APPLICATION NOTE **PRD-08367**

EV CHARGING POWER TOPOLOGIES DESIGN GUIDEBOOK

By Anantpreet Aulakh, Product Marketing Engineer - EV Charging

PRD-08367 REV 1.0, January 2024 EV Charging Power Topologies Design Guidebook

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INTRODUCTION: EV CHARGING DEMANDS GROWING

As the trend towards electrification and decarbonization is gaining momentum worldwide, the demand for electric vehicles (EVs) is increasing in tandem at a forecasted 10% CAGR. All the major economic countries are offering various incentives and rebates in one form or another to make the transition from ICE engines to EV vehicles faster, like EU's "Fit for 55".It is making a legal obligation to reduce EU emissions by at least 55% by 2030. According to International Energy Agency (IEA), after considering the government policies intended to fuel this adoption, nearly 50 million EVs are projected to be on the road by the end of 2025.

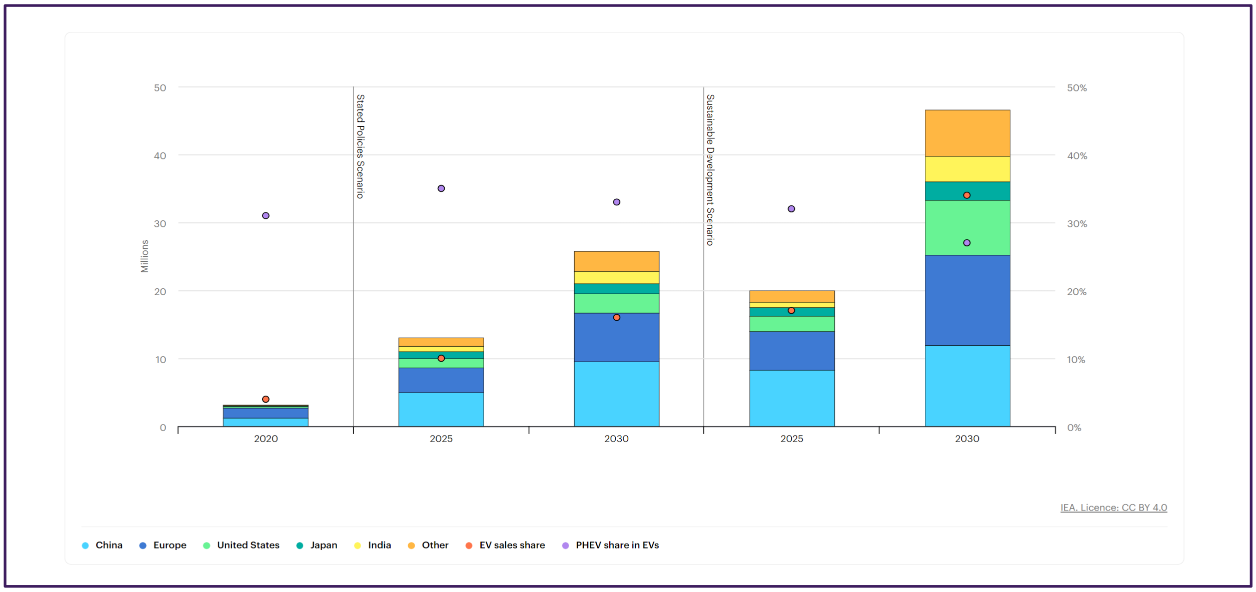


Figure 1: EV Market growth projection by region (number of vehicles)

Take for example the US, where the target from the federal government is to fully decarbonize the US power sector by the end of 2035. At this scale, the current EV share, which stands at fewer than 3 million vehicles, will grow more than 15 times to 48 million vehicles by 2030. This would equate to approximately 15% of all vehicles on the roads.

