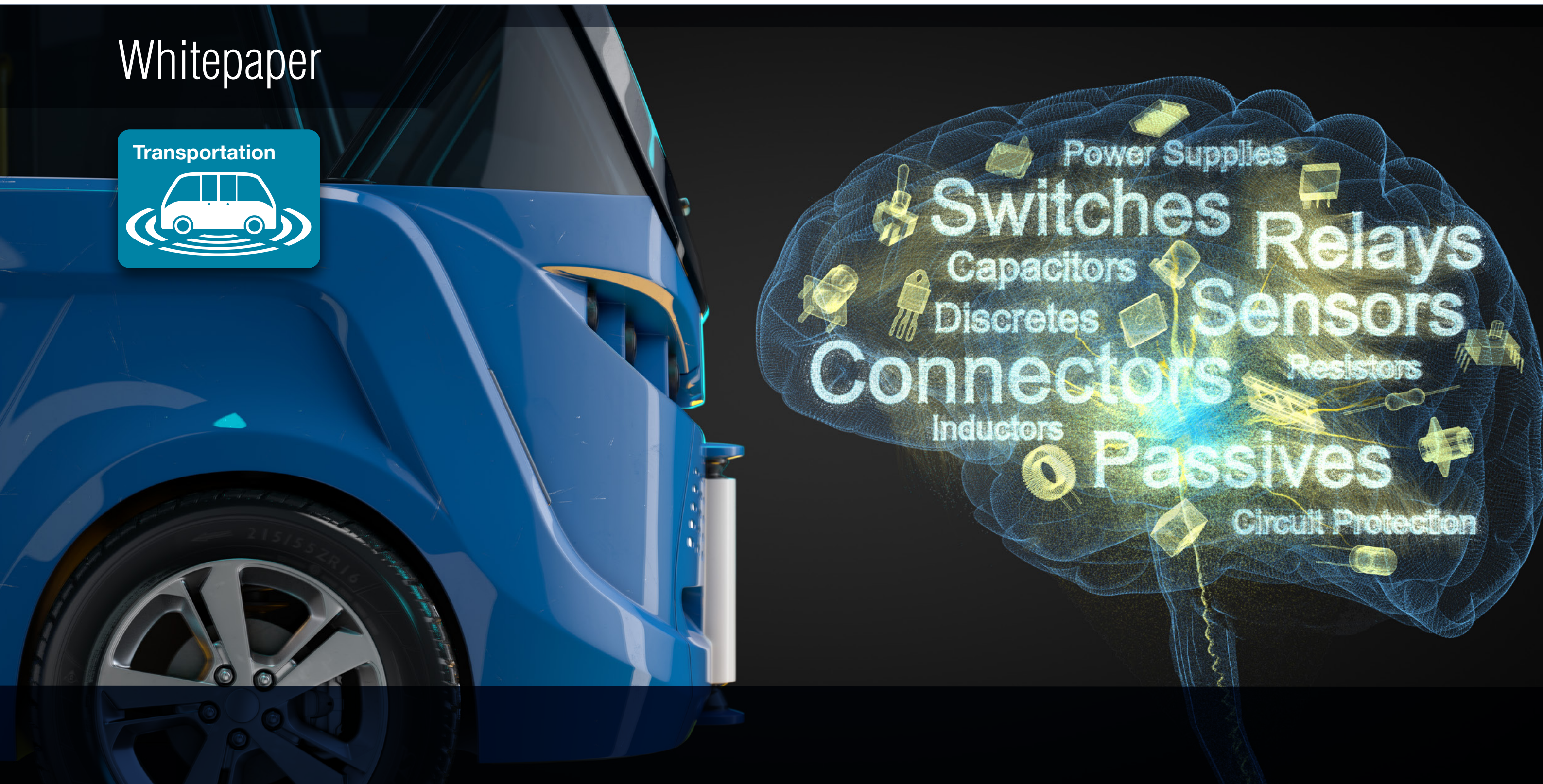
Whitepaper

Transportation



Charging Electric Vehicles

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Executive Summary

Electric vehicle batteries need to be charged either using an on-board AC-DC converter or with high voltage DC from public charging stations. Speed of charging and the energy efficiency of the process are major concerns, pushing manufacturers of charging systems to utilize the latest technologies in power conversion with the best of components. This white paper examines some of the challenges and their solutions available today.

