overheating, especially during high load scenarios. Therefore, the cooling circuit was quite simple and consisted only of coolant lines, a pump, a surge tank and a radiator. The fluid absorbed the heat of the engine and was pumped through the coolant lines to the radiator, which emitted the engine heat to the outside. However, with increasing electrification of the powertrain the cooling and air conditioning of the vehicle has become a more and more complex thermal management. Thermal management is a key technology for the acceptance of electric mobility in terms of battery life and range, as well as interior comfort. In order to solve these tasks, coolant circuits of different temperature levels are required. The demand-oriented supply of optimal media temperatures for efficient energy use and the temperature control of temperature-sensitive components such as batteries or electronics are now the main tasks of thermal management. (Wawzyniak et al., 2017)

4.1 Thermal Management for Plug-In-Hybrid Electric Vehicles

Because of the combination of ICE and electric motors in plug-in hybrid electric vehicles (PHEV) the thermal management gets more complex compared to conventional vehicles. Circuits of different temperature levels are needed because of the following requirements (Wawzyniak et al., 2017):

- The li-ion battery needs to be kept in the comfort temperature range of 20 to 40 °C and therefore a heating and cooling circuit is required.
- Cooling of the electrical machine to a maximum temperature of 140 °C for the windings and 120 °C for the magnets.
- Because of the sensitive semiconductors, the power electronics have a maximal operating temperature of 60 °C.

In Figure 20 the impact of the temperature on capacity and internal resistance of li-ion battery with 50% SOC can be seen. As mentioned in chapter 3.3.2.2, it can be said that a temperature increase of 10 °C outside of the comfort temperature leads to half the lifetime of a cell. This explains why the cell loses much more capacity at 65 °C compared to 50 °C cell temperature during the test period in the figure below.

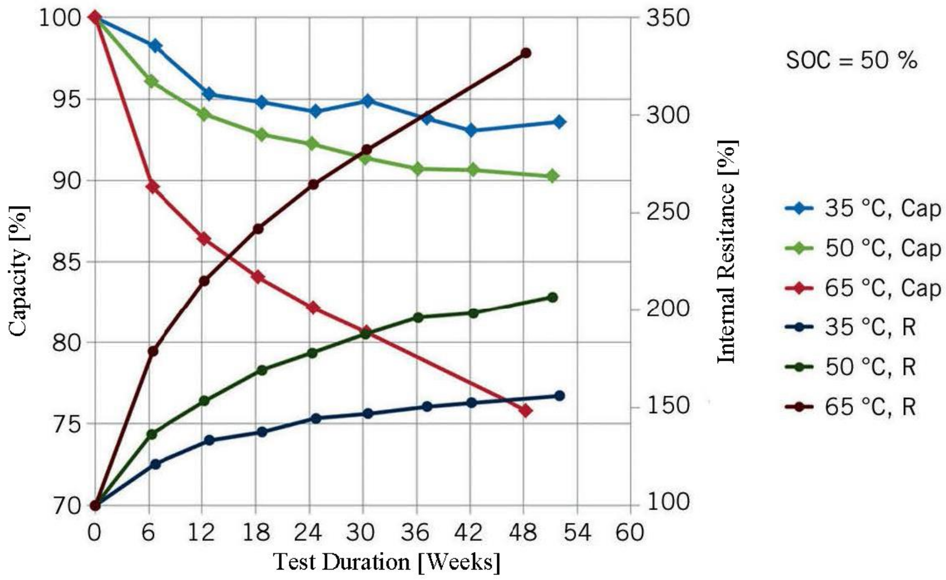

Figure 20: Typical development of capacity (Cap) and inner resistance (R) of a li-ion battery with 50% SOC at different temperatures. (Ecker and Sauer, 2013)

The battery needs to be tempered and conditioned, within a small temperature window, because the quality of the battery conditioning, which also means constant temperature across the cells, is significant for the performance and lifetime of a battery. A passive cooling circuit is not able to fulfill these requirements. As can be seen in Figure 21, besides the passive low temperature cooler, an active chiller, which is connected to the vehicles air conditioning circuit, cools the battery when needed. At cold ambient temperatures a positive temperature coefficient (PTC) heater is used to keep the battery above the lowest operating temperature. The Li-ion battery is connected by a cooling plate to the cooling circuit, whereby the temperature difference between cooling entry and exit must be as low as possible to guarantee an even temperature distribution across the cells. (Wawzyniak et al., 2017)

Furthermore, Figure 21 shows the other needed cooling circuits and their respective temperature levels. Carried over from non-hybrid vehicles is the ICE cooling circuit, with a passive cooler and the intercooler, in case of a turbo charged ICE. The waste heat of the engine is also used to heat the cabin and an evaporator of the air-conditioning cools the cabin when needed. In hybrid vehicles an additional passive cooling circuit for the electric motor and power electronics must be installed. Because of the significant higher operating temperature of the electric motor (120 °C) compared to the power electronics (60 °C), one circuit can be used for both components. Obviously, the power electronics must be arranged before the electric motor in the cooling circuit.

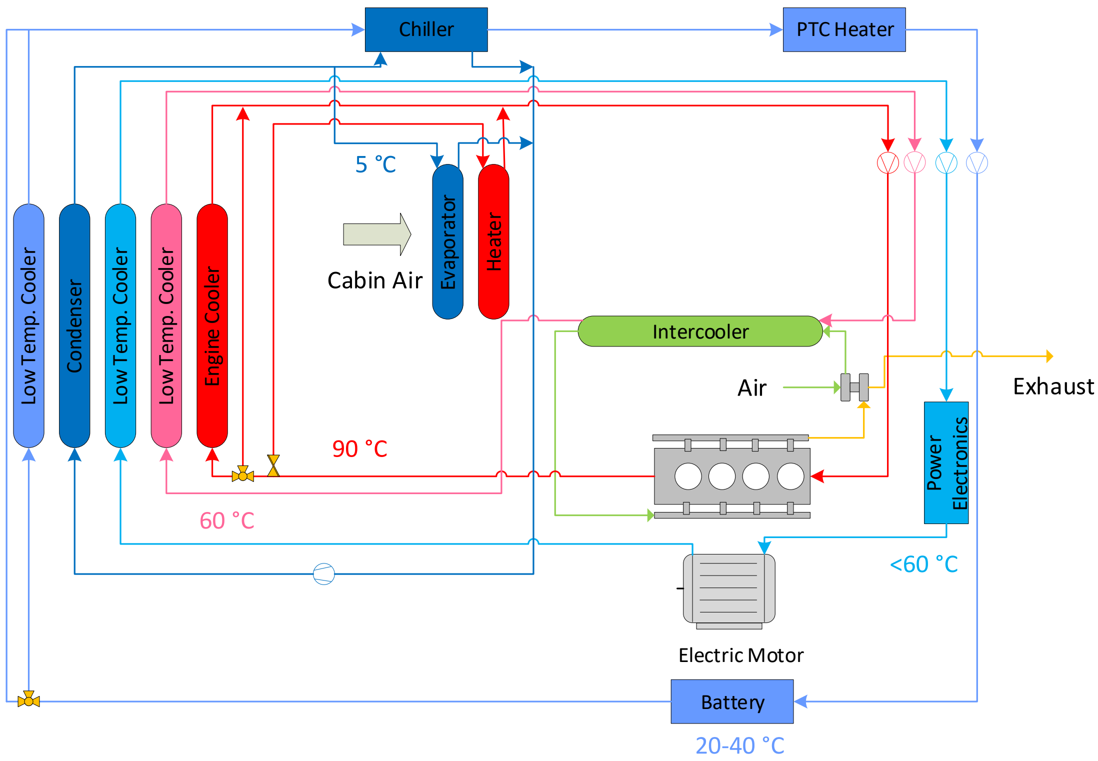

Figure 21: Thermal Management for Hybrid Vehicles (cf. Wawzyniak et al., 2017)

4.2 Thermal Management for Battery Electric Vehicles

At first sight, because of less cooling circuits, the thermal management in an electric powered vehicle seems less complicated, but it isn't. The powertrain loses the combustion engine, which is the most important heat source. During winter days, the comfort and safety relevant interior temperature has a significant impact on the valuable electric range and therefore it is mandatory to use the small amount of waste heat effectively. One simple way to provide the needed interior heat is the use of a PTC heating element, which can be mounted either on the air or on the coolant side. Figure 22 shows the thermal management system of a battery electric vehicle with a coolant side PTC, used to heat the cabin. All other elements are equal to the previously described hybrid vehicle layout. The downside of this uncomplicated thermal management system is that the needed energy must be provided to 100 percent by the traction battery. Especially compact electric vehicles suffer from this during city driving, because more energy is needed for heating than for propulsion, as will be shown later. (Wawzyniak et al., 2017)

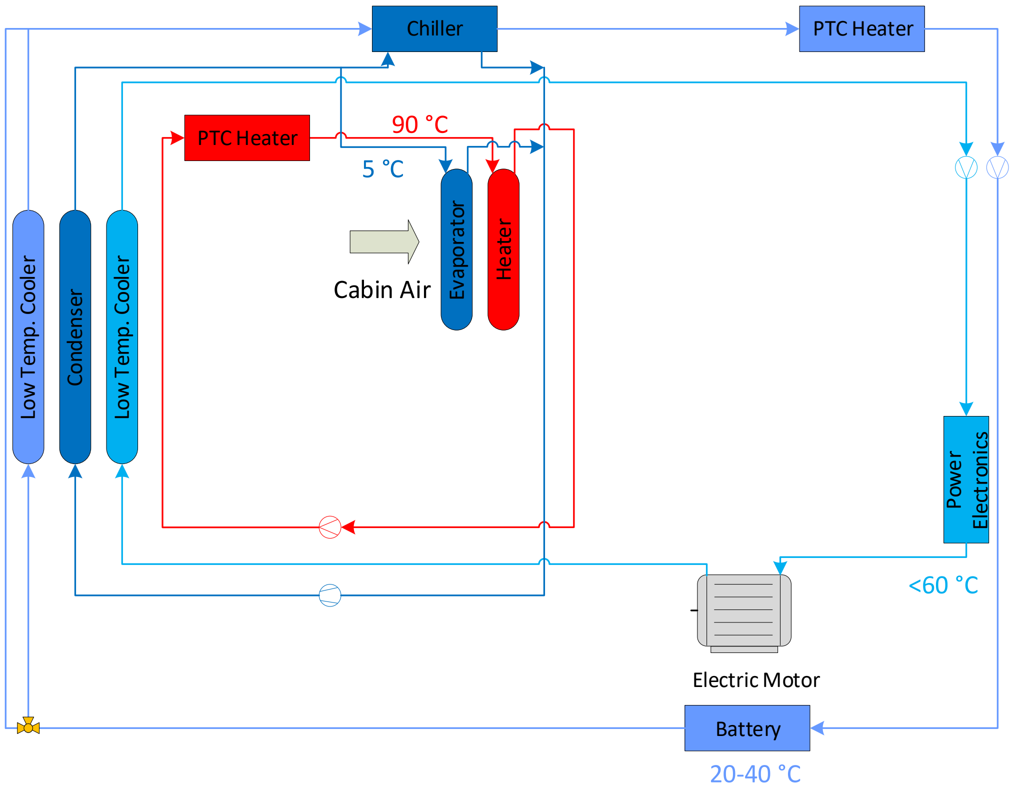

Figure 22: Thermal Management of a BEV with PTC Heater. (cf. Wawzyniak et al., 2017)

If one uses the low, but nevertheless existing waste heat of electric motor and power electronics in conjunction with a heat pump, the range can be increased. The reason for this is the significantly higher efficiency of the heat pump. In contrast, the greater installation effort and the more complex thermal management are considered as downsides. It should also be noted that the benefits of a heat pump with increasing drive power or size of the powertrain decreases. (Wawzyniak et al., 2017)

Figure 23 shows a possible thermal management system of a battery electric vehicle equipped with a heat pump, in heating mode. The waste heat of power electronics and motor is transferred via a chiller and indirect condenser to the cabin heating circuit. As refrigerant most system use R1234yf, which consists of fluorine compounds. When the waste heat is not sufficient to heat the cabin, a PTC heater provides additional heat.

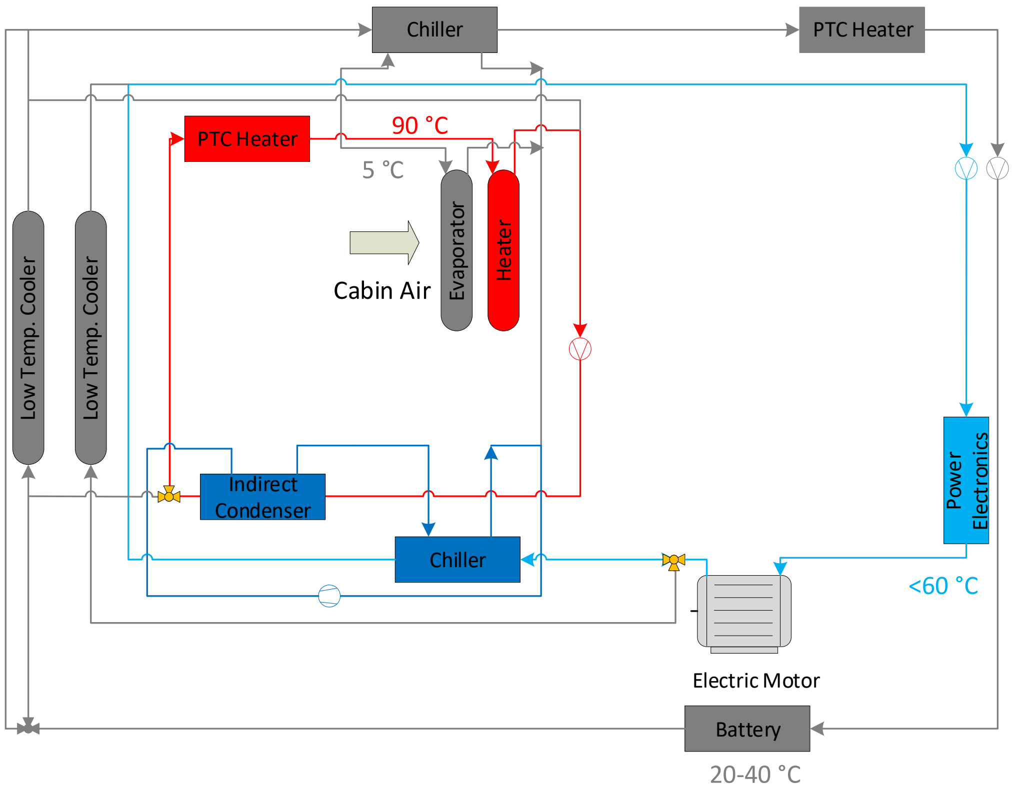

Figure 23: Thermal Management of a BEV with a heat pump, during heating condition. (cf. Wawzyniak et al., 2017)