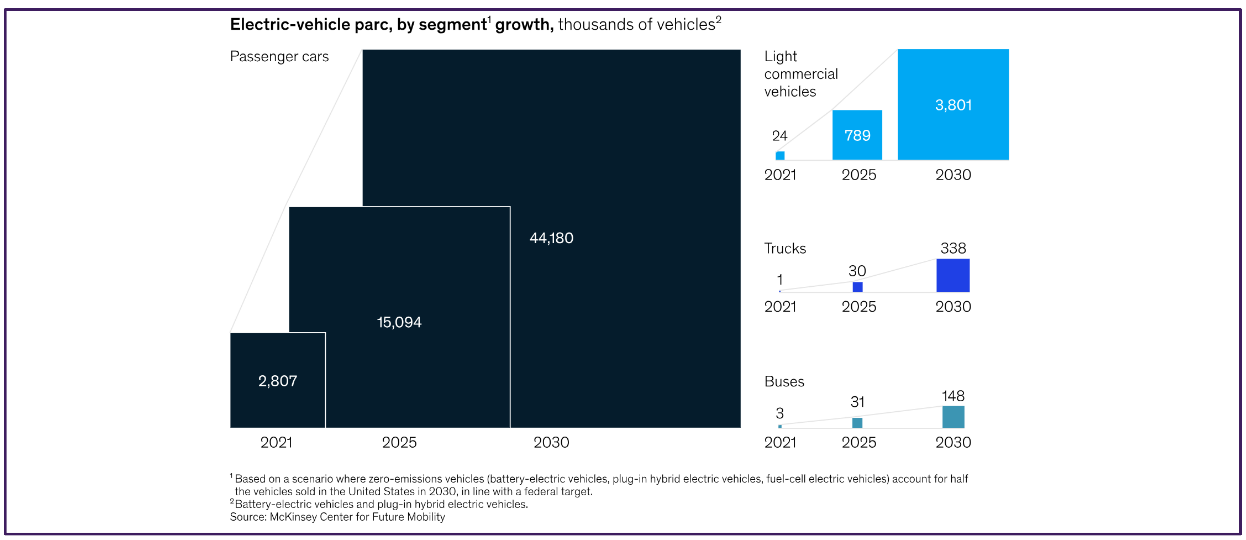


Figure 2: EV market growth projection segmented by type of vehicles

With the increase in the EVs on the roads, the demand for the electricity that is needed to charge them is also rising at an exponential rate. It is estimated around 230 TWh of energy will be needed in 2030 to charge these vehicles compared to the 11 TWh demand of today. To serve this many cars and the accompanying electricity demand, nearly 30 million chargers will be required. While most of the chargers will be installed at personal homes, **more than 1.2 million public chargers** will need to be installed to service EVs on the go.