Introduction

The electrification of vehicles is in full swing across Europe. As consumers, we are probably well aware of the various campaigns and initiatives governments and other national state authorities are promoting to lessen our dependence on fossil fuelled transportation. These apply not only to our automobiles but to a wide range of vehicles on our roads, including commercial vehicles such as vans and trucks, public transit vehicles such as buses and coaches in addition to the many specialist vehicles used in agricultural and construction.

Fundamental to the design of an electric-powered vehicle is the provision of a method of charging the vehicle's batteries. This can be achieved two ways: EVs are equipped with an onboard charger that requires an AC mains input that is converted to DC for charging the batteries. This AC source is a dedicated EV charging station or a domestic AC outlet located within the owner's home or at their place of work. The other approach is to use a fast charging station that can deliver a high current DC to charge the batteries directly in the vehicle. Thanks to the Combined Charging System (CCS)/CharIN, a standard plug and socket arrangement found on most electric vehicles today, both methods of charging are possible.

In this white paper we investigate the architecture of electric vehicle chargers, the types of functions involved and some of the many electronic components (MOSFETS, passives, rectifiers, magnetics) used in the design of on- and off-board charging systems. Interconnection is an essential part of provisioning an AC or DC supply, so example connectors are also highlighted from leading manufacturers such as Amphenol, ITT Cannon and TE Connectivity. This whitepaper covers the Combined Charging System & CharIN initiative and highlights the trend towards high current DC charging, and in particular, the emerging trend of having even higher current capacity through liquid cooled cables. In the final part of the whitepaper, the emphasis is on high current charging stations, the design of a DC Fast Charger (TDK) and the other connector standards that are starting to be used including the CHAdeMO standard supplied by manufacturers like JAE.

Electric-Car Boom

The move away from fossil fuels for transport is accelerating with the increased introduction of electrically powered vehicles. Most are very aware of the high-profile manufacturers specializing in EVs such as Tesla, but the traditional vehicle suppliers are also in the game. Volkswagen, for example, plans to be producing around 50 different battery-electric models across its 12 auto brands by 2025. Even muscle cars are morphing into EV SUVs with a Ford 'Mustang'-like all electric offering coming in soon. How many more could you name? Figure 1 shows the scale of what's planned through 2020.

