48-Volt Electrical Systems –
A Key Technology Paving to the Road to Electric Mobility

German Electrical and Electronic Manufacturers' Association

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April 2016

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1. Introduction

The automotive industry can only barely continue or no longer meet the challenge presented by the CO_2 targets defined by the European Commission purely by improving standard internal combustion engine technology. Alternative drive concepts that make it possible to drastically reduce average fleet CO_2 emissions will need to be deployed.

While today's hybrid vehicles meet this technical criterion, they are not yet available at sufficiently attractive price points. This is, above all, due to the high cost of meeting the safety requirements that arise as a consequence of the electric drive function in these vehicles being realized using voltages in excess of 60 volts (the maximum permissible contact voltage).

Architecture:

The new 48-volt voltage level (figure 1) opens up more cost-effective opportunities for hybridisation. The development of these multiple-voltage architectures in vehicles requires detailed investigation at both the systems and components levels.

As part of this process, a third voltage level of 48 volt has been defined to supplement the voltage levels of 12/24 volt and high-voltage (> 60 volts). The primary purpose of this new voltage level is to reduce CO_2 emissions by means of recuperation and start-stop features and to power electrical components classed as high-power loads (such as air-conditioning compressors, electrical heaters, pumps and steering drives). Over and above this, the deployment of 48-volt technology providing additional torque enables more dynamic handling and performance (a "boost" effect).

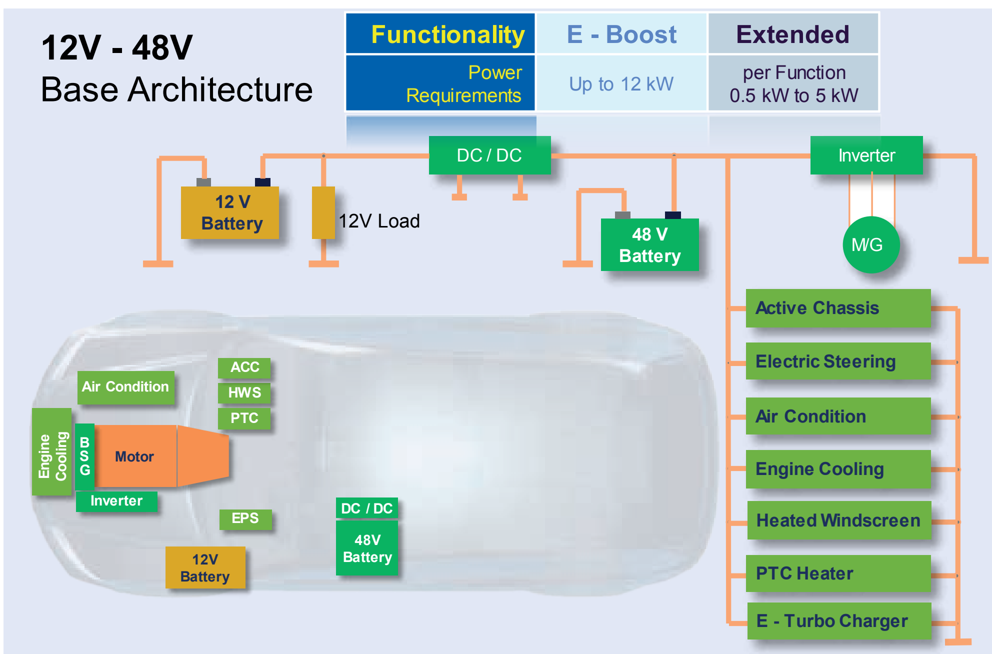


Figure 1: Base architecture – source: Delphi

1.1 CO_2-limits: the discussion and results

In many countries around the world, attempts are being made to regulate the CO_2 emissions of road transport (figure 2). While the current absolute limits set for cars vary from region to region, all locales demand substantial reductions over the coming years.

"Transport accounts for approximately 26 per cent and thus for a significant portion of total CO_2 emissions in the EU. Car traffic, with a total share of approximately 12 per cent, is responsible for almost half of these emissions."1 From 2021 on, all newly registered passenger cars in Germany will be subject to a limit value of 95 g CO_2 per km. That corresponds to an average fuel consumption rate of about 58.8 mpg (gasoline engines) or 65.3 (diesel). Further reductions in the years after 2021 are under discussion. From 2050 on, new cars should not emit any CO_2 at all. The European regulations take account of the weight of vehicles. The limit value of 95 g CO_2/km applies only to vehicles with a "standard weight" of 1,350 kg. Heavier vehicles may emit somewhat higher levels of CO_2, while lighter vehicles must emit less.

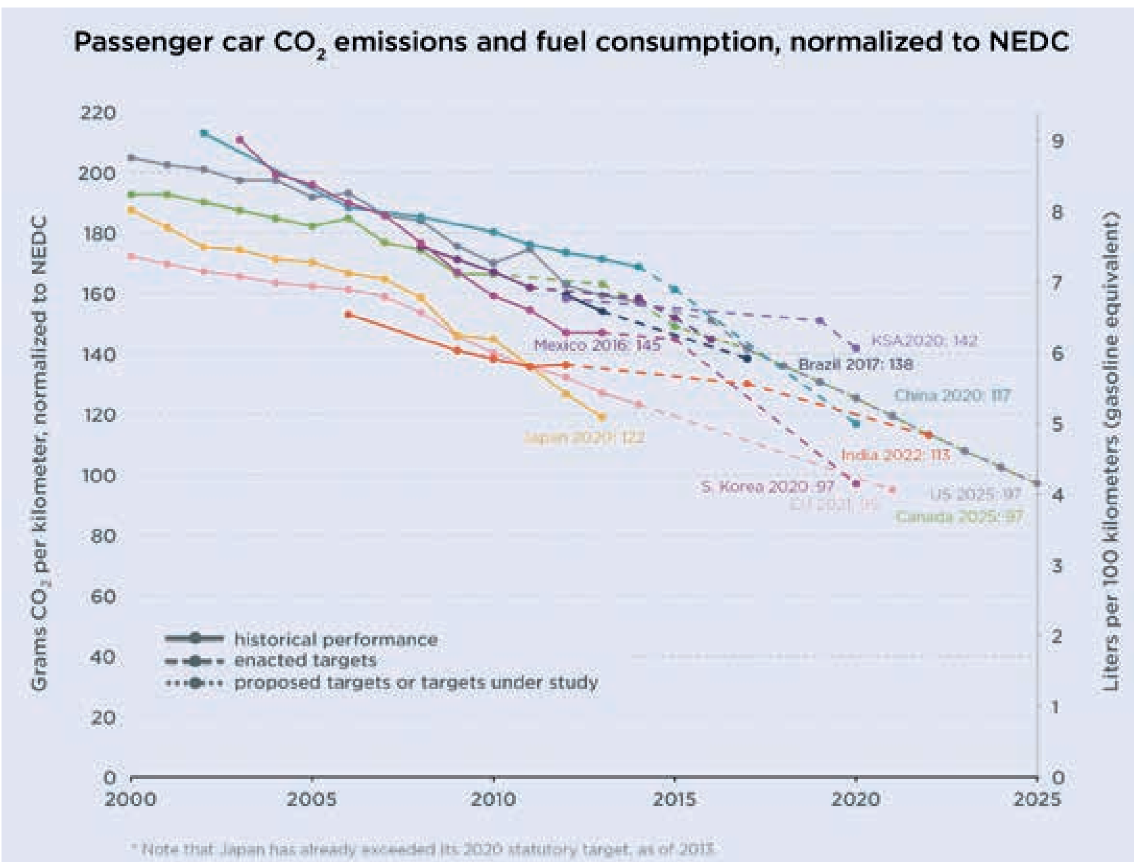


Figure 2: International CO_2 targets – source: The International Council for Clean Transportation

The automotive industry has to make considerable efforts to meet both the limit values currently defined and those that will apply in the future. All stakeholders are aware that actions focusing solely on enhancing the efficiency of the IC engine will not be sufficient. Additional measures are necessary to reach the target. These include improved aerodynamics, lightweight design, low rolling resistance tires, LED lighting, more efficient transmissions (automatic dual-clutch transmissions) and the electrification of auxiliary components. Water pumps and air-conditioning compressors can, for example, be driven electrically and at speeds dictated by current requirements rather than directly from IC engines.

The introduction of a 48-volt starter generator to make a "boost and coast" function possible and allow considerably enhanced recuperation vis-à-vis 12-volt systems is particularly attractive.

1.2 A look back at the debate on 42-volt systems in 2000

At the beginning of the 90s, as the advanced development departments of major vehicle manufacturers were evaluating the advantages of higher-voltage systems, the international 42-volt consortium was founded providing a forum for discussions between automobile manufacturers and suppliers. At the time, a 42-volt system was being debated as a replacement for conventional 12-volt systems. What was termed a 42-volt system was effectively a 36-volt system with a 36-volt battery - and therefore three times the voltage of conventional 12-volt systems. This voltage (36/42 volts) was chosen with the aim of ensuring that voltage in on-board power systems would never exceed 60 volts after all tolerances had been factored in, since this would avert the need for costly contact protection. The new on-board power system was, however, named for the charging voltage rather than the battery voltage in order to lend emphasis to the innovative nature of the new solution.

Initially, several arguments seemed to come down in favour of the new system: power consumption and demand were continuing to rise, a need for higher-powered generators to meet this increase in demand was perceived, and in the rationale of the time, higher voltages offered the only chance of achieving this. Power requirements of well over one kW – for solenoid valve control, for example – could not be realised by 12-volt systems, even when only needed very briefly. Finally, the need to introduce start-stop systems driven by environmental regulations geared to reducing emissions was also a factor, as were the weight decreases achievable through the smaller cross-sectional area of cables in 42-volt systems.

In the further course of the 90s, this solution was not phased in on a widespread basis, apart from two car models in Japan and the US, as the increased costs associated with the new system were not matched by functional benefits. In the interim, generator sizes of 3 kW and higher had come to the market for 12-volt systems, while systems with extremely high energy demand were not realised. Solenoid valve control, for example, was not introduced. Start-stop systems integrated into 12-volt systems gained ground. It seemed that higher voltages were no longer going to be needed.

The 48-volt debate which took off in 2011 may seem superficially similar to this earlier discussion, but the approach now being pursued sets different priorities. 48-volt on-board power systems (48 volts = four times the nominal voltage of 12-volt systems) are being championed as a supplement to 12-volt systems and not as a replacement for them. The contact protection limit of 60 volts is, however, also of critical importance today.

The chief motivation for introducing an additional vehicle electrical system voltage at this point in time can be identified in the above-mentioned EU regulations specifying an average limit value of 95 g CO_2/km for passenger cars from 2021 on. The threat of financial penalties for exceeding these new limit values justifies the deployment of relatively costly measures. 48-volt systems make it possible to build on start-stop systems to develop mild hybrids with remarkable recuperation and "boost and coast" features. This leads to a drop in energy consumption and emissions that can stretch into two-digit percentages.

At this point, most European automotive manufacturers have already decided to introduce 48-volt technology to reduce the consumption of their fleets and meet the new European CO_2 limits applicable from 2021 on (figure 3).

