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VEHICLE COMPONENTS AND CONFIGURATIONS

Sonja Tidblad Lundmark
Mikael Alatalo
Torbjörn Thiringer
Emma Arfa Grunditz
Department of Energy and Environment, Chalmers University of Technology*

Bengt-Erik Mellander
Department of Applied Physics, Chalmers University of Technology**

* Division of Electric Power Engineering
** Division of Solid State Physics
Chapter reviewers: Anders Nordelöf, Environmental Systems Analysis, Energy and Environment and Anders Grauers, Automatic control research group Signals and Systems, Chalmers

INTRODUCTION

The main objective of this chapter is to describe components and configurations of electric drive systems used for electric or plug-in hybrid electric vehicles. Components such as the battery and the battery charger are also included. The aim is to describe different alternatives, possibilities and bottlenecks associated with such components and configurations. We also outline some of the key factors that influence automobile design.

One key issue, for instance, relates to cost reduction methods, which are important for commercialisation. Another issue is space requirements. The way in which components are packaged within vehicles is a key design issue that relates to an efficient use of the available space.

SYSTEM COMPONENTS

Batteries are one of the most important components for electromobility and must be combined with a battery charger. In addition to *battery packs* and *chargers*, the following components are essential for vehicle electrification:

- The *electric machine(s)* – used as a traction motor and sometimes as a generator.
- *Propulsion power converters* – such as DC/DC and DC/AC converters, operating both in inverting and rectifying mode.
- *DC/DC converter* – with 12V output for auxiliary equipment (windshield wipers, heating, radio, lights etc). Replaces the alternator in an ordinary car. The DC/DC converter is connected to a 12V battery.
- *Safety equipment* – to break high currents and to monitor the battery, for instance.
- *High voltage cables* – DC cables between battery and power electronics and cables between power electronics and the electric machine (unless those components are placed adjacent to each other). May have a total weight of around 10kg in hybrid vehicles but may be lower for a pure electric vehicle since the battery, motor and converter can be placed closer to one other.
- *Electric cooling compressor* – to keep the batteries from overheating, may also be used to cool the passenger compartment.

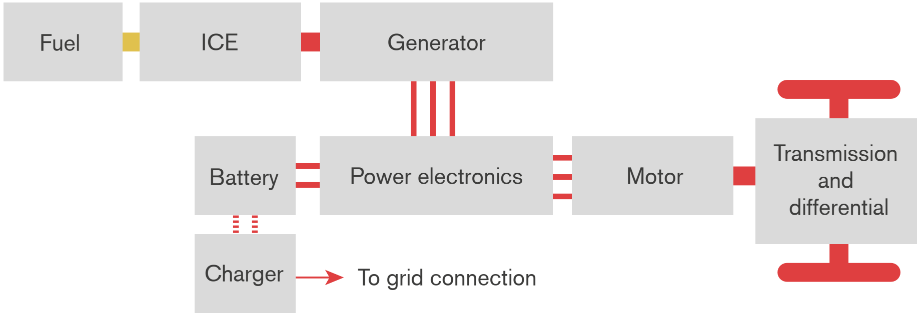
Note that an alternator may still be used to charge the 12V battery in hybrid vehicles. Otherwise, the 12V battery can be charged using a DC/DC converter and a traction battery.

SYSTEM TOPOLOGIES

Hybrid electric vehicles (HEVs) can be classified into four kinds: series hybrids, parallel hybrids, series–parallel hybrids (dual mode), and complex hybrids. These classifications refer to the way in which electric drive systems (battery, power electronic converter, and electric motor) are connected with mechanical drive systems (fuel tank, Internal Combustion Engine (ICE), transmission and differential). A plug-in HEV (PHEV) is a hybrid vehicle whose battery is charged externally. See Figure 3.1 for system overviews. A pure electric vehicle (EV or BEV) has no fuel tank and no ICE.

