



Key aspects to enable multi-megawatt fast charging

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Received: 25 February 2022 / Accepted: 18 May 2022 / Published online: 21 June 2022
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Abstract At present, the mobility sector in Europe is in the middle of a transition phase. Combustion engine-based vehicles (CV) are meant to be replaced by electric vehicles of the same type in order to fulfill the zero emissions targets within the next decades. This requires a collaborative approach from the industry, research institutes, and national governments in order to prepare both the necessary vehicle technology and infrastructure accordingly. Even though various attractive charging solutions in the hundreds of kilowatt range already exist commercially, heavy-duty vehicle charging in the multi-megawatt range is still a topic to be investigated in more detail in the scientific community. Therefore, this publication discusses different strategies to enable fast charging in the megawatt range and presents a concept that is directly connected to the medium voltage grid while enabling distributed charging and an optimized carbon footprint due to the adoption of renewable energy systems.

Keywords Multi-megawatt fast charging · Medium voltage · Charging infrastructure · Wide bandgap semiconductors

Schlüsselaspekte zur Umsetzung des Multi-Megawatt-Schnellladens

Zusammenfassung Derzeit befindet sich der Mobilitätssektor in Europa inmitten einer Transformationsphase. Fahrzeuge mit Verbrennungsmotor sollen durch Elektrofahrzeuge desselben Typs ersetzt wer-

den, um die vorgegebenen Emissionsziele innerhalb der nächsten Jahrzehnte zu erreichen. Dies erfordert ein gemeinsames Vorgehen von Industrie, Forschungsinstituten und Politik, um sowohl die dafür notwendige Fahrzeugtechnologie als auch Infrastruktur entsprechend vorzubereiten. Obwohl bereits verschiedene attraktive Ladelösungen im Bereich hunderter Kilowatt kommerziell existieren, ist das Laden von Schwerfahrzeugen ein Thema, das in der wissenschaftlichen Gemeinschaft noch genauer untersucht werden muss. Daher werden in dieser Publikation verschiedene Strategien zur Umsetzung des Schnellladens im Megawattbereich untersucht und ein Konzept vorgestellt, welches Schnellladen direkt über das Mittelspannungsnetz erlaubt. Dabei sollen bekannte Konzepte wie verteiltes Laden und eine verbesserte CO₂-Bilanz durch den Einsatz erneuerbarer Energiesysteme ebenfalls ermöglicht werden.

Schlüsselwörter Multi-Megawatt-Schnellladen · Mittelspannung · Ladeinfrastruktur · Wide Bandgap-Halbleiter

1 Introduction

Due to the worldwide growing impact of climate change and the thereby intensifying social pressure on policymakers and industry to reduce GHG emissions, various national and international initiatives, mission targets and funding frames, which are focusing on the reduction of CO₂ emissions, evolved. Some examples are European high-level targets such as the EU 2020 climate and energy package or programmes such as “The Green Deal” [1] and the “Circular Action Plan” [2]. The “Green Deal Initiative”, such as presented in [3] and [4] claims that the transportation sector is responsible for roughly 25% of the EU’s GHG emissions. This coincides with a recent publication (Austria’s

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Annual Greenhouse Gas Inventory 1990–2017) from the Environment Agency Austria (Umweltbundesamt, Österreich) published in 2019. There, it is mentioned that transportation as sub-sector of the energy sector contributed to the total national GHG-emissions by around 29% in 2017 (energy sector: 68% of all GHG-emissions, and transportation as subsector: 43%). In addition, it is worth noting that heavy-duty vehicles are responsible for nearly 5% of the overall GHG emissions in the EU and represent about 27% of CO₂ emissions from road transport. Thus, to cover charging of a wide range of different cars (from private cars, vans up to heavy duty vehicles), new charging infrastructure approaches are required, which allow a smart integration into the existing energy system and at the same time provide varying charging power capability from kilowatt to multi-megawatt to serve the demand of different vehicle types. The trend for electric vehicle (EV) fast charging is clearly pointing towards higher voltage and current levels for battery stacks and battery charging, to enable higher power ratings and to reduce the effective charging time per vehicle. Especially multi-megawatt fast charging is seen as the next big milestone for electrified 40 t trucks and busses in order to reduce downtimes of fleets, number of vehicles and required staff (hence cost) of such fleets. The non-availability of the EV for 20 min up to even several hours whilst charging, is still seen as one of the major weaknesses of EVs compared to the classical combustion engine-based crafts.

This is supported by an example comparing two different types of cars (CV and EV) as commercially available, a VW Passat B6 2.0TDI and a Tesla Model S. The VW Passat comes with a fuel tank capacity of 70 L and a range of approximately 1000 km average driving distance (dependent on driving behaviour, weather conditions etc.). Public gas stations in general allow a flow rate of 26 L per minute which is the assumed estimate for the given case at hand. Thus, refuelling the CV will take 2–3 min. In comparison to the CV, its fully electrical competitor, as for example a Tesla Model S, comes with a battery capacity of 100 kWh, all-wheel drive (AWD) and a range of 671 km NEDC (new European driving cycle). This results in an average energy consumption of 14.9 kWh/100 km. In order to reach a charging time of 2–3 min for a range of 1000 km (upscaled—currently not existing), a charging power of 3–4.5 MW would be required under the assumption that a battery pack with dedicated capacity and power rating would exist for such a Tesla Model S. The battery pack of a Tesla Model S is operating at a nominal voltage level of approximately 400 V. A charging power of 3 MW would result in current ratings of up to 7.5 kA, which would lead to unrealistic cable cross sections of 25 cm² if a current density of 3 A/mm² (uncooled) is assumed. This would lead to an unreasonably high copper weight of 45 kg per meter cable (including two round copper bars for positive and negative bus and

a unity weight of 8940 kg per m³ copper). This clearly shows utilizing multi-megawatt fast charging requires higher operating voltage levels to reduce the current stress and volume of bus bars, cables, connectors etc. Thus, two things are key to successfully implement multi-megawatt fast charging:

- Batteries with even higher nominal voltage levels than today's 800 V batteries need to become commercially available for electric vehicles.
- If a standard charging concept via cables is preferred, the cable must include at least a water-cooling concept to further reduce the required copper cross section (current density of e.g., 10 A/mm² or even higher)

Due to the high amount of volume that would be required to implement a 1 kV₊ battery with megawatt charging capability, this type of ultra-fast charging is irrelevant for passenger cars due to space constraints but more attractive for busses and trucks.

In this paper a smart charging infrastructure and relevant considerations during a first design phase will be discussed. This is addressing power electronic architectures, different components and the effect of integrated DC technologies such as renewable energy systems.

2 Charging concepts

In general, all charging concepts can be classified into two main categories—wireless and conductive charging—and several dedicated subtypes. The difference between wireless and conductive charging is, that for wireless charging no wired connections between the power source and the battery to be charged is required. Conductive charging, however, requires a physical connection via cables, wires, contactors etc. between source and battery. The low, medium or high frequency transformer that is prerequisite to fulfil given safety standards is seen as conductive element within the definition of a conductive charger.