4.3 Effect of Cabin Temperature Control on Electric Range

For the customer acceptance of BEVs it is important not to disregard the high thermal comfort for the vehicle passengers that has become standard in recent years. Heating is even a safety-related aspect due to the risk of fogged or icy windows at low ambient temperatures. Both air conditioning in summer and the heating during the winter should not significantly reduce the electric range on which customers rely. The challenge with interior heating is that, especially in electric powertrains, significantly less usable waste heat is available and at a lower temperature level than in combustion engine driven vehicle. A pure electric heating of the cabin is due to the high electrical energy consumption in direct conflict with the electric range. (Wawzyniak and Wiebelt, 2016)

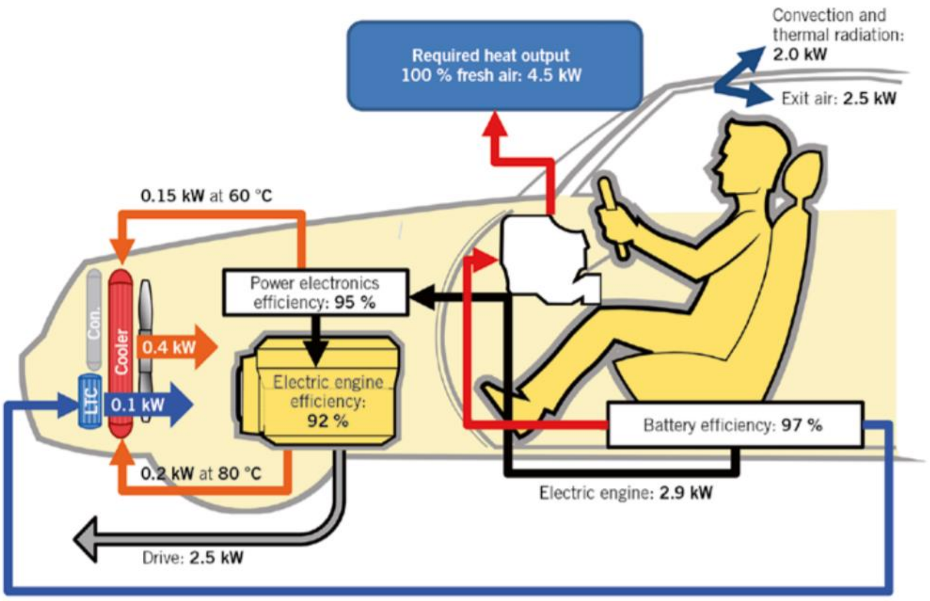

Figure 24: Energy Flow in a Battery Electric Vehicle. (Jung et al., 2011)

To assess the heating and cooling requirements, the climatic conditions must be taken into account. In the averaged European climate profile, the temperature-range from -14,5 to +36 °C covers 99.5 % of all occurring climatic conditions per year. Figure 24 shows in simplified terms the energy flows in a purely electrically driven vehicle at an ambient temperature of -15 °C and an average speed of 18.3 kilometers per hour, which is the average city cycle speed (ECE) in the New European Driving Cycle (NEDC). In order to maintain a cabin temperature of 22 °C at a mass air flow of 5 kg/min during fresh air operation, a total of 4.5 kW of heating power is required. The heating power consists of 2 kW, which are lost through convection and thermal radiation via windows and body to the environment, and 2.5 kW, which escape as exhaust air via the vehicle ventilation to the environment. On the other hand, the average power for propulsion of approximately 2.5 kW and the high efficiencies of the electric motor and the power electronics lead to a heat supply of only about 0.4 kW, which is delivered to the coolant. The waste heat of the battery, which is dissipated by the low temperature cooler (LTC), is with 0.1 kW also very low. These heat sources are not enough to heat the interior accordingly. This shows the conflict between interior heating and electric range. Nearly two times the amount of energy is needed for heating as for propulsion. (Jung et al., 2011)

During summer driving (boundary conditions: ambient temperature = 36 ° C and 25% relative humidity, air volume 5 kg/min, cabin temperature = 22 ° C) the main heat input is solar radiation of up to 1 kW/m^2 and convection. The main air conditioning "cold loss" is the exhaust air from the cabin. Altogether, about 2.8 kW of cooling capacity is needed, taking into account the coefficient of performance of the air conditioning circuit, a total of about 2 kW must be applied by the battery for maintaining 22 ° C cabin temperature. This is 80% of the average power needed for propulsion in the NEDC city cycle. (Tschöke, 2014)

To visualize the impact of heating on the electric range in real world driving scenarios the Common Artemis Driving Cycles (CADC) were chosen, because of the more realistic driving behavior. The CADC driving cycle, was devolved during the EU project ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) to determine fuel consumption and pollutant emission more realistically, however till now this test cycles are not mandatory. The three CADC cycles, which are called urban, rural and motorway can be seen in Figure 25. The CADC urban cycle consists mainly of stop-and-go maneuvers and the maximum speed is around 60 km/h. The CADC rural cycle in contrast has only a short urban driving part on the beginning and the average velocity is much higher. Finally, the CADC motorway cycle includes only one stop in the urban pre-motorway section and has with 130 km/h the highest top speed of all cycles.

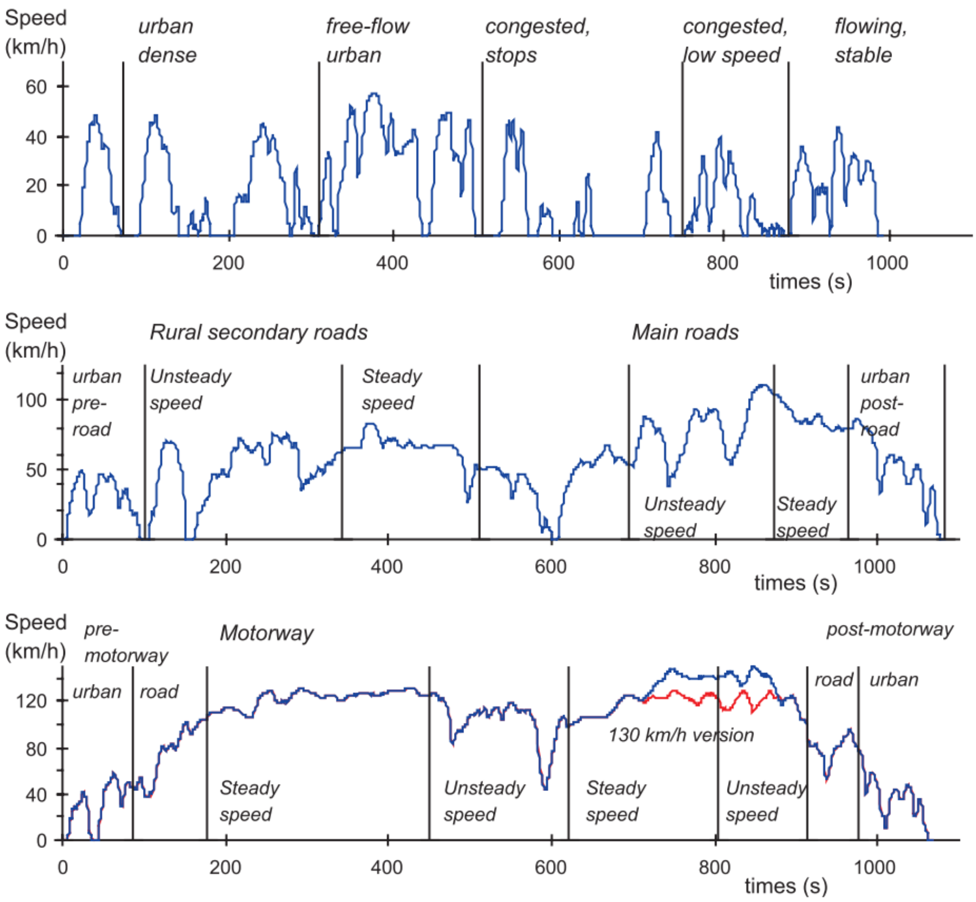

Figure 25: ARTEMIS urban, rural-road and motorway driving cycles. (André, 2004)

When heating is needed (ambient air temperature 0 ° C), in the for BEVs important sub-compact segment (average required drive power in city operation about 3 kW) approximately 2 kW heating power is needed to maintain the interior comfort temperature. This leads to a reduction of the electrical range by about 40%. Due to the significantly higher drive power of approximately 9 kW and a practically equal heating power, the range loss in the mid-range segment of around 21% is not quite as dramatic, but still noticeable. If one uses the low, but nevertheless existing waste heat of the electric motor and power electronics in conjunction with a coolant-coolant heat pump, the range (at 0 ° C) can be increased by up to 23% compared to the PTC heater. The reason for this is the significantly higher coefficient of performance (COP) of 3,2 of the heat pump. (Wawzyniak et al., 2017)

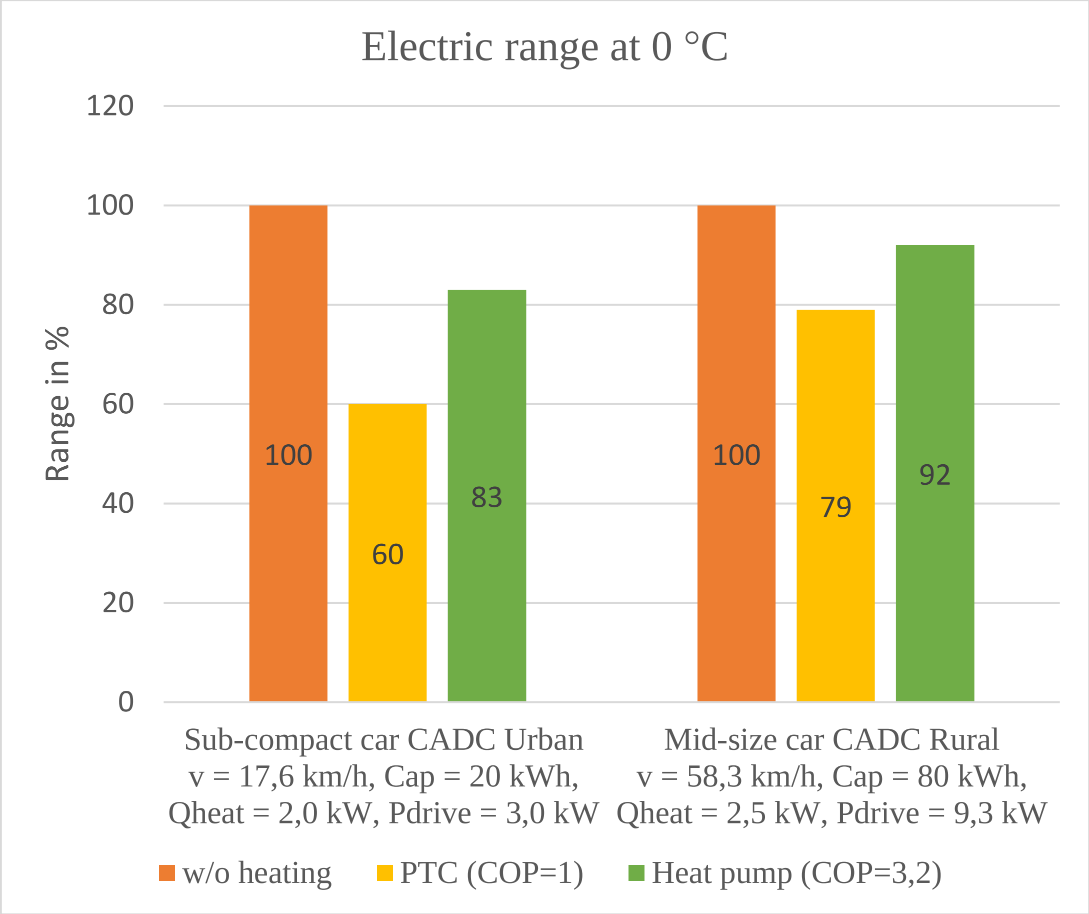

Figure 26: Electric range of BEVs at 0 °C ambient air temperature. (cf. Wawzyniak et al., 2017)

Besides the shown advantages of heat pumps there are also critical operation conditions. At high humidity, for example when sleeting, freezing of the outdoor heat exchanger may occur during heating of the cabin. In the event of excessive icing, the efficiency of the heat pump drops to such an extent that the outdoor heat exchanger must be deiced, for example via a connection of the heat pump cycle to a warmer coolant cycle. During this period, the interior heating via the heat pump is not available. In addition, below a certain limit temperature of the ambient air, the efficiency of the heat pump decreases so much, due to the thermodynamic properties of the refrigerant used, that it alone can no longer cover the heating power requirement of the vehicle cabin. Finally, at even lower temperatures, the heat pump can no longer be operated, because the lubrication of the compressor can no longer be ensured, due to the viscosity increase of the refrigerant. These means the when heating is needed the most, as during extreme cold temperatures, heat pumps fail. In these cases, the power deficit must be covered by a PTC heater. (Jung et al., 2011)

4.4 Battery Cooling during Fast Charging

Another requirement for modern, electrical mobility is the significant reduction in the still long charging times of the electrical energy storage. However, in contrast to refueling, charging the battery is physically lossy. The faster the charging process, the higher the necessary current and the higher the losses due to heat generation. In order to realize a quick charge of the battery and at the same time to protect it against premature aging, as shown before, it requires an outdoor temperature-dependent, active cooling, depending on the outside temperature with the participation of all existing cooling circuits. For fast charging, the air conditioning at high outside temperatures must provide up to 12 kW of cooling power only for temperature control of the battery (100 kWh battery capacity, fast charge in 15 min, 80% SOC). At moderate and low outdoor temperatures below about 15 °C, this amount of heat can be dissipated through the installed low temperature cooling circuit. Above this temperature, the cooling circuit must actively cool. The design of such a rapid charging system for the critical case (ambient air temperature of 40 °C) must also take into account the maintenance of the cabin temperature (about 3 kW), so that a total of up to 15 kW must be dissipated. By comparison, today's systems dedicated purely to interior cooling provide around 8 kW of cooling power. (Wawzyniak et al., 2017)