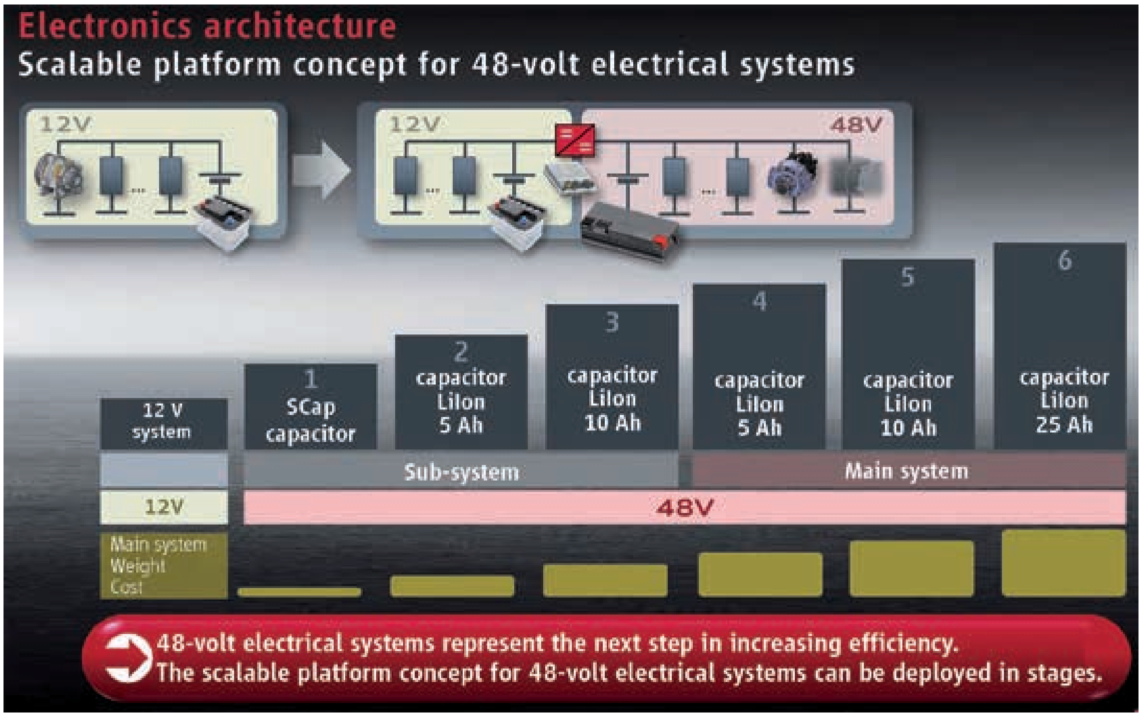


Figure 3: Scalable platform concept for introducing 48-volt electrical systems – source: Audi

1.3 The market for hybrids – issues and trends

While the cost-benefit calculations of the majority of car buyers still do not seem to be tipping in favour of hybrids, the question remains, as to how the electrification of the powertrain as a mass-market technology could contribute to reducing CO_2 emissions.

In the foreseeable future, start-stop systems, 48-volt systems and high-voltage electrification will all exist alongside one another in most fleets. A strong global trend towards plug-in hybrids has emerged. In China, however, all-electric vehicles are particularly in demand. 48-volt systems still have their development nucleus in Europe, although their advantages have now been recognised by many automotive manufacturers and global programs have been started accordingly.

With an eye to avoiding high investment costs, minimising complexity and facilitating easier maintenance, emphasis is largely being placed on finding simple solutions that are easy to integrate. This applies, in particular, to the high-volume market for compact and mid-size cars (figure 4), which is subject to strong cost pressures. In the most basic case, the alternator is replaced with a belt-driven starter generator (BSG) that operates more efficiently at 48 volts and starts the IC engine extremely rapidly and with minimal noise and vibration. Electric assist boosts the responsiveness of the IC engine by supplying extra power in specific driving situations. This allows additional torque to be mobilised. In general, the 12-volt starter battery is supplemented with a 48-volt battery that is charged via the BSG in recuperation mode during deceleration phases.

This allows the implementation of many functions familiar from hybrid systems with significantly higher voltages. Where high-voltage hybrids allow CO_2 emissions reductions of about 20-25 per cent (CO_2/km), initial results suggest that 48-volt mild hybrids can achieve reductions of 10-15 per cent in per-km CO_2 emissions. A comparison of the extra costs shows that the 48-volt mild hybrids are only 30-50 per cent as cost-intensive as high-voltage hybrids. As such, the 48-volt system represents an intelligent and, in particular an affordable supplement to full and plug-in hybrids. Furthermore 48-volt systems can more easily be integrated into existing vehicle powertrains and architectures – fewer extensive modifications are required. As such, it can be expected that the 48-volt voltage level will rapidly become established in the market.

Figure 4: Mid-sized and compact cars are the volume drivers – source: Continental

In addition to the benefits of hybridisation, the additional 48-volt system also makes it possible to operate a selection of electrical components in the vehicle at higher voltages. This is significant because the number of electrical components is continuing to expand dramatically, especially in the mid-size and luxury car markets. High-power components run more efficiently at higher voltages, and transferring them to the 48-volt on-board power system also reduces the load on the 12-volt system.

Market forecasts predict that 25 per cent of newly registered cars will have an electrified powertrain by 2025 (figure 5) and that almost half of these will feature 48-volt technology. From the year 2020 onwards, global potential for up to four million 48-volt systems could unfold.

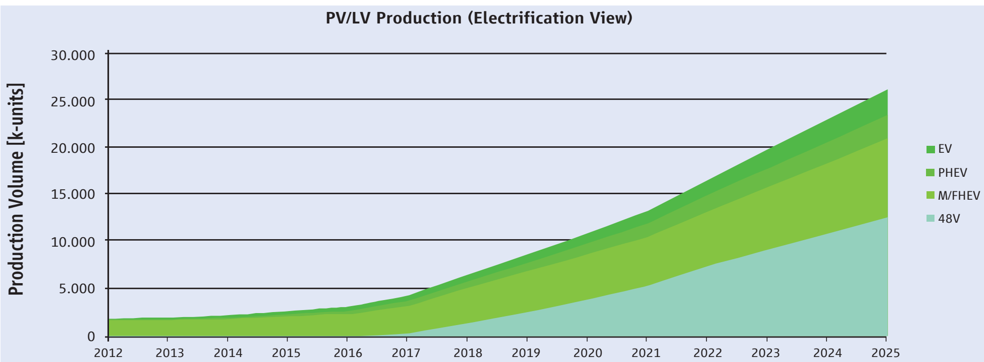


Figure 5: Market forecast electrified powertrain by 2025 – source: Continental

1.4 Economic context

In addition to a long list of technical challenges, moves to introduce 48-volt on-board power systems have also been flanked by intensive discussions on their economic feasibility. As the previous sub-chapters have shown, the main drivers behind the trend towards 48-volt systems are the continuously increasing power requirements of auxiliary components and, in particular, the need to continue to reduce CO_2 emissions.

At the beginning of the last decade, the additional costs of 42-volt electrical systems (compared to the costs of more powerful 12-volt systems) were estimated at approximately 600–1,000 euros. It is reasonable to assume that the additional costs for 48-volt systems will be similar now, depending on the respective degree of implementation (starter generator, power electronics, battery, power distribution). If the need to introduce a 48-volt system (to reduce CO_2) is accepted as a given, then it would seem that these extra costs are ultimately unavoidable.

Given the high cost of R&D and manufacturing, the quantities of 48-volt components sold will be of decisive importance. Only if the widespread introduction of 48-volt systems is successful will the necessary scale effects be realised. While the development of 48-volt batteries can piggy-back on to the established production of the traction batteries powering battery electric vehicles (BEV), the development of auxiliary components may well proceed in the other direction: 48-volt systems could become the major force driving developments here.

Today's BEVs use specially developed high-voltage components such as air-conditioning compressors and electrical heaters. Developing and manufacturing these components is highly cost-intensive due to the complex safety measures required as a consequence of the high voltages in use. These components can, as a rule, only cover a limited range within the high-voltage spectrum, for example 250 to 450 volts. As the development of high-voltage electrical systems continues to progress, voltages of 800 volts and higher will probably be introduced in the near future. Many high-voltage auxiliary components would need to be so heavily modified for these higher voltages that designers would essentially be starting from scratch, driving unit costs to even higher levels.

While the prospect of on-board power systems with three different voltage levels might seem economically infeasible at first sight, it could yet prove to be an opportune solution precisely for economic reasons: 48-volt auxiliary components are significantly less costly than their high-voltage equivalents. Power outputs of up to five kW, and more in some cases, can be controlled effectively with existing technology. Such components are typically produced in a fashion closer to the 12-volt or 24-volt versions than to high-voltage versions. That is also true for the costs associated with them. If high-voltage systems start to utilise very different voltage levels in the medium term, sourcing BEV components from the 48-volt platform concept will become an increasingly interesting proposition. Both all-electric vehicles and 48-volt hybrids would stand to profit from such a development.

It will not, however, come about overnight. Fundamental questions relating to architectures remain to be clarified. The systemic approach has not yet been fully thought through and will continue to develop and evolve over the coming years. What it is clear enough, however, is that the 48-volt system will only enjoy a lasting future if it is proves possible to standardise key components and to rapidly raise the number of units produced to significant levels.

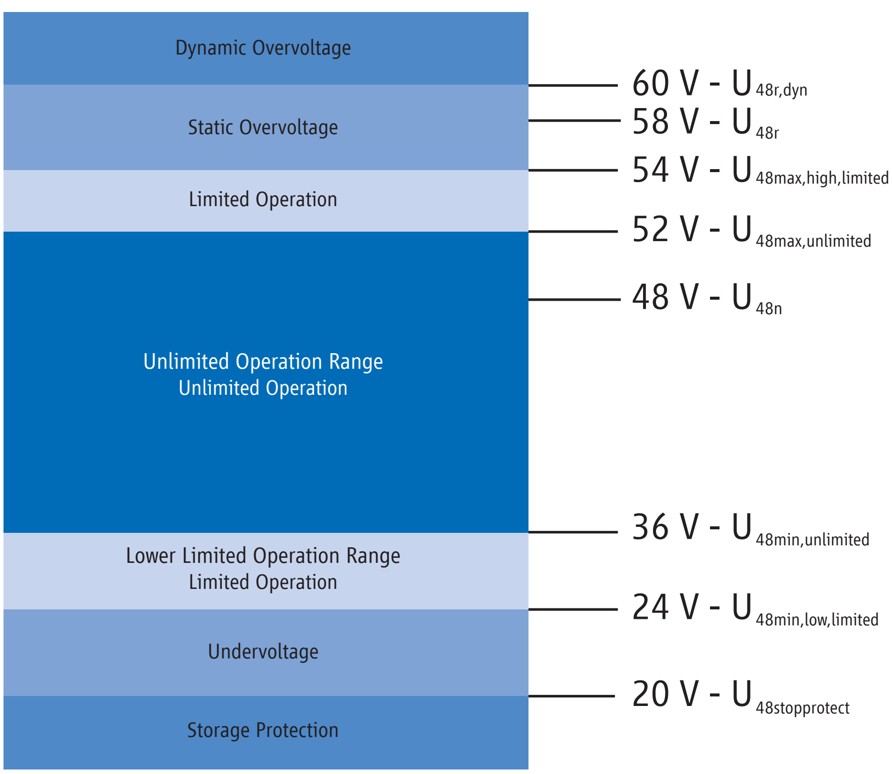
1.5 VDA Recommendation 320

The VDA Recommendation 320 covers electric and electronic components in motor vehicles for the development of a 48-volt power supply. It was elaborated in the VDA's Working Group "Electronics", project group "48-Volt Power Supply".

The document defines requirements, test conditions and tests performed on electric, electronic and mechatronic components and systems for use in motor vehicles with a 48-volt on-board power supply. Unless otherwise indicated, the tests described in it are not electric service life tests.

The voltages have been defined as follows (figure 6: excerpt from VDA 320):

Figure 6: Definitions of voltage ranges – source: VDA 320, last updated July 2014



The range between U_{48r} and $U_{48r,dyn}$ represents the tolerance.

Upper limited operation range

The range between $U_{48max,unlimited}$ and $U_{48max-,high,limited}$ is intended for calibrating the storage medium and for the uptake of recovered energy.

Unlimited operation range

The range between $U_{48min,unlimited}$ and $U_{48max,unlimited}$ allows the components to operate without restriction.

Upper limited operation range

The system may operate only temporarily in the range from $U_{48min,low,limited}$ to $U_{48min,unlimited}$. Countermeasures should be taken to bring about a return to the unlimited operation voltage range.

Undervoltage

All voltages below $U_{48min,low,limited}$ are defined as undervoltages. The storage protection voltage is $U_{48stoprotect}$.

Storage protection voltage

All voltages below $U_{48stoprotect}$.

General requirements

Assumptions regarding components with 48-volt connection

- Static direct voltages ≤ 60 volt occur with a maximum ripple of 10 percent RMS.
- A single error in the wiring harness must not cause the 48-volt supply to short circuit to the 12/24-volt system.
- There is a common ground for the 12/24-volt system and the 48-volt system, which are connected via physically separate grounding bolts/connections.
- All the voltage and current information refers to the component (terminal voltage).
- The polarity of the 48-volt supply is prevented from reversing by appropriate measures in the vehicle.
- Jump starting with the 48-volt power supply is prevented by appropriate measures applied in the vehicle.