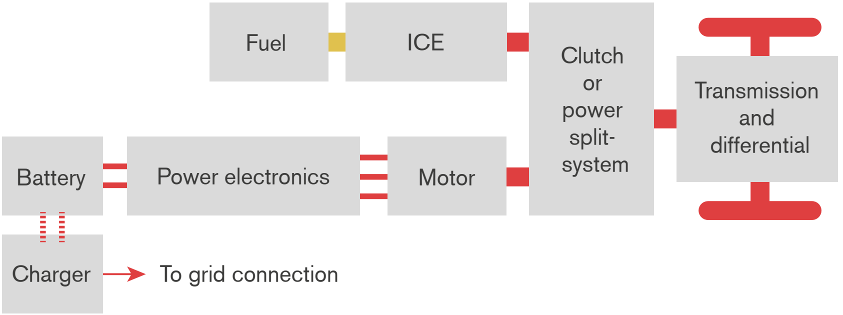
The series hybrid configuration has various benefits. For example, the working point of the ICE can be chosen freely to be that which gives the best efficiency and lowest emissions. The ICE can also be turned off so that the vehicle can be driven in a purely electric mode giving zero emissions (for a limited range). Furthermore, the ICE and generator set can be placed in a separate location to that of the traction motor, alleviating the packaging issue. However, the series hybrid configuration has low system efficiency due the number of energy conversions. Additionally, the electric motor and the battery pack need to be of a high rating, and the generator adds extra weight and cost compared to the parallel configuration, which only requires one electric machine.

The series configuration is particularly advantageous for PHEVs, as the electric motor and the battery pack are already of a high rating. However, the pure series hybrid is rare for the first generation of plug-in vehicles, which are to be rolled out between 2012 and 2014. The mechanical drive train of the series configuration is different to an ordinary drive train (where the ICE is mechanically connected to the transmission system), and most first generation PHEVs are configured to allow conventional mechanical drive train designs, such as parallel or series-parallel configurations.



Series hybrid

A series hybrid drivetrain: the fuel tank and the engine are coupled to an electric generator which can be used to charge the battery. The electric drive (converter and motor) is connected to the battery. Between the generator and the battery there are also power electronic converters.



Parallel hybrid

A parallel hybrid drivetrain: the engine supplies its power mechanically to the wheels similar to a conventional ICE-powered vehicle. It is assisted by an electric motor that is mechanically coupled to the transmission. The powers of the engine and electric motor are coupled together by a mechanical coupling.

Figure 3.1 Hybrid vehicle configurations

In parallel HEVs the operating point of the ICE may also be chosen relatively freely to give the best efficiency. Both the ICE and the electric drive system (battery and electric motor) can be used at the same time to cope with peak loads and to provide extra acceleration. Parallel configurations require fewer electrical components than series configurations – the generator is no longer needed since the traction motor can also be used to generate electricity (charging the battery via regenerative braking). Less power electronics is needed, and the rated values of the electric motor and battery can be lower.

Combinations of the series and parallel configurations are often used to create systems that derive advantages from both configurations, but with higher complexity and cost. In the series–parallel hybrid, the series and parallel systems could either be used independently with a clutch that switches between the two systems or simultaneously (a split system). Figure 3.2 shows a schematic diagram of a dual mode PHEV.

Complex hybrids are similar to series–parallel hybrids but with additional power electronics. Complex hybrids allow for versatile operating modes that cannot be offered by the series–parallel hybrid, such as electric or ICE-assisted four-wheel operation. Similar to series–parallel HEVs, complex hybrids suffer from higher complexity and cost.