4.5 Thermoelectric heat pump for Lithium-Ion batteries

The thermoelectric heat pump represents an interesting alternative for the tempering of lithium-ion batteries and other vehicle aggregates compared to classical tempering methods. The thermoelectric heat pump (TEHP) utilizes the Peltier effect, which allows the pumping of heat from a cold to a warm side. To realize this heat pump effect thermoelectric modules (TEM) are used, which consist of semiconductor elements. Depending on the direction and intensity of the current, a temperature gradient that can be used for heating and cooling occurs. In addition to the Peltier effect, the Joule heat and the heat conduction are further influencing factors in thermoelectric modules. While the electrical resistance leads to a warming of the TEM (Joule heat), the heat conduction in the TEM causes a heat flow from the warm to the cold side against the active heat flow of the TEM Peltier effect. Furthermore, due to the strong influence of the temperature difference on the COP, a good heat transfer between TEM and cold or hot side is essential for efficient operation. Because of the Joule heat the COP for heating and cooling is different and the

COP for heating is higher by 1 than the COP for cooling ($COP_H = COP_C + 1$). In simulations carried out by Mahle Behr GmbH & Co. KG, COPs from 2 to 2,5 where reached. (Wehowski et al., 2013)

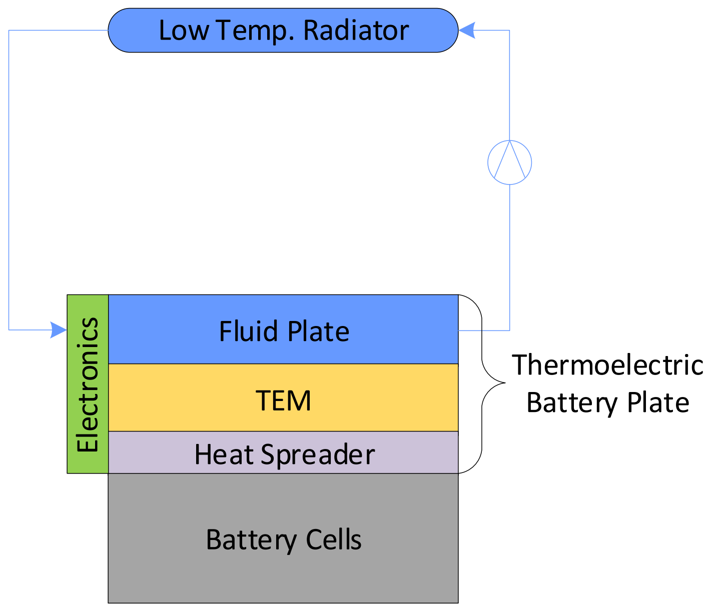

Figure 27: Elements of a Thermoelectric Battery Plate. (cf. Wehowski et al., 2015)

Figure 27 shows the elements of a thermoelectric battery plate in a schematic manner. A heat spreader is used to provide a thermal contact between the TEMs and the battery cells. The TEMs cool the battery cells to a temperature level that can be even below the ambient temperature. A low temperature coolant circuit connects the waste heat side of the TEMs to a low temperature cooler via a fluid plate. The temperature level of this low temperature circuit is higher than that of a corresponding battery cooling system without TEHP, so that, while maintaining the maximum battery temperature, the heat can be dissipated to the environment. To heat the battery during cold ambient temperatures, the current direction of the TEHP is reversed, so that heat flows from the water glycol mixture of the low-temperature circuit through the TEMs to the battery. Additional heating component like PTC heaters, which were discussed earlier, are not needed in case of a thermoelectric battery plate. Due to its independence from the air conditioning circuit and the integrated heating function, thermoelectric battery temperature control systems offers great advantages over the classic battery temperature control systems, especially for PHEV and BEV. (Wehowski et al., 2015)

Figure 28: Thermoelectric Heat Pump realized in form of a Thermoelectric Battery Plate. (Wawzyniak and Wiebelt, 2016)

A realization of a thermoelectric heat pump, which is integrated into a thermoelectric battery plate can be seen in Figure 28. The fittings for the connection to the low temperature cooling circuit can be clearly recognized and also the electric terminals, which power the thermoelectric module, can be seen in the middle of the plate.

5 Electric Axle Drives

5.1 Why E-Axles are used

In order to meet future CO_2 requirements, the entire automotive industry is increasingly focusing on the electrification of the powertrain. Hybrid powertrains have a huge impact on driving cycles without the limited range of battery electric vehicles. 48 V systems are a cost effective intermediate step from today's 12 V board networks, which are not able to propel vehicles effectively, to high voltage plug-in hybrid or battery electric vehicles. The voltage is increased, because the higher the voltage, the smaller the currents and thus the losses. But electric axles not only offer improved fuel economy and CO_2 reduction through recuperation, but also come with other customer benefits. These are better driving performance through boosting, improved safety and comfort through all wheel drive and good weight balance of the vehicle. The first challenges that arise during the development of electric powertrains are package and weight targets. Because these powertrains are often implemented in existing vehicle platforms the available space is very limited and very high-power densities are needed to reach the performance goals. These performance goals are not only high peak and continuous torque and power, but also high efficiency, response and torque accuracy in all wheel drive applications. The last but probably biggest challenge are the very tight price targets. To overcome these challenges the automotive industry focusses on integration through electric axles.

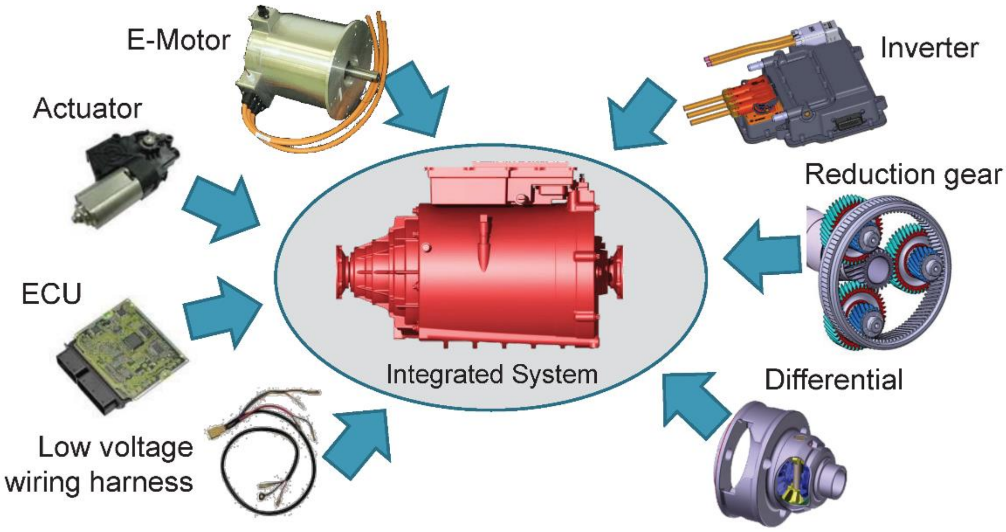

Figure 29: Integration of Components into an Electric Axle. (Schermann, 2015)

Integration means to include all necessary components in one compact package to reduce parts and interfaces. The main components, which can be seen in Figure 29, are reduction gearing, differential, electric motor and power electronics (inverter). But there are also sub components like actuators, control units and wiring harness. The electric axle, which contains all those components, is therefore a highly integrated system.

5.2 Powertrain Layout with E-Axles

As covered in chapter 2, there are different ways to classify hybrid drivetrain layouts. Because this thesis focusses on electric axle drives, it is from interest to narrow down the drivetrain architectures according to the use of e-axles. The first possible classification is the degree of hybridization, as mentioned in chapter 2.1. The so called micro hybrid, which has the least degree of hybridization, is basically a start-stop system to reduce fuel consumption during stand still. This micro hybrid systems are mostly realized by belt driven starters and so the electrical energy is not used to propel the vehicle. This means that micro hybrids don't use electric axles. The next category are mild hybrids. These hybrid concepts are a cost-effective intermediate step on the way to full hybrids and mostly rely on a 48 V electrical system. A major cost advantage are the lower safety standards for 48 V systems compared to high voltage systems, which use DC voltages over 60 V. Mild hybrids can be realized with 48 V electric axles. It is obvious, that from there on in all other hybrid concepts, which are full hybrids and plug-in hybrids, electric axles can be implemented. Of course, battery electric vehicles (BEV) and range-extended electric vehicles (REEV) most often use electric axle drives. Table 6 summarizes the possible use of e-axles.

Table 6: Use of E-Axles in Hybrids Classified by Degree of Electrification.

	Operation modes	Voltage of e-axle	Power of e-axle
Micro hybrid	Start-stop systems	No e-axle used	No e-axle used
Mild hybrid	Boost & recuperation	48 V	5 - 20 kW
Full & plug-in hybrid, BEV, REEV	Purely electric driving possible	> 200 V	> 20 kW

The next possible classification of hybrid drives is by power flow. As mentioned in chapter Hybrid Drives, one distinguishes between the series hybrids, parallel hybrids and combined hybrids. Here most HEV today use the parallel or combined layout, but to show the use of e-axles the parallel hybrid needs to be broken down further.

The electric machine of the parallel hybrid powertrain can basically be positioned at different points in the drivetrain, which results in specific advantages and disadvantages. To denote this, a nomenclature originally defined by Daimler AG has become standard in the automotive industry. Basically, it designates the parallel hybrid drivetrain according to the position of the electric motor in the drive train with P1 to P4, Figure 30. The P stands for parallel and the number indicates the installation location of the electric motor in the drive train. The P1 hybrid powertrain features an electric motor, which is directly attached to the engine and fixed to the crankshaft. If the electric machine is not installed directly on the combustion engine, but is instead located at the main gearbox input with an intermediate clutch, it is called a P2 arrangement. The next possible layout is the P3 drivetrain and here the electric motor is located at the transmission output. Finally, we come to the P4 layout, which is the primary application of electric axle drives. The characteristic feature of the P4 arrangement is that the electric motor and the internal combustion engine act on different axles and therefore this layout is called axle-split hybrid. Since in this case the traction of both drive systems is added up on the road, this also represents a parallel hybrid powertrain. The P4 arrangement is further characterized by the advantage of an easy implementation of four-wheel drive, without the increased fuel consumption of conventional systems. (Görke, 2016)

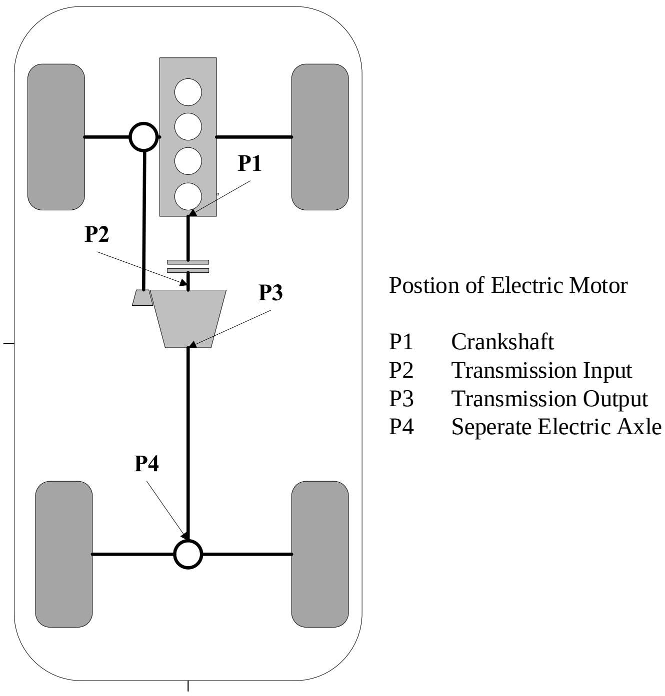

Figure 30: Position of Electric Motor Integration, when converting a Conventional All-Wheel Drive Layout to a Parallel Hybrid (P1-4).

5.3 Mechanical Layout of E-axles

Electric drive systems consist in general of an inverter, which converts the DC voltage of the battery into a corresponding three-phase current, one or more three-phase electric motors and one or more gearboxes. The electric motor is used to convert the electrical power into mechanical power. The torque of the motor shaft is transferred via a transmission with a differential to the wheels. Basically, there are different architectures of an electrical axle, which can be categorized as coaxial or offset layout. Coaxial designs use planetary gearings, whereas offset designs use helical gearings. In some cases, a combination of both planetary and helical gearings is used. Figure 38 shows for example an electric axle with a planetary gearing and a final helical gearing. Often the requirements, in terms of packaging, are derived from existing vehicle architectures, where there is little room left for additional installations. That’s why very compact architectures are necessary that fit in the limited space. (Schermann, 2013)

5.3.1 Coaxial Design

A coaxial axle architecture is very compact and per definition the motor shaft and gearbox have the same rotational axis. To realize this, it is based on a planetary gearing in combination with a hollow motor shaft. In most cases two-stage planetary gearings are used to provide a high transmission ratio, but a single-stage solution would be possible for smaller transmission ratios. A coaxial arrangement of transmission and electric motor uses a planetary stage whose sun gear is seated on the hollow motor shaft, through which the second drive shaft is guided. The rotor of the electric motor is constructed around the hollow shaft. The torque of the motor drives through the sun gear the two-stage planetary gearing, of which the first planet meshes with the sun and the second planet with the housing mounted ring gear. Both planets share the same pin, which is mounted on the differential case. Figure 31 shows a possible construction of an electric axle with coaxial layout in a schematic manner.

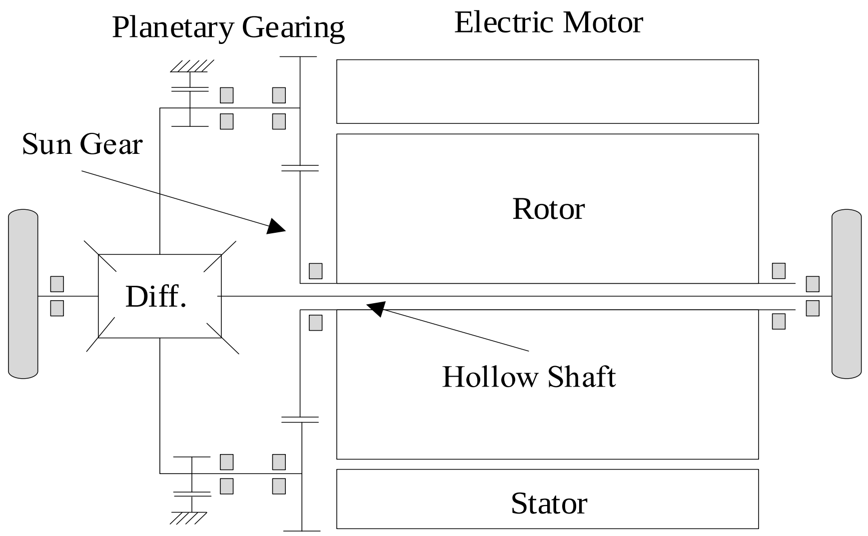

Figure 31: Schematic Layout of Gearing and Electric Machine of a Coaxial Electric Axle.