Models by style and range available through 2020

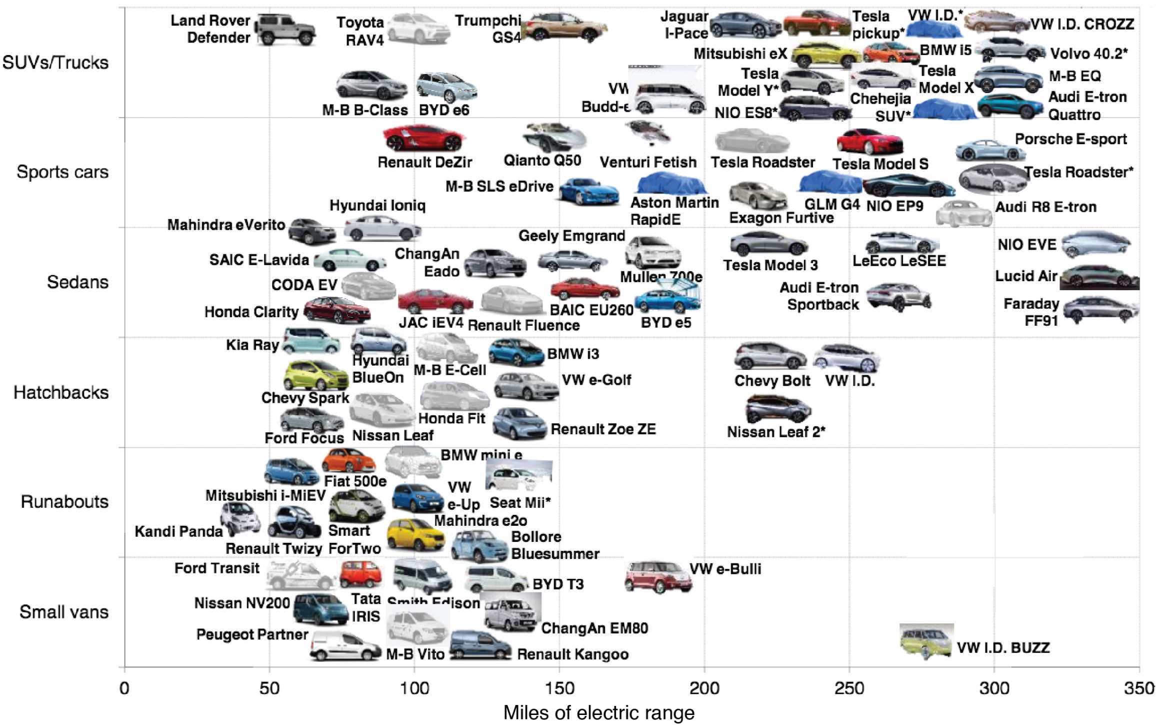


Figure 1: Electric car models by style and range available through 2020 – source Bloomberg - https://www.bloomberg.com/news/articles/2017-04-25/electric-car-boom-seen-triggering-peak-oil-demand-in-2030s

This is just cars; vans, buses, trucks, agricultural and construction vehicles are being increasingly battery powered as well, not to mention rail and even aircraft from companies such as start-up Wright Electric with 180 seat airliners planned for 2027 for European short-haul flights.

For vehicles, there are of course various degrees of electrification from Full to mild/micro hybrid with differing architectures for battery charging and traction. There is normally the option to charge from a domestic or work-place AC source through an on-board charger or with high voltage, high power DC directly to the traction batteries from roadside or fuelling station outlets. Although quicker and more efficient, the high infrastructure cost of high voltage/power DC charging is unlikely to replace on-board AC input charging for the average user so both are likely to feature for the foreseeable future. AC charging can still however be relatively quick - with 3-phase installations, where available, it can be up to around 22kW rating for standard industrial 400V/32A connections. Single phase domestic supplies are limited to around 3kW for standard 230V/13A outlets or 7.5kW for 32A. Given that EV batteries are sized between 10kWh and 40kWh (Tesla up to 100kWh), charging from these AC sources can be as slow as 10 hours or as quick as around 40 minutes for 30kWh batteries. As a guide, 30kWh equates to about 100 miles/160 km range.

High voltage DC charging can be much faster, with outlets rated at 120kW giving a little more than 15 minutes charge time for 30kWh batteries with inefficiencies factored in, faster than a coffee break at a gas station. Table 1 gives a summary.

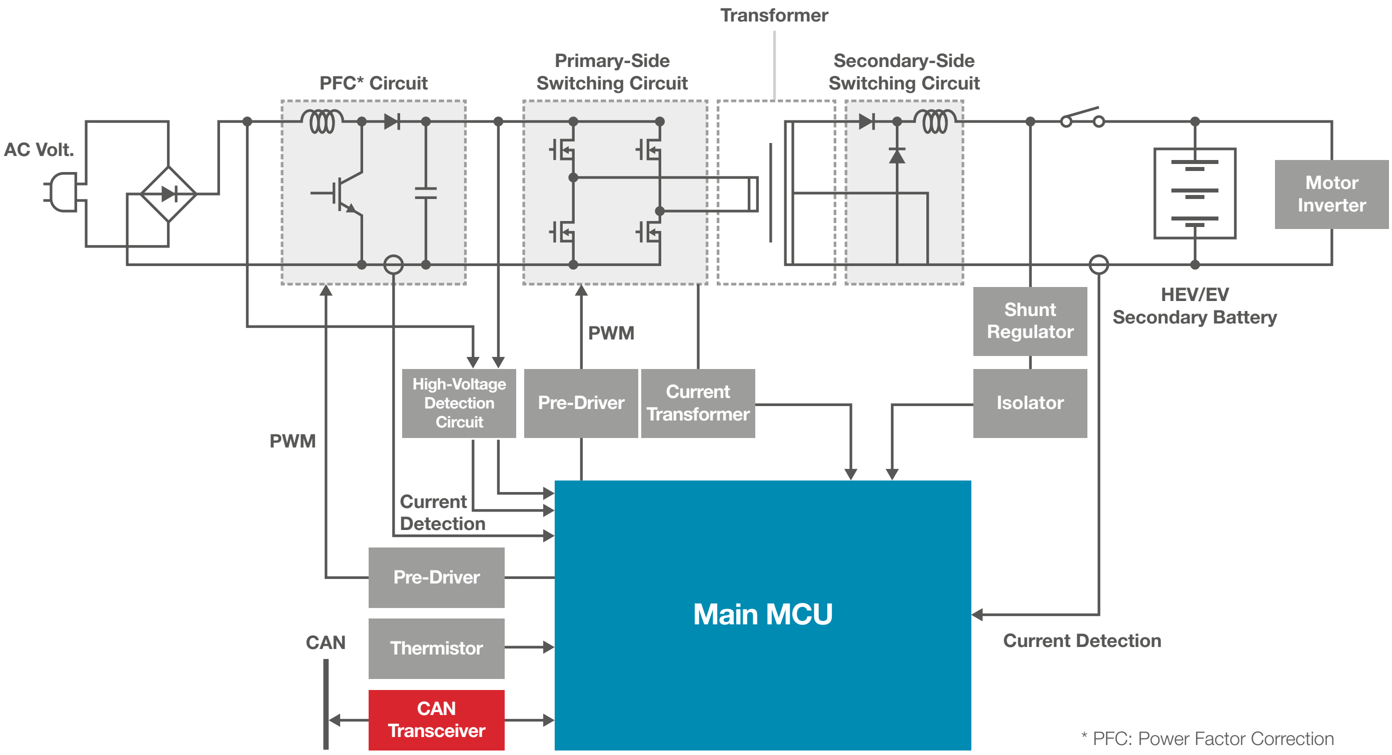
Table 1: Approximate time to charge EVs from different sources (source - Spirit Energy)