2.1 Low voltage wireless charging

A generic setup of a wireless charging station is defined by the following energy conversion stages:

- AC/DC rectifier (bidirectional/unidirectional)
- Transmitter (resonant DC/AC converter stage)

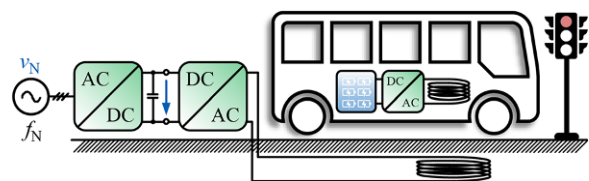


Fig. 1 Simplified block diagram of a static wireless charging principle based on [5]

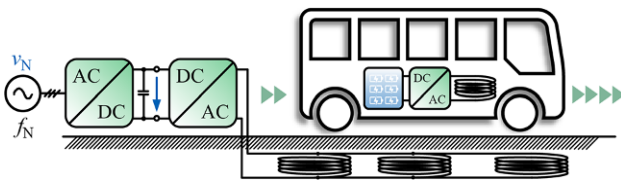


Fig. 2 Dynamic WPT for bus or car in motion whilst battery getting charged as discussed in [6]

- Receiver (AC/DC rectifier)—bidirectional/unidirectional
- DC/DC converter (optional)—bidirectional/unidirectional

The basic schematic is illustrated in Fig. 1. The power transfer is based on electromagnetic induction. It has to be noted that the primary and secondary side coil are based on air core technology. As no magnetic core is involved to couple primary and secondary side, grid connected AC/DC converter, high frequency transmitter coil and dedicated power stage are utilized off-board (not located on the electric vehicle) whereas receiver coil, high frequency rectification and optional step-up or step-down DC/DC stage are carried within the vehicle.

The main advantage of wireless charging concepts is to get rid of heavy, bulky and long cables and plugs. Eventually, it should be noted that wireless charging can be further split into 2 different subgroups:

- Static Wireless Power Transfer (WPT) and
- Dynamic WPT.

The difference between static and dynamic WPT (illustrated in Fig. 2) is the motional aspect of the vehicle. For static WPT the electric vehicle must be parked or at least remain still whilst charging within a specific labelled area. Dynamic WPT concepts on the other hand can charge EVs while it is moving on a WPT ready road. In general, power ratings of commercially available solutions based on wireless charging are ranging from several kilowatts to approximately 22 kW. Each converter stage shows a rather high energy efficiency (in general ranging from 94–98%, depending on switching frequency, power density etc.). However, increasing the power level of wireless chargers beyond 22 kW appears so far to be impractical as system losses are dependent on a high coupling factor of transmitter and receiver coil, which heavily relies on the charged vehicles positioning. Based on the EVs mispositioning and thus the misalignment of both transmitter and receiver coil, the total system efficiency can drop even below 90%. This issue could be improved when utilizing automated driving and/or artificial intelligence for optimal positioning in static (as discussed in [7]) or dynamic (see [8]) wireless charging. Also, hybrid solutions (inductive+capacitive wireless charging) have been introduced in [9], to reduce the negative impact

adhering to this positioning predicament. However, this type of hybridization and dedicated control, results in much higher complexity compared to standard topologies. More importantly, it should be noted, that despite the aforementioned drawbacks and limitations related to wireless charging, it is mentioned in [10], that a 300 kW wireless charging infrastructure has been developed as well. Thus, it is expected that wireless charging will see a further technology push and market adoption during the transformation phase towards electromobility. However, it can be concluded that wireless charging technology is at present not a competitive candidate for multi-megawatt fast charging due to obvious limitations.

2.2 Low voltage conductive charging

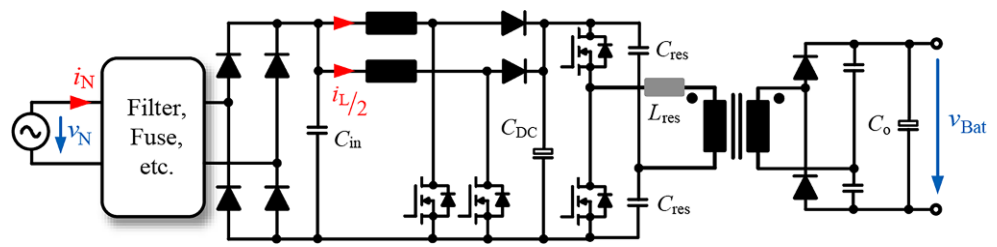
For conductive charging a wired connection between the supply and the battery to be charged exists. In addition, a transformer (primary and secondary side coupled via a magnetic material/core) provides isolation between the source and the load for safety reasons and additional protection. Conductive chargers are realized as either on- or off-board solutions. On-board chargers are typically used for vehicles where charging powers in the lower kW range are still sufficient. The on-board charger benefits from the extensive amount of single-phase and three-phase power outlets available in public buildings or private homes. On-board chargers are currently limited to a charging power of around 43 kW to minimize weight, volume, cost, improve life cycle assessment figures (i.e. CO₂ footprint) and still taking advantage of available 16 A, 32 A or 63 A AC-connectors. Therefore, charging power of different on-board configurations and **AC-chargers** is restricted to AC equipment characteristics and categorized as per IEC 61851-1 or [11]:

- **mode 1–1 ph.:** 3.3 kW (single phase, 240 V, 16 A)
- **mode 1–3 ph.:** 10 kW (three phase, 400 V, 16 A)
- **mode 2–1 ph.:** 7 kW (single phase, 240 V, 32 A)
- **mode 2–3 ph.:** 24 kW (three phase, 400 V, 32 A)
- **mode 3:** 43 kW (three phase, 400 V, 63 A)

Due to the rather low charging power, lifetime reduction due to battery temperature or heating effects are not as relevant as for high-power off-board charging solutions.

On-board chargers for low voltage equipment in the hundreds of watts up to the very view kilowatt range are typically realized via a diode bridge rectifier followed by a boost power factor correction stage to guarantee sinusoidal mains currents while minimizing manufacturing cost. As the DC-link voltage provided via the PFC stage is generally limited in terms of voltage swings (absolute minimum DC voltage $V_{DC} = V_{N,pk}$; typically operating at around $V_{DC} = 16/13 V_{N,pk}$, which corresponds to 400 V for a 230 V_{rms} AC input) an additional isolated DC/DC converter is required to charge batteries with lower voltage ratings

Fig. 3 Typical power electronics setup of a three-phase on-board or off-board battery charger



(e.g. 48V battery systems). This DC/DC converter includes a DC/AC converter followed by a medium or high frequency transformer for isolation and a secondary side AC/DC rectifier. The system intrinsically benefits from the fundamental step-down characteristics which can be specifically designed via the primary-to-secondary winding ratio of the transformer. There are various topologies available to realize such an isolated DC/DC converter. Some prominent examples are the unidirectional LLC converter which is based on resonant setup or the bidirectional dual active bridge converter (DAB). One state of the art solution that is currently found in most single-phase battery chargers for power ratings higher than 75 W is illustrated in Fig. 3.

For higher power levels (mode 1–3 ph. or 7 kW₊), both on-board and off-board chargers are transitioning towards three-phase grid-connected power stages. As 3-phase plugs are not as commonly accessible as their single-phase counterparts, AC-chargers with standardized connector types have been developed. The off board AC-charger wall box only consists of protective circuits and metering equipment, whereas the on-board power electronics is based on the aforementioned three-phase AC/DC power stage, followed by an isolated DC/DC converter based on a similar solution as discussed beforehand.