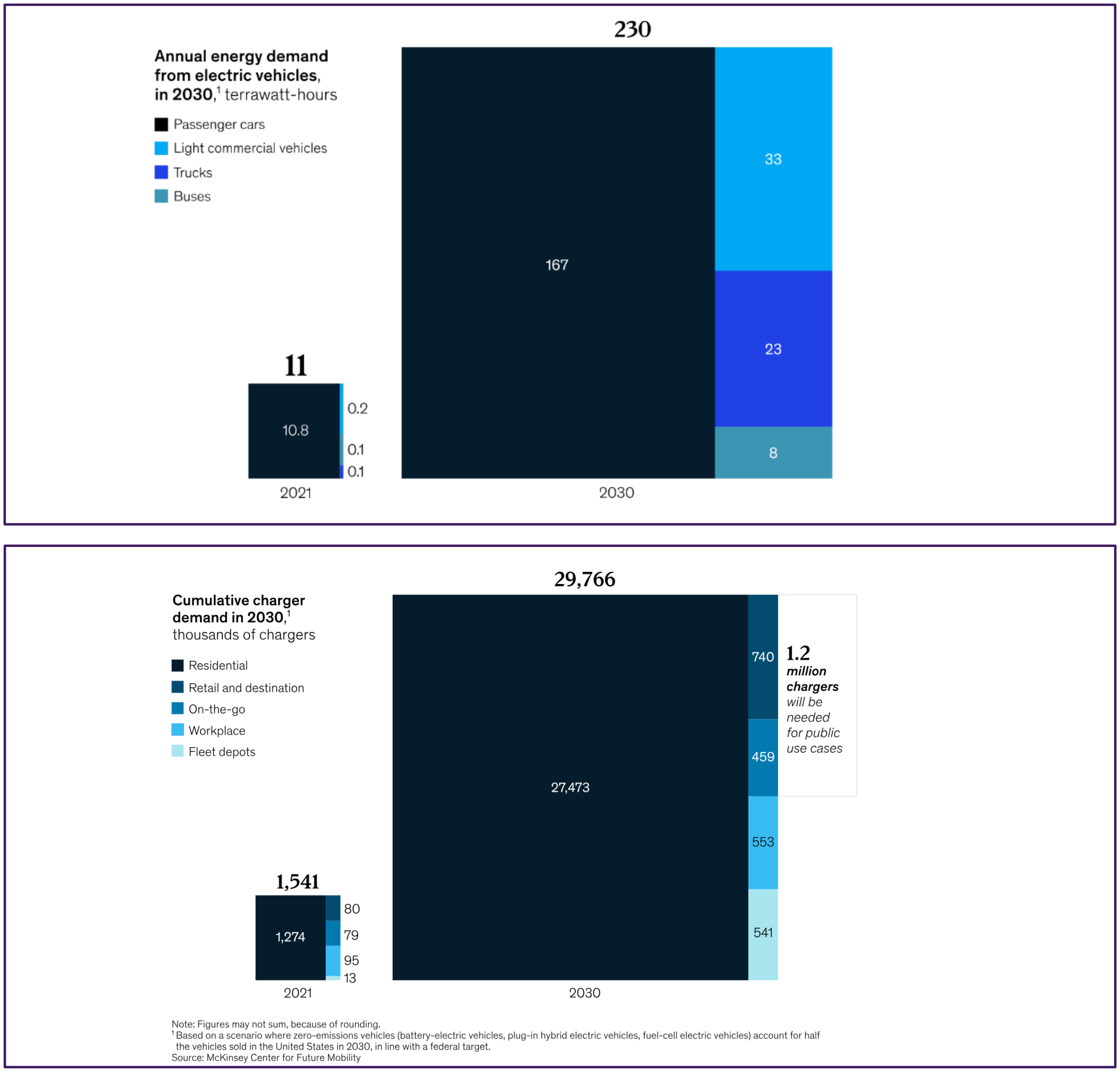


Figure 3(a): Annual Energy Demand from EVs; (b): Cumulative Charger demands need for EVs

Home chargers typically use the common, readily available AC power supply. On the other hand, public chargers are designed to provide a fast and reliable charging experience like when refueling a traditional internal combustion engine (ICE) vehicle. This means that public fast chargers need to have enough power delivery capability (up to 600kW) to provide a full charge to EVs in less than 15mins. This is only possible with DC charging.

1. TYPES OF CHARGING

AC charging refers to charging using the normal power available in a typical home, which is available in the form of alternating current (AC), hence the name. This kind of charging requires an on-board charger (OBC) in the EV that converts the power from AC into DC, which is required for charging the battery.

1.1 AC CHARGING

LEVEL 1 AC

This is the most basic charger which receives 120-240Vac (13-16A) from the grid and then supplies it to the EV with a charging cable. It is the slowest charger type, but it is also the most portable and can be plugged in almost anywhere. Most models are usually rated up to 1kW.

Figure 4: A level 1 AC charger

LEVEL 2 AC

A level 2 AC charger still uses the readily available 120-240Vac power supply. The main difference is that it is rated for higher current (32-40A). These AC chargers can usually be found permanently wired to homes and to poles in public spaces. They are usually rated up to 11-22 kW.

Figure 5: A level 2 AC charger

1.2 DC CHARGING

To decrease charging times for EVs, the only way to go is DC charging. DC chargers deliver power directly to the EV battery by bypassing the on-board charger in the EV.