Supply Type/Charger rating		**AC/DC**	**Rated Power kW**	**Time to charge 10kW**	**Time to charge 30kW**
Standard 13A socket	Slow	AC	3.0	3h 20m	10 hours
Single ph 16A	Slow	AC	3.7	2h 40m	8 hours
Single ph 32A	Fast	AC	7.4	1h 20m	4 hours
3-phase 16A/ph	Fast	AC	11	55 mins	2h 45m
3-phase 32A/ph	Fast	AC	22	27 mins	1h 22m
3-phase 60A/ph	Rapid	AC	43	14 mins	42 mins
DC	Rapid	DC	50	12 mins	36 mins
DC	Rapid	DC	120	5 mins	15 mins

AC input on-board chargers

There are various ways of implementing it[1], but a first-generation single-phase AC input on-board charger block schematic might look like Figure 2, a relatively conventional switched mode power supply with power factor correction (PFC) – a scaled up version of a desktop PC power supply. The principle is that AC is rectified to high voltage DC, 'chopped' at high frequency which is then passed through a transformer whose output is scaled and rectified to high voltage DC for the battery, typically 400V. As with the lithium-ion batteries in your cell phone, the voltage applied and the current allowed has to be carefully controlled to prevent stress and maximize battery life/run time. The power factor correction stage is necessary to meet legislation which mandates that line current has to be taken sinusoidally which would not be the case otherwise. Three-phase AC input versions exist for some cars that are compatible such as the Tesla varieties and the supply is likely to be at a workplace rather than a domestic location which only has easy access to single-phase power.

Figure 2: AC-DC on-board charger block schematic (source TTI)



In practice, modern on-board chargers have evolved for better efficiency and to enable the possibility of bi-directional power flow. There are economic benefits available to users who allow utilities to draw power back from the car battery through the on-board charger 'in reverse'. This allows a degree of grid energy storage that utilities can call upon, for example during the night when the car is plugged in with a full battery. As intermittent alternative energy sources such as solar and wind become a larger part of the mix, this forms a valuable grid 'back up' which utility suppliers will pay for.

In a bi-directional converter, the rectifier and PFC stages merge typically into a 'totem pole PFC' arrangement with high voltage MOSFETs, perhaps from the Vishay range of automotive-qualified parts. MOSFETs are also used for the main conversion stage and to replace the output diodes in Figure 2 to form synchronous rectifiers, again necessary for bi-directional power flow. Vishay again has parts that might be used.