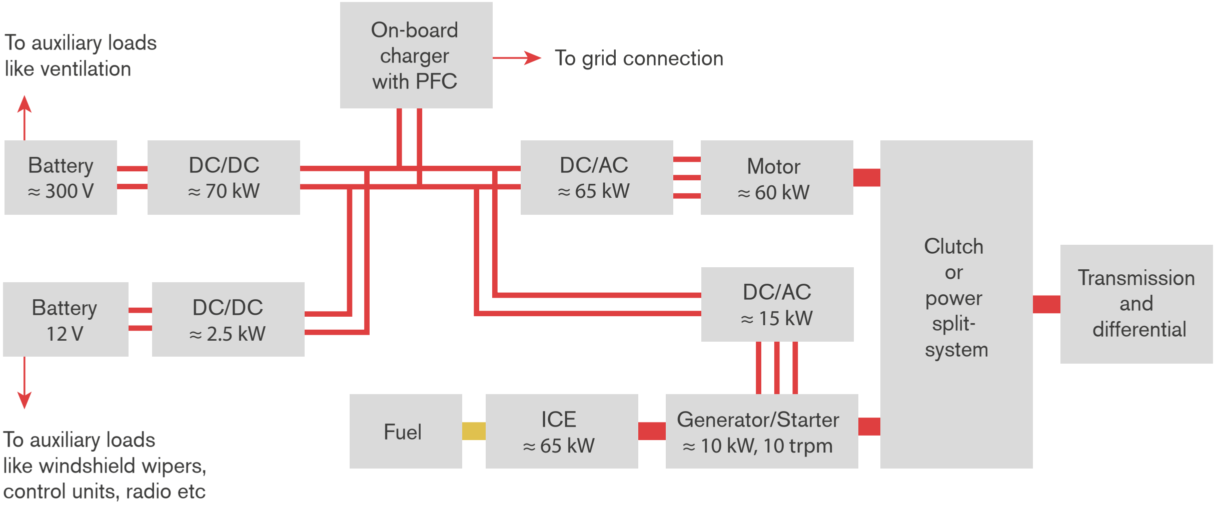


Figure 3.2 Plug-in hybrid vehicle with a parallel configuration with a dual mode. The grid power charges the battery through a power factor corrected (PFC) charger. The inverter and motor control unit drive the electric motor and is one source of mechanical torque, the ICE being the other. The generated torque drives the vehicle through a torque coupler, differential and wheels. The generator can charge the battery/batteries and/or feed electric power to the electric drive system. The generator may also be used as a motor (starter) for the ICE, although a small separate starter is neither big nor expensive. If the generator is to be used as a starter, the DC/AC converter must be bidirectional. Some other auxiliary parts are required, as shown in the figure.

In sum, the size and rated values of vehicle system components and the power value ratio between motor types can be altered in many different ways. Similarly, vehicle weight and differences in drive cycles should be considered. There is no single system configuration that is suitable for all circumstances.

BATTERIES

Electric vehicles require on-board energy storage devices that store energy in a form which is easily converted to electricity in an efficient and cost-effective way. Batteries are presently the most favoured energy storage devices. In particular, lithium-ion batteries are the most attractive option for EVs and PHEVs given their high energy and power densities.[1] Other storage systems such as supercapacitors (also known as ultracapacitors) are more advantageous than batteries in that they can be charged and discharged more rapidly and are sturdily and reliably constructed. The power density of supercapacitors is relatively high (in the order of 5kW/kg), but the energy density is low (usually below 6Wh/kg). Supercapacitors can be used for short power surges but are not sufficient for storing larger

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[1] Energy density is measured in kWh/kg or kWh/l, and power density in kW/kg or kW/l. Chapter 6 examines geopolitical implications of using lithium-ion for batteries in EVs.

amounts of energy. A lithium-ion battery is better for this purpose due to its considerably higher energy density, which is typically between 50-200Wh/kg. The lower value refers to cells optimised for delivering high power. The power density of lithium-ion batteries varies considerably for different types of cells, with typical values in the range 100-3000W/kg. These values represent individual cells. For a complete battery system these values should be halved. Hence supercapacitors should not be regarded as competitors to batteries – the two types of devices are complementary.

Lithium-ion batteries consist of two electrodes, an anode and a cathode, separated in most cases by a liquid lithium-ion conducting electrolyte soaked into a polymer separator. Lithium-ions are shuttled between the electrodes during charging and discharging. The anode typically consists of lithium intercalated into graphite while for automotive applications the cathode is often based on $LiFePO_4$. The choice of $LiFePO_4$ (usually shortened to LFP) compared to $LiCoO_2$-based materials (which are often used in portable consumer products) is due to stability, superior safety and lower cost – despite the fact that $LiCoO_2$-based materials are slightly better as regards performance.

A single lithium-ion battery cell provides a voltage of about 3V. Several cells are connected in series to obtain the voltage levels necessary for electric vehicles. Strings of cells, connected in parallel, are packed into modules. Modules are assembled into packs to obtain the proper voltage and current specifications. The construction of modules and packs is delicate and aside from the pure electrical properties, several other factors must be considered at the design stage. The cells, modules and packs have to be monitored to avoid damage to the cells. The cells must be actively balanced so that they are in equal states. Cells must be maintained within a certain temperature range. The pack must also protect the battery in case of a collision or a fire, and gases must be vented safely (see Chapter 4).