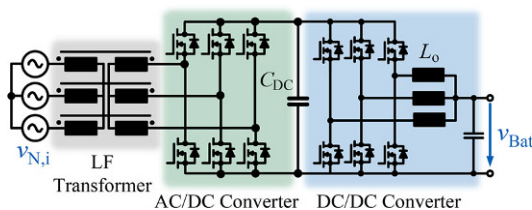


Fig. 4 Topology example of a DC-fast charger for a nominal power in the tens of kW range

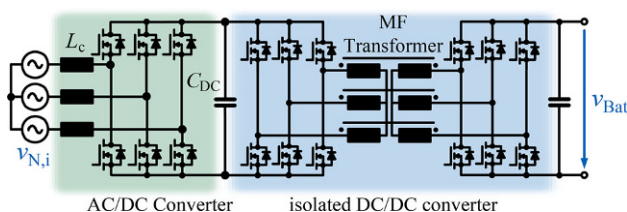


Fig. 5 Topology example of a DC-fast charger for a nominal power in the tens of kW range employing a three-phase dual active bridge converter

In comparison to on-board chargers, where the electrical isolation is realized via medium or high-frequency transformers, high power off-board chargers (100 kW₊) are prone to guarantee electrical safety via 50/60 Hz transformers. (Fig. 4).

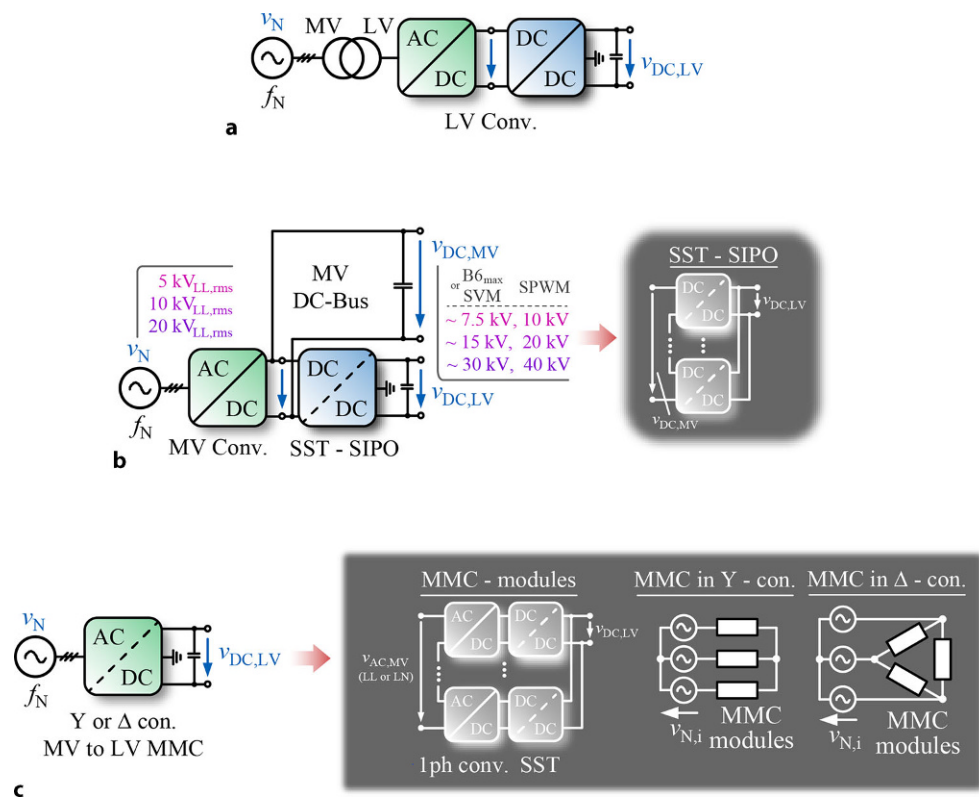
These high-power **DC fast chargers** are already commercially available for power levels of up to 500 kW (DC/DC fast charger) and research projects are already running, innovating on solutions for even higher charging power. Nonetheless, also, in the 100 kW+ power range medium frequency transformers can be an attractive solution to optimize power density. One example could be the three-phase DAB converter (shown in Fig. 5). Besides benefits such as bidirectional behaviour, low volume and weight, one of the main drawbacks of the three-phase DAB is the imbalance of transformer parasitics such as leakage inductances leading to unbalanced currents and unevenly disturbed current stress of semiconductors. Therefore, an increased effort in terms of controls is required to guarantee balanced currents and reduce their impact on the performance of the system (discussed in [12]).

In order to harmonize established DC fast-charging strategies, common standards have been established. Especially in the field of cabling and connectors many different standards already exist. Some of the most relevant ones are listed in [13] and defined as follows:

- **GB/T 20234.3-2015 (China, India):** for DC-charging up to approx. **250 kW** (950 V, 250 A).
- **CHAdeMO 2.0 (global):** for DC-charging up to approx. **400 kW** (1000 V, 400 A). Liquid cooled cables are required to process the dedicated power.
- **CCS1 (US):** for DC-charging up to approx. **500 kW** (1000 V, 500 A). Liquid cooled cables are required to process the dedicated power.
- **CCS2 (EU, South Korea, Australia):** for DC-charging up to approx. **500 kW** (1000 V, 500 A). Liquid cooled cables are required to process the dedicated power.
- **Tesla (Global):** for DC-charging up to approx. **250 kW** (410 V, 610 A). Liquid cooled cables are required to process the dedicated power.

As previously mentioned, many different research projects are heading towards higher charging power and voltages already. Therefore, also new standards considering even higher voltages and currents are already under development:

Fig. 6 Different architectures for medium voltage based multi-megawatt fast charging. **a** Via a medium-voltage to low-voltage transformer followed by low-voltage converter stages. **b** Employing a medium voltage rectifier with dedicated solid-state transformer. **c** Utilizing modular multi cell converters with dedicated solid-state transformer



- **New GB/T standard:** for DC-charging up to approx. **900 kW** (1500 V, 600 A). Liquid cooled cables are required to process the dedicated power.
- **CHAdemo 3.0 or Chaoji-2** (global): for DC-charging up to approx. **500 kW** (max. 1500 V, max. 600 A). Liquid cooled cables are required to process the dedicated power.
- **HPCVC:** for DC-charging up to approx. **3–4.5 MW** (1500 V, 2000–3000 A). Liquid cooled cables are required to process the dedicated power.

3 Medium voltage multi-megawatt fast charging

3.1 Architectures, concepts and topologies

The previous sections so far identified two relevant insights:

1. According to international efforts there is an upcoming demand for multi-megawatt fast chargers and/or dedicated equipment.
2. Due to this high charging power in the multi-megawatt range, battery voltages of 400 V would result in unreasonably high currents and therefore it can be expected that batteries for such applications will evolve beyond even the currently adopted 800 V voltage class.

Furthermore, connecting multi-megawatt charging equipment to the low voltage grid (e.g. 400 V_{LL,rms}) will negatively affect nearby loads and can also impact the grid stability at the point of common coupling.

Therefore, one solution to safely deploy megawatt fast charging is via connecting the power electronics conversion stages to the medium voltage grid.

In general, there are three different types of architectures available to connect the power electronics circuit to the medium voltage grid. The basic concept is shown in Fig. 6a–c. The most commonly and thus state-of-the-art approach is illustrated in Fig. 6a. A medium voltage-to-low-voltage transformer is converting the input voltage to lower voltage levels where commercially available active or passive semiconductor with blocking voltages of up to 1200 V are applicable. The major benefit is simplicity as standard control concepts can be applied and converters merely need to be paralleled if semiconductor modules with available current ratings still do not meet the system requirements. The drawback of this concept is, that it relies on a low frequency transformer which has to process the full power at the mains frequency (50 Hz for European grid applications). Due to the rather low fundamental frequency such a transformer comes with high volume and is therefore not suitable for those applications and locations with space restriction or infrastructure limitations. Therefore, Fig. 6b and c depict two alternatives which are based on a direct connection of the power electronics converter to the medium voltage grid. Fig. 6b is based on a medium voltage rectifier.