Requirements for components with 48 connection

- A single error must not cause a short circuit between the 48 volt supply and the 12/24-volt supply.
- Components simultaneously supplied at 48 volt and 12/24 volt, and interfaces based on 12/24 volt, need their own ground connections for both supply voltages. These ground connections must be physically separated from one another.
- If a 48-volt component loses its ground (terminal 31 and/or terminal 41), this must not disrupt or destroy communication networks or the electrical networks.
- Overcurrent tests should be detailed in the component specifications.
- No component may cause the voltage to enter the dynamic overvoltage range (e. g. through a load dump or resonance peaks).
- If the voltage enters the overvoltage range up to U_{48r}, countermeasures should be taken via the component that is feeding energy back in/causing entry into the overvoltage range, so that the voltage exits the overvoltage range at the lower boundary.
- If the voltage enters the lower limited function range, countermeasures should be taken so that the voltage returns to the unlimited operation range.

1.6 Additional technical challenges

- **Safety measures**

  From a technical point of view, the 48-volt voltage level meets key criteria defined in the course of the discussion on 42-volt standardisation around the turn of the millennium. As was already, and wisely, concluded back then, staying under the maximum permissible contact voltage (< 60 volt) averts the need for extensive personal safety measures such as contact protection, equipotential equalisation and insulation control. The “hot plugging” effect must, nevertheless, be given due consideration even at 48 volt, since opening an electric circuit under load can be enough to destroy plug-in contacts. Safety measures here can either make it impossible to interrupt circuits under load, or ensure that their disconnection is detected early enough for the circuits to be deenergised in good time.

EMC is also, given the high switched currents, a significant factor that deserves consideration. For these reasons, 48-volt electric circuits are occasionally implemented with shielded cables. In comparison to high-voltage systems, the 48-volt voltage level does not present any risk of personal injury. Costly personal safety measures are therefore not required.

- **48-volt electricity and power distribution**
In addition to the obvious difference in voltage levels, several further technically significant differences between the 48-volt supply voltage and the 12-volt voltage level can be noted.
While breaking an electric circuit under load in a 12-volt system causes very little arcing, breaking loaded circuits at 48 volt can trigger electric arcing that could lead to extensive thermal damage at contact points. Creeping short circuits, in particular, inevitably release considerable amounts of electric arc energy and cannot be de-energised using conventional safety fuses.
As such, safety fuses used today are by themselves not adequate to ensure that all sources of faults in 48-volt systems are detected and safely switched off. It follows from this that electric circuits must, in addition to safety fuses, also be equipped with electronic sensing to detect creeping short circuits and the formation of electric arcs and switch off the relevant circuits in the event of a fault.
As the number of 48-volt loads is still manageable, load circuits are connected directly to the power electronics and monitored there. As the number of 48-volt high-power loads rises, it will become necessary to use electric power distributors to monitor current paths electronically (in addition to the deployment of safety fuses) so that even creeping short circuits can be detected and switched off in the event of a fault. Over and above this, it must be ensured that the separation of both the 48-volt and 12-volt systems is maintained. A 48/12-volt short circuit would cause considerable damage to all 12-volt control units and loads.

VDA recommendation 320 specifies that the respective power distribution systems should be spatially separated. Each should have its own routing, and the wiring harnesses should have separate grounding points. All 48-volt components should be clearly distinguishable by their colour from other components to ensure they are recognised as such.

- **Electric arcs**[1]
As already mentioned, the introduction of voltage levels higher than 12 volts is accompanied by a risk of electric arcs forming if loaded circuits in the on-board power system are interrupted. This could happen as a result of the intentional isolation of electrical contacts in relays, but it could equally be the result of a fault in a wire or connector..

1 Tschierse, Dietmar: „Translates as requirements for relays in the new dual-voltage system“.
In: Elektronik Praxis 20, 20 Oct.2014.
Automotive Electronics // Bordnetz pp. 50-53.
Vogel Business Media GmbH & Co. KG, Würzburg.
URL: http://www.elektronikpraxis.vogel.de/automotive/articles/463717/
[Stand: 24/11/2014]

This (figure 7) is what takes place when arcing occurs:

- As the two contact surfaces separate from each other when a connector is unmated, the reduced contact force before they open at the breaking point leads to increased contact resistance in the contact zone.
- Formation of a bridge of molten metal (the contact points begin to open: the increase in the strength of the electric field causes material to begin to melt.)
- As the gap between the contacts gets larger, the temperature of the bridge rises until the melting voltage of the contact material is reached.
- A metal vapour arc/anode arc/cathode arc then forms (the temperature required for an arc to ignite depends on the specific materials, but if the burning voltage of the material is reached, an arc will ignite).
- A gas/plasma arc forms.
- If measures are not then taken to extinguish the arc – by further increasing the distance between the contacts or using arc chambers with magnets – very high temperatures in the arc could lead to thermal damage in its surroundings.

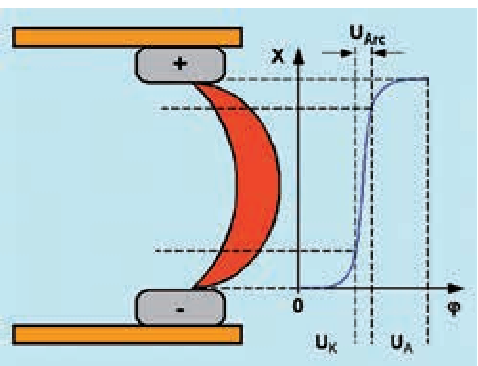


Figure 7: Potential curve of an electric arc between two electrodes – source: TE Connectivity

As soon as the arc has ignited, the cathode drop and anode drop voltage is present at the opening contacts. The arc voltage increases linearly with the distance between the electrodes until the arc is driven into the quenching chamber and the arc voltage rises sharply. The current is limited by the switch arc and forced to zero. The electric arc is quenched and the normal on-board voltage is present at the contacts.

Using relays to switch loads under 12 volt and 24 volt is a known and safe practice in passenger and commercial vehicles. In 48-volt applications, new challenges present themselves. In principle, steadily burning DC arcs can form when switching conventional 12-volt relays. This mainly depends on the contact spacing. If the distance between contacts is too small, the electric circuit might not be interrupted when the contacts open, and the continuously burning arc could destroy the relay.

- **Load limit curve**

  The switching capacity of a relay is normally estimated using what is generally termed the load limit curve 2. This gives the load current – load voltage pairs in which safe shutdown can be realised for Ohmic loads.

  Figure 8 shows the load limit curve of a switching relay K (with single contacts) and of a switching relay K-B (bridge contact) for resistive loads. Values below the respective load limit curve indicate that arcs are sure to extinguish within, at most, ten ms. Values above the load limit curve indicate that a stable arc forms – one which does not extinguish even when the contacts are fully open.

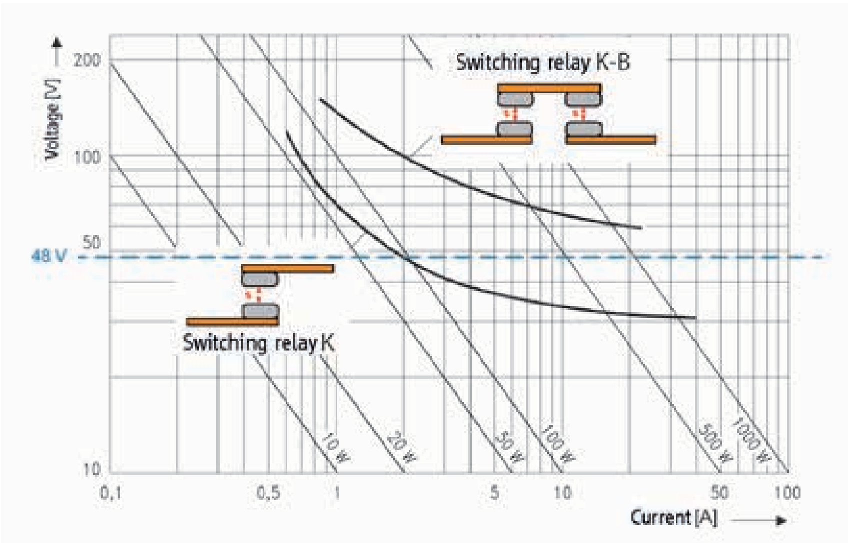


Figure 8: Load limit curve for the switching relay K-B and the switching relay K – source: TE Connectivity

If a single interruption with a given contact spacing does not suffice to switch off a circuit, various options for the design of the switching contacts are available to increase the arc voltage:

- Greater spacing between contacts
- Multiple interruption (e. g. by utilising a bridge contact that divides the arc into several partial arcs in series)
- Lengthening the arc column using a special electrode shape (e. g. classic horn shape) with/without additional isolation ribs
- Arc extinguishing plates: Separation of the arc into several partial arcs (addition of voltage drops of several drop areas: Deion principle). Here, the arc is driven into the arc extinguishing plates of an appropriate plate chamber and divided into partial arcs, resulting in a substantially increased total voltage drop.
- Cooling the arc using cooling or insulating material chambers.

2. Architectures

2.1 Powertrain

Several powertrain topologies are feasible due to the various options to mechanically connect and integrate the 48-volt electrical machine (usually as a starter generator in 48-volt technology) into the drivetrain, and the different types of 48-volt electrical machines available for selection. The powertrain topology chosen significantly influences the performance and characteristics with which the aforementioned functions can be implemented, as well as the costs involved. Carmakers and automotive suppliers are currently analysing and evaluating four major powertrain topologies. Depending on the e-machine configuration, the topologies vary in terms of their potential for energy recuperation and electrical boost capacity.

Figure 9 illustrates a topology where the internal combustion engine (ICE) and e-machine cannot be separated. Consequently, IC engine friction takes place in recuperation and electrical driving mode, reducing the performance of the IC engine. In contrast, the topologies in figures 11 and 12 show an IC engine that can be decoupled. This increases the potential amount of recuperable electrical energy and reduces the electrical power required for the desired driving function.

This is in principle also possible with the topology shown in figure 10, provided that additional coupling is implemented between the IC engine and the 48-volt electrical machine (P2 hybrid).

ICE mounted (e.g. belt) – mHEV

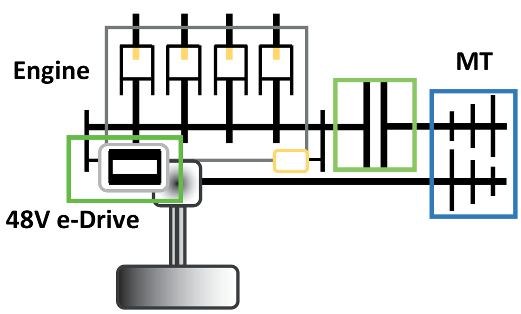


Figure 9: Belt-driven 48-volt electrical machine – source: Robert Bosch

Crankshaftmounted (ISG) – mHEV

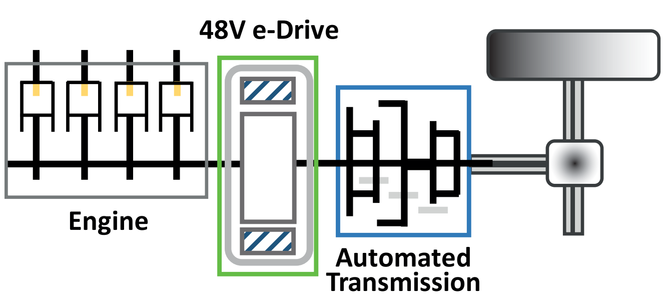


Figure 10: Crankshaft-mounted 48-volt electrical machine – source: Robert Bosch

The introduction dates and prioritisation of the individual topologies differ between the various manufacturers, and depend on the efforts required to achieve defined CO_2 target values, on regional requirements and on the scope of features offered to the end customer.

The easiest mode of integrating the electrical machine and the most extensively analysed topology to date is illustrated in figure 9.