LEVEL 2 DC CHARGING / LEVEL 2+ / DC WALLBOX

For power levels around 20-25kW, a common solution would be referred to as a “level 2” DC charger, even though there is no official naming convention. These can be found in both residential and commercial locations.

The biggest difference compared to AC charging is that there is an additional built-in power block converter that performs the rectification from AC to DC (e.g., “AFE” - active front end). Then, this DC current is fed into the car via a charging cable to charge the battery. Depending upon the selection of the power devices, it can also provide bi-directional functionality which will be discussed in the later section.

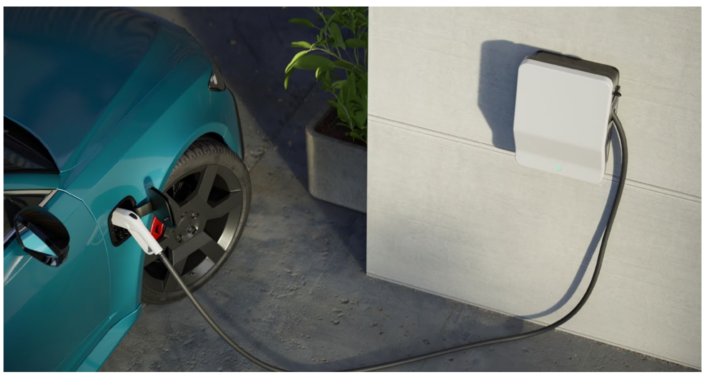


Figure 6: A level 2 DC charger

LEVEL 3 DC FAST CHARGING (DCFC)/ RAPID / SUPERCHARGERS

Level 3 DC chargers are often called DC fast chargers (DCFCs) or superchargers. The power levels for this type of charger can easily vary from 50kW to up to 1MW. These chargers are made of multiple power blocks of 20, 30, 50, 60kW or even higher to obtain the desired power level. Depending on the capacity, these fast chargers can charge a typical EV battery in less than 20 mins.

Figure 7: A level 3 DC Fast Charger

1.3 CHARGING STANDARDS

Just like we have different charger levels to differentiate power levels, there are also different standards for the connectors used.

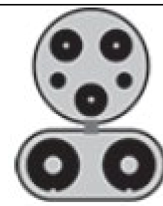
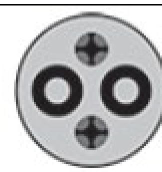
Connector Types		
Level 1	**Level 2**	**DC Fast charging**
 **J1772 connector**	 **J1772 connector**	 **CCS Connector**
		 **CHAdeMO connector**
		 **J3400 Tesla/NACS connector**

Figure 8: Types of charger connectors

SAE J1772

This connector is the industry standard for all Level 1 and Level 2 charging.

CHAdeMO

This is one of the first connectors introduced in the global market. It was developed by a collaboration of five Japanese automakers and was implemented to be an industry standard. This is the most prominent connector in Japan for use with EVs manufactured by Japanese auto manufacturers. It only supports DC charging and EVs need an additional J1772 cord to achieve Level 1 or 2 charging.

CCS

CCS is short for Combined Charging System, which was also introduced around the same time as CHAdeMO. The biggest difference between CCS and CHAdeMO is that it allows for either AC or DC charging on the same port. It has become a preferred connector among European and American car manufacturers.

J3400 – Tesla® / NACS connector

This connector was exclusively designed for Tesla EVs and its supercharging network. The Tesla supercharger network has grown exponentially since its introduction. With Tesla cars and its network gaining popularity in North America, the company decided to open the charging network to non-Tesla EVs in the middle of 2023. Major American and European car manufacturers have announced partnerships with Tesla to utilize its supercharging network along with new major non-Tesla EVs being equipped with the Tesla designed connector.

This motivated a change in the name to "**North American Charging Standard**" or **NACS connector**. This is set to become the new standard for EV charging in North America over the next few years.