Like semiconductors, passive components in the circuit need automotive AEC-Q qualification and range from resistors through capacitors, fuses magnetics and discrete components. The automotive environment is fraught with EMI problems, so extensive protection against voltage and current transients is needed. Littelfuse specialize in protection components in automotive applications with a range of devices for over-current, over-voltage and ESD protection. Capacitors, and all varieties of passive components are available from Vishay and AVX with AEC-Q qualification, and Nichicon, a company well known for their electrolytic capacitor offering may also have suitable types. Magnetic parts such as transformers and inductors are often custom-made for the application but standard parts are available from Vishay and companies such as Pulse and Standex-Meder. Planar types are often favored for their power density and ease of heatsinking – a particular problem in automotive where electronics is often sealed or even encapsulated to provide environmental protection.

Size and weight of the on-board charger are important issues – it is wasteful to use battery energy to pull around heavy electronics and cabin space is always maximized, so new semiconductor technology is being introduced in the form of 'wide band-gap devices' fabricated with Silicon Carbide (SiC) or even Gallium Nitride (GaN) materials. These devices can switch much faster than older Silicon (Si) types while keeping losses low. High frequency switching then allows smaller passive components; particularly magnetics. Smaller size and fewer losses directly lead to material savings in the form of smaller heatsinks and component costs while occupying a smaller footprint within the vehicle. SiC devices are available as diodes from TT Electronics for example, as well as switches. TT Electronics is also a source of AEC-Q qualified magnetics.

DC charging stations use similar conversion techniques

Figure 3: High voltage DC charging station (source ABB)

High voltage DC charging stations use a similar technology for converting utility power to the traction battery voltage, but at much higher power levels, Figure 3. The AC input will invariably be 3-phase, but bi-directionality is not a requirement, as roadside stations will always be required just to provide power to the vehicle. Efficiency of the charging process is, as ever, important for energy savings, but size and weight not so much so, as is the case for on-board chargers. The charging station may therefore use relatively low frequency switching for low losses using IGBTs as switches rather than MOSFETs.

Connections are key

With so many EV manufacturers across the world with varieties of single-phase or three-phase AC and DC charging options with different power capabilities, connections between charging source and the vehicle have been an issue. In 2011, a 'Combined Charging System' or CCS was proposed for a single connector pattern that could be used worldwide and is now formalized under IEC 62196, 'Plugs, socket-outlets, vehicle connectors and vehicle inlets – Conductive charging of electric vehicles'. An association of car makers, suppliers and interested parties, the 'Charging Interface Initiative' or CharIN[2] was also set up to promote CCS. The first CCS compliant charging stations were rated at 50kW, but that was increased to 150kW in 2015 with plans for 350kW and perhaps higher in the future. The features of CCS include communications over a dedicated connection, the Control Pilot contact (CP), which ensure that connectors are fully mated before charging starts and that the source and vehicle capacities match. Basic signaling (BS) according to IEC 61851-1 uses a Pulse Width Modulation (PWM) signal to achieve simple functions while High Level Communication (HLC) based on DIN 70121 and the ISO/IEC 15118 series allows for more complexity such as scheduling of the charge rate for grid load-balancing. There are other competing standards for DC charging connections: CHAdeMO[3] in Japan and a GB/T standard used in the important Chinese market.

Feature	CCS 1.0	CCS 2.0
Power	< 80kW	< 350kW
Voltage	< 400V	200 - 1000V
Current	< 200A	< 500A
Vehicle Connector	Combo 1 or 2 (IEC 62196-3)	Combo 1 or 2 (IEC 62196-3)
Vehicle Inlet	Combo 1 or 2 (IEC 62196-3)	Combo 1 or 2 (IEC 62196-3)
Charging Communication	High Level Communication: • DIN SPEC 70121:2014	High Level Communication: • DIN SPEC 70121:2014 (< 80kW) • ISO/IEC 15118-2:2014 ED1 (<350 kW) • ISO/IEC 15118-3:2015 ED1 (<350 kW)
Load Balancing	Reactive	Reactive and Scheduled
Charge Authorization Mode	External Payment	External Payment and/or Plug and Charge (mandatory from 2020 on)
Charging Station	IEC 61851-23	IEC 61851-23