A battery management system (BMS) is required to monitor and maintain various parameters (voltage, current, temperature) that ensure proper operation of the pack. The BMS also provides signals to actuate relays for balancing cells, and provides cut-off protection in case of severe malfunction. Thermal monitoring is important because lithium-ion batteries have a limited operating temperature range. The pack is sensitive to overheating and should be kept at temperatures between 0-45°C, depending on battery chemistry. Temperatures around 25°C are ideal. This means that efficient control of cooling and heating is required.

Although existing lithium-ion battery technology allows for the construction of battery systems that provide EVs with reasonable performance and range, future battery systems with improved energy densities would provide better ranges. Developing batteries with higher storage capacities is a focal point for research efforts around the world.[2] Battery development is, however, a very slow process. Lithium-ion battery technology is continuously being improved and will likely be the preferred choice for at least the next few years. One promising technology is the

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[2] R. Marom, S.F. Amalraj, N. Leifer, D. Jacob, and D. Aurbach, (2011)"A review of advanced and practical lithium battery materials", Journal of Materials Chemistry, 2011, Vol. 21, p. 9938

lithium-air battery. Current research efforts aim to develop batteries that can make EVs comparable to petrol-driven vehicles vis-à-vis range. The lithium-air battery uses an air-cathode and an encapsulated lithium metal anode. Despite promising results several barriers must be overcome before lithium-air batteries can be commercialised.[3]

ELECTRIC MOTOR DRIVE SYSTEMS

The most common motors in EVs are the induction motor (IM), the permanent magnet synchronous motor (PMSM), the direct current motor (DCM) and the switched reluctance motor (SRM). It is also possible to use the axial flux motor (AFM), the transverse flux motor (TFM) or synchronous reluctance motors (SyncRM). These have only recently been developed for vehicle applications and currently exist as prototypes or experimental motors.

In the selection and design of electric motors for automotive applications, weight, volume, cost, energy efficiency and reliability are important criteria to consider. Environmental impacts of materials and manufacturing (see Chapter 6), recyclability and noise levels are also important. Table 3.1 summarises some of the advantages and disadvantages of the abovementioned motor types. No single motor performs well in terms of all of these criteria, which is reflected by the range of motors selected for existing vehicles. Each motor type is being continuously developed. For example, a recent trend is to construct the IM rotor with copper instead of aluminium bars, which improves its efficiency. Another trend is to add permanent magnets to the SyncRM in order to improve its efficiency and torque density (yielding a permanent magnet assisted synchronous reluctance machine).

Table 3.1 Comparison of electric motor types. Red indicates less favourable, yellow medium and grey more favourable.

	IM[a]	**DCM**[b]	**SRM**[c]	**PMSM**[d]	**SyncRM**[e]	**AFM & TFM**[f]
Weight and volume	🟥	🟥	Medium	Good	Medium	Good
Energy efficiency	Medium	🟥	Medium	Good	Medium	Good
Fault tolerance, Robustness	Good	🟥	Good	Medium	Medium	Medium
Cost	Good	Good	Medium	🟥	Medium	🟥
Recycling	Good	Good	Good	🟥	Good	Medium

[a] Induction motor, [b] DC motor, [c] Switched reluctance motor, [d] Permanent magnet synchronous motor,
[e] Synchronous reluctance motors, [f] Axial flux motor & Transverse flux motor

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[3] G. Girishkumar, B. McCloskey, AC Luntz, S. Swanson, W. Wilcke (2010) “Lithium-air battery: Promise and challenges” Journal of Physical Chemistry Letters 2010, Vol. 1(14), p. 2193-2203,

When comparing weight, it is most often the active mass that is considered and not, for instance, covers and ventilation systems. Low *weight* and *volume* is achieved with machines with high power and torque density, i.e. machines with high power, or torque, per weight or volume. Electric motors with permanent magnets (PMSM, AFM and TFM) give the highest power and torque density.