In December 2023 SAE international standardized the connector, naming it **J3400**, which will ensure any supplier or manufacturer will be able to deploy it on EVs and charging stations across the continent.

1.4 UNI-DIRECTIONAL VS BI-DIRECTIONAL CHARGING

In uni-directional charging, the current flows in one direction: from the power grid to the EV. This is the same approach used for all other electronics used in daily life.

In comparison, bi-directional charging means power can flow in both directions; from power grid to the EV as well as in reverse. There are many benefits to having a bi-directional charger, as an EV by itself is a big energy storage unit that can act as an emergency power supply to the home in the event of a blackout without investing separately in a backup system. Bi-directional charging can also provide power back to the grid during peak hours to provide stability and afford incentives to the owner by selling this energy in locations where it is permitted.

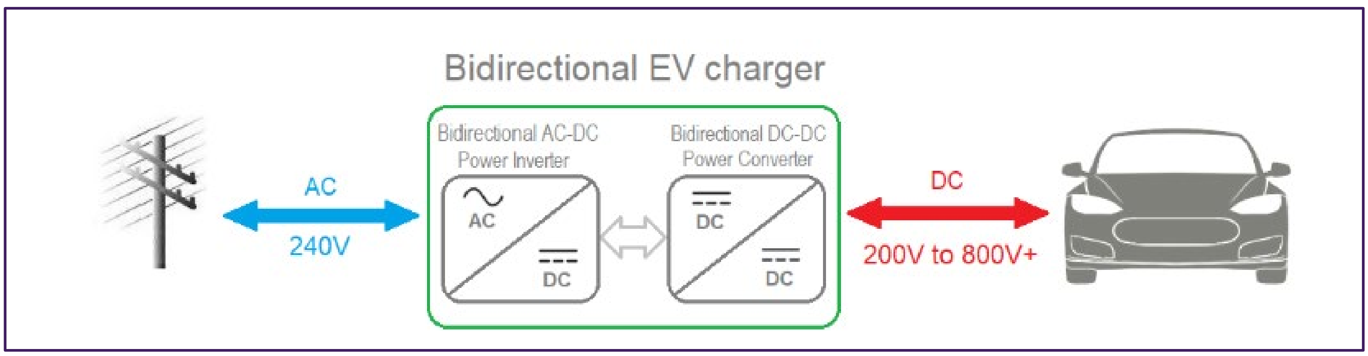


Figure 9: A Bi-directional power block for EV charger (Source: Clean energy review)

There are different applications where bi-directional charging provides the most significant benefits. The most common are:

- V2G or Vehicle to Grid – EV provides power back to support the power grid
- V2H or Vehicle to Home – EV provides power back to the home
- V2L or Vehicle to Load – EV provides power to support equipment or appliances

There is a lot of excitement about V2G as it has enormous potential if we consider thousands of EVs all plugged in at the same time. This can create a huge energy storage pool that will be readily available during operating peak hours to help stabilize power grids.

In V2H, the EV can be used as an energy storage unit to store excess energy from renewable energy sources and even provide power to the home.