This rectifier forms a medium voltage DC-link ($v_{DC,MV}$). The voltage level of this DC-link depends on the topology and modulation strategy and will be dis-

cussed in more detail in the upcoming section. Some initial values for different solutions and grid voltage levels are already indicated in Fig. 6b. For all scenarios, the DC-link voltage is higher than the grids line-to-line voltage. Therefore, an additional DC/DC stage is required to re-convert the medium voltage DC-link to a voltage level that equals or is lower than 1.5 kV. Furthermore, isolation requirements still need to be fulfilled. Thus, a medium frequency transformer must be utilized within the DC/DC converter. This type of solution is also known as solid state transformer (SST). The DC/DC converter consists of two separate power stages. Similar to the previously discussed LLC or DAB solution the SST consists of a DC/AC circuit to transform the DC input voltage to an AC signal with high switching frequency followed by the medium- or high-frequency transformer and a dedicated AC/DC power stage. In order to sustain the total voltage of $v_{DC,MV}$, several SSTs must be connected in series at

the primary side of the transformer. To form a low voltage and high current output, the secondary side of all converters must be connected in parallel. Therefore, this concept is also denoted as SIPO (serial input parallel output).

Fig. 6c illustrates a second version of a medium voltage rectifier-based on SST technology. This architecture is utilized by several low voltage or medium voltage converter modules, where each module consists of a single-phase rectifier and dedicated solid state transformer for isolation purposes. These modules are then implemented in SIPO configuration. Due to the modularity of the concept, it is also designated as modular multilevel converter (MMC). As already highlighted in Fig. 6c, the MMCs can be connected in star (Y)- (generating their own artificial star point) or delta (Δ)-configuration (each MMC branch connected between two mains phases). Due to the modular origin of the setup, modules can be easily extended and

Fig. 7 Different architectures for power electronics, directly coupled to the medium voltage grid. **a** and **b** Medium-voltage AC/DC rectifier followed by solid-state transformers in SIPO configuration with and without additional non-isolated DC/DC charger, respectively. SIPO connected modules including an AC/DC rectifier and solid-state transformer in **c** STAR and **d** DELTA configuration

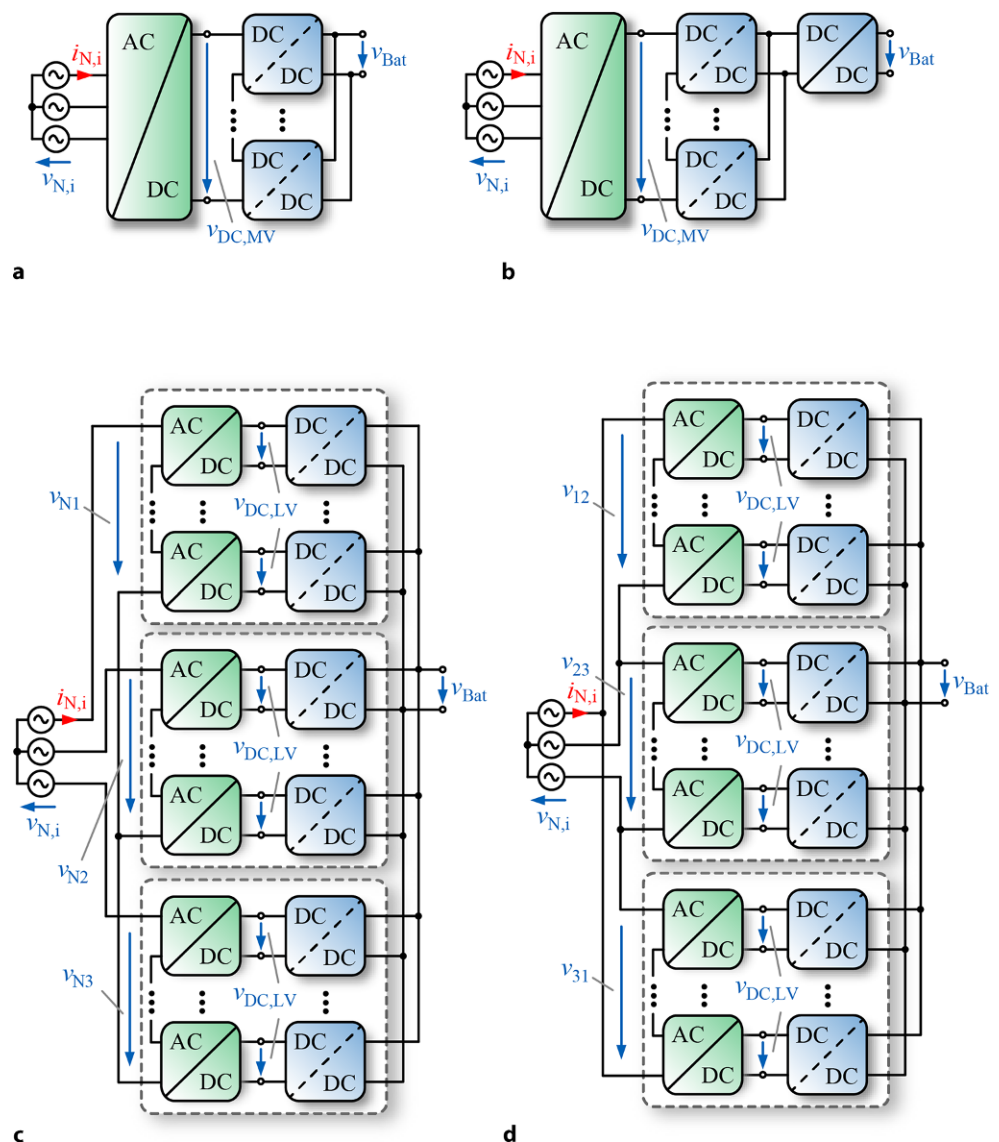
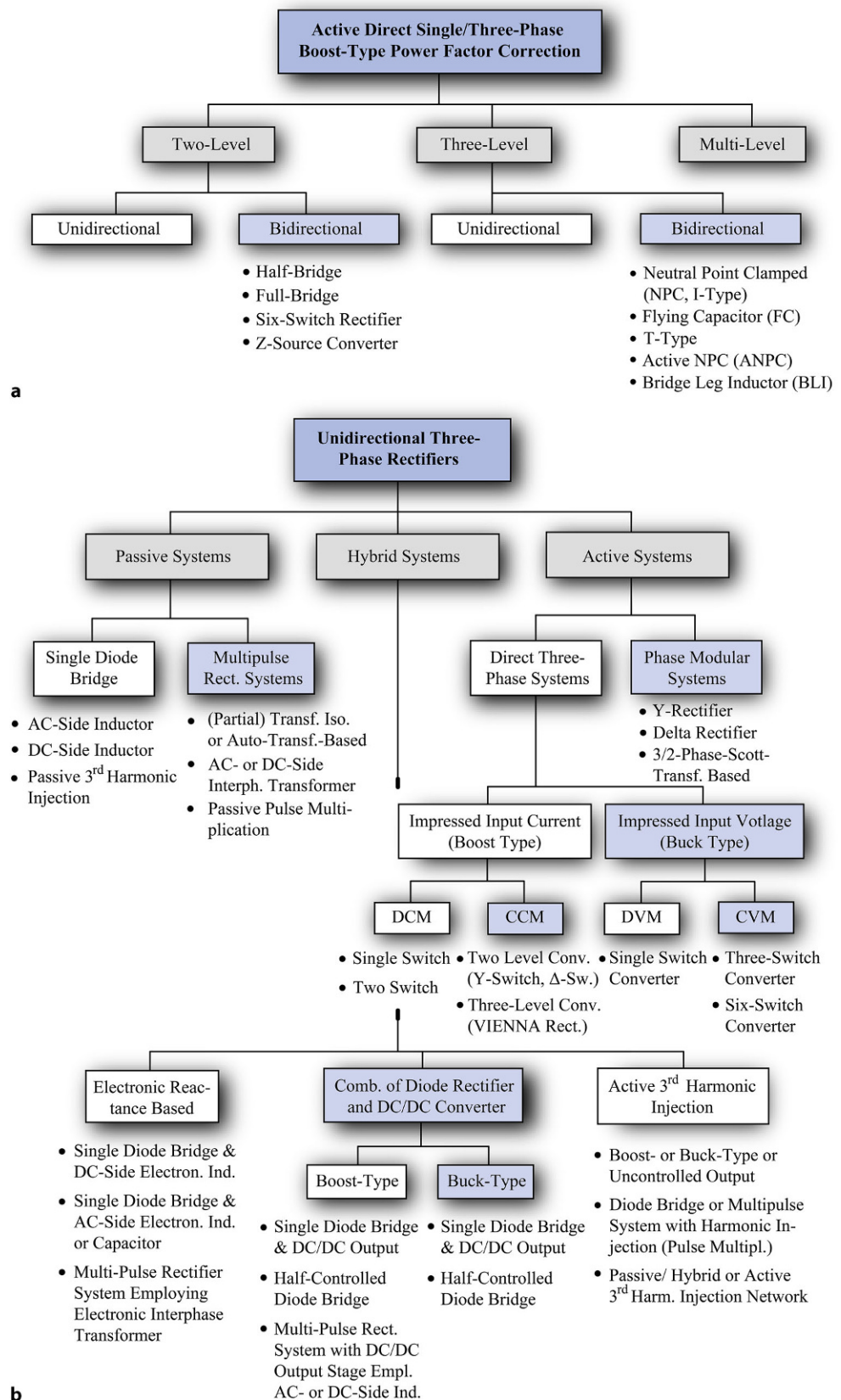