Cost is partly related to material requirements and complexity of production. Comparisons between different motor types are difficult and cost comparisons in the literature are often based on material and manufacturing costs in very general terms. The materials used in electrical machines are mainly copper or aluminium for conductors, steel laminations (or in some cases pressed iron powder), and permanent magnets. Material costs depend on the scale of production (purchase volumes) and change over time due to price movements on raw materials markets (see Chapter 7). For example, the price of copper has increased whereas the steel price remained relatively constant during the last decade. For many years, the price of neodymium magnets was 20-30 EUR per kg, but has fluctuated recently, peaking at 150 EUR per kg. This creates incentives to design machines using fewer permanent magnet materials. High material costs also increase the incentive to design for recycling. However, recycling permanent magnets is difficult and not often considered economical. The conventional technique for recycling smaller electric machines (<10 kW) is grinding. Traction motors in hybrid or electric cars are usually of a power rating larger than 10 kW and can therefore not be ground – they have to be disassembled. The recycling process is simplified if the machine steel parts are made of pressed iron powders or made of segments.

Generally, DC motors and induction motors are inexpensive. They use approximately the same amount of material and are manufactured via well-developed techniques. SR motors are inexpensive due to the simple design of stators and rotors. However, manufactured volumes are low and standard power electronic converters cannot always be used, which increases the cost of the drive system. Permanent magnet machines may, as mentioned, be more expensive depending on magnet costs. On the other hand, such motors may be made smaller than an induction motor, for instance, but with the same performance. Hence less copper and steel are required. The AFM and TFM may be particularly expensive due to a complicated design and underdeveloped manufacturing techniques.

In some electric vehicles, two or four motors are used instead of one. This creates the possibility of integrating motors into the wheels, which increases the controllability of the vehicle. However, the inclusion of several motors requires several converters and more transmission devices, resulting in increased costs.

Costs are also related to energy efficiency over the whole speed range (see also Chapter 5). Higher efficiency means less energy-use (fuel or electricity) – but it also means less heat production and therefore reduces the need for cooling. This cuts cost and allows for better packaging. Efficiency decreases with increasing losses. In the electrical machine there are resistive losses in current-carrying conductors; core losses in the steel laminations; and mechanical losses due to ventilation and friction. Larger electrical machines are more efficient than smaller ones because resistive losses decrease with scale. A larger amount of copper, for instance, implies lower current density and resistance. Core losses can be reduced by using better materials (like thinner laminations); using lower frequency; or by adding core material. There is also a possibility to increase efficiency by increasing the motor's maximum speed. This is due to the fact that power output rises in direct proportion to speed while electric losses remain about the same for a given torque. To increase rated speed, higher voltages are required, which in turn require better insulation materials.

Reliability is related to fault tolerance. A fault-tolerant machine is a machine that can continue to operate in a satisfactory manner after a fault event, normally with reduced performance. The most successful design approach involves a multi-phase drive in which each phase may be regarded as a single module. That means that there should be minimal electric, magnetic, and thermal interaction between the phases of the motor drive. Several requirements of fault tolerance are met in a switched reluctance motor (SRM).

POWER ELECTRONIC COMPONENTS

The power electronic components addressed in this section are the power converters and their semiconductor components. The main converter types are DC/AC converters, often called inverters; AC/DC converters, often called rectifiers; and DC/DC converters. The converters should fit the desired voltage, current rating and switching frequency. The latter should be high enough to reduce volume, noise, filter size and EMI and low enough to reduce energy losses. High conversion efficiency is valuable and the converters need to be able to operate in tough environments. A proper cooling arrangement is also required.

The main semiconductor components are the switching components, the transistors. The choice of semiconductor material, or type of transistor, depends partly on power but mostly on voltage levels – IGBTs for higher power levels and voltages above 300-400V and MOSFETs for lower power levels (see below for further descriptions of transistor types).

Research increasingly points towards the use of converters as integrated battery chargers and drive system components[4]. Furthermore, using multi-level converters in conjunction with the battery management systems (BMS) yields certain advantages, such as the possibility for increased efficiency of the complete electric drivetrain for certain drive cycles[5]. New and better semiconductors, such as SiC-components are being developed.[6]

The DC/AC converter is located between the battery and electric motor. The converter is bidirectional, which allows for regeneration (energy is fed from the motor to the battery) during braking. The converter is typically a pulse width modulated (PWM) converter, but can be a multi-level converter. PWM converters switch

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[4] Haghbin, S., Lundmark, S., Alaküla, M., and Carlson, O. (2013) Grid-Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution. IEEE Trans on Industrial Electronics, Vol. 60, No. 2.