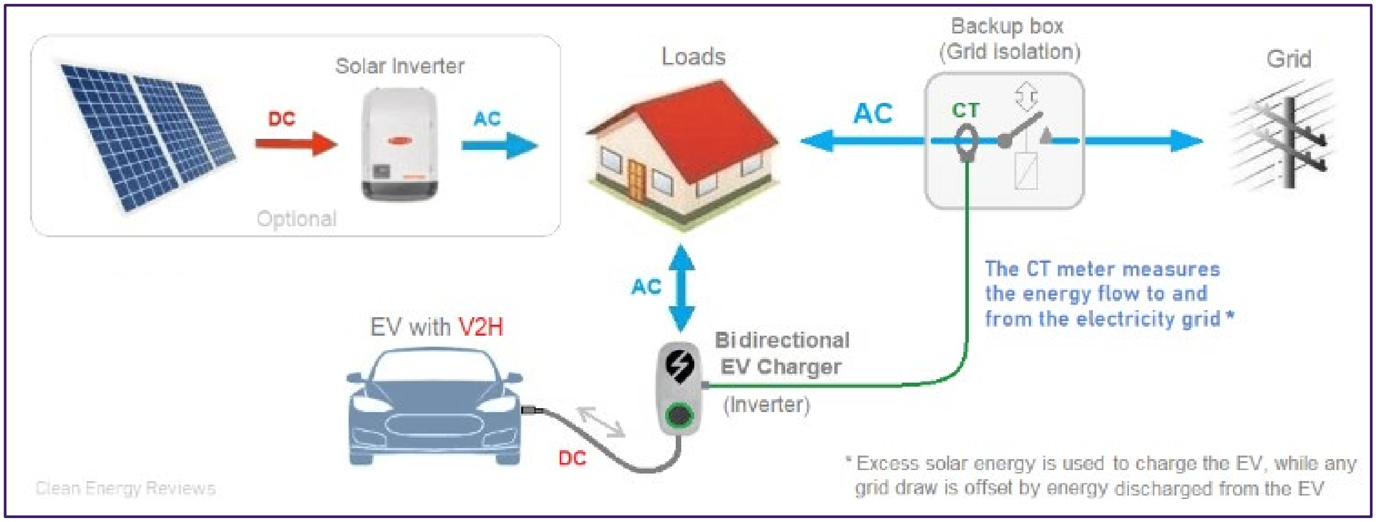


Figure 10: A typical V2H power block (Source: Clean energy review)

1.5 COMMON AC-DC TOPOLOGIES

For AC/DC power conversion, single-phase and three-phase topologies can be used. Single-phase topologies are most common for home charging or when power levels are less than 6.6kW, while three-phase topologies are better suited for higher-power charging blocks (>11kW).

To assist engineers with developing their charger designs, Wolfspeed has developed the SpeedFit™ Design Simulator tool, the industry's most comprehensive system-level circuit simulator for silicon carbide (SiC) power applications. The first step in evaluating Wolfspeed's MOSFETs, Schottky diodes or power modules is to select the right devices for your application. Users can quickly run simulations to predict conduction and switching losses, evaluate how performance varies with Rg, and compare different device and thermal configurations.

[SpeedFit Design Simulator] offers an easy-to-use interface for evaluating the most common silicon carbide (SiC) power topologies ranging from buck and boost converters to a fully bi-directional totem pole PFC with resonant DC/DC converter, accelerating customer evaluation and decreasing their time to market for EV chargers.

1.5.1 SINGLE-PHASE TOPOLOGIES

TOTEM POLE / BOOST PFC

Totem pole PFC topology is a conventional boost PFC haswhere one half of the bridge contains two active silicon carbide (SiC) switches (S1 and S2) and the other half of the bridge contains two diodes (D1 and D2).