5.3.2 Offset Design

An alternative to the discussed coaxial layout is the offset layout. As the name implies the axis of motor shaft and gearbox output have an offset. This version uses instead of the planetary gearing a conventional helical gearing. Two achieve high transmission ratios again mostly two-stage gearings are used. As Figure 32 shows, the input gear, which is directly mounted on the motor shaft, drives through the two-stage helical gearing the differential housing. The differential housing is mounted on the final ring gear, like in conventional axle drives. From the differential, which has in most cases a bevel gear layout, the drive shafts reach to the wheels.

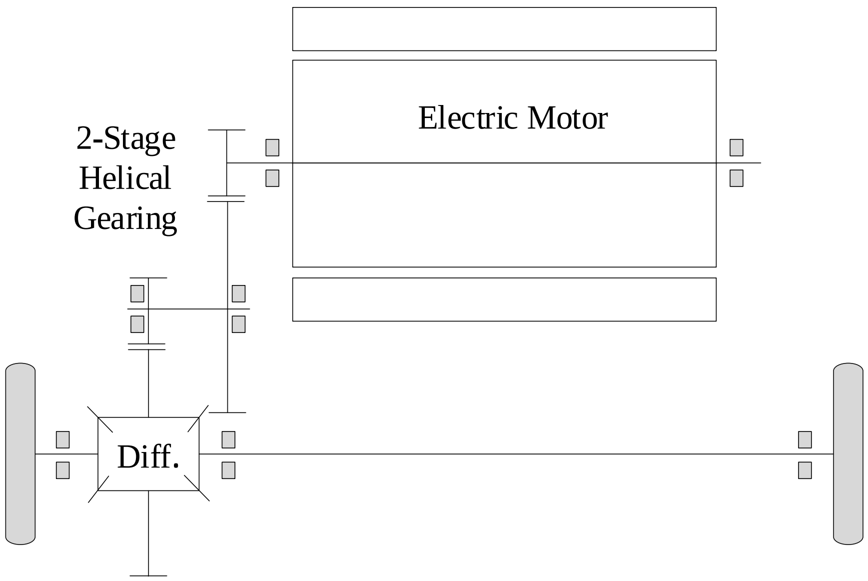

Figure 32: Schematic Layout of an Electric Axle with Offset Layout.

This layout has generally a little disadvantage compared to the coaxial layout in terms of building height, Figure 33, because the drive shaft is not routed through the electric motor. Instead the side shaft is guided outside of the motor. But often the offset design can be built narrower, because the differential can be shifted closer to the center of the axle. Or when the packing is the same the electric motor can be built longer, but the top mounted inverter needs to be lower to compensate for the higher building of the axle.

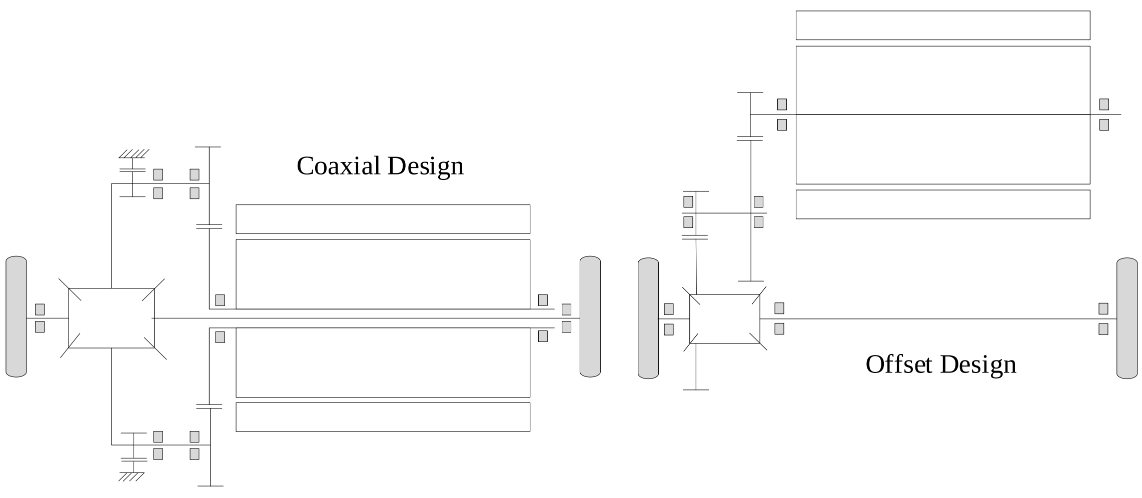

Figure 33: Dimensional Comparison between Coaxial and Offset Design.

5.3.3 Differentials used in E-Axles

Differentials are commonly used for speed compensation at a given torque distribution. When used in axle drives the torque distribution between both wheels must be equal. The second possible application is the use as a center differential. In this case other torque distributions may be desired, either by driving dynamics requirements or due to a vehicle configuration with different wheel sizes between the front and rear axles. Such an unsymmetrical differential uses gears with different numbers of teeth. Widely used for axle applications are bevel gear differentials, which are a special design of planetary gear stages, in which the sun and ring gear are equal to ensure an equal torque distribution. In order to enable equal sizes of sun gear and ring gear, bevel gears with an axial angle of 90 degree are used. The driven differential cage carries the differential bevel gears, called spider and side gears, which can rotate on a common axis. The output takes place on both sides via the side gears. Figure 34 shows a differential in schematic manner. (Fischer et al., 2016)

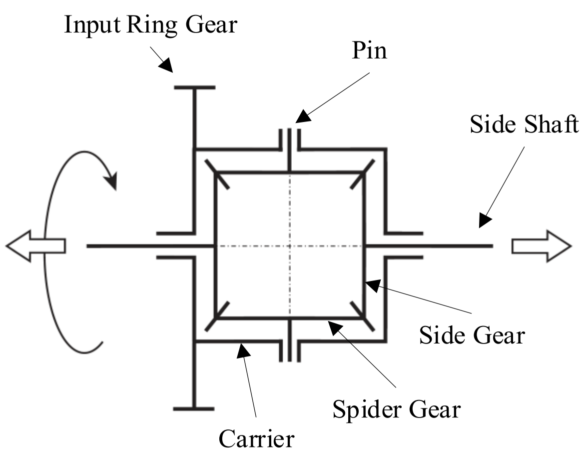

Figure 34: Schematic view of a differential. (Fischer et al., 2016)

Because as above mentioned the sun and ring gears have the same diameter the stationary transmission ratio (fixed carrier) for a differential can be calculated by:

$$i_0 = \frac{n_{Sun}}{n_{Ring}} = \frac{n_{Side\ Gear\ 1}}{n_{Side\ Gear\ 2}} = \frac{n_1}{n_2} = -1$$

With this stationary gear ratio, the relative rotation speeds of the gears in a differential can be calculated with the Willis equation,

$$n_1 - i_0 * n_2 - (1 - i_0) * n_{Carrier} = 0$$

which leads to:

$$n_{Carrier} = \frac{1}{2} * (n_1 + n_2)$$

This means that the rotation speed of the carrier is the arithmetic mean of both wheel rotation speeds.

5.3.3.1 Bevel Gear Differential

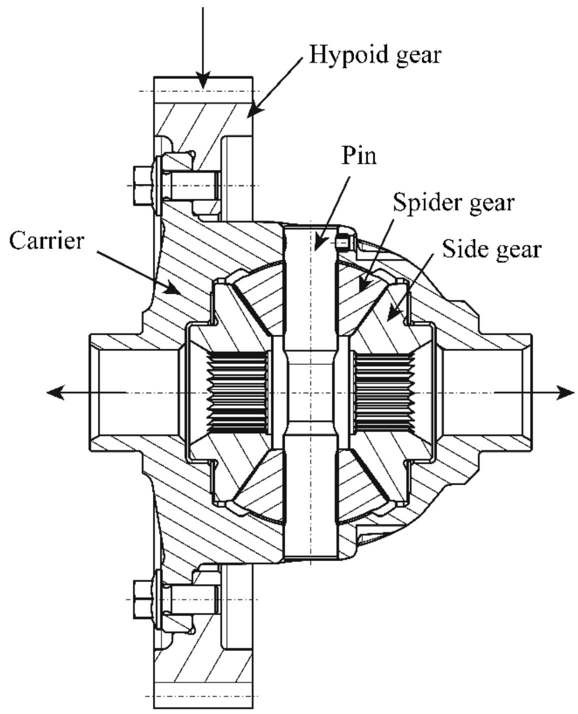

Figure 35: Cross section of an axle differential. (Fischer et al., 2016)

Figure 35 shows the main parts of an axle differential. The torque input takes place via the input gear (mostly a hypoid gear is used) and rotates the differential cage. When the vehicle drives in a straight line and the dynamic tire radius r_{dyn} is the same for both wheels, the bevel gears don't rotate. But when a corner is driven the differential needs to compensate for the different turning curves. This means that the outside wheel has to rotate faster than the inner wheel. In this case the spider gears, which are mounted on the differential pin, rotate to allow a different rotation speed of the side gears, which are connected via drive shafts to the wheels. The limitations of such an open differential, because of the equal torque distribution to both wheels, is that if complete traction is lost on one wheel the vehicle loses drive. This problem can be overcome by using a locking differential, traction control system or twin clutch system, which is covered in chapter 5.3.3.3.

5.3.3.2 Planetary Differential

An alternative to the bevel gear differential is the planetary differential, which is able to reduce weight and assembly space by a significant margin. Figure 36 shows an example of such a differential with a symmetric layout and with helical toothing.

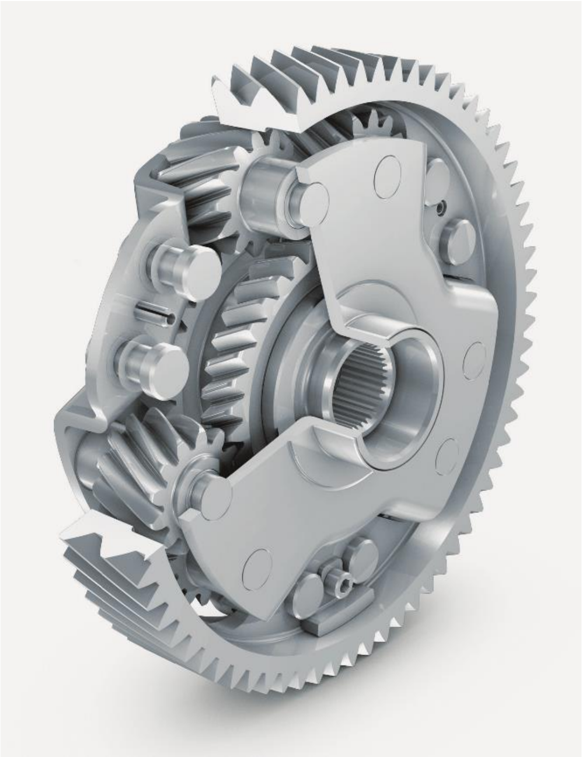

Figure 36: Symmetric Planetary Differential with Helical Toothing. (Smetana and Biermann, 2011)

The tooth contact of the planetary differential gears lies on a circle diameter, which is roughly twice as large compared to a bevel gear differential. This leads to significantly lower gear forces at the same torque level. In addition, the torque is transferred by a larger number of planet gears, which contributes to a more homogeneous load on the housing. In planetary differentials, either spur or helical gears can be used. The helix angle is primarily used to increase the locking value of the differential. During acceleration the sun gears are pressed against the wall of the differential housing. The desired friction level is achieved by the integration of friction discs between both sun gears and the differential housing. The differential behaves comparable to a limited-slip differential, whereby the locking value can be influenced by the helix angle and the friction discs. The axial support of the sun gears through the housing has a further function-relevant effect. During load, the differential builds up internal axial forces that increase the preload of the bearings. As a result, the rigidity of the bearing system is varied depending on the torque. To further increase the power density of the differential, an asymmetrical design of the toothing, Figure 37, with different radial dimensions of the sun gears is possible. The difference in size is achieved by contrasting tooth profile shifts. All gears continue to have the same toothing module. Despite the difference in size of the sun gears, the number of teeth is identical to ensure symmetrical torque distribution between the two sun gears. (Smetana and Biermann, 2011)

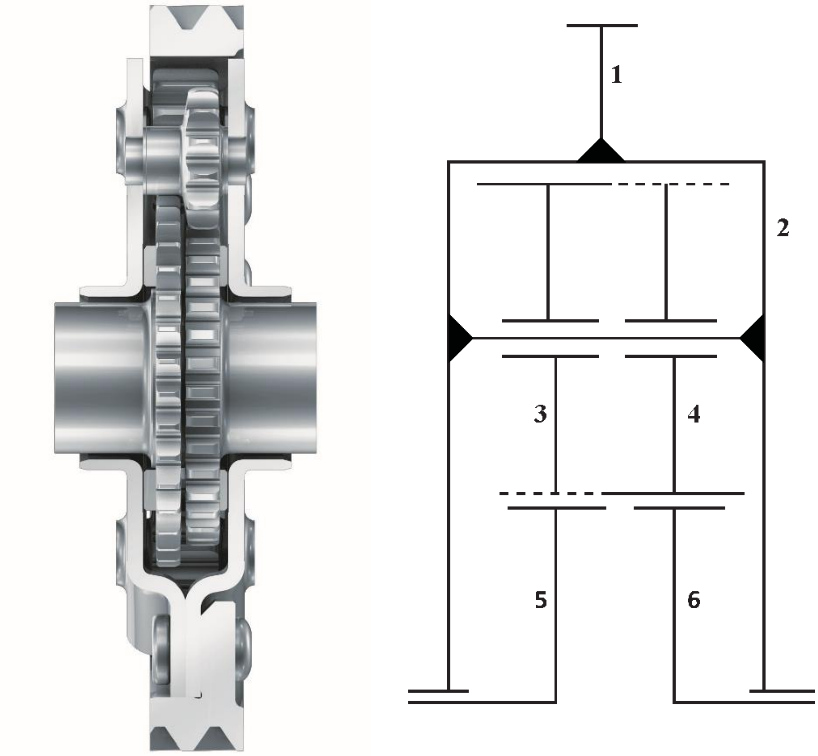

Figure 37: Asymmetric Spur Gear Differential with Input Gear (1), Housing (2), Planets (3, 4) and Sun Gears (5, 6). (Smetana and Biermann, 2011) & (Biermann et al., 2010)

During a project for the development of a lightweight differential the company Schaeffler Technologies GmbH & Co. KG has achieved impressive results with planetary differentials. The company decided to develop a spur gear differential for the MQ350 gearbox from Volkswagen AG. The gearbox is a six-gear manual transmission with integrated differential for a front transverse engine layout. The input torque rating of 350 Nm translates to an output torque of 5500 Nm in first gear. One of the boundary conditions for the design of the new differential was that the diameter of the helical input gear is equal to the one of the conventional reference differential, so that the spur gear differential can be easily implemented. As shown in Table 7, it is possible to optimize the differential either in weight, or in torque capacity. Both variants reduce the bearing distance significantly, in case of the weight optimized variant up to 75 %, which leads to a very compact design. Another advantage is the symmetric layout compared to a conventional differential. Another effect of the weight reduction is that the inertia of the low weight version is drastically reduced, which leads to better acceleration. It also worth to mention that both variants have an increased static safety by 10 % and the noise level could be reduced by 10 dB. (Smetana and Biermann, 2011)

Table 7: Comparison between bevel gear differential, weight optimized spur gear differential and torque optimized spur gear differential. (Smetana and Biermann, 2011)

	Conventional	Low Weight	High Torque
Maximum Torque in Nm	5500	5500	8000 (+45 %)
Input Ring Gear Diameter in mm	195,1	195,1	195,1
Bearing Distance in mm	128	32,6 (-75 %)	56 (-56 %)
Weight in kg	8,95	6,01 (-33 %)	8,00 (-11 %)
Inertia in kg*m^2	0,040	0,0124 (-69 %)	0,042
Relative Static Safety in %	100	110	110

Because of the mentioned benefits of the spur gear differential an implementation in an electric axle drive, where weight and assembly space are primary objectives, could solve existing engineering challenges. A downside in comparison to conventional bevel gear differentials are the higher manufacturing costs because of the more complex design.