[5] Josefsson, O. , Thiringer, T., Lundmark, S. and Zelaya, H. (2012) Evaluation and comparison of a two-level and a multilevel inverter for an EV using a modulized battery topology. The 38th Annual Conference of the IEEE Industrial Electronics Society (IECON), Montreal, Canada, 25-27 October 2012.

[6] Rabkowski, J., G. Tolstoy, D. Peftitsis and H.P. Nee (2012) Low-Loss High-Performance Base-Drive Unit for SiC BJTs. IEEE Transactions on Power Electronics, Vol. 27, No. 5.

the battery voltage on and off in order to provide a certain voltage to the motor. Multi-level converters consist of many low voltage converters, each connected to a fraction of the battery.

The AC/DC converter is located between the generator (which in turn is connected to the ICE) and the traction battery. These converters are used in series hybrids or in series–parallel hybrids. If the semiconductor components of the AC/DC converter are transistors then the electric machine may operate not only as a generator but also as a motor. It can thus be used as a starter motor for the ICE.

Two types of *DC/DC converters* can be used. A high power DC/DC converter can be used between the high voltage traction battery and the DC/AC converter of the electric machine. Additionally, a small, low power DC/DC converter is used to connect the low voltage battery with the high voltage DC-link or traction battery.

The high power DC/DC converter is optional and can be used to provide a constant DC-link voltage. Without the converter, voltage would vary due to variations of the battery. The DC/DC converter also allows a higher DC-link voltage than the battery voltage. The higher voltage gives higher efficiency in the drive system components (power electronics and electric machines). Disadvantages include higher cost and losses from the DC/DC converter itself.

The low power, DC/DC converter connects the low voltage (12V) battery with the high voltage battery, or with the DC-link if there is a high voltage DC/DC converter. The low voltage is normally 12V for cars and 24V for buses and trucks, but 36V and 48V could also be used as the low voltage level. The 12V battery has one (the negative) terminal connected to earth via the vehicle chassis. Since the 12V battery is connected to the chassis (earth) and the high voltage battery is on a floating potential (with no electrical connections to the chassis), there is a need for galvanic insulation in the low power DC/DC converter in order to disconnect the two systems.

Regarding the converters' *semiconductor components* – the control is made with switching the components on/off using a high frequency PWM-pattern (when the power is higher than some 100 W). With this technique the voltage to a transformer or a machine can be controlled in a fast and precise manner, but not without losses where the switching loss is one important loss component. Semiconductors should give low losses and be able to handle the given power, voltage and current.

IGBT's are most frequently used in high-power applications. The device is widespread and used in applications from 1kW up to several MW. In order to cope with the propulsion power of a passenger car, IGBTs of around 200kW may be needed. *MOS-fets* are typically used in smaller DC/DC-converters, such as the low power DC/DC converter described above, and the main benefit is the ability to handle high frequencies (up to 1MHz). Figure 3.3 shows an IGBT module and a MOS-fet. *Silicon Carbide* (SIC) is a recently developed semiconductor material that allows for high switching frequencies, high-voltage operation and higher temperature capabilities. This can help to simplify the cooling system of the vehicle. Normally, hybrid cars have a high-temperature cooling circuit (of 105°C) and an additional low-temperature cooling circuit for the power electronics and in some cases the motor (of 60 -70°C). SiC makes it possible to exclude the additional low-temperature cooling circuit. This type of component is undergoing rapid development and will likely be commercialised in the near future.