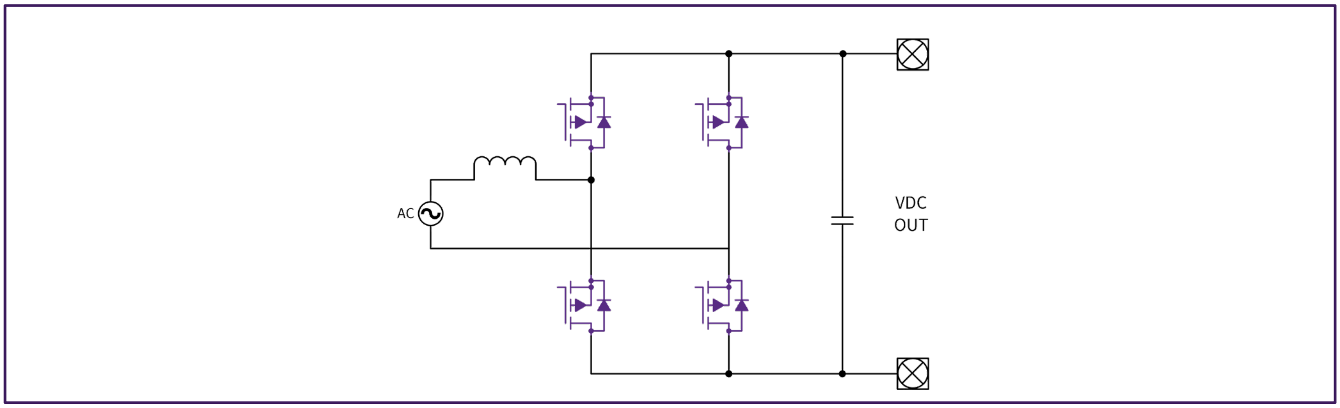


Figure 11: A totem pole PFC

In a typical 3.3kW PFC power block with 230V AC input and 400V DC output, primary switches S1 & S2 utilize two C3M0060065K (60mΩ 650V) or four E3M0060065K (automotive grade 60mΩ 650V) silicon carbide (SiC) MOSFETs thatact as the fast switching leg. The second leg S3 & S4 are slow switches that can be either a MOSFET or diode. Wolfspeed's 2.2kW , 3.6kW & 6.6 kW Bridgeless Totem-Pole PFC reference design guides are available to support the design build along with recommended products.

The main advantage of using this topology is that it provides improved efficiency when compared to a conventional boost PFC. If the S3 and S4 sockets are replaced with an active switch, they can provide bi-directionality for OBC and V2G applications.

The reverse recovery losses in silicon-based switches limit the operation to only discontinuous conduction mode (DCM) or critical conduction mode. With ultra-low Qrr for silicon carbide (SiC) devices, this allows the system to operate even in continuous conduction mode (CCM).

NPC PFC

NPC refers to "neutral point clamped" PFC. In this topology we find the usual two legs that contain active silicon carbide (SiC) devices and a neutral leg that is clamped to each phase leg with the help of a diode in between the active switches. This in turn creates a multi-level topology, and now each leg will have a lower dv/dt stress on each of the active switches.

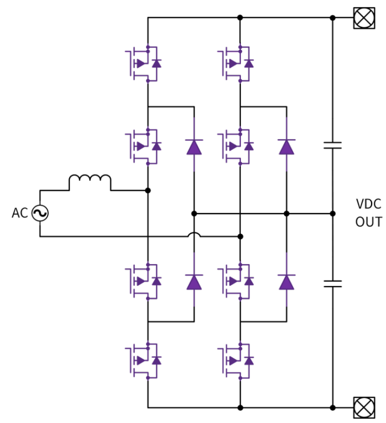


Figure 12: A typical NPC PFC

The main benefit NPC brings is that each switch now can use 650V devices (25mΩ C3M0025065K is a great SiC MOSFET selection for a 12kW system) instead of 1200V devices. Each leg can be clamped with a 650V, 20A (such as C3D20065D or E3D20065D) silicon carbide (SiC) diode. Lower voltage rated devices reduce the cost per switch and lower dv/dt stress means smaller EMI radiations, thus reducing the size of input filters needed. By empowering the circuit with silicon carbide active switches, designers can achieve bi-directionality, higher power density, and improved efficiency.

The main drawback of using this topology is that it requires a higher part count and increases the complexity of the control system.

1.5.2 3-PHASE TOPOLOGIES

If faster charging times and higher power density is the goal, three-phase topologies are the preferred route. Depending upon the end design requirements, three-phase configurations can be divided into two sections, two-level and multi-level topologies, with each providing their own unique benefits.

2 LEVEL – AFE PFC

AFE “Active Front End” PFC is the most common three-phase two-level topology used in EV charging. For an 800V DC bus system, each leg contains two active 1200V silicon carbide switches (SiC), for a total of six switches. For a 22kW power block (400Vin AC & 800V DC bus output), 32mΩ 1200V C3M0032120K and E3M0032120K are the most common SiC MOSFETs.