Table 2: CCS system specifications for DC charging

Table 3: CCS specifications for AC charging

Feature	CCS 1.0	CCS 2.0
Vehicle Connector	Type 1 or 2 (IEC 62196-2)	Type 1 or 2 (IEC 62196-2)
Vehicle Inlet	Type 1 or 2 (IEC 62196-2) Combo 1 or 2 (IEC 62196-3)	Type 1 or 2 (IEC 62196-2) Combo 1 or 2 (IEC 62196-3)
Charging Communication	Basic Signalling: • IEC 61851-1:2010 ED2 High Level Communication: • ISO/IEC 15118-2:2014 ED1 • ISO/IEC 15118-3:2015 ED1	Basic Signalling: • IEC 61851-1:2010 ED2 High Level Communication: • ISO/IEC 15118-2:2014 ED1 • ISO/IEC 15118-3:2015 ED1
Load Balancing	With Basic Signalling only: • Reactive With High Level Communication: • Reactive and/or • Scheduled	With Basic Signalling only: • Reactive With High Level Communication: • Reactive and/or • Scheduled
Charge Authorization Mode	With Basic Signalling only: • External Payment With High Level Communication: • External Payment and/or • Plug and Charge	With Basic Signalling only: • External Payment With High Level Communication: • External Payment and/or • Plug and Charge (mandatory from 2020 on)
Charging Station	IEC 61851-1	IEC 61851-1

Tables 2 and 3 (source – Wikipedia[3]) summarize CCS specifications. CCS 1.0 is current and CCS 2.0 is the next version for higher power and more features.

Connector types stated in the tables are 'Type 1, Type 2 and Combo 1, Combo 2. CCS originally was based on Type 1, a North American standard for single-phase AC connection and Type 2, as described in European standard IEC 62196-2, able to charge with three-phase AC. For combined high voltage DC and AC charging, new connector designs were adopted: Combo 1 and 2 associated with Type 1 and 2. Power inlets on vehicles have all pins populated corresponding to the charge possibilities while couplers, the connectors on the charging cable, just have the pins fitted for that source: AC or DC. Invalid combinations such as a Combo 1 coupler and an AC only inlet do not mechanically mate. Tables 4 and 5 show the combinations. (Source - Wikipedia).

Inlet/Connector	TYPE 1 	COMBO 1 
TYPE 1 	AC Charging Single Phase	Does not mate
COMBO 1 	AC Charging Single Phase	DC Charging

Table 4: Mating options for Type 1 and Combo 1 couplers

Inlet/Connector	TYPE 1 	COMBO 1 
TYPE 1 	AC Charging Single Phase or Three Phase	Does not mate
COMBO 1 	AC Charging Single Phase or Three Phase	DC Charging

Table 5: Mating options for Type 2 and Combo 2 couplers

Couplers and inlets must be very sturdy to withstand everyday outdoor use, so manufacturers such as Amphenol have designed their parts for more than 10,000 cycles (unloaded). Their Excel Mate CC -200A IEC Combo parts are rated for 63A AC and 200A DC with IP44 environmental protection rating (mated). Phoenix Contact have versions of both Type 1 and Type 2 inlets rated up to 32A/480V three-phase and 200A/850V DC while Aptiv (formerly Delphi) have a wide range of automotive connectors including Type 1, Type 2 and versions for the Chinese GB/T standard. TE Connectivity is another major player in the market.

Future connector and cable technology

Consumers want ever-faster charging rates, so charger powers of 500kW (0.5 MW) are planned giving potentially 60 miles/100km of range within three to five minutes charging. This corresponds to a current of about 500A at 1000V DC presenting tough challenges to connector and cable design. A proposed solution developed by ITT Cannon is liquid cooling using an environmentally friendly hydrofluorether. The coolant is routed through the electrical cable, into the connector and round the contacts, providing such effective cooling that cable diameter and losses can be kept low along with flexibility and low weight for ease of handling. Versions are available for CCS Type 1 and 2.

For all cables and connectors, safety is a prime concern, not only for mis-mating but also for insulation against the dangerous voltages present. Signaling in the connectors provides interlocks so that power is not applied until the connector is fully mated, sealed and with contacts then inaccessible. Connector manufacturers have to guarantee this level of safety even in the potentially harsh environments of outdoor use worldwide. Well-known manufacturers such as those mentioned can be relied upon to give this guarantee with parts supplied through established distribution[2].