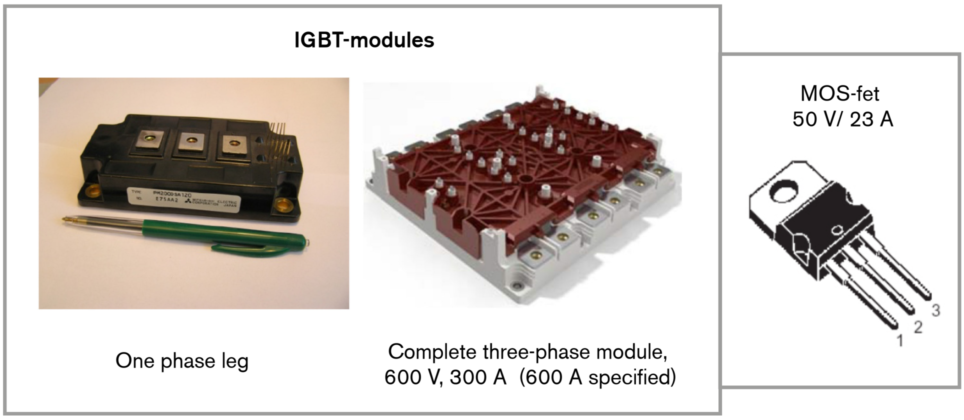

Figure 3.3 Examples of semiconductor components – two IGBT modules and one MOS-fet transistor.

BATTERY CHARGERS

Electric vehicles are usually recharged whilst parked. However it is also possible to charge EVs whilst they are in motion (continuous charging) using 'slide-in' technologies (see Figure 2.1). Different types of chargers are available, including off-board fast chargers, on-board chargers, and 'slide-in' wireless chargers. The latter combine transmission coils in the ground with receiving coils in vehicles. Chargers can also be conductive or inductive. For a conductive charger, power flows through metal-to-metal contacts. In contrast, inductive coupling transfers power magnetically rather than via direct electrical contact.

Off-board chargers can be large and bulky when volume is not a vital constraint. This keeps costs down, and off-board chargers can be placed at charging stations similar to ordinary petrol stations. This arrangement also allows for high-power fast charging. A disadvantage compared to on-board charging is lower availability since the number of charging stations will always be limited. Charging times are typically 15 minutes, but can be more.

On-board chargers are more common at present. On-board charging means that vehicles can be charged wherever electricity is available but with the disadvantage of slower charging and extra weight, cost and space requirements within vehicles. On-board charging typically requires 1 hour of charging per 20km[7]. Increasing the charging speed would require higher power and a larger charger, and thus additional weight, volume and cost.

To alleviate some of the abovementioned disadvantages it is possible to utilise traction drive system components to construct an integrated charger. A battery

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[7] At 230V and 16A (3.7kW)

charger is basically a voltage transformer with a converter and such a charger can be made by using the electrical motor and the power electronic converter (see above).[8]

Wireless systems allow for inductive charging at dedicated parking spots or whilst driving. Wireless charging could be an important enabler for electromobility and is currently a focal point for R&D efforts. The efficiency is however lower compared to conductive charging and there are several safety concerns.

AUXILIARY LOADS

High voltage auxiliary loads (100-500V) like electric climate control and power steering need relatively high power from high voltage traction batteries. Power consumption must be considered carefully when designing vehicle systems and controllers. Low outdoor temperature, for instance, could result in a high portion of the available vehicle power being used for climate control. In HEVs, the ICE can be used to provide heat due to engine losses, but cold weather will result in shorter driving ranges for hybrids operated in all-electric mode. Furthermore, it is important to consider electromagnetic capability (EMC) when dealing with the auxiliary loads, so that the loads, the drive system or cables do not disturb other loads in the system.

Low voltage auxiliary loads (12V) such as windscreen wipers, control units, radio and electric fuel pumps are operated at lower voltages. Traditionally they require 12V lead-acid batteries. However, power requirements are increasing as more electronic equipment is added to modern vehicles, such as GPS navigation systems (see also Chapter 7 on how the trend to add more electronic devices affects the use of rare materials in vehicles).

CONCLUDING REMARKS

There are many alternative components and configurations of electric drive systems used for electric or plug-in hybrid electric vehicles. There is no single combination or configuration that works well for all vehicle applications, which is reflected in the span of different drive systems and battery solutions in existing vehicles.

Generally, there is a need to improve efficiency and decrease component volume/weight without compromising on costs. Battery materials, for instance, are typically selected by focusing on cost and safety criteria at the expense of performance. Similarly, motor designs that minimise the use of permanent magnets are attractive because of their lower cost, which again reduces vehicle performance. There are several ways to integrate components whilst improving packaging and lowering costs. Integrated battery chargers and the use of SiC in power electronic converters (which allows for the combination of temperature cooling circuits) are two such examples.

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[8] Haghbin, S., Lundmark, S., Alaküla, M., and Carlson, O. (2013) Grid-Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution. IEEE Trans on Industrial Electronics, Vol. 60, No. 2.