Fig. 8 Different active direct boost type (a) and (b) unidirectional three-phase solutions for low voltage grids as possible solutions for medium voltage module-based solutions (as published in [14])



stacked for higher voltage levels, as long as the integrated solid-state transformer is able to sustain the required isolation between primary- and secondary-side of the medium/high-frequency transformer. This also applies for the SST-SIPO power stage from Fig. 6b. Additionally, the reliability of the modular converter stages scales and improves with additional modules that can be activated or disabled if one or more of the original modules observe any type of malfunction (short circuit, lifetime of modules due to high temperature etc.).

A more detailed implementation of the medium voltage-based concepts as illustrated in Fig. 6b and c are shown in Fig. 7a–d. Fig. 7a and b are depicting two different versions of a setup of medium voltage rectifiers and dedicated SST-SIPO based DC/DC converters. In general, a version such as highlighted in Fig. 7a, already fulfils EV charging requirements a CC/CV charging via can be implemented within a superimposed controller. However, this solution normally comes with power limitations if a wide output voltage range is preferred (e.g., from 200–1500 V), assuming that the multi-megawatt charger should service also distributed charging (various types of cars and busses with lower power and voltage ratings). In order to overcome power and efficiency limitations, additional (non-)isolated and interleaved buck or buck-boost type high-power DC/DC converters (one for each parking slot) provide additional flexibility (cf., Fig. 7b). This also simplifies the control of the SST SIPO converter as it merely needs to keep a fixed voltage level at its output as for example 1.2 kV.

An MMC SIPO SST based solution in Y- and Δ -configuration is depicted in Fig. 7c and d, respectively. As previously mentioned, the major difference between both solutions is the connection of the three-phase power stage with reference to the mains grid. In Y-connection (Fig. 7c) a virtual neutral point is generated. This results in a lower peak-to-peak voltage at the input of each MMC branch ($V_Y = V_{\Delta}/\sqrt{3}$) compared to the Δ version. However, it should be noted, that if the single-phase input stage utilizes purely passive diode rectification, the Y-configuration is prone to circulating currents which are injected via adjacent branches of opposing mains lines. These circulating currents elicit additional losses within each power stages. Therefore, rectifiers with power factor correction operability are recommended. Regarding Δ -based MMCs, processed currents of each module are lower compared to their Y-connected counterparts, due to the higher input voltage.

Based on the aforementioned architectures, a set of relevant and most feasible topologies has been derived. The topologies are reflected in Fig. 8a and b. In principle most topologies as already known from low-voltage solutions and can be extended for medium voltage operability.

The most prominent examples for the different architecture types are:

Three-phase medium voltage rectifiers:

- Three-phase diode bridge rectifier (unidirectional)
- Third harmonic injection concepts (unidirectional)
- MMC converter (bidirectional)
- Multi-level NPC converter (bidirectional) or similar types

Single-phase AC/DC rectifiers for MMC converters:

- Single-phase diode rectifier (unidirectional)
- Single-phase diode rectifier + PFC circuit (unidirectional)
- Full bridge (bidirectional)
- Multi-level converters (bidirectional)

Isolated DC/DC converters for SST SIPO solutions:

- LLC converter (unidirectional)
- Dual active bridge, single-phase or three-phase (bidirectional)

Non-isolated interleaved DC/DC converters for IV charging extensions:

- Buck converter (unidirectional)
- Boost converter (unidirectional)
- Buck-boost converter (unidirectional)
- Half-bridge-based buck converter (bidirectional)
- Half-bridge-based boost converter (bidirectional)
- Half-bridge-based buck-boost converter (bidirectional)

3.2 Voltage class requirements for medium voltage architectures

In order to better understand the applicability of the three different main architecture types (MV rectifier, MMC Star, MMC Delta), for various grid voltages (5 kV_{LL}–30 kV_{LL}) the total DC-link voltages for each architecture and different topologies are investigated. These voltage levels are relevant for the transformer design as each medium-voltage medium-frequency transformer must be able to withstand the full DC-link voltage in case of a short circuit event or critical malfunction. In order to reliably benchmark the three-different architectures in terms of DC-bus voltage, they have been further split into two sub-categories, namely passive and active solutions. For active three-phase medium voltage rectifiers there are additional modulation strategies available that directly impact the minimum DC-link voltage required when operating directly at the three-phase grid. Thus, for this comparison the standard pulse width modulation (PWM) and a space vector modulation including 3rd harmonic injection (SV3) are considered. The respective equations to derive the different voltage levels for the maximum voltage of a B6 rectifier ($V_{DC,B6,max}$), the DC-bus voltage of an medium voltage rectifier based on standard PWM ($V_{DC,Act,PWM}$) and the DC-link voltage of a medium

voltage rectifier operating in SV3-mode ($V_{DC,Act,SV3}$) are defined as follows:

$$V_{DC,B6,max} = V_{LL,rms}\sqrt{2} \quad (1)$$

$$V_{DC,Act,PWM} = V_{LL,rms} \frac{2}{M_{PWM}} \sqrt{\frac{2}{3}} \quad (2)$$

$$V_{DC,Act,SV3} = V_{LL,rms} \frac{1}{\sqrt{3} \cdot M_{SV3}} \quad (3)$$

M_{PWM} and M_{SV} denote the modulation index for a standard PWM and a space vector modulation including 3rd harmonic injection principle, respectively. Standard values of 0.8125 and 1.088 were applied for the corresponding parameters M_{PWM} and M_{SV3} in this study.