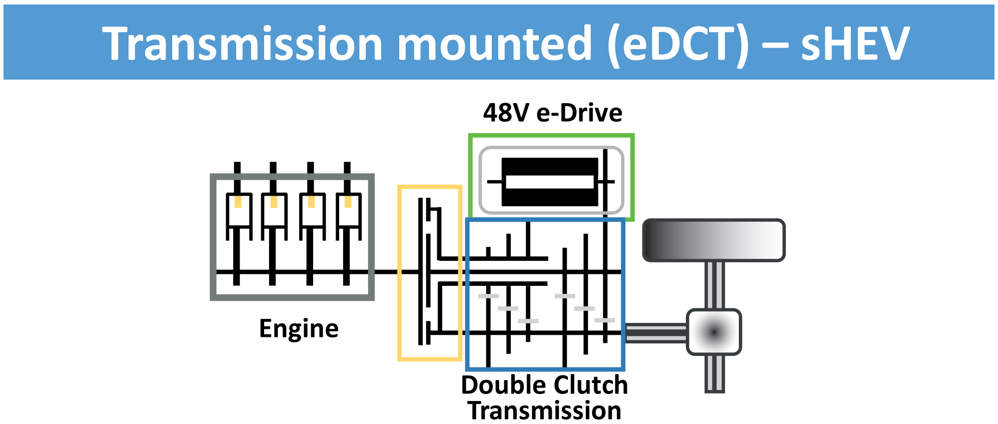


Figure 11: Dual-clutch transmission-mounted 48-volt electrical machine – source: Robert Bosch

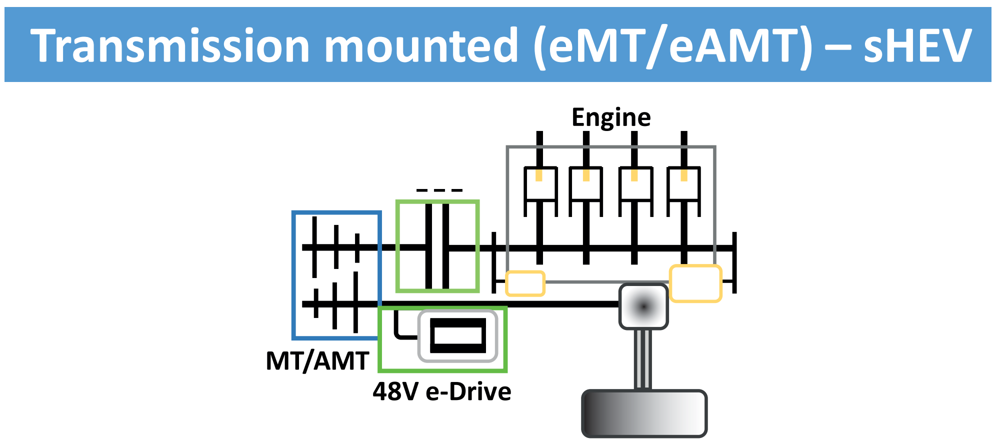


Figure 12: 48-volt electrical machine mounted to the transmission output shaft – source: Robert Bosch

2.2 Types of electrical system topologies

The maximum and continuous current determine the configuration of the electrical system. 12-volt electrical systems will be equipped with lead-acid batteries for the foreseeable future due to their ability to start the engine even at very low temperatures. In addition, this low-cost solution has been tried and tested for many decades.

The current limit is to be set to 250 A continuous current for both systems. However, short peak currents may be significantly higher. Higher continuous currents require larger cable cross-sections, which adds bulk and drives up costs. Since the 48-volt system primarily supplies high-power components, it is currently switched off in most applications when the vehicle is not moving.

- **Traditional 12-volt electrical systems**
  In traditional 12-volt systems, the maximum current flows when the IC engine is started. This current must be fully supplied by the 12-volt lead battery. When the engine is running, the generator feeds the electrical system with currents of up to 350 amperes. The system voltage is then 14 volts (figure 13 and 14).

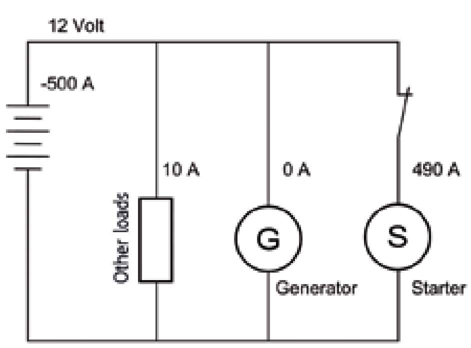


Figure 13: 12-volt start process – source: Leopold Kostal

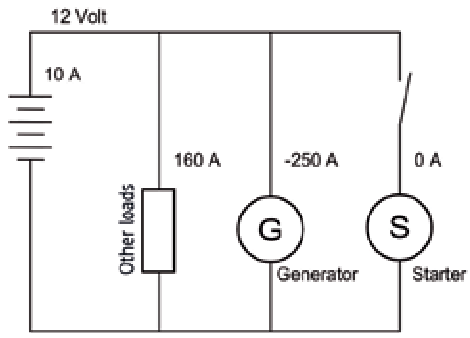


Figure 14: 12-volt full load – source: Leopold Kostal

- **12-volt systems with higher voltage loads**
  Higher voltages are already used in vehicles to supply headlights and windshield defrosters. These power-consuming devices produce the required voltage themselves locally (figure 15).

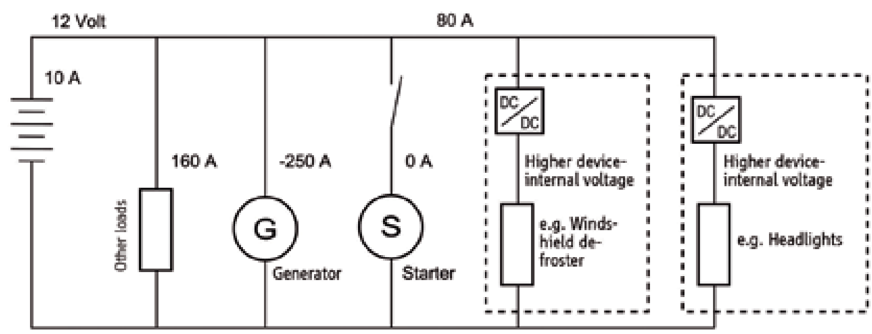


Figure 15: 12-volt electrical system with higher voltage devices – source: Leopold Kostal

- **12-volt electrical systems with 48-volt stand-alone solutions**
  In systems with short-term high power requirements, e. g. for roll stabilisation or electric turbochargers, a DC/DC converter is used to increase the voltage from 12 to 48 volts. The higher voltage level features an energy storage medium that covers the energy peaks and reduces the load on the generator of the 12-volt system and on the DC/DC converter. Compared to a 12-volt electrical system, the system components and wiring of this application have smaller dimensions. The DC/DC converter can be unidirectional.

Capacitors can also be used to store electric power in addition to batteries. The 12-volt lead-acid battery still supplies the power to start the engine (figure 16).

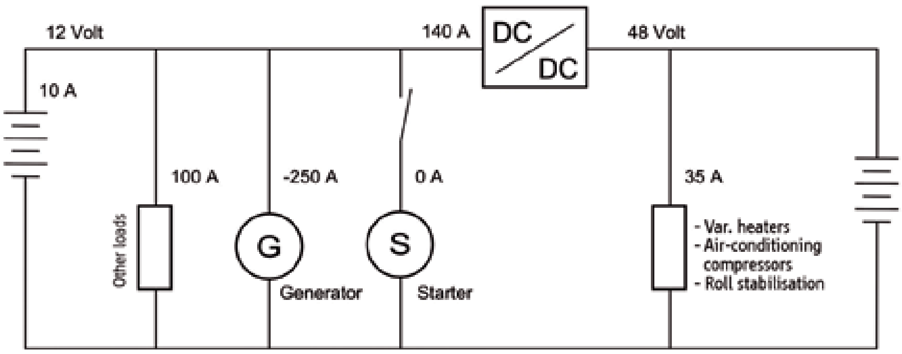


Figure 16: 12-volt electrical system with generator and 48-volt electrical system without generator – source: Leopold Kostal

- **12-volt system combined with a 48-volt system**
  The power to start the IC engine is usually supplied by the lithium-ion battery in the 48-volt electrical system. The starter generator is a closed-loop controlled electrical machine using electronic devices to limit power consumption. According to the current state of technology, the starter generator can feed up to 15 kW into the 48-volt system when the IC engine is running. The DC/DC converter transfers part of this energy to the 12-volt system to supply its components and charge the lead battery (figure 17).

The topology of this system features high-power components in the 48-volt system; the power transfer to the 12-volt system could be as low as just one kW. However, at extremely low temperatures, the lithium-ion batteries can no longer supply sufficient energy to start the engine. In this case, the 12-volt lead battery comes into play, powering a traditional starter in the 12-volt system or using a bidirectional DC/DC converter to power the belt-driven starter generator (BSG) in the 48-volt system (figure 18).

It can be assumed that mild hybrids will operate without a starter in the 12-volt system after a transition phase, and that the lattermost system topology described will become established.

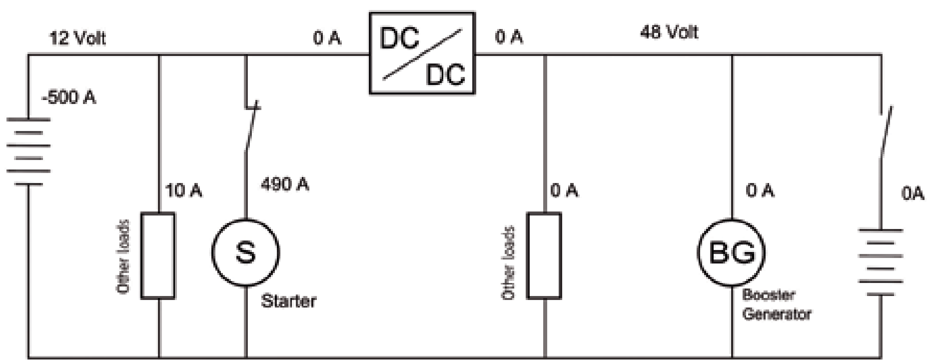


Bild 17: Start of an IC engine with 12-volt starter, when the lithium-ion battery is too cold – source: Leopold Kostal

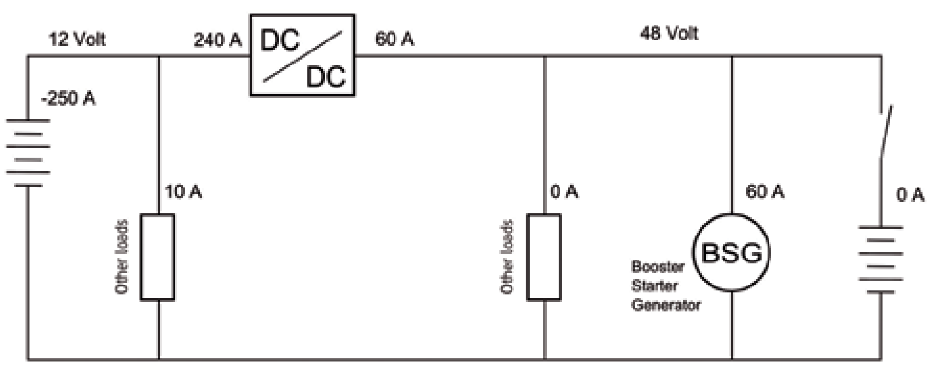


Figure 18: Start of an IC engine with 48-volt starter and transfer of power from 12-volt system via DC/DC converter, when the lithium-ion battery is too cold – source: Leopold Kostal

3. Components

3.1 Generators and motors

It is envisioned that 48-volt systems of all types will operate without the traditional 12-volt generator, since the 48-volt machine takes over the generator function. Thanks to the higher voltage, the machine's performance and efficiency will improve.

In contrast to 12-volt generators, electric machines fulfil two different functions. They operate both as generators and starters or rather electrical motors to support propulsion. Consequently, situations requiring torque and high electrical power at the same time are a challenge for the energy management of the electrical system. Key parameters include the total system load, the charging status (SOC and SOH) and the dimensioning of the batteries. The energy management system controls the activation of individual functions, such as the charge, boost or recuperation modes, in the context of the specific driving situation.

While 12-volt generators are claw-pole machines due to their system design, the introduction of 48-volt systems will lead to the coexistence of different technologies. Two machine technologies exist – synchronous and asynchronous machines (figure 19).

Synchronous machines are subdivided into machines with exciter winding, either of the salient-pole or claw-pole rotor type, permanent magnet synchronous machines and reluctance machines. Asynchronous or inductance machines are also known as squirrel-cage machines due to their rotor technology. The cage can be made of aluminium or copper.

The speed, efficiency and power density of the machines may vary subject to the power and maximum current of their respective rectifiers. It is therefore difficult to classify any single machine as per se the best type, e more so since the automotive industry also requires additional factors such as package space, costs, robustness and standardisation to be considered. This explains why different technologies will be come to be used in 48-volt motor generators.