5.3.3.3 Twin Clutch Differential

To overcome the described disadvantages of an open differential during low traction scenarios and to improve handling in general it is possible to implement a torque vectoring capable axle. Torque vectoring is covered in detail in chapter 5.3.4. A conventional torque vectoring rear axle uses two faster rotating superposition gearings and two multiple disc clutches to connect the superposition gears to the drive shafts. Because such a torque vectoring axle is significantly bigger, heavier and more expansive than a conventional axle with open differential, the industry developed axles without differentials that rely only on clutch packs for rotation speed compensation. Figure 38 shows such an axle developed by GKN PLC.

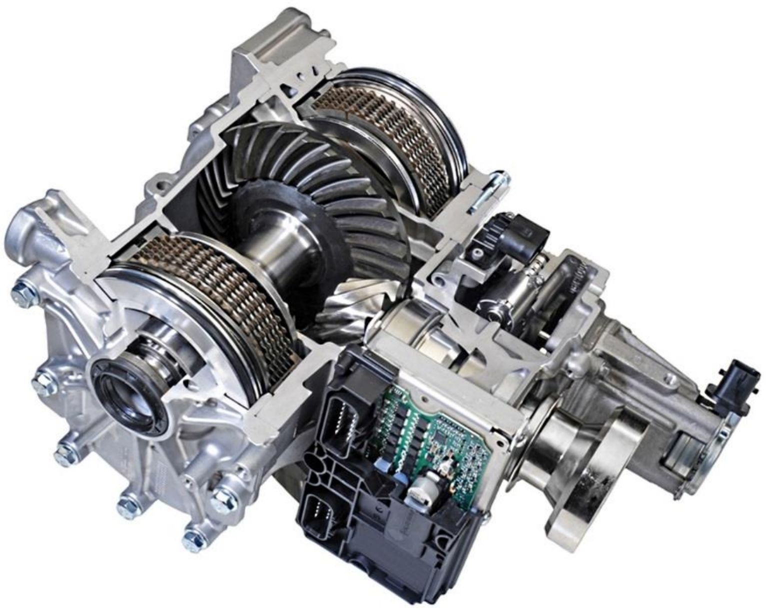

Figure 38: Twin Clutch Rear Axle without Differential by GKN PLC. (Höck, 2015)

The use of two clutches allows regulation of the torque distribution between the front and rear axles (longitudinal distribution) and between the wheels of the rear axle (transverse distribution). This torque regulation has the advantage that traction is improved in one-sided low traction scenarios. Since no differential is installed and to avoid tensioning moments in the drivetrain, the necessary speed compensation during cornering must be compensated by clutch slip. The geometrically caused slip is depending on the steering angle. This slip characteristic is stored in the clutch control unit and the torque to the wheels is controlled accordingly to prevent tension in the drivetrain. An advantage of twin clutch systems compared to traction control systems, which use brake intervention, is that they can compensate very early for the occurring understeer by the addition of a yaw moment. This asymmetric torque distribution on the rear axle creates the effect of a lower steering angle requirement and in addition an increase of the lateral acceleration of about 15 % can be achieved. (Höck, 2015)

The mentioned benefits make a twin clutch system also very interesting for electric axle drives. Hybrid vehicles also often need disconnect systems, which are covered in detail in chapter 5.3.5, because often the speed of the electric axle is limited, so that the ICE alone powers the car at high speeds. Because the clutches can be opened at any speed, such a disconnect system is not needed in a twin clutch layout. Figure 39 shows a possible implementation of a twin clutch in a schematic manner.

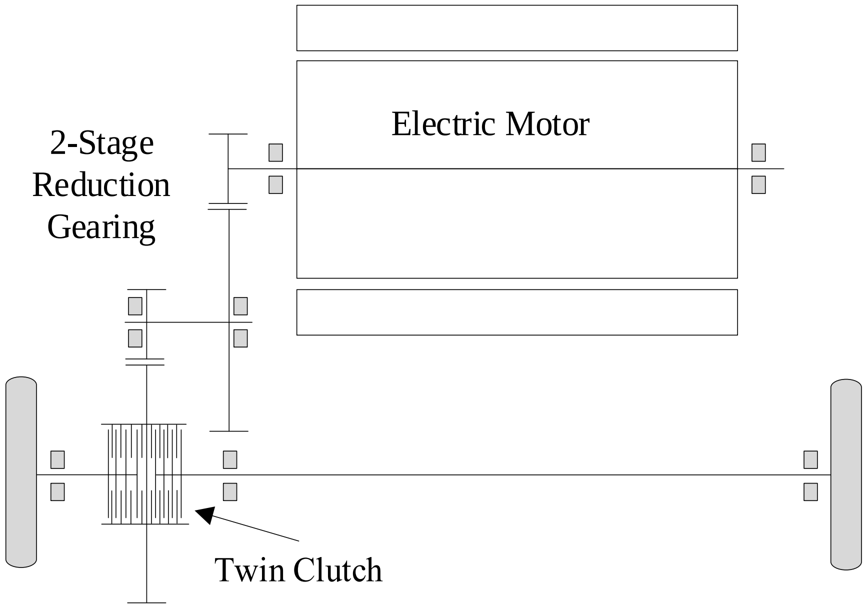

Figure 39: Schematic view of an E-Axle with Twin Clutch and Reduction Gearing.

Another advantage is the torque limiting feature of clutches. Conventional axle transmissions are usually designed with a so-called shock factor of 2 to 2.5. For an axle drive with a nominal torque of 3500 Nm, this results in maximum design layout of up to 8500 Nm. This noticeably increases weight and costs. Due to the precise and highly dynamic control of the clutches, the real load of the transmission can be limited in all driving situations so that all components can be designed only for nominal torque, which saves a considerable amount of weight and cost. That’s why a weight-neutral design compared to conventional electric axes is possible despite a slight increase in the weight due to clutches and actuators. (Gassmann et al., 2017)

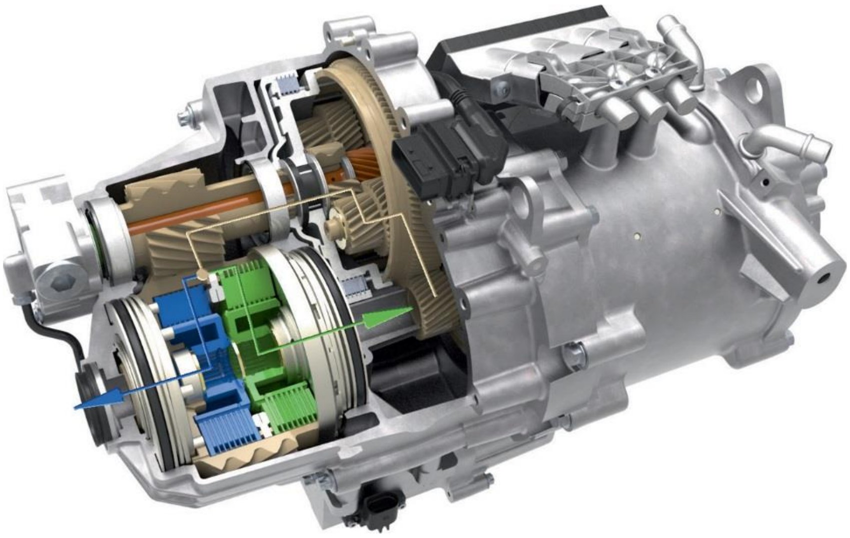

Figure 40: Partial Section of Twin Clutch E-Axle from GKN PLC. (Gassmann et al., 2017)

Figure 40 shows a realized e-axle with twin clutch layout developed by GKN PLC. Furthermore, it combines a helical gear stage, which drives the clutch basket, and a planetary stage with two gears.

5.3.4 Torque Vectoring

Torque vectoring (TV) is not only in the focus of the industry since the introduction of e-vehicles, but because electric drivetrains offer new ways to realize TV and because of the customer benefit in form of improved driving performance, the interest in TV axles is growing. Behind the term TV is a wheel-individual distribution of braking or drive torque. This technology increases vehicle safety and agility. The principle is to create a yaw moment on the vehicle by different wheel torques and thus a changed driving dynamics behavior. To realize TV different systems are used. One possibility to achieve a jaw moment and a locking effect under acceleration is an active brake intervention, which can be implemented by the ESP system without additional components. Depending on the traction potential, braking torques are controlled in such a way that, for example, an understeering behavior is neutralized at an early stage and agility is therefore increased. The more sophisticated way is the use of active differentials, which make it possible to distribute torques between the wheels of an axle as desired. A noticeably increased agility is the result. Basically, the control strategies of TV systems are based on a model-based, nonlinear control algorithm, since the transverse dynamics of vehicles can only be accurately reproduced with non-linear models. The setpoint values of all relevant state variables, like yaw rate, slip angle, and so on, are determined and a feed forward control ensures that the target vehicle behavior is maintained exactly. If model uncertainties or external disturbances happen, they are compensated by a feedback, which compares actual and desired state variables and adds a compensatory proportion to the control variable. The yaw moment, which is the control variable, is formed by wheel-specific drive torques. A visualization of a basic TV control algorithm can be seen in Figure 41. The goal of the TC control algorithm is, besides reaching higher cornering speeds, also a vehicle that “feels” better to the driver. This is realized by altering the self-steering gradient of the vehicle to give a more agile feel in low speed scenarios and at the same time a less sensitive feel during high speed scenarios. Another benefit is that the balance (understeer / neutral / oversteer) of the vehicle can be adjusted. Although this can also be done by making adjustments on the chassis (stabilizers, springs and dampers), a TV system has the advantage that these settings can be made via software speed and dynamics dependent. (Folke et al., 2010)

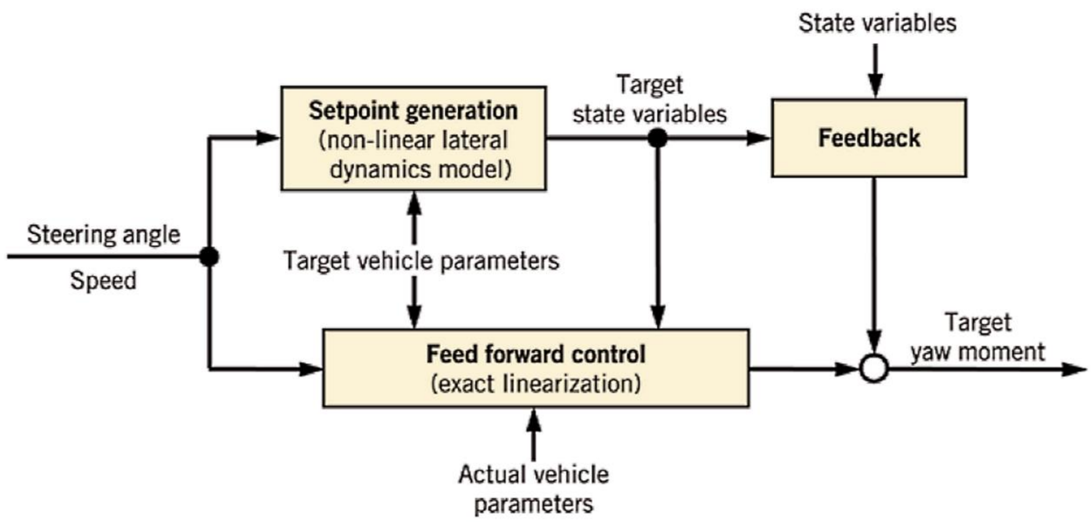

Figure 41: Torque Vectoring Control Algorithm. (Folke et al., 2010)

Besides the discussed twin clutch differential there are also other ways to implement torque vectoring into electric axles. One obvious way is an independent electric machine for each wheel. Such single-wheel drive systems can lead in last consequence to wheel hub motors, because the elimination of the gearing reduces losses and inertia. Because the focus of this thesis is on electric axle drives, single-wheel drive systems will not be further discussed. Another very popular way to achieve torque vectoring is the implementation of a superimposing gear unit, which is also used in conventional TV axles. Basically, this technology relies on a second gearings and wet clutches to alter torque distribution to the drive shafts. Figure 42 shows the layout of a two-stage planetary superimposing unit in a schematic manner.