Delta- and Star-connected MMC rectifiers rely on single phase strategies. Therefore, the total DC-link voltage can be derived on single-phase formulas, while utilizing the three-phase line-to-line voltage as representative parameter. Hence, the sum of the nominal DC-link voltages of N modules connected in series results in

$$\sum V_{DC,\Delta/Y,B4,max} = V_{LL,rms} \sqrt{\frac{2}{3}} \quad (4)$$

$$\sum V_{DC,\Delta/Y,PFC} = V_{LL,rms} \frac{1}{M_{PWM}} \sqrt{\frac{2}{3}} \quad (5)$$

$$\sum V_{DC,\Delta/Y,ML} = V_{LL,rms} \frac{2}{M_{PWM}} \sqrt{\frac{2}{3}} \quad (6)$$

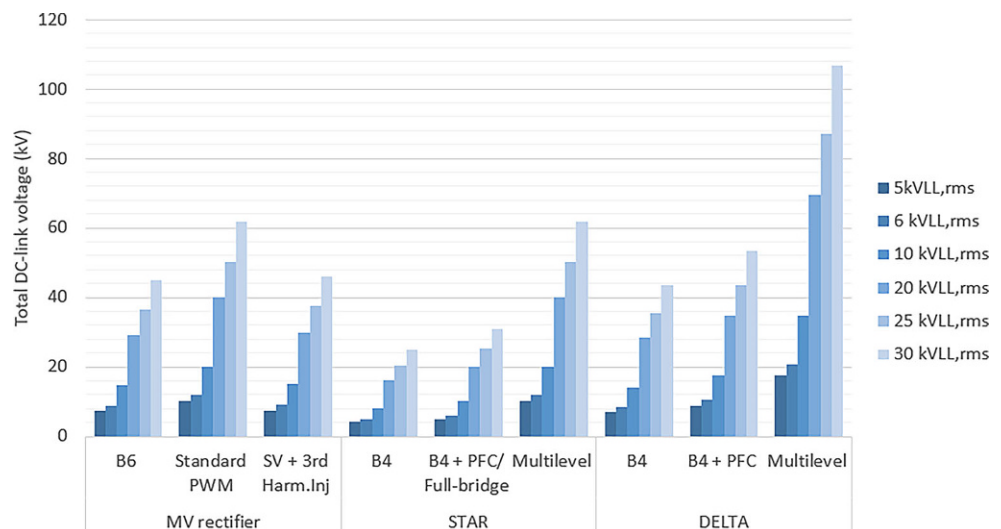
for passive rectification with ($\sum V_{DC,\Delta/Y,PFC}$) and without ($\sum V_{DC,\Delta/Y,B4,max}$) power factor correction circuits and multi-level topologies ($\sum V_{DC,\Delta/Y,ML}$). Those parameters as highlighted in red are an additional conversion factor that must be taken into account when transferring the equations from Delta- to Star-connected MMC topologies. The results of the derived equations for the three different architectures and their defined subsets

are illustrated in Fig. 9. Obviously, the MMC rectifier in delta-connection appears to be impractical for medium voltage converters above mains voltages of 10 kV_{LL,rms} or higher, as they result in a distinctly higher cell and power semiconductor count, implementation effort and exacerbate transformer isolation requirements. The MMC Y-based solution on the other hand shows the lowest DC-link voltage levels when comparing it to the remaining two architectures. If multi-level circuits such as the NPC or T-type converter are incorporated within a MMC rectifier setup, the required DC-link voltage is higher compared to B4, full-bridge or PFC solutions.

Furthermore, based on the aforementioned insights, also a first set of considerations for a medium frequency transformer for medium voltage applications can be derived:

1. Each transformer must be isolated to withstand the full DC-link voltage. This consequently results in the design guideline, that the number of cells should be always chosen to remain at a local minimum. Thus, for each converter cell, semiconductors should be implemented with at a blocking voltage of at least 1.2 kV or higher (ideally 3.3 kV if available). If 10 kV SiC-MOSFETs will be commercially available within the next years they might be the most competitive choice to optimize both, the transformer, and the converter cell design.
2. The leakage inductance of the transformer should be as low as possible to minimize the voltage drop at the output of the isolated DC/DC converter and maximizes the output power for e.g. DAB solutions. The effect of the parasitic inductance is less relevant if either (i) the DC-link voltage per cell is further increased, (ii) a low operational current or (iii) a low operational frequency is implemented.
3. According to (1) and (2), currently silicon (Si) and silicon carbide (SiC) based semiconductors such as

Fig. 9 Total DC-link voltage levels based on different architectures (MV rectifier, MMC Star, MMC Delta) and topologies (passive, active and different types of modulation)



Si-IGBTs or SiC-MOSFETs are required for an optimized design. Due to the restrictions regarding the transformer design, and the fact that Gallium Nitride (GaN) HEMTs (high electron mobility transistor) are currently only commercially available for blocking voltages less than 650 V, they are at present not seen as feasible solution for these types of architectures, even though they would allow a higher switching frequency. However, this can change of course already in the near futures when 1.2 kV+ parts become available.

4. 3-phase transformers can introduce an intrinsic conversion factor without changing the primary-to-secondary side winding ratio.

3.3 Low-frequency vs. medium-frequency transformers

The main advantages of the low-frequency MV/LV transformer are the clearly defined isolation against the medium voltage grid, forming a low voltage output, featuring a high efficiency and reliability as well as coming with long lifetime. However, there are several drawbacks adhering to such transformers as well. For high power applications the volume of the transformer is linearly scaling with the nominal power of the system (shown in Fig. 10). Due to the low fundamental frequency of the transferred energy which must be processed by the transformer, the volume of the required core, and chassis for proper mounting result in a large volume and weight which is severely affecting the power density of the total setup.

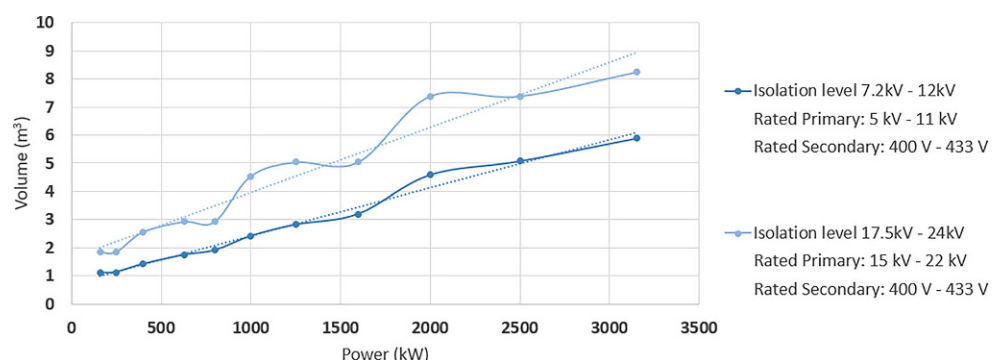
This can be critical especially for applications with space constraints. Another aspect to consider is the high current at the output of the transformer due to the transformer scaling law ($I_{\text{prim}}/I_{\text{sec}} = N_{\text{sec}}/N_{\text{prim}}$ – where I_{prim} , I_{sec} , N_{prim} and N_{sec} are denoting primary and secondary currents and windings, respectively). In order to process those high secondary side currents and minimize losses due to wiring, much more copper is required compared to a setup which relies on higher voltage levels. Thus, substituting the low frequency transformer via solid state transformers will shift the isolation to a different power electronics stage, namely the isolated DC/DC converter. There the power will be