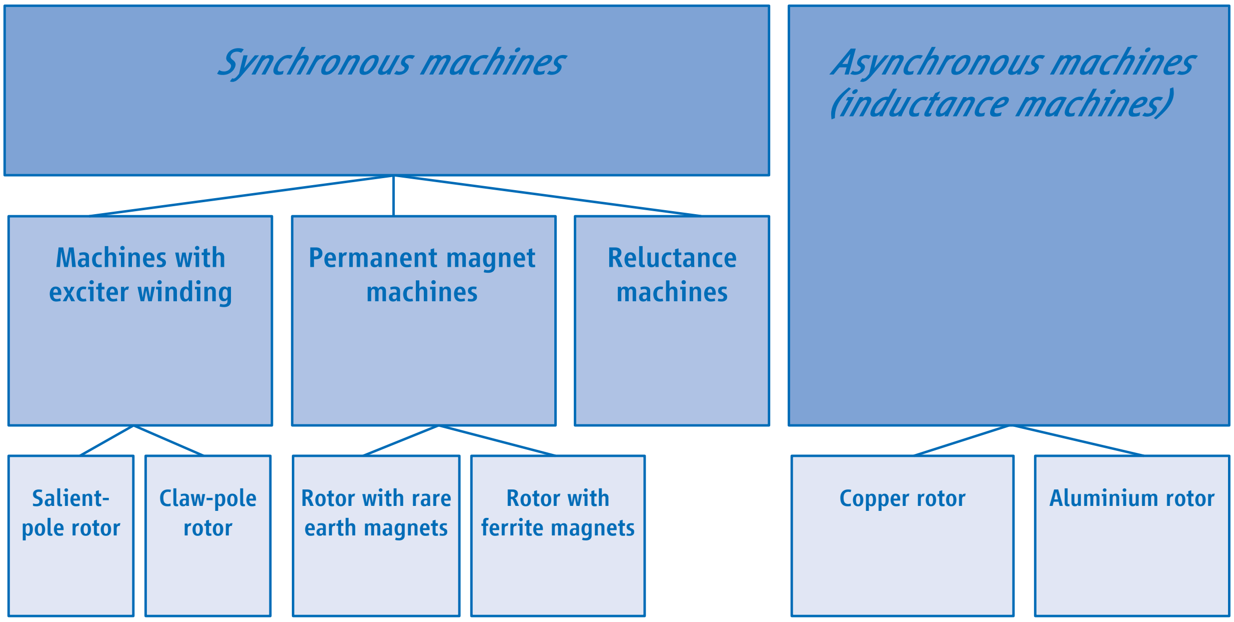


Figure 19: Classification of electric machines – source: Valeo

Figure 20: Belt-driven e-machine – source: Valeo

However, the topology of the powertrain significantly influences the machine technology:

- In the future, 48-volt e-machines with belt drive (figure 20 and figure 9, section 2.1) will replace traditional 12-volt generators. It is likely that inductance machines will be used in addition to the claw-pole technology known from standard 12-volt architectures. Inductance technology is already employed in series production of belt-driven machines. The inverter electronics are usually integrated into the machine. The machine or electronics can be either air or water-cooled subject to requirements.

- Crankshaft-mounted motors/generators, also known as ISG (figure 10, 2.1.), are usually flat machines that must meet high requirements in terms of package space and ease of integration regarding their diameter (determined by the IC engine or gear) and length. This is why machines with the maximum possible power density are preferably used, which in turn makes permanent magnet machines an obvious choice.

- Transmission-mounted machines (figure 21 and figure 12, section 2.1) are, whether integrated into manual or dual-clutch transmissions, cylindrical in shape, like belt-driven machines. Since they are cooled with transmission oil, these machines must be brushless. The use of permanent magnet or inductance machines instead of claw-pole machines is under consideration for this reason. The torque that can be supplied in the specified package space is key to the decision since it is higher in permanent magnet machines than in inductance machines.

As a result of the multiple topologies and machine types available, no single "standard architecture" or "standard machine type" will dominate. In fact, the introduction of the 48-volt system will lead to variabilisation as a result of different factors such as the required torque, existing platforms, costs, package space, robustness and CO_2 targets.

3.2 Heaters and additional heating systems

- **Electrical heaters**
  It is advisable to integrate the electrical heater, a high power-consuming device in 12-volt systems, into the 48-volt electrical system, where it can access a power range between three and five kW.

Figure 21: Transmission-mounted e-machine – source: Valeo

- **Air heaters**
  Air heaters are usually used in 12-volt systems. This type of heater directly heats the air that is directed to the passenger compartment and is thus integrated into the air-conditioning system. It quickly heats up the vehicle interior and defrosts the windshield with minimum heat transfer loss.

Having already become accepted in 12-volt systems, this heater technology will most likely be the first to be used in 48-volt systems due to its easy transferability. Other heating technologies (wire heaters, layer heaters) are also conceivable. Which technology will prevail still remains to be seen, since it will depend on multiple factors such as costs and the electrical behaviour of the heaters in the on-board power system. If necessary, an additional heater will be used to heat the lithium-ion battery.

- **Water heaters**
  The water heater is tied into the hydraulics of the engine coolant system (figure 22).

The air-conditioning system uses the air-to-water heat exchanger of the cooling circuit to heat the vehicle interior and defrost the windshield. Compared to an air heater, the heat transfer loss is higher since the heat is transferred twice. However, by heating the coolant, the IC engine can be brought quickly to its operating temperature and the temperature of the 48-volt battery can be controlled with the heating system.

Figure 22: Electric water heater – source: Webasto

3.3 Air-conditioning compressors

Operating an electric compressor independently of the engine makes it possible to improve the energy efficiency of the air-conditioning system as part of an overall energy management strategy, and provides additional thermal comfort in summer by pre-cooling the car. Belt-driven compressors ranging from three to six kW are currently dominating the market.

Electric compressors are nowadays used in almost all electric vehicles and in many types of hybrid vehicles (figure 23). The inverter, electric motor and mechanics form a single unit. The necessary power is provided by the existing high-voltage system with controllable electric amperages. Modern electric compressors can take voltages between approx. 120 and 450 volts. Their protective features eliminate the risk of contact and isolate the high-voltage system from the low-voltage system.

The change to 48-volt supply voltage leads to significantly higher electric currents with peaks of around 240 amperes. The winding of the electric motor and the dimensioning of the inverter must be adjusted to the electrical conditions. High currents and current densities lead to higher power losses in electronic components and hence to higher waste heat flows. This must be taken into consideration when dimensioning the cooling management of electronic components.

Figure 23: Electric compressor – source: Mahle Behr

Figure 24: Electric coolant pump – source: Brose

The use of 48-volt compressors is technically feasible but requires substantial changes to the electric system. Space requirements, weight and costs all increase as a result. The defined package space must be adjusted to the dimensions of 48-volt compressors.

3.4 Pumps

The 48-volt system promotes the use of powerful electrically-operated auxiliary components. These include various pumps (for oil, coolant, air, fuels). They can be activated on demand and controlled, thus reducing energy consumption and emissions while also minimising wear and tear. The maximum output increases from currently around one kW to six kW. A clear market trend towards higher power outputs in combination with better control and analysis options can currently be identified.

Electric coolant pumps contribute to the implementation of beltless IC engines (figure 24).

Transmission fluid and engine oil pumps (figure 25) can fully replace today's mechanical main pumps and electric auxiliary oil pumps, while optimising the costs and efficiency of automatic transmissions and maintaining the oil pressure after the IC engine has been switched off.

Figure 25: Electric oil pump – source: Brose

3.5 Windshield defrosters

Electric windshield defrosters have been in use for many years. They often use thin heating wires embedded in the glass. Another increasingly used variant are layer-heated windshields. The windshield is heated by a transparent, electrically conductive coating, usually applied to one of the glass surfaces. The heating structure is no longer visible to the driver.

As a result of increasingly larger glass surfaces and higher requirements for the melting speed, power peaks of more than one kW occur in these systems. Power densities of 1,000 W/m2 are usually necessary to achieve subjectively quick defrosting (figure 26).

In modern vehicles, window heaters primarily perform a comfort function when the engine is started. It usually takes only a few minutes to thaw frost from the windows. The heating is also used to prevent or clear condensation.

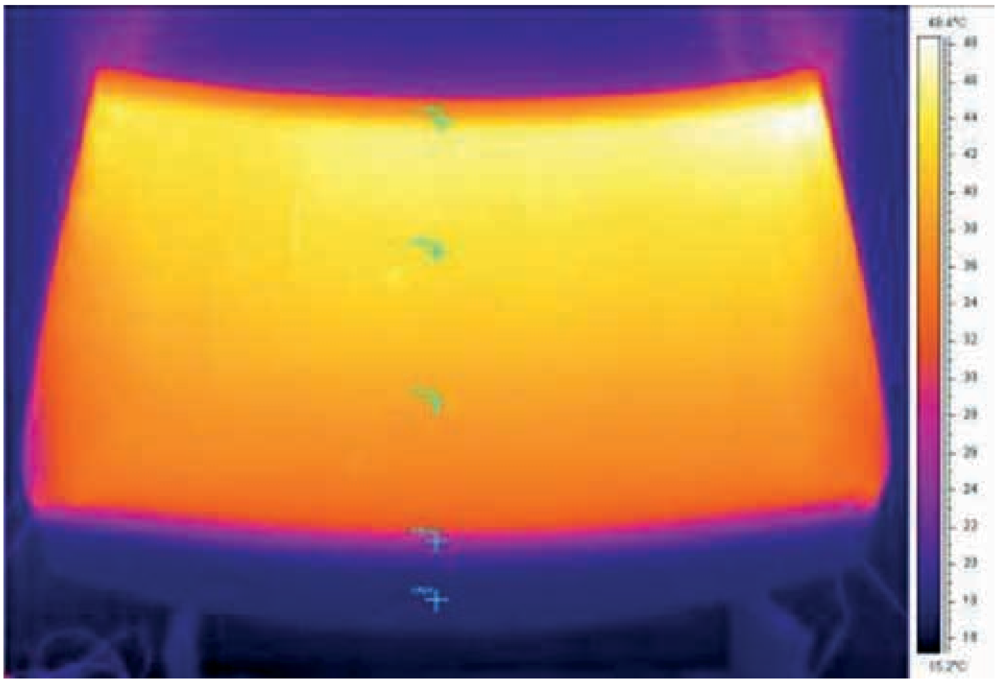


Figure 26: Thermal image of an electrically heated windshield – source: NSG

It is therefore safe to assume that window heaters will become more important, especially in future electric vehicles without IC engines where they are likely to be deployed more often. Careful energy consumption is essential in these vehicles since the use of HVAC can sometimes reduce the driving range of an electric car quite significantly.

However, lower energy usage for cabin heating and air-conditioning will considerably increase the risk of fogging and condensation on all windows. In addition to defrosting the windows when starting the car, window heaters will most likely also be used in continuous operation to prevent fogging and condensation while the vehicle is moving.

Direct electric heating of the window is more efficient and can be controlled better than indirect heating with hot air. In this context, extension of electric heating to other car windows also appears desirable. Complete heating of all windows would require a connected load of up to 2.5 kW for a total surface area of 2-3 m^2. 48-volt systems can help provide the high power required for window heating, which may sometimes be drawn for extended periods of time, as an integral component of the car's air-conditioning system.

3.6 Chassis functions

The power consumption of electrically powered chassis systems with peaks in the kilowatt range is high for the on-board power systems of passenger cars. Examples are electric power steering (EPS), rear steering, roll stabilisation and active suspension/damping. As a result of the power requirements, chassis systems are automatically candidates for a 48-volt supply, which is even already demanded by some chassis systems.

Electric power steering and roll stabilisation are described in more detail below.

- **Electric power steering (EPS)**
  Until the end of the nineties, the notion prevailed that EPS could only handle front axle loads in small to mid-size cars. The energy provided by the 12-volt motor was insufficient to ensure adequate power steering support. Executive and luxury cars were fitted with hydraulic power steering. Technological developments in electric power steering enabled increasingly higher axle loads. EPS running on 12 volts can nowadays be used in almost all passenger cars and is likely to replace hydraulic power steering.