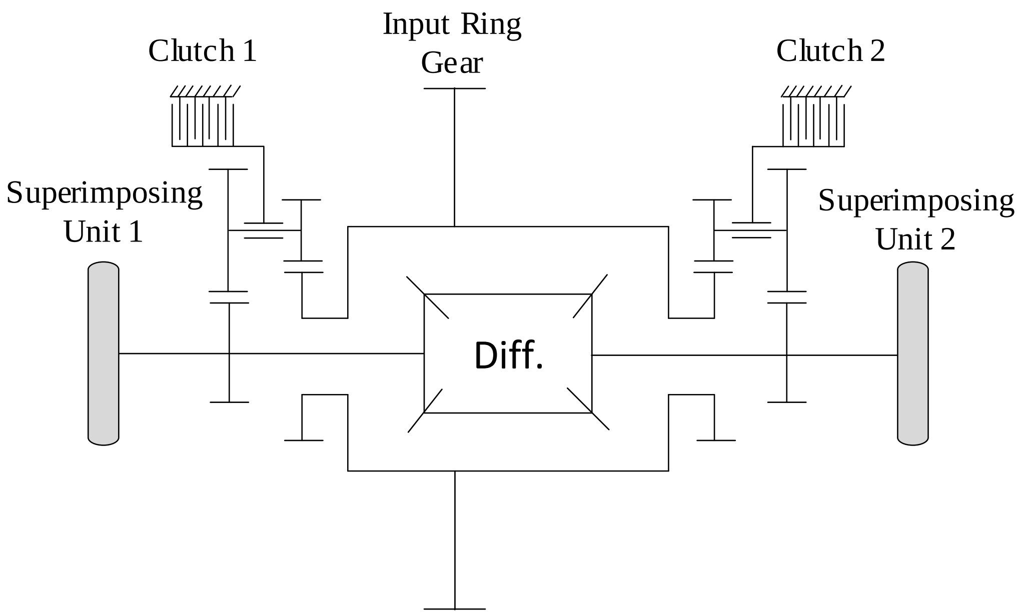

Figure 42: Schematic View of an Axle with a TV Superimposing Unit.

Like in a conventional axle the input ring gear is connected to the differential housing, which contains the side and spider gears. The two-stage planetary superimposing unit is driven by the inner sun gear, which is connected to the differential housing. On the outer side the planet meshes with the outer sun gear, which is connected to the drive shaft. The planet carrier of the superimposing unit is positively locked with the inner toothed clutch plates. The outer toothed clutch plates are positively locked with the axle housing. In this case the clutch acts as a brake and so it delivers negative torque to the planet carrier. This results in an acceleration of the outer sun gear and the desired yaw moment is produced.

Another possible layout of the superimposing unit was developed by Magna Powertrain AG & Co KG and is in use as Audi Quattro Sport Differential. In contrast to the above-mentioned solution, this system is based on a ring gear drive and therefore doesn’t use any planetary gears.

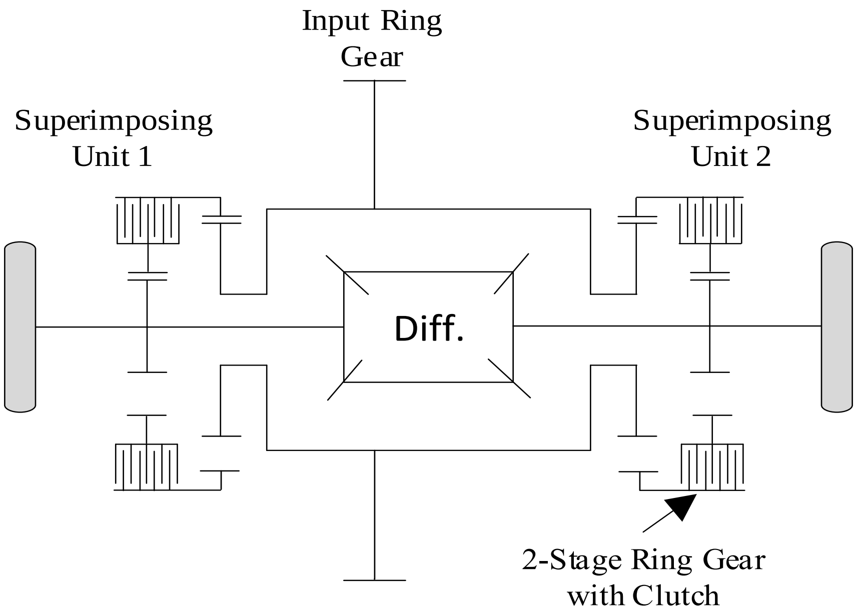

Figure 43: Schematic View of an Asymmetric Ring Gear Superimposing Unit. (cf. Meissner et al., 2010)

As can be seen in Figure 43 the two-stage ring gears and clutches are mounted with symmetry axis offset in respect to the differential and therefore no planetary gears are needed. The differential housing is again connected to the inner sun gear, but this time the sun gear meshes directly with the ring gear, which is at the same time positively locked with the outer toothed clutch plates. The inner toothed clutch plates are positively locked with the outer ring gear, which acts therefore as a hub for the clutch. Because the outer ring gear has the same axle offset, it is able to mesh directly with the outer sun gear. Finally, the outer sun gear is again mounted on the drive shaft. When the clutch is closed the desired amount of torque is shifted to one side and introduces the jaw moment. The difference between the input torque and TV torque is evenly distributed to both wheels as with a conventional differential. Figure 44 shows a cross section of the Audi Sport Differential with a sketched power path during TV mode. Another stand out feature of this axle drive is that the actuation of the clutches is hydraulically, which offers fast and precise torque control. For optimal performance two separate oil circuits are used, one for the hypoid toothing and one for the superimposing units. The reason is that the high Sulphur content of hypoid oil, which is needed for wear resistance of the toothing, leads to a stick-slip effect of the clutch. This effect, which is also called judder or moaning, is noticeable through torque fluctuations.

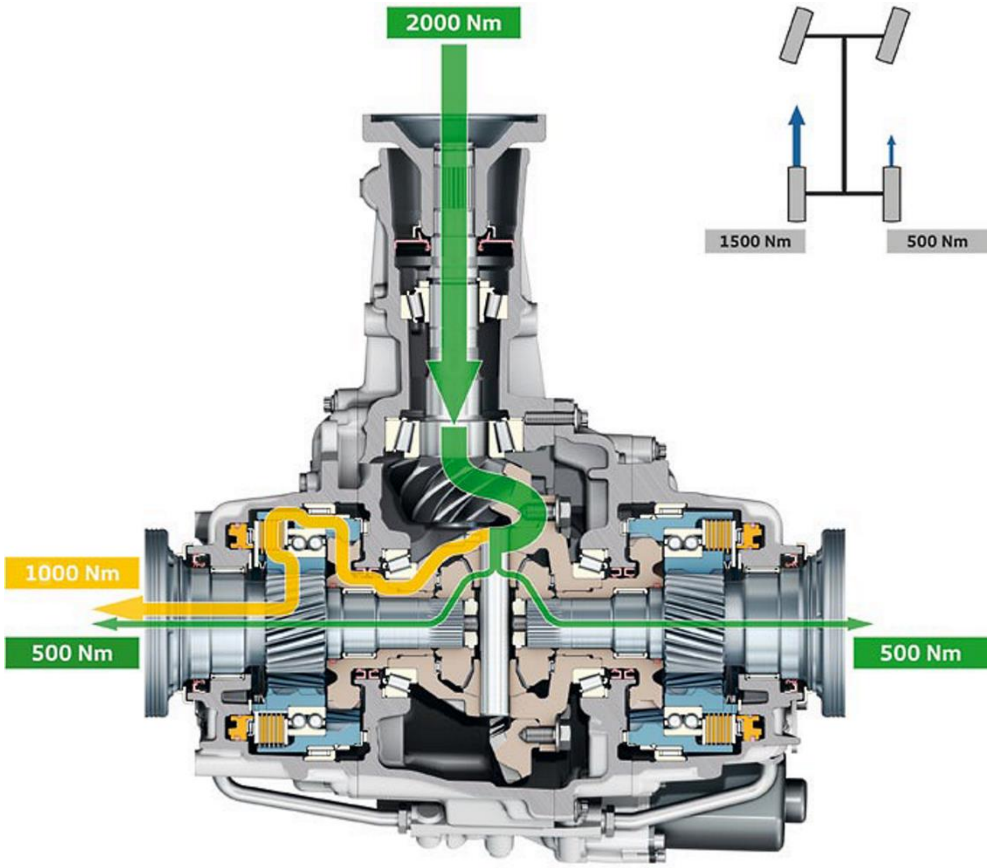

Figure 44: Cross Section of the Audi Sport Differential with Torque Vectoring. (Meissner et al., 2010)

To summarize it can be said that the presented ways to realize torque vectoring are well proven in conventional axles and an application in electric axles is obvious. The effort in engineering and manufacturing is rewarded in terms of handling and safety. To make electric or hybrid vehicles more attractive to potential buyers, these customer benefits have the same importance as efficiency.

5.3.5 Disconnect System

The maximum velocity that can be reached with an electric axle depends primary on the gear ratio and the maximum rotational speed of the electric motor. The transmission ratio of the electric axle needs to balance torque and speed. High torque figures are needed for good acceleration and driving dynamics, whereas an acceptable electric top speed is beneficial for motorway driving. On the one hand a too small transmission ratio leads to a limited top speed and on the other hand a too big transmission ratio needs a big and heavy motor to supply an adequate amount of torque. Possible solutions are multi gear electric axles, but the increased complexity, engineering effort and cost prohibit an implementation in many cases. Single gear electric axles have usually transmission ratios from 8 to 10 and the electric motors used today have maximal rotation speeds between 12000 and 14000 revolutions per minute. With a standard tire size of 225/45-R17, which corresponds to a dynamic tire radius of 0,308 m, the top speed can be calculated by:

$$v_{max} = \frac{2 * r_{dyn} * \pi * n_{motor} * 60}{i * 1000}\ in\ km/h$$

For i =10 and n_{motor} = 12000 the calculated electric top speed is about 140 km/h. This means that hybrid vehicles, which typically run faster than this, need a system to disconnect the electric motor from the drivetrain in order to prevent over-revving. A battery electric vehicle does not need a disconnect system because the electric top speed is the overall top speed of the vehicle. When a twin clutch differential, which was covered earlier, is used, the implementation of a disconnect function is very easy. To enable this both clutches can be fully opened to allow the drive shafts to spin free. But a disconnect system can also be implemented in axles that use conventional bevel gear differentials. A simple way is the use of a dog clutch in the interface between drive shaft and one side gear. Because a dog clutch needs synchronization, the speeds of motor and drive shaft must match precisely, to allow a reconnection during driving. A control algorithm can be implemented with the help of the motor power electronics, which know the rotational speed of the electric machine, and the ABS sensors.

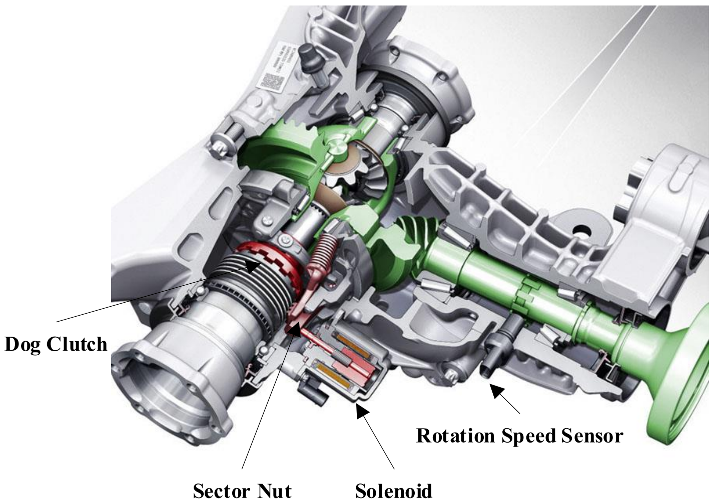

Figure 45: Disconnect System of an Audi Quattro Ultra Rear Axle. ("Audi quattro ultra | Automobil Revue," n.d.)

Figure 45 shows the disconnect system of an Audi Quattro Ultra axle. Basically, this system consists of a rotation speed sensor on the pinion, a dog clutch on the right drive shaft and a solenoid. The solenoid moves the sector nut to the worm gearing, which rotates at wheel speed, and the emerging axial force opens the dog clutch. Although the system is installed in a conventional axle, it is conceivable to use a similar system in an e-axle.

6 E-Axle Design Guideline

As shown in this thesis there are lots of variations in electric axle design and depending on the requirements some layouts and features are more preferable than others. In this chapter a small design guideline should be presented to show available options during the basic conception of an electric axle. Besides this thesis two other theses are in progress at the TU Graz Institute of Production Engineering that focus in general on production of electric axles and in detail on electric motor and housing. This design guideline addresses primarily the mechanical layout. Based on all three theses an electric axle configurator, based on a graphical user interface, may be realized in a following project.

It was decided that on the first level the vehicle class should be defined. The range of vehicle classes should cover variations from subcompact cars (e.g. Renault ZOE), over full-sized cars (e.g. Tesla Model S) to sports utility vehicles (e.g. Volvo XC90). This superordinate classification is an important step to quantify a first proportion of predefined constraints, which are needed for basic mechanical design. These constraints are the vehicle mass m in kg, the dynamic wheel radius r_{dyn} in m, the drag coefficient C_D and the cross-sectional area A in m^2. In the next step several resistances have to be considered to calculate the maximum speed and gradeability of the vehicle, Figure 46.