processed at a higher frequency (in the kHz+ range) and results in a reduction of volume and weight of such a transformer. The transformer box volume V_T is related to the area product which is related to the cross section of the core and the cross section of the copper winding window. The peak flux density is furthermore dependent on the loss density $P_{\text{core}}/V_{\text{core}}$ which is in general specified in the datasheet of the magnetic core. The loss density can then be fixed to a maximum efficiency and specific temperature constraints. As discussed in [15], a **10× increase in switching frequency, results in a volume and weight reduction by a factor of 4–5**. Moreover, volume and weight are decreasing with increasing switching frequency until both performance indices reach a local minimum, which is in this specific case of [15] for low power DC/DC converters located at approximately 400–600 kHz and is normally even lower for standard switched mode power supplies (SMPS). After that local minimum, volume and weight are starting to increase again as the maximum flux density for a fixed loss density is decreasing steeper than the switching frequency is increasing. Furthermore, it must be considered that those medium frequency transformers as discussed in [15] are based on low voltage applications. The turn-over for medium-voltage medium-frequency transformers is expected to appear at lower frequencies due to stricter isolation demand per transformer. However, still a higher power density can be expected compared to a conventional design based on a MV/LV transformer if the following design rule is considered:

$$V_{Tr,MF} = \frac{V_{Tr,50Hz}}{N_C M_B k_{fsw}} \quad (7)$$

$V_{Tr,MF}$ indicates the maximum target volume for a SST transformer, $V_{Tr,50Hz}$ denotes the volume of a competitive MV/LV 50 Hz transformer, N_C and M_B are highlighting number of cells in series and total branches in parallel, and k_{fsw} resulting in the conversion factor of reduced volume due to a higher operating switching frequency.

Fig. 10 Volume of MV/LV transformers dependent on their nominal power rating and primary-side input voltage specification (dark blue: 5–11 kV, light blue: 17.5–24 kV)



3.4 Wide band gap technology and its role in medium-voltage multi-megawatt fast charging

There are various power electronic topologies, control and modulation strategies to operate the architectures as presented in Fig. 6. In all of these different scenarios, the **power semiconductor and its characteristics play a crucial role in terms of efficient and reliable implementation.**

Therefore, to design a multi-megawatt medium-voltage fast charger most efficiently and with optimized power density, also latest wide bandgap (WBG) materials and technology (Silicon Carbide—SiC; Gallium Nitride—GaN) must be taken into account in the development process. As very well-known from literature, silicon-based semiconductors (Si-based IGBTs, MOSFETs, Cool-MOS, diodes etc.) have been dominating the power electronics market to date and probably still prevail within the upcoming years. However, during the last decades, two new different breeds of power semiconductors based on wide bandgap materials (in this case specifically referring to SiC MOSFETs and diodes and GaN high electron mobility transistors) reached market readiness and are already commercially available for different power and blocking voltage levels. Based on their physical material properties and compared to Si devices, both GaN and SiC materials come with a higher critical electric field, larger energy bandgap, thermal conductivity (for SiC) or maximum electron velocity. An overview of relevant material parameters is illustrated in a radar diagram in Fig. 11.

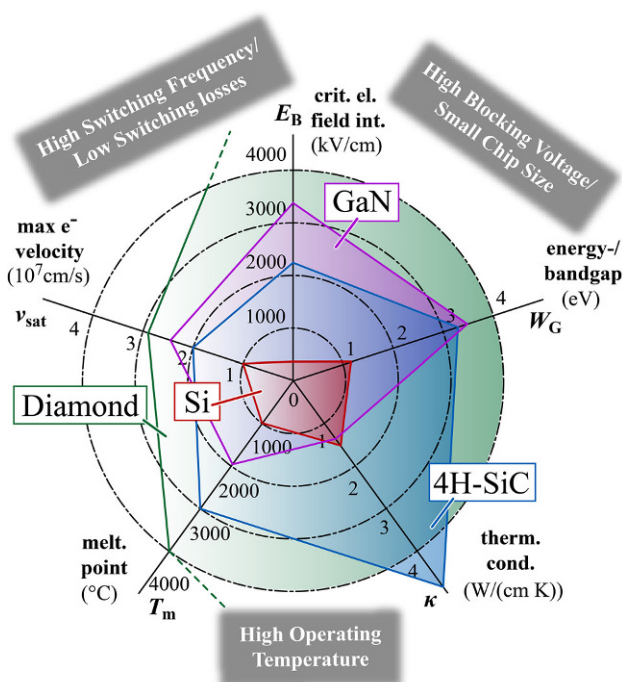


Fig. 11 Radar chart including most relevant physical parameters of Si, SiC, GaN and diamond as extended version from [16]

The relevance of these key property distinctions is briefly discussed in the following:

- Critical electric field intensity (E_B) and energy-/ bandgap (W_G): A large value of these two parameters is beneficial when it comes down to either utilize semiconductors with high blocking voltage capability or rather small chip size. As GaN and SiC both show a higher value in terms of critical electric field intensity and bandgap compared to silicon it can be expected that a matured device of both technologies can be manufactured either more compact in terms of chip size at the same current and voltage blocking ratings or would result in a higher blocking voltage with a fixed chip size for Si and WBG solutions. As for example looking at SiC power semiconductors, there is already a wide variety of components commercially available. These devices are ranging from 600V to 3.3kV and even up to several hundreds of amps in terms of current handling capability. 10kV SiC MOSFET product samples can be already purchased from different suppliers. Furthermore, 10kV₊ SiC MOSFETs and even IGBTs including dedicated packages are under development. GaN HEMTs are currently available for voltage classes only up to 650V.
- Thermal conductivity (κ) and melting point (T_m): These two characteristics are indicating the temperature handling of the semiconductor. Therefore, a large value prefigures a higher maximum junction temperature and thermal conductivity. However, this also results in new challenges for packaging materials.
- maximum electron velocity (v_{SAT}): For a smaller chip size, higher maximum electron velocity of a component in general would enable a higher maximum switching frequency (f_{sw}) at a similar or the same efficiency level compared to a device with lower v_{SAT} values. On the other hand, if the switching frequency is fixed, devices with higher v_{SAT} would allow increased power system efficiency and smaller heatsink requirements.

For SiC MOSFETs there are at present devices commercially available with blocking voltages of 650V, 900V, 1.2kV, 1.7kV and 3.3kV. GaN Transistors however can be currently solely found in the low voltage area (e.g. 15V, 100V, 200V, 650V). Due to the aforementioned advantages of WBG over Si, an efficiency increase and consequently a reduction in power consumption of WBG devices can be expected, which equally results in a factored decrease of CO₂ emissions. However, there is no rule of thumb to derive a general efficiency, power density or GHG emission improvement, as these characteristics mainly depend on various factors such as the application, system parameters, topologies, operating-modes, switching operation, control strategies, and especially the live cycle/end-user behaviour itself. Therefore, it always must be investigated in detail based on pre-require-

ments whether WBG can unleash its full potential for a specific application i.e., medium-voltage based multi-megawatt fast charging.