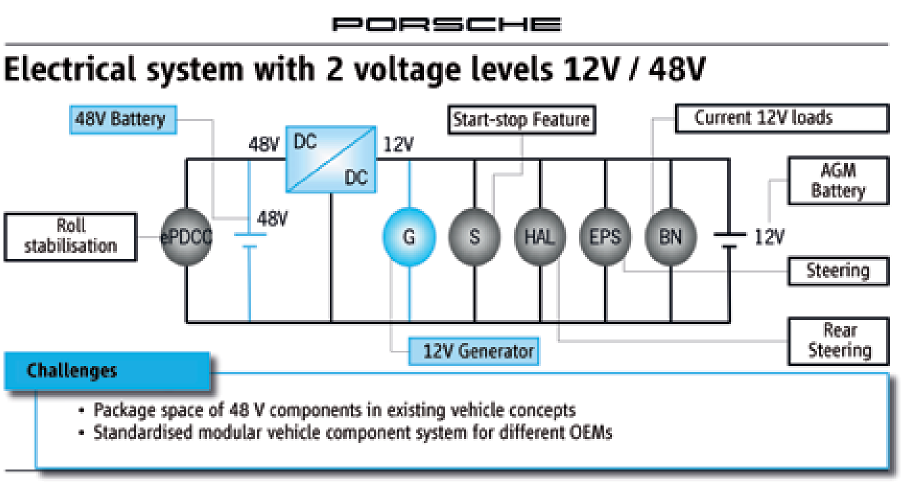


Figure 27: 48-volt supply for electric roll stabilisation – source: Porsche

In this respect, EPS does not require a 48-volt supply. The question as to whether the benefits of EPS using a 48-volt motor may justify conversion still needs clarification. Consequently, EPS is not a driving force behind the introduction of 48-volt electrical systems. However, it is rather likely that the possibility of 48-volt EPS will be investigated as soon as such 48-volt systems have been realised. The 48-volt solution can offer particular benefits for vehicles equipped with EPS and rear steering. The steering systems on the front and rear axle are controlled simultaneously and thus require higher peak power from the electrical system. The use of a 48-volt system could significantly reduce the loads, which the 12-volt system has to supply.

- **Roll stabilisation**
  In 2014, a major carmaker presented an electric roll stabilisation system running on 48 volts (figure 27).

  The concept features a standard 12-volt on-board power system and a DC/DC converter that generates 48 V for the exclusive supply of the electric roll stabilisation system. Consequently, it is not a 48-volt on-board power system but rather a 48-volt stand-alone solution. This stand-alone solution can be considered as the first step towards 48-volt electrical systems.

- **Advantages of electromechanical chassis systems**
  Electromechanical chassis systems only need power from the electrical system for actuating components, and they provide significant benefits in efficiency compared to hydraulic systems. In addition, electric motors can provide much faster actuation than systems using hydraulic fluid. As a result of these benefits in efficiency and dynamics, carmakers favour the electrification of chassis components.

- **Effects on the electrical system**
  Ride control (e. g. compensation of uneven road surfaces) and highly dynamic driving manoeuvres place high demands on chassis

dynamics that are reflected in power peaks in the electrical system. 12-volt electrical systems cannot meet these dynamic power requirements and quickly reach the limits of their performance capability. In addition, the current required to flow in a 12-volt system would result in high power losses in the energy distribution. The more chassis components are electrified in vehicles, the more frequently power peaks will occur in electrical systems. This can be addressed through the introduction of a higher voltage level, underlining the necessity of 48-volt systems.

- **Package space**
  In terms of package space, 48-volt systems provide no benefits for chassis actuators. While 12-volt actuators have a lower number of turns than 48-volt actuators, their wire cross-section is higher. If winding space and power requirements remain unchanged, 48-volt actuators will provide no significant package space benefits compared to 12-volt systems.

The advantages of 48-volt technology are particularly evident in dynamic handling characteristics, in the packaging and assembly technology of electronic components and in the performance requirements of electromechanical chassis systems. In addition, the introduction of a higher voltage level considerably reduces power losses in supply lines. A higher voltage level is also imperative for optimal performance of chassis components during energy demand peaks. The 48-volt platform will enable comprehensive electrification of chassis components and distinctively improve the dynamic properties of vehicles.

3.7 Fan motors

Loads with high power throughput are generally more likely to be implemented in 48-volt systems. Given the issues presented by power losses in supply lines and in the magnetic circuit, and given the high thermal requirements applicable to the integration of their power units, high-performance fans used for purposes such as engine cooling particularly benefit from the higher efficiency levels which are possible in 48-volt systems.

The following two examples show cooling fan drives (figures 28 and 29) in different scalable power classes for a wide range of dimensioning variants.

Figure 28: Cooling fan drive for low performance classes (up to 600 W output power) – source: Brose

Figure 29: Cooling fan drive for high performance classes (up to 1,000 W output power) – source: Brose

The advantages of a high supply voltage are particularly evident in the higher performance classes. Smaller cable cross-sections, less stress on connectors and reduced current loads on the necessary semiconductors and passive system filter elements are all benefits that outweigh the disadvantage of the necessary higher dielectric strength. Depending on the application, the difference between the supply voltage and the internal useful voltage of logic devices may require more Changes to the circuitry to be made. The 12-volt and 48-volt systems have been appropriately separated. Special attention was given to creepage distance and clearance.

The ground connection of the drives is designed as a star grounding system and ensures low-interference operation thanks to capacitive coupling to ground.

3.8 Connecting systems

The question as to which electrical connection system should be used for 48-volt systems can be answered by looking at the technical challenges arising from the increased system voltage. Connector systems that have been tried and tested in cars (14 volt) or heavy goods vehicles (28 volt) for many years represent a cost-neutral solution for 48-volt systems.

Adopting the high-voltage connectors (which are typically shielded and have built-in contact protection) that have been developed for use in electric and hybrid vehicles up to 850 volts would be technically feasible, but cost and package space considerations make it seem inadvisable.

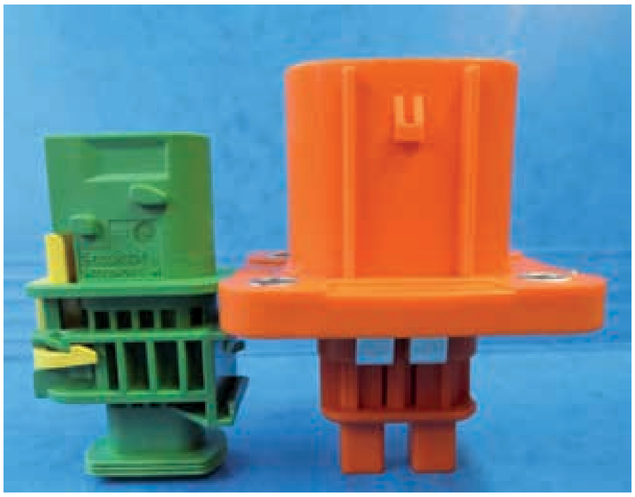


Figure 30: Size difference between 48 volts (green) and high-voltage (orange) – both configured for 2.5 mm^2 – source: TE Connectivity

Traditional automotive connectors used in 48-volt systems, must always be checked for compliance with creepage distance and clearance requirements according to DIN EN 60664-1 (insulation coordination for equipment within low-voltage systems) and evidence of compliance must be demonstrated.

For determining the creepage distance and clearance, the connectors must meet the requirements for pollution degree 2 and an altitude of 5,500 m asl. Most of the watertight connector systems fulfil these requirements, since they observe the necessary clearances between the contact pairs. By contrast, connector systems that are not watertight, and especially miniaturised systems, do not fulfil these specifications or only meet them partially. The housing design plays a key role in this context. To ensure that housings meet creepage distance and clearance requirements, a design where contacts are inserted only in every second chamber could be deployed.

However, the technical challenges arising from the introduction of 48-volt systems should not be entirely disregarded, e. g. pulling a connector under load and the electrolytic processes following the ingress of electrolyte-containing moisture in energised connectors. The use of watertight connectors is therefore recommended. It would also be advantageous to separate and individually seal the contact chambers (figure 31). A systemic architecture should be selected for disconnecting a connector under load to ensure that any interrupted contact is detected and the relevant path is de-energised.

Figure 31: 2-pin connector with individually sealed chambers for 48-volt applications – source: TE Connectivity

3.9 Wiring harnesses

Since modern 12-volt wiring harnesses and their components are specified for voltages up to 60 volts, the unrestricted use of all components would be theoretically possible in 48-volt systems. It is nevertheless necessary to analyse the systemic effects that result from the combined use of two different voltage levels in one environment. The main challenge will be the provision of fuse protection isolating the two systems from one another. If both systems reliably detect short circuits, a short circuit involving both voltage circuits can lead to significant disturbances. Therefore, it is essential to introduce an intelligent control mechanism and/or to spatially separate both voltage levels reliably.

Compared to high-voltage systems, the 48-volt system meets the demand to provide more electrical power at a lower cost. Virtually all vehicles in the mid-size to luxury segment feature start-stop systems and have high power requirements. In these car segments it is likely that a 48-volt system (in addition to a 12-volt system) could prove viable for all non-high voltage vehicles.

However, the 48-volt system cannot fulfil the requirements for all-electric cars or full hybrids. The 48-volt system is not an alternative but an addition to high-voltage technology, one that will be more viable and sustainable the lower the costs are.

With regard to the system architecture, cost savings result from the following reduced requirements:

- no contact protection required in connectors
- no special dielectric strength (creepage distance and clearance) required
- no shielded cables required
- no HVIL pilot line (to prevent disconnection under load) required
- no isolated grounding (B-) requiredh

In 48-volt systems, the following cost drivers are likely to be avoided:

- high-quality contact systems with low contact resistance
- wiring harnesses with separate routing paths and costly cable protection
- sealed systems (anti-corrosion protection)
- modification of connecting systems

However, reducing the requirements mentioned above (e. g. HVIL) will affect the safe use of components. For instance, disconnecting a connector under load should also be avoided in 48-volt systems. The 48-volt electrical system may turn out to be as complex and cost-intensive as the high-voltage system due to safety and EMC considerations, and will perhaps be even more expensive in the first few projects as a result of the initial outlay required. Moreover, abandoning safety measures installed in high-voltage systems will make additional protection features such as the frequently discussed arcing detection necessary.

The need to avoid particular short circuit scenarios will require complex and expensive fusing and cable routing solutions resembling those used in high-voltage systems. A system with e. g. 15 kW power potential could be designed as a high-voltage system with considerably smaller connectors and cables than a comparable 48-volt system. Today's high-voltage systems are not optimised for this power class. When systems with a similar level of functionality are compared, the high-voltage systems emerge as the winners in some areas.

3.10 Inverters

A bidirectional inverter is required for operating a starter generator. This inverter transforms the battery's direct current into a 3-phase alternating current, supplying the individual windings of the electrical machine with electric energy. The energy flow is reversed for recuperation. In this case, the inverter transforms the alternating current generated into direct current to charge the battery. In terms of its functional configuration, the inverter of 48-volt systems is similar to that of the high-voltage inverters used in full hybrids or all-electric cars (figure 32).

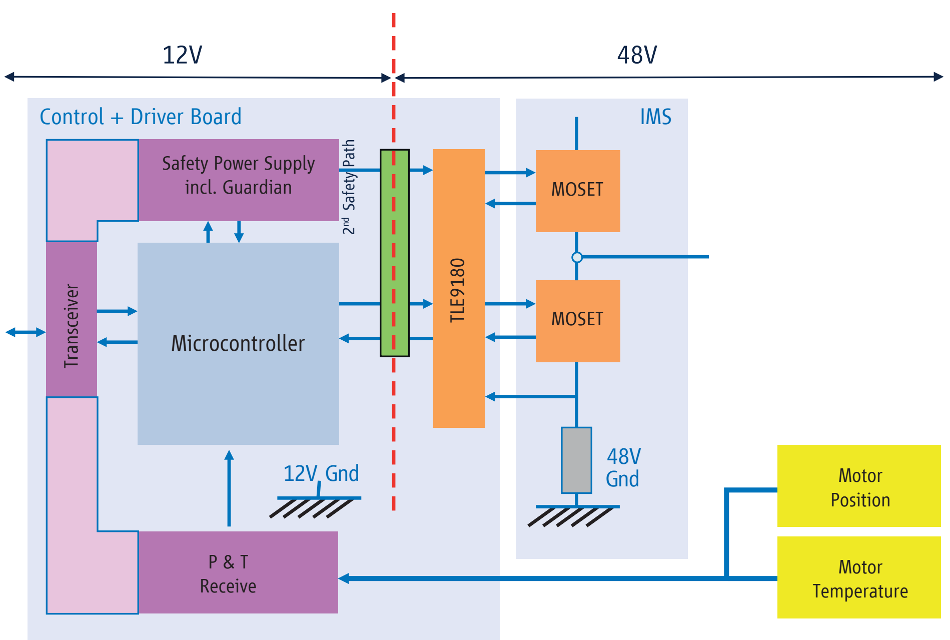


Figure 32: Block diagram of inverter electronics – source: Infineon Technologies

One of the main differences lies in the power semiconductors used. Unlike the high-voltage systems using primarily IGBTs (Insulated Gate Bipolar Transistors), MOSFETs are predestined for use as switching elements in inverters for starter generators due to their lower voltages. To control a 3-i-phase machine, MOSFETs are configured as three half-bridges.