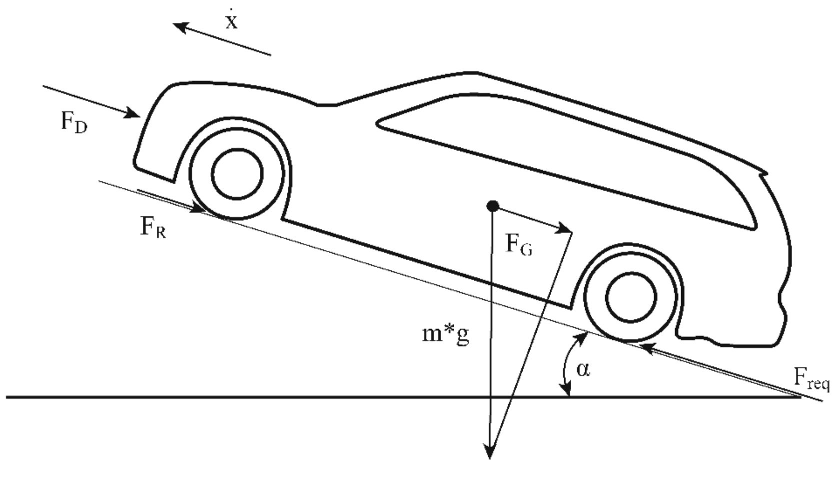

Figure 46: Resistance of Motion of a Vehicle. (Fischer et al., 2016)

The first resistance is the drag force, which is defended by

$$F_D = \frac{1}{2}\rho C_D A(v - v_W)^2 \; in \; N.$$

The drag equation includes also the air mass density ρ in kg/m^3, which is 1,2 at sea level, the vehicle speed v in m/s and the wind speed v_W in m/s. The next needed equation is the rolling resistance

$$F_R = C_{rr} mg \cos\alpha \; in \; N,$$

which contains the rolling resistance coefficient C_{rr}, which is 0,011 – 0,015 for car tires on tarmac (“Rollwiderstand – Wikipedia,” n.d.), the earth's gravity g = 9,81 in m/s^2 and the gradient angle α in rad. Finally, of course the gradient resistance

$$F_G = mg \sin\alpha \text{ in N}$$

has to be taken into account. All these resistances can be summed up to the required tractive Force

$$F_{req} = F_D + F_R + F_G \text{ in N.}$$

This equation describes the balance between the resistances of motion and the required tractive force, which has to be allocated by the vehicles drive, during steady motion. This tractive force needs to be brought up by the drive torque T_{Drive} that can be calculated by

$$T_{Drive} = T_{Motor} * i_{total} * \eta_{total} \text{ in Nm.}$$

The drive torque equation contains the motor torque T_{Motor} in Nm, the total transmission ratio i_{total} and the total drivetrain efficiency factor η_{total}. The drive torque can be converted in the belonging drive force F_{Drive} with the help of the dynamic wheel radius,

$$F_{Drive} = \frac{T_{Drive}}{r_{dyn}} \text{ in N.}$$

The relation between motor speed n_{Motor} in 1/s and vehicle speed v in m/s is given by

$$v = \frac{2 * \pi * r_{dyn} * n_{motor}}{i_{total}} \; in \; m/s.$$

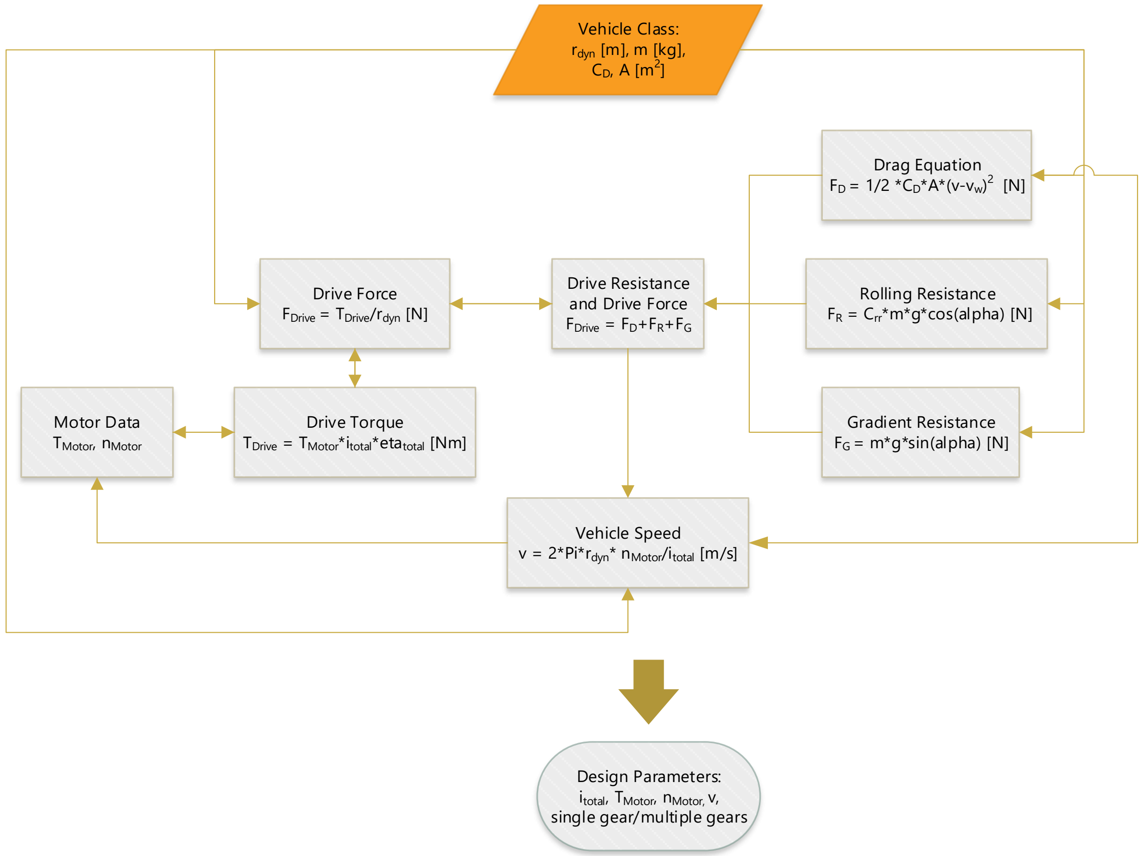

Figure 47: Selection of the Basic Design Parameters of an Electric Axle.

Figure 47 shows in a flowchart that with the help of the above-mentioned equations it is possible to calculate the basic design parameters. These are the total gear ratio of the axle i_{total}, the motors torque T_{Motor}, motor rotational speed n_{Motor} and achievable speed v. Depending on input parameters it is either possible to find the right gear ratio for an available motor, or to calculate the needed motor performance for desired vehicle speed. With the gradient resistance it is also possible to evaluate the gradient performance of the electric axle, which is important for mountain roads or parking garages. The acceleration potential during a specific driving situation can be judged with the difference between drive force and resistance forces. Furthermore, the decision can be made if the axle should have multiple gears or if a single gear layout is sufficient. Multiple gears have the benefit of a wider gear ratio spread. A short first gear can improve gradient performance and acceleration, whereas a higher second gear makes a high vehicle speed possible. Another advantage of a multiple gear layout is its ability to keep the electric motor in an optimal efficiency area for a broader vehicle speed range. That's because an electric motor has the best efficiency only in a certain rotational speed range, like a combustion engine.

In a next step the mechanical design of the electric axle needs to be further determined with the help of the above selected basic design parameters. Figure 48 shows a basic way for finding the appropriate gearing layout in form of a flow chart.

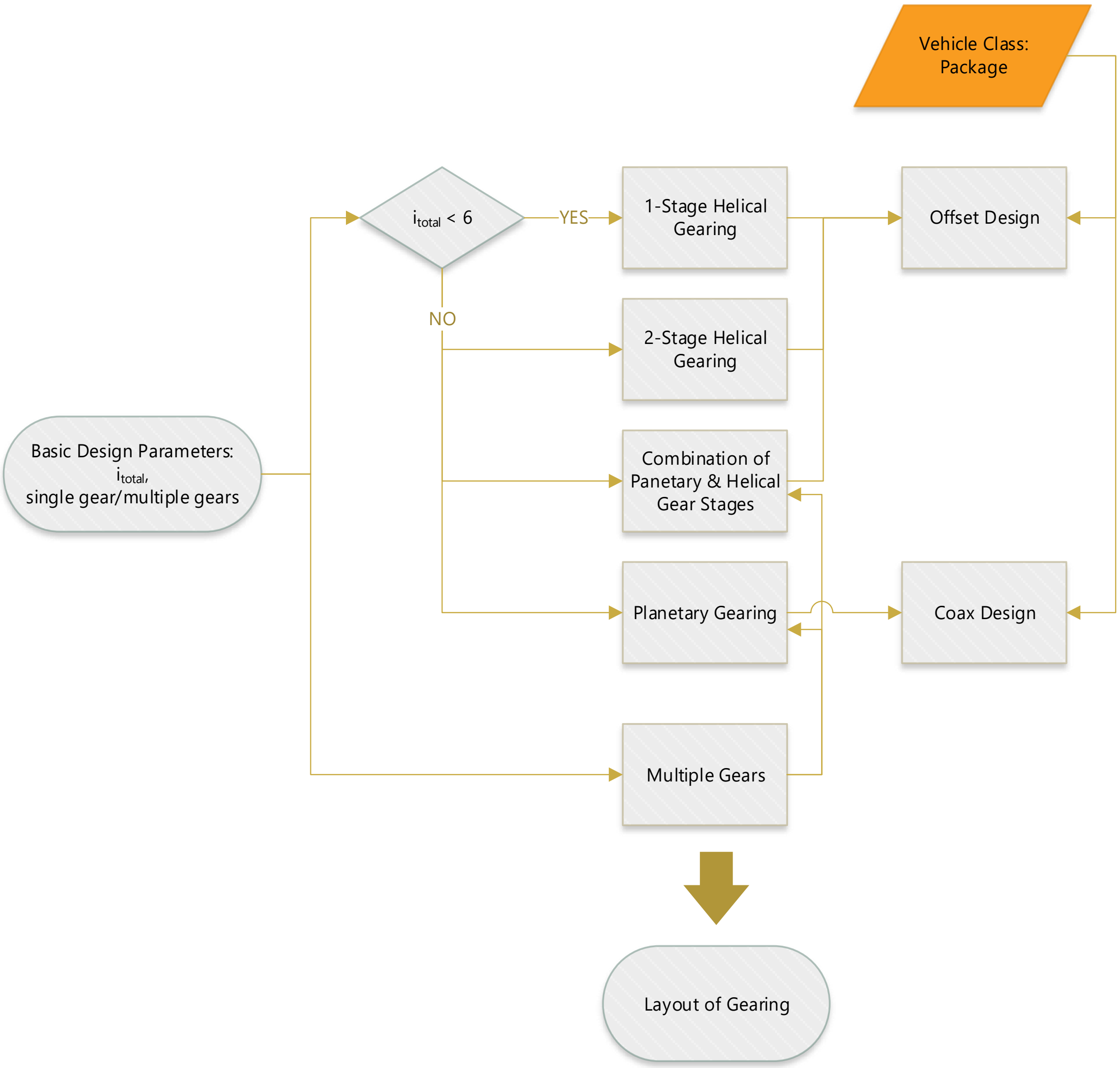

Figure 48: Mechanical Layout of the Gearing of an Electric Axle.

One of the most important constraints for this step is the gear ratio i_{total}, because it affects the possible types of gearings and number of gears. There are many opinions about the maximum achievable transmission ratio for a single stage helical gearing, mostly they vary between 6 and 8. For this thesis a value of 6 has been chosen as a conservative approach (Klocke and Brecher, 2016). This means that if i_{total} is bigger than 6, a single stage helical gearing makes no sense. The possible solutions are then a two-stage helical gearing, a planetary gearing and a combination of planetary and helical gearing. The decision between these layouts depends very much on the actual transmission ration, price, weight and volume targets.

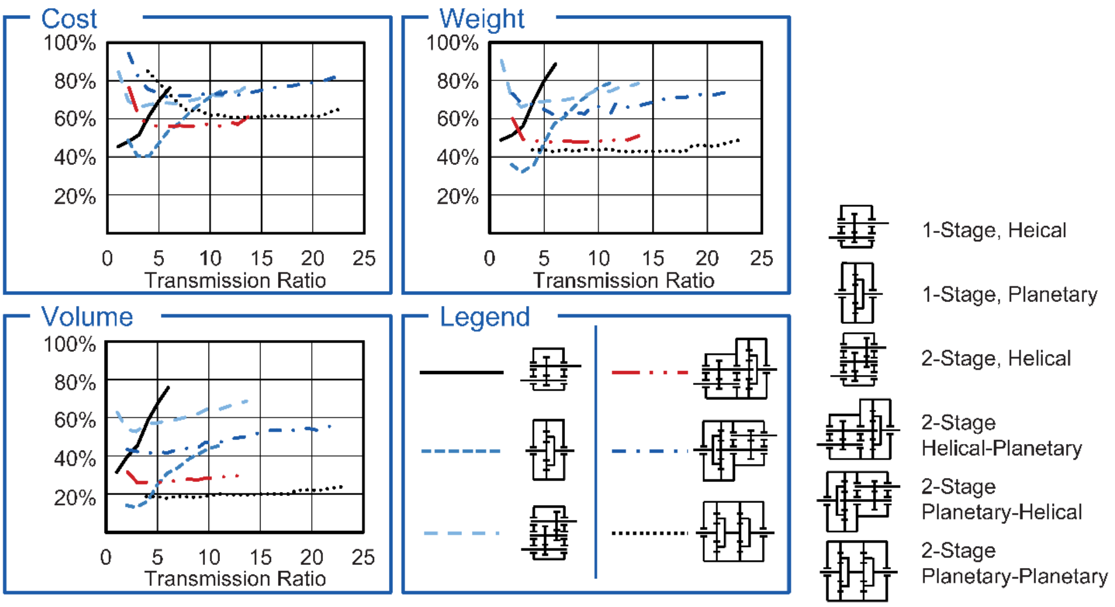

Figure 49: Comparison of different Gearing Designs in respect to Cost, Weight and Volume. (Klocke and Brecher, 2016)

Figure 49 shows the relation between transmission ratio and cost, weight and volume for each gearing type. As mentioned it can be seen that a single stage helical gearing is very limited in its application because the achievable transmission ratio is small compared to the other variants. A single-stage planetary design is obliviously the top performer in the lower transmission ratio when it comes to weight and volume. As mentioned before, most electric axles use transmission ratios from 8-10 and in this range a layout that combines a helical and a planetary stage offers almost the performance of a two-stage planetary layout at reduced cost. Also, a multiple gear design is easier to achieve with planetary gearing with the help of brakes that alter the transmission ratio, this method was described in the chapter 5.3.4. The two-stage planetary layout is clearly the way to go for high transmission ratios, because it offers excellent characteristics in terms of weight and volume. Newer designs of electric axles use high RPM motors to generate the same power with less torque and therefore less weight and in those scenarios two-stage planetary gearings will gain importance. It’s also important to mention that purely planetary layouts (both single and dual stage) lead to a coaxial design of the axle, all other variants lead, without big effort, to an offset design. Here plays the package, which is defined by the vehicle class, an important role. For small vehicles a planetary layout is, because of the reduced height, beneficial. But also, hybrid vehicles have often tight package requirements, because the electric axles are implemented into conventional vehicle platforms and large electric axles reduce the usable space of the luggage compartment considerably. These requirements lead in the end to an optimization task, with different weighting of the criterions depending on the vehicle, to find the most appropriate mechanical e-axle layout.