4 RES and their role for multimegawatt fast charging concepts

Due to their low carbon footprint in terms of CO₂ eq/kWh compared to the supplied energy drawn from the grid, the integration of renewable energy sources (RES) can play an important role when it comes down to an optimization of the carbon footprint of EV technology. The low-voltage DC-bus at the output of the

megawatt charger allows the smart efficient integration of DC-technologies such as solar, battery storage or other DC technologies (cf., Fig. 12). Thus, the megawatt station can even act as low voltage DC-hub for future power grids and also offers a MV DC interface (if a medium voltage rectifier is implemented). Based on the grid voltage level and the power electronics converter there are different types of DC-link voltages and output voltages that can be achieved. On each of the DC-bus connections, DC-technology could be introduced. Depending on the approach (medium voltage rectifier, SST-SIPO or MMC) different types of interoperable connections do exist. Es-

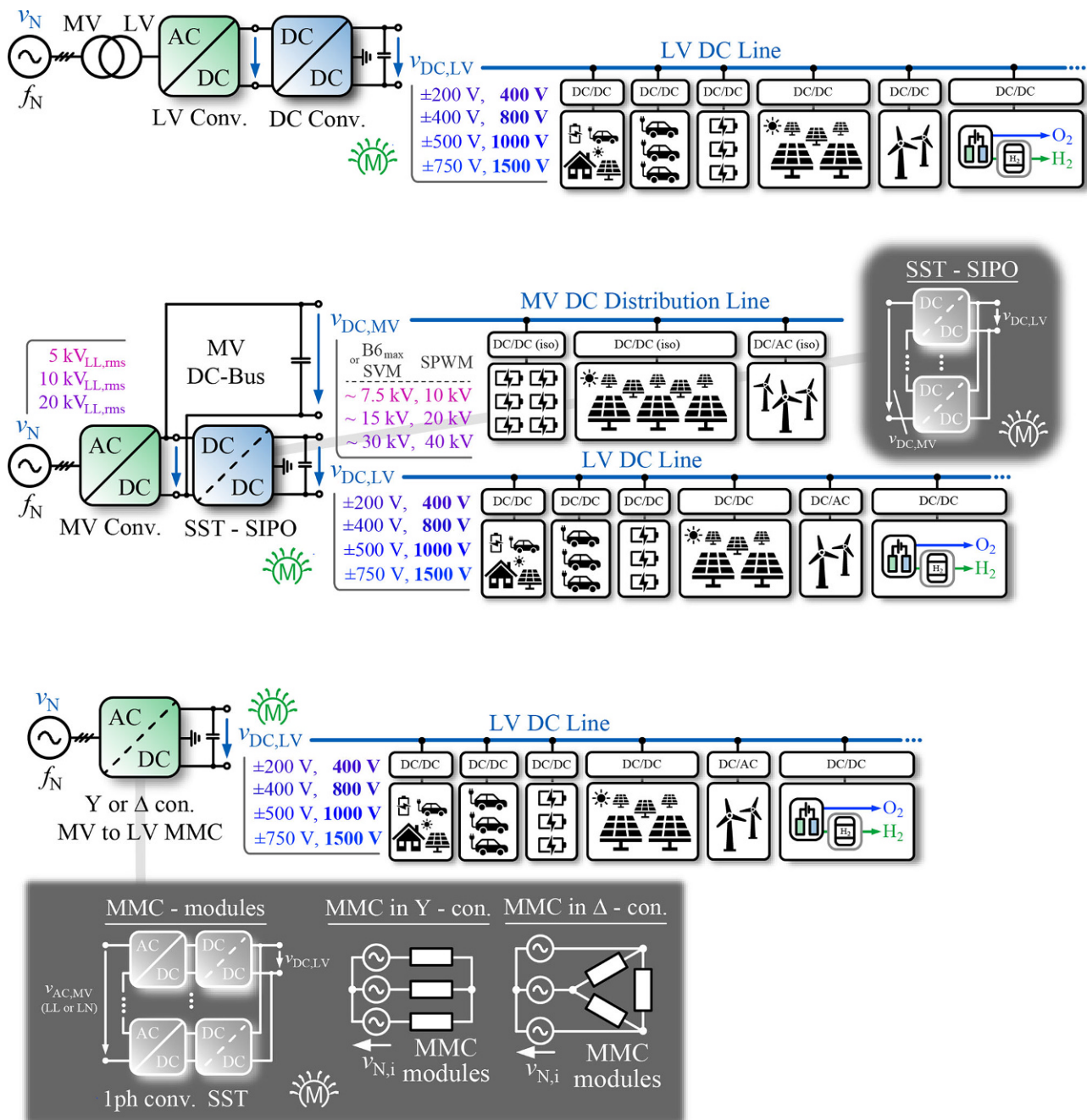


Fig. 12 Medium voltage rectifiers as hub for DC-technologies

pecially the solution with a medium voltage rectifier improves the reliability of the system, as in case of an outage of the AC-grid, low voltage loads could still be fed via generators connected to a MV DC distribution line.

One of the main advantages of integrating on-site RES and BESS for megawatt fast chargers is the opportunity to reduce the required energy drawn from the grid for each charging cycle. This will further reduce CO₂ emissions, as energy which is produced via solar panels is currently responsible for approximately 40–50 g CO₂ eq/kWh if the whole life cycle assessment is considered. This value however is based on a power stage including AC/DC and DC/DC converter. If the PV converter is integrated directly on DC-side only a DC/DC converter would be required which will further reduce the CO₂ footprint. In comparison to that, the CO₂ share for those energy supplied by the grid, depends on the national energy mix and daytime. For Austria this parameter varies between 200 and 400 g CO₂ eq/kWh. An electricity map for Austria can be found in [17]. Thus, assuming a more optimistic scenario of 250 g CO₂/kWh for charging a 150 kWh battery of a Tesla S with a range of 1000 km (currently not existing) purely from the AC-grid, would result in 37.5 kg CO₂ eq, thus **37.5 g CO₂ eq/km (Austria)**. If a DC-side PV/battery combination is considered which would allow to fully charge the EV, the CO₂ emissions would reduce to **7.5 g CO₂/km** (assuming 50 g CO₂/kWh) In comparison to the electric vehicle, a conventional combustion engine-based (as e.g. the VW Passat as referred to from the previous example) currently comes with CO₂ emissions of **123–184 g CO₂ eq/km**. Thus, exploiting the existing medium voltage and low-voltage DC-bus of the multi-megawatt charger to integrate renewable energy systems is an important step to further reduce the carbon footprint of electric vehicles and dedicated charging technologies. Additionally, it should be noted that, if the megawatt charger comes with bidirectional capability, the integration of RES would allow medium voltage grid support.

5 Conclusion and outlook

In this paper, different concepts for multi-megawatt fast chargers are discussed and benchmarked. The role and critical aspects for different relevant components such as the medium frequency transformer and power semiconductors are discussed. Furthermore, the role and benefits of integrating renewable energy systems on the low voltage DC-side are evaluated.

Summarizing, it could be determined that there will be an upcoming demand for megawatt fast charging in the future and standards for such a charging power are already under preparation. Different solutions to implement such a multi-megawatt fast charger have been derived and discussed. For those solutions based on 50 Hz transformers, large medium voltage trans-

formers are required which are scaling linearly with increasing charging power. For those concepts employing solid state transformers, the medium voltage rectifier or Star-connected modular multilevel converter are identified as most attractive architecture. In both scenarios, the medium frequency transformer plays a crucial role and directly affects the selection of power semiconductor components. RES in combination with BESS can further optimize the carbon footprint per charging cycle and foster grid support if required.

Future work will focus on the analysis of different power electronic topologies. Furthermore, based on that analysis, a small-scale prototype will be developed. After successful validation, a large-scale demonstrator which will be connected to the 20 kV grid should be realized.

Acknowledgements This work is part of the “MEDUSA-Phase 1” project and funded by the Climate- and Energy Fund and the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology in the frame of the Zero Emission Mobility program under the FFG grant 885053. Project partners are the Austrian Institute of Technology GmbH, AVL List GmbH, EnerCharge GmbH, Infineon Technologies Austria AG and Xelectrix Power GmbH.

Funding Open Access funding enabled and organized by AIT Austrian Institute of Technology GmbH.

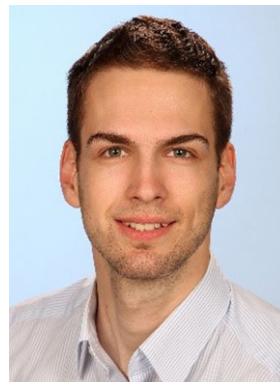
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