Three-phase fast DC chargers

The fractional-megawatt charging rates proposed cannot practically be supplied as AC to vehicles since the on-board AC-DC converter would be prohibitively large and expensive, so DC input straight to the battery through an on-board charge controller is the only solution. Domestic or kerb-side fast chargers with three-phase input and DC output are often modular in construction so that capacity can be added as necessary. The Tesla design for example, has more than ten, 10kW power units to achieve >100kW. The design might look like Figure 4, typically with some blocks common to the 'stack' such as AC-DC rectification, EMI filtering and protection such as contactors to rapidly connect and disconnect power under fault conditions. The main isolation and conversion stage noted as 'DC-DC HF Rectifier' is duplicated to achieve the desired power level and will typically be a full bridge resonant topology for maximum conversion efficiency. Output rectifiers although shown diagrammatically as diodes, will often be MOSFETs configured as synchronous rectifiers, again for the lower losses incurred: a 20kW module at 400V DC output will source 50 amps which would cause around 100W dissipation in a regular diode bridge.

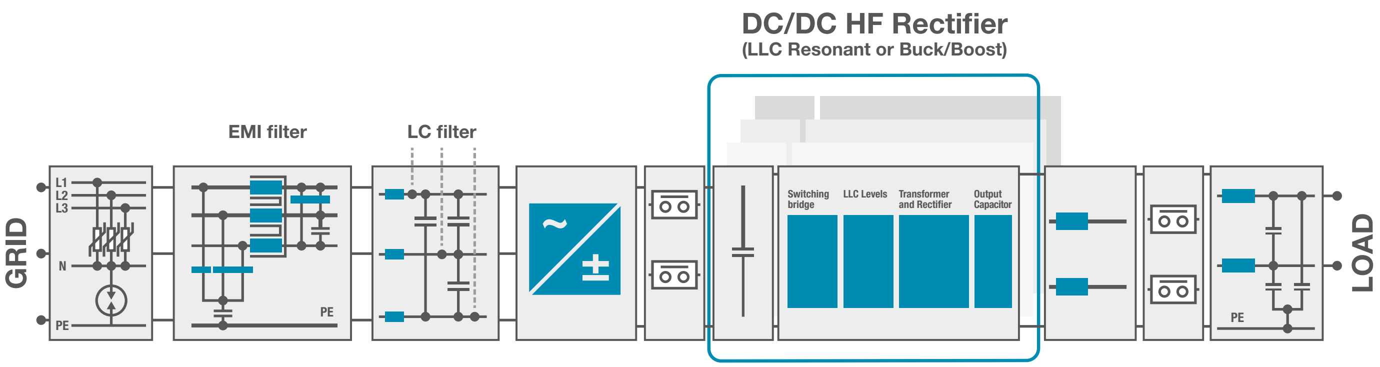


Figure 4: Modular three-phase fast charger outline (source TDK)

As with on-board chargers, power factor correction is necessary for efficiency and statutory reasons and will again be typically a 'totem pole PFC' arrangement, which effectively combines AC rectification with the switches required for power factor control, minimizing losses. EMI filtering is an important feature as, again, there are statutory limits to comply with. TDK has a wide range of passive components that find application in this circuit from EMI suppression components such as chokes and X/Y capacitors through power capacitors for energy storage and snubbers, to protection components such as sensors and high voltage contactors.

Conclusion

The comparisons between re-fuelling an internal combustion engine and an electric vehicle could not be more extreme. Both involve a hazardous operation but with EVs, there is the added complication of AC or DC charging, differing power levels and the different standards of connectors on the vehicle and charging station. The CCS system with its Combi connectors is allowing convergence with a degree of future proofing, with innovations such as liquid cooling of cables and connectors. The technology advances hold out the possibility of significant charge/range being available, with automated payment, within minutes – about the same time as it might take to fill a tank with gas, grab a coffee and queue to pay. Major manufacturers have made components for both on- and off-board charging systems available with distributors such as TTI providing application support and stockholding.

[1] *Ivan Subotic, Nandor Bodo, E. Levi , Boris Dumnic, Dragan Milicevic, Vladimir Katic: 'Overview of fast on-board integrated battery chargers for electric vehicles based on multiphase machines and power electronics': IET Electr. Power Appl., pp. 1–13: 24th August 2015*

[2] *https://www.charinev.org*

[3] *https://www.chademo.com*

[4] *https://en.wikipedia.org/wiki/Combined_Charging_System*

[5] *TTI Europe www.ttieurope.com*

About TTI

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