After the most appropriate design for the gearing has been found, the layout of the differential needs to be thought of, the basic proceeding can be seen in Figure 50. As in most technical processes an iteration is necessary if the outcome is subpar.

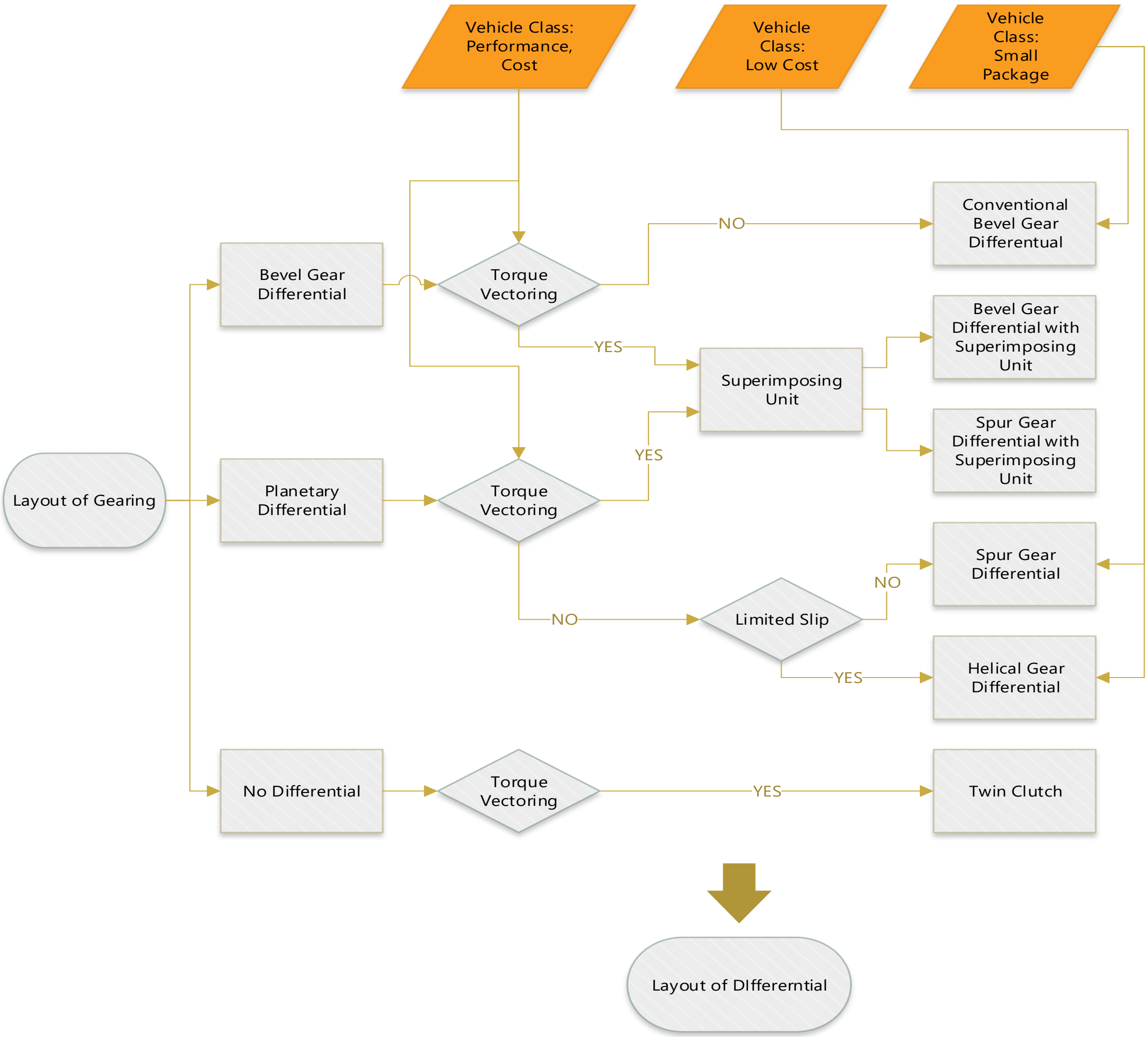

Figure 50: Layout Options of Electric Axle Differentials.

The earlier discussed options are a bevel gear differential, a planetary differential and twin clutch system. Another option would be a Torsen differential, which could be easily implemented instead of a bevel gear differential, but because it changes nothing in the axle layout because of similar dimensions it will not be further discussed. One major decision is, if the electric axle should be capable of torque vectoring or not. The performance gain comes with the tradeoff of higher costs and weight. Here an input from the vehicle class is mandatory, because for example the low target price of subcompact cars make an implementation of torque vectoring systems hard to realize. On the other hand, high performance vehicles benefit the most from the torque vectoring technology and additional customer values, in terms of handling and safety, are created. If torque vectoring is not required a conventional bevel gear differential is a well proven and inexpensive way to realize the differential of an electric axle, because the standard components of this design are also used in conventional axles. The fact that standard bevel gear differentials are simple, because no rotation speed sensor, actuators or clutches are needed, also lowers costs. If torque vectoring is required, a superimposing unit is needed for active torque distribution. The operating principle of a superimposing unit is described in the chapter 5.3.4 in detail. The added weight and costs of the additional gears, clutches and actuators must be considered. An interesting way to save weight and space is a planetary differential. These differentials can either be built with spur or helical gears. The Spur gear variant is the most compact design of all differentials and if torque vectoring is desired a superimposing unit can be added. But there is also an intermediate step between an open differential and torque vectoring. This intermediate step is a limited slip differential which is based on a planetary differential with helical gears. The helical gears generate an axial force, which pushes the sun gears either to the differential housing or against each other. By altering the friction coefficient of the contact surfaces between sun gears and housing, the locking characteristic in coast and drive can be controlled independently. The last option is a twin clutch system, which is per definition not a differential, because it uses two independently controlled clutches to compensate for the different rolling distances of the wheels during a turn. Because of the mechanical design of twin clutch systems torque vectoring can be implemented without the need of any additional components. Finally, with these considerations the mechanical layout of the electric axle differential can be found.

Another component that possibly needs to be implemented in an electric axle is a disconnect system. Figure 51 shows the design options for the implementation of a disconnect system in an electric axle in a schematic manner.

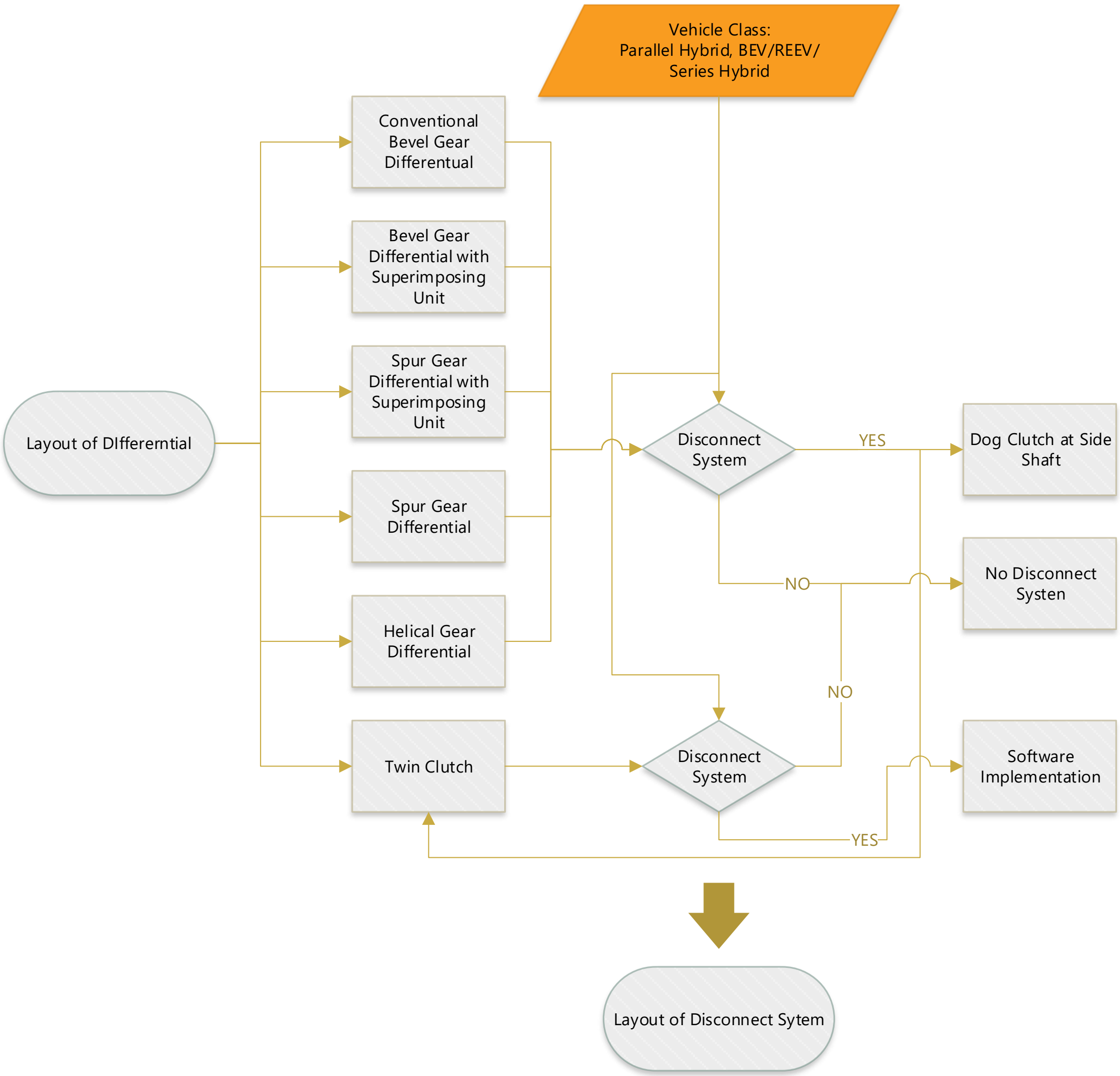

Figure 51: Layout Options for the Implementation of a Disconnect System into an Electric Axle.

The input parameters are on the one hand the differential types, which were covered before, and on the other hand again the vehicle class. From the vehicle class the information is needed, if the electric axle will be used in a hybrid vehicle or in a battery electric or range extended vehicle. As covered earlier electric axles are used in parallel hybrids with a P4 architecture. This means that usually the electric rear axle is not mechanically connected to the front axle, which is powered by the internal combustion engine. Therefore, both energy converters can propel independently from each other. Often electric axles are, because of the maximal electric motor rotation speed and transmission ratio, limited to a top speed of around 140 km/h. Above that speed the disconnect system is needed to disconnect the electric motor from the drivetrain. Such a system is typically not needed in layouts where the electric machine is the only energy converter with mechanical connection to the wheels (battery electric, range extended and series hybrid vehicles). When an implementation is necessary a common solution is a dog clutch on one differential side gear. When this dog clutch is open the electric motor can be powered down. It must be taken into account that the differential gears have then to compensate the rotation of the one still connected wheel and rotate even when driving in a straight line. The contact surfaces between differential gears and differential housing and the oil supply have to be designed accordingly to minimize wear. The twin clutch system again doesn’t need any additional components, because a disconnection of the electric machine can simply be realized by opening both clutches. If torque vectoring and a disconnect system is required a twin clutch system may be preferable if any other differential type was considered before, because of the simple layout. That is pictured with a back loop in the flowchart in Figure 51.

With all these considerations the design guideline should help to find appropriate solutions for all major mechanical components of electric axles.

7 Conclusion and Outlook

The hybrid powertrains discussed in this thesis have recently experienced a tremendous upswing. Micro hybrids in the form of start-stop systems are integrated in almost all current vehicles. Also, the OEMs are forced by the lowered fleet consumption to push forward the degree of electrification of their model ranges. Furthermore, the negative image of combustion engines and especially Diesel engines recently call for alternative solutions to satisfy customer needs. This means an increased use of powerful full and plug-in hybrid powertrains. Hybrid electric vehicles offer significantly improved pollutant emissions and fuel consumption and therefore help OEMs to reach future regulations, without the limited range and charging infrastructure dependence of battery electric vehicles. Battery electric vehicles are also on the upswing and play a key role in sustainable mobility, but they need a breakthrough in battery technology the most. Nevertheless, all these architectures demand highly integrated electric axle drives to increase efficiency and in turn reduce price and weight. Particularly in terms of weight and package, the discussed planetary differentials and twin clutch systems are interesting innovative designs. In contrast to the entry level car class another trend can be found in high performance electric vehicles. For these vehicles, from which well-known car manufacturers are constantly presenting new prototypes, the torque vectoring systems shown are interesting to increase the performance. Finally, the new generations of power electronics and batteries will play their part in the breakthrough of electric axle drives. As part of the cooperation with the Institute of Production Engineering, two further theses are already in work. These will, building up on this work, focus in detail on the manufacturing aspects of motor and housing. With these findings, the discussed design guideline can be expanded and then also practically realized in the form of an application including a graphical user interface.

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List of Abbreviations

AC	*Alternating Current*
APU	*Auxilary Power Unit*
ARTEMIS	*Assessment and Reliability of Transport Emission Models and Inventory Systems*
BEV	*Battery Electric Vehicle*
CADC	*Common Artemis Driving Cycles*
DC	*Direct Current, Direct Current*
DLC	*Double-Layer Capacitor*
EMF	*Electromotive Force*
EV	*Electric Vehicle*
HEV	*Hybrid Electric Vehicle*
ICE	*Internal Combustion Engine*
IGBT	*Insulated Gate Bipolar Transistor*
IM	*Induction Machine*
IPM	*Interior Permanent Magnet Machine*
Li-Ion	*Lithium-Ion*
MMF	*Magnetomotive Force*
MOS-FET	*Metal-Oxide-Semiconductor Field-Effect Transistor*
NEDC	*New European Driving Cycle*
NiMH	*Nickel-Metal-Hydride*
OEM	*Original Equipment Manufacturer*
PHEV	*Plug-In Hybrid Electric Vehicle*
PMSM	*Permanent Magnet Synchronous Machine*
PTC	*Positive Temperature Coefficient*
PWM	*Pulse Width Modulation*
REEV	*Range-Extended Electric Vehicle*
RPM	*Revolutions per Minute*
SEI	*Solid Electrolyte Interface*
SOC	*State of Charge*
SPM	*Surface Permanent Magnet Machine*
TEHP	*Thermoelectric Heat Pump*
TEM	*Thermoelectric Modules*
TV	*Torque Vectoring*