3.11 DC/DC converters

A voltage converter (DC/DC converter) is used to transfer energy between the two subsystems of a dual voltage system. Since it mostly transfers energy from the 48-volt system to the 12-volt level, it is primarily operated as a step-down converter. In this energy transfer direction, the DC/DC converter replaces the generator for the traditional 12-volt system. Scenarios with converters operating in step-up mode usually only involve partial load requirements to ensure 48-volt operation. Alternatively, they can be stand-alone system solutions without a 48-volt generator.

The evaluation of various application scenarios of 48-volt implementation with and without 48-volt components reveals that the voltage converter needs to be implemented in different power classes from one to three kW. To ensure cost-efficient production, a modular and scalable converter architecture is necessary to support the different power classes. The scalable converter must be configured with multi-phase half-bridges (figure 33 and 34), polarity reversal protection for 14 volt, anti-touch protection and short-circuit protection, and it must be protected against single-point failures in the components carrying current. Several cooling concepts can be used: active or passive air cooling or water cooling.

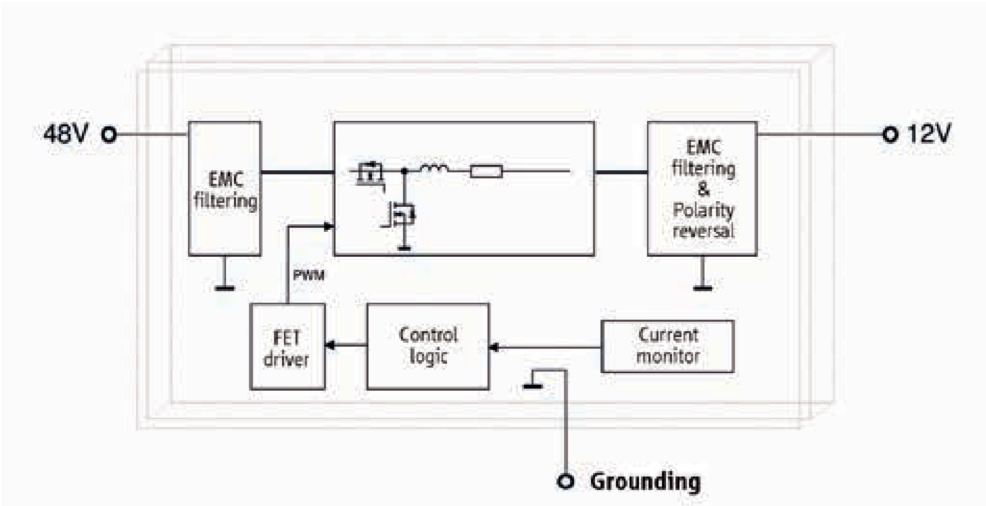


Figure 33: Block diagram of scalable 48 volt/12 volt DC/DC converter in half-bridge topology

Figure 34: 48 volt/12 volt DC/DC converter – source: Hella

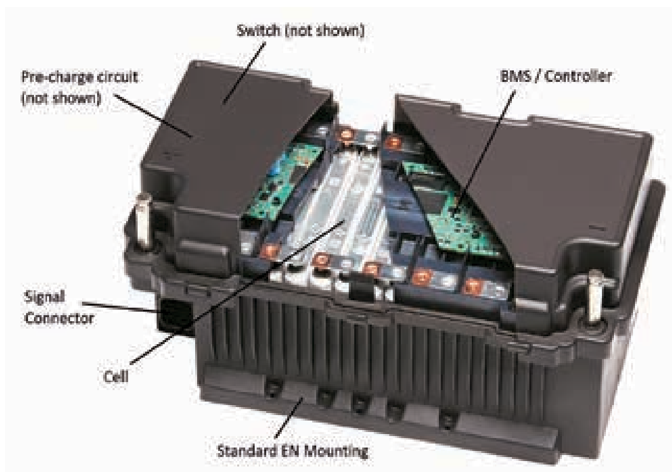


Figure 35: 48-volt lithium-ion battery – source: Johnson Controls

3.12 Energy and battery management

The dual-voltage system considered in this section comprises a 12-volt lead acid starter battery and a 48-volt lithium-ion battery. The 48-volt lithium-ion battery (figure 35) supplies high-power loads such as the A/C system, water pump, active chassis control and electric drive support, and stores electric recuperation energy generated during braking. The 12-volt lead acid battery supplies all other system components such as lighting, entertainment electronics and other standby power loads such as clocks and safety systems. It serves as a fallback solution in the event of the supply from the 48-volt system being interrupted.

Comprehensive standardisation of different components (electronics, connectors, software) and the definition of standardised package spaces and vehicle interfaces are key to reining in the costs associated with a 48-volt battery.

The main requirements for 48-volt batteries typically relate to the supply of pulsed power in the charging and discharging directions, and to the need for a sufficiently high charge level and temperature range to ensure the availability of adequate power.

The battery always consists of the following component groups:

- cell pack (energy storage)
- battery management system (monitoring, measuring and controlling)
- thermal management
- housing, peripheral devices and interfaces (mechanical protection, fixing, vehicle connection)

The cell pack consists of a number of cells determined by the cell chemistry selected and connected together in series. Depending on the required battery capacity and the individual capacity of the selected cells, several cells or battery strings can be connected in parallel. Although prismatic cells or pouch cells are preferably used, round cells are also available. Voltage levels and limits under different operating conditions are defined in standards such as VDA 320.

The voltage level and cell capacity are determined by the anode and cathode types used. Most commercial cells currently employ a graphite, hard carbon or lithium titanate (LTO) based anode. The cathode is usually made up of lithium nickel manganese cobalt oxide (NMC) or lithium iron phosphate (LFP). The materials used for the anode and cathode affect the battery's performance in addition to the voltage level.

The battery management unit (BMU/BMS) enables the following functions:

- maintenance of an optimal operating range to ensure the battery can meet the requirements of the application and to prolong battery life,
- ensuring safe and reliable operation,
- communication with the control and management system of the host application (vehicle).

To control the operating range of the battery, it is necessary to measure the current, individual cell voltages and the temperature at selected points. The battery system typically uses a communication interface to communicate with the electrical system. Battery current and voltage are controlled based on the battery status (charging status, maximum charging and discharging rate, current limits). Lithium-ion batteries are typically operated at a temperature range between -30°C and +60°C, but full discharge performance is only achieved within a range from approx. 0°C to 35°C. Refrigerants, cooling liquids or air can be used to keep the battery temperature within a defined temperature range. Passive temperature control can also be sufficient in certain cases..

The dimensions of current lead starter batteries can be used as a guide when developing 48-volt batteries. However, they may vary subject to the installation space and environment or mounting concept. A range of safety standards that are specific to the automotive industry have been developed for lithium-ion cells and batteries in recent years and must also be considered in the development of 48-volt lithium-ion batteries.

3.13 Active electronic components

The electronic control units of 48-volt systems always follow the same fundamental structure as those used in 12-volt or high-voltage systems. However, the semiconductor elements selected for 48-volt applications must take the different voltage level and different loads into account. They are mainly used in 48-volt systems to control electric motors and other electric loads in addition to connecting the 48-volt and 12-volt system levels by means of a DC/DC converter. The necessary semiconductor elements can be classified as sensors, microcontrollers and power ICs, supply, communication and driver ICs.

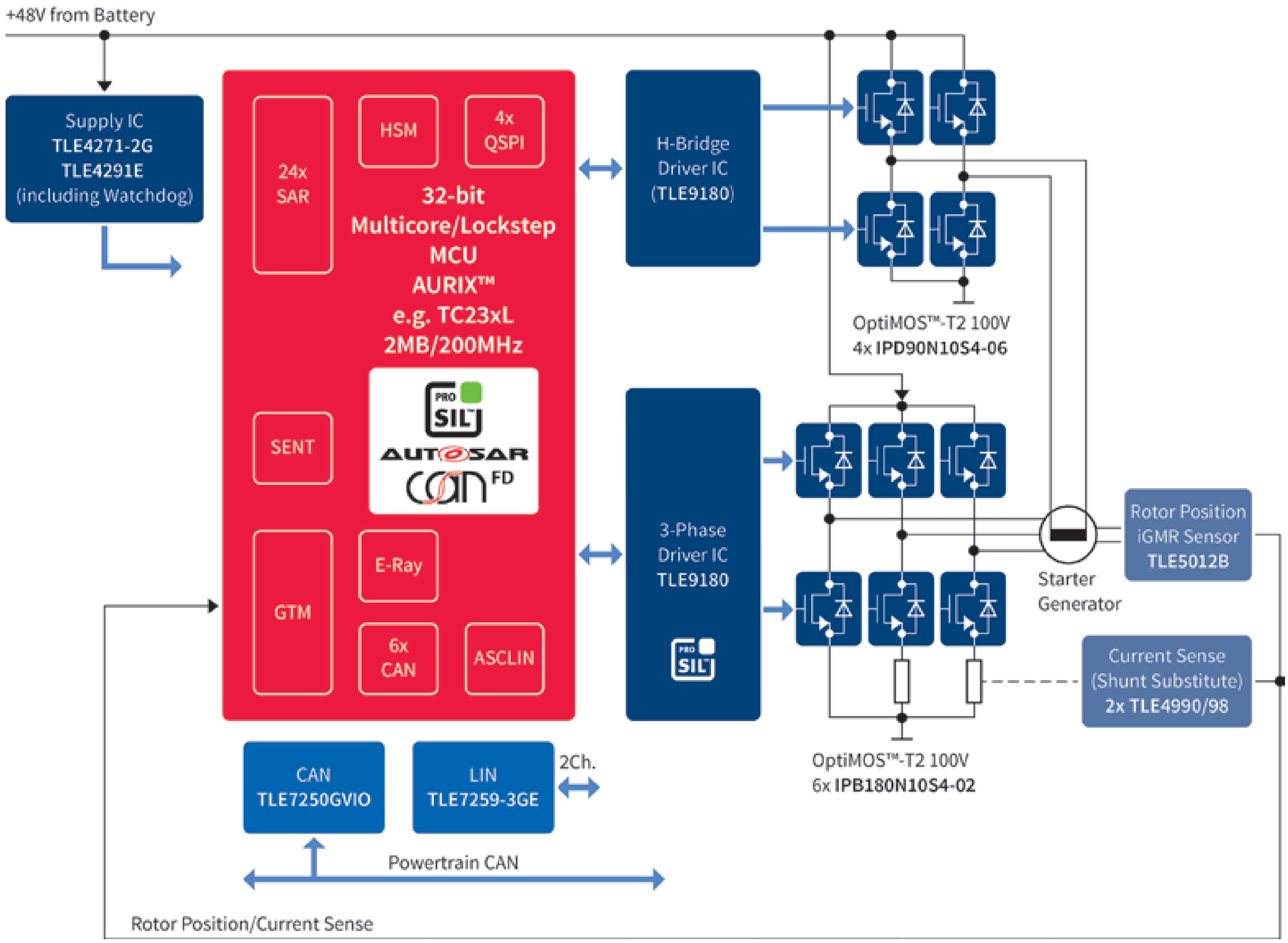


Figure 36: Semiconductor elements for start/stop and generator control in a 48-volt system – source: Infineon Technologies

The block diagram (figure 36) depicts the basic structure of semiconductors for the control of the starter generator in a 48-volt system. It includes an extra output stage to control the exciting current during generator operation in addition to the output stages required for the motor control. For the voltage supply of the microcontroller, the system voltage (48 volts) is reduced to a level commonly used for microcontrollers and other ICs. This is the main task of the supply IC. It also performs additional tasks relating to functional safety. The microcontroller is the "brain" of the control system and ensures the field-oriented control of the electric motor as well as the control of the exciter winding during generator operation. Complex timer units have been implemented for this in the microcontroller. The microcontroller also communicates with other control units in the vehicle using several communication buses. The sensor signals are processed to determine the current motor and inverter status. The microcontroller uses appropriate circuitry components to support the implementation of security features to guard against manipulation (hardware security module, HSM).

MOSFETs are often used in 48-volt systems as power output stage ICs. Compared to IGBTs, their performance regarding switching and conduction losses is significantly better in the voltage range of 48-volt systems. In addition to the actual configuration of semiconductor switches for currents of more than 100 amperes, it is also very important to ensure sufficiently good dissipation of lost heat (cooling) by choosing appropriate power semiconductor case styles. Different case styles are possible subject to the configuration of the control unit, ranging from standard-TO-cases for single transistors and the integration of output stages (one or all stages) into one power module to the direct integration of power components into the motor.

Driver ICs are another important element. Their primary purpose is to adjust the (PWM) signals generated by the microcontroller to control the motor to the level required for the power output stages. It may sometimes be necessary to use several drivers to ensure this is achieved.

The sensors are used to detect the rotor's position in the electric motor and the actual currents flowing in the inverter, and to transmit this information to the microcontroller. The rotor position can be detected using encoders or magnetic field sensors (figure 37). In the latter case, a magnet is attached to the rotor hub. A suitable magnetic field sensor stationed near the rotor then detects the angular position and speed of the rotor. Intelligent sensor ICs can already process the measured data internally within the ICs and transmit this data as digital values to the microcontroller via a sensor bus.

For the accurate control of the motor, it is also necessary to transmit the currents in the individual drive trains to the microcontroller. Shunt resistors in the inverter are required for this, or magnetic field sensors to measure the currents. A DC/DC converter ensures the electric coupling of the 48-volt and 12-volt systems.

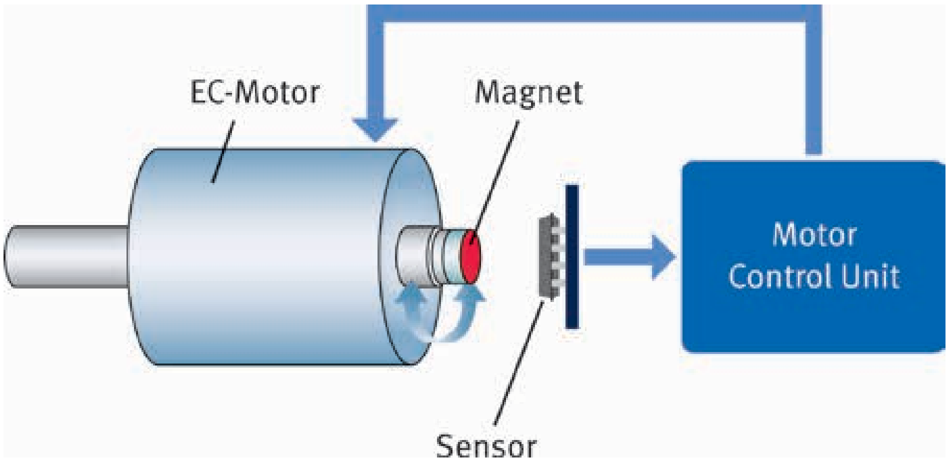


Figure 37: Rotor detection with highly-integrated magnetic field sensors (schematic illustration) – source: Infineon Technologies

Multiple options are possible for the design of a DC/DC converter depending on individual requirements. The most important requirements are:

- converter performance,
- power loss (efficiency),
- package space/volume (W/l),
- uni or bidirectional power transfer,
- galvanic coupling or separation,
- functional safety classification.

These result in different circuit topologies (single-phase, two-phase or multi-phase). The choice of converter frequency is also important. Semiconductor components such as microcontrollers, driver ICs and power output stages, supply and communication ICs are also used here to perform this function. The selection of the types depends on the definition of the parameters mentioned above. This applies particularly to the selection of power ICs and driver ICs.

3.14 Passive components

A new key application is the coupling of voltage levels with bidirectional DC/DC converters. These belong among the most important assemblies in 48-volt technology. In addition to power semiconductors, passive components such as capacitors and inductors in the converters perform key functions: they store electrical energy, smooth voltages, suppress electromagnetic interference (EMI) in circuits and in this way ensure EMC. Over and above this, the starter-generator combination in vehicles with 48-volt electrical systems also needs to be regulated during recuperation, the recovery of braking energy.

Passive components for the new 48-volt technology must meet the same high quality requirements as components used in 12-volt or 24-volt electrical systems. In particular, they must operate at a broad range of temperatures between -40 °C and +150 °C. In addition, the products deployed must demonstrate a high level of mechanical stability and be resistant to shock and vibration, while at the same time their electrical properties must remain stable in the long-term. Finally, a high degree of efficiency is also demanded of such components so that losses can be avoided. Only through such properties can the demand for DC/DC converters with efficiency levels of up to 98 per cent be met.

- **Capacitors**

  Capacitors stabilize voltages and are used as storage and smoothing elements in the DC links of converters and inverters. Aluminium electrolytic capacitors and film capacitors are the principle candidates used within these areas of application. Aluminium electrolytic capacitors (figure 28) with axial leads and rated voltages of 63 volt DC are particularly suited to 48-volt applications. They are also characterized by a highly robust design with a vibration stability of up to 45 g.

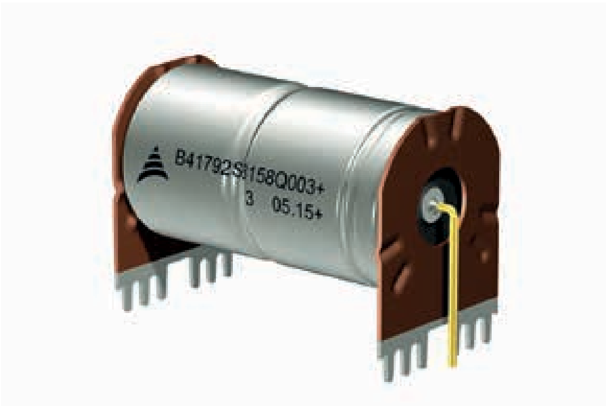


Figure 38: Aluminium electrolytic capacitor for 48-volt electrical systems – source: Epcos

Figure 39: Multi-pin film capacitor for use in DC links – source: Epcos

Film capacitors with multi-pin connectors (figure 39) also boast particularly high current capability in DC link applications. An additional function of the capacitors is EMI suppression. Again, film capacitors or multi-layer ceramic capacitors are suited for use in this constellation (figure 40).
The latter are especially suited for EMI suppression at the level of inverters or, with higher capacitance values, in the DC link in DC/DC converters.

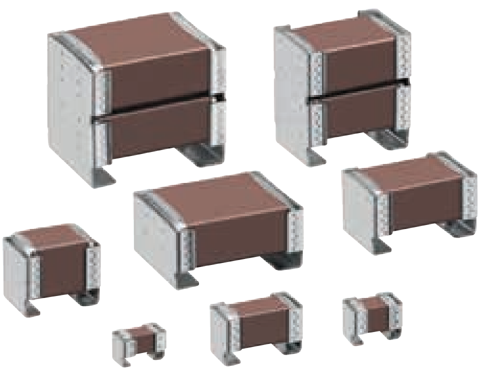


Figure 40: Ceramic capacitors are suited for use as IGBT snubbers, or as DC link capacitors in DC/DC converters – source: TDK Corporation

The most important task of power inductors (figure 41) is the short-term storage of energy in the form of magnetic energy. As storage chokes, they are key components in buck and boost converters in 48-volt electrical systems. High-power inductors can, for example, be deployed as storage chokes in DC/DC converters. Flat wire winding ensures a high copper fill factor which in turn reduces losses.

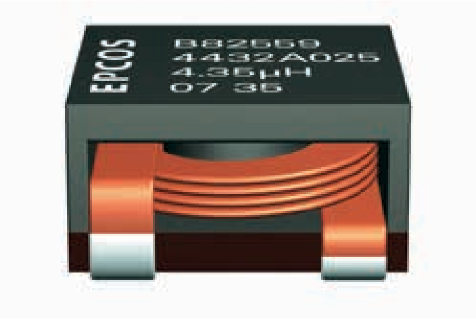


Figure 41: High-power inductor as storage choke in DC/DC converter – source: Epcos

Miniaturized SMD inductors (figure 42) serve to suppress interference currents in all assemblies in automotive electronics. These miniature power inductors are used as storage chokes in small DC/DC converters or to smooth currents in other assemblies. Their magnetic shielding ensures high electromagnetic compatibility.

Figure 42: Power inductors as storage chokes for relatively small DC/DC converters or for smoothing currents in other assemblies – source: Epcos

- **Filter chokes and common-mode chokes for EMC filtering**
  In addition to storage chokes for storing electric energy, filter chokes and common-mode chokes (figure 43) are used for EMC filtering. Solutions using nanocrystalline cores have proven effective for the common-mode chokes. Single core solutions are a good choice here because of the high currents and the resulting necessity for copper conductors used together with ring cores made from nanocrystalline ribbon wire. The high permeability of the nanocrystalline magnetic material ensures excellent smoothing over a broad range of frequencies with minimal temperature dependence.

Figure 43: Common-mode chokes (CMC) – source: Vacuumschmelze

- **Magnets**
  It is important that the overall efficiency of hybrid vehicles be as high as possible. As a result, generators and electric motors not only need to be as efficient as possible, but they must also be built in a way that saves weight. The magnets used (figure 44) play a decisive role in achieving this. New neodymium magnets offer more than 10 times the energy density of ferrite permanent magnets. These excellent values are achieved through lower oxide contamination of the magnetic material and a significantly finer microstructure.

Figure 44: Strong neodymium magnets for powerful electric motors and generators – source: TDK Corporation

4. Summary and Outlook

The introduction of an additional voltage level in vehicles offers many advantages in comparison to high-voltage hybrid vehicles. It facilitates the realisation of attractive reductions in CO_2 emissions at acceptable cost levels, and it allows features to be realised that are technically difficult to implement in today's 12-volt environment. These include electric turbo-chargers, air-conditioning compressors and various pumps that operate independently of engine speed. With features like these, it becomes possible to efficiently switch loads on and off or to trim them in the context of the applicable driving situation. The advantage lies in the optimisation of the dynamic properties of vehicles – electrically supported acceleration and environmentally friendly braking.

Drivers will immediately notice the twin benefits of increased propulsive power and simultaneously reduced fuel consumption. This is enormously significant for both luxury and compact cars.

The technical implementation of the 48-volt voltage level into the powertrain is more straightforward than the realisation of high-voltage hybrid designs, since existing powertrain concepts can largely be retained. As such, it can be assumed that developments in this area will progress rapidly to series production. Implementation will demand, of course, that components and systems are developed at every level and integrated and validated in this context. Manufacturers are already working intensively towards this goal.

5. List of Abbreviations

A
Amperes

AC
Alternating Current

Ah
Ampere-hour

BDSG
Belt-Driven Starter Generator

BEV
Battery Electric Vehicle

BG
Booster Generator

BSG
Belt-driven Starter Generator

C
Celsius

CMC-Drosseln
Common Mode Choke (stromkompensierte Drossel)

DC
Direct Current

DIN-EN
German adoption of a European Norm (EN)

EMC
Electromagnetic Compatibility

EMI
Electromagnetic Interference

EPS
Electric Power Steering

G
Generator

HSM
Hardware Security Module

HVAC
Heating, Ventilation and Air Conditioning

HV
High Voltage

HV-Hybrid
High Voltage hybrid

HVIL pilot line
High Voltage Interlock Loop pilot line

IC engine
Internal Combustion Engine

ISG
Integrated Starter Generator

kW
Kilowatt

M/G
Motor/Generator

LIN
Local Interconnect Network

MCU
Microcontroller Unit

MOSFET
Metal Oxide Semiconductor Field Effect Transistor

OEM
Original Equipment Manufacturer

PWM
Pulse-Width Modulation

RMS
Root Mean Square

S
Starter

SOC
State of Charge

SOH
State of Health

V
Volt

VDA
German Association of the Automotive Industry

VDE
German Association for Electrical, Electronic and Information Technologies

W
Watt

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