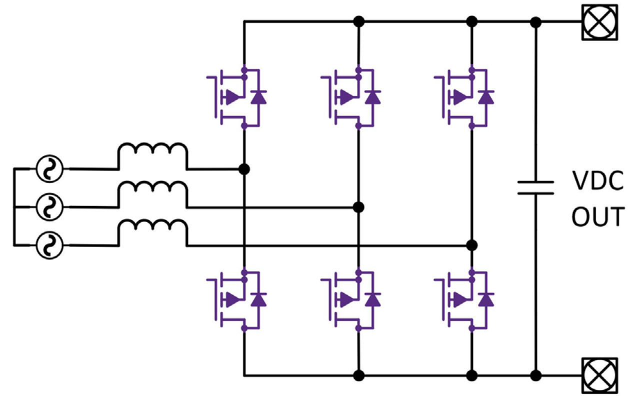


Figure 13: AFE converter

The main benefit of using this topology is that it is the easiest to implement and has a simplified control scheme. With the presence of active switches for each leg, the AFE converter can provide power in either direction. With increased market traction for EV chargers to become bi-directional, this topology is the easiest to design along with the benefits of providing higher power. Being a two-level converter, the main drawback of this topology is that it requires large input filters to reduce the EMI to acceptable levels when compared to a multi-level converter.

A reference design guide for [22kW Bi-Directional Active Front End (AFE)] is available from Wolfspeed and can used as a starting point for new designs.

3 LEVEL – VIENNA RECTIFIER

For high-power conversion, especially for level three EV charging, the Vienna rectifier is the most common topology being used in the three-phase, three-level conversion scheme. The main advantage of this topology is the inherent three-level conversion that produces low stress on the switches and its ability to operate in CCM.

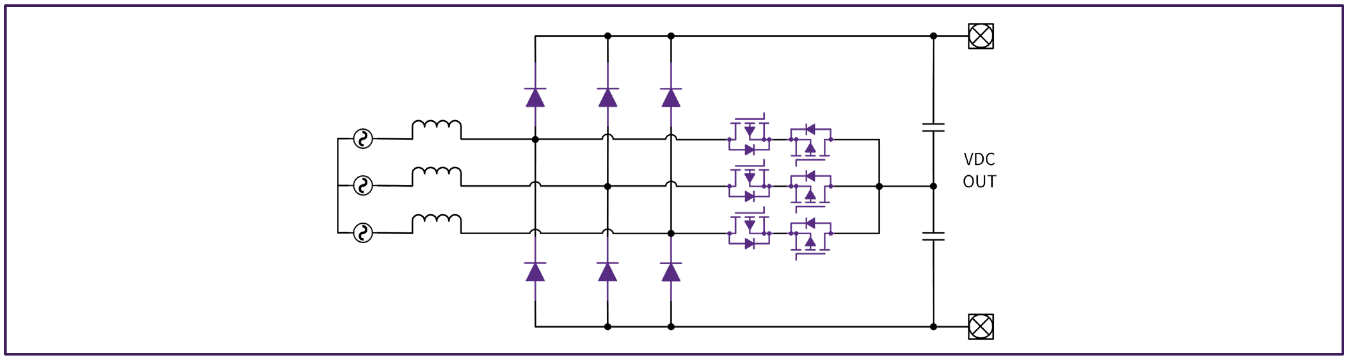


Figure 14: Vienna Rectifier

There are different versions of the Vienna rectifier topology, with the above T- type the most common. This version uses the combination of six 1200V SiC Schottky diodes and six 650V active MOSFET switches.

In a 25kW power block, 45mΩ C3M0045065K 650V silicon carbide (SiC) MOSFETs along with 40A C4D40120D 1200V diodes are currently widely adopted in the market.

Since all the active switches are neutral point clamped (NPC), the active switches can be rated for only half of a typical 1200V device. The main drawback of this topology is that it can only provide uni-directional power.

3 LEVEL – T-TYPE PFC (TNPC)

The main difference between this topology and a Vienna rectifier is that the 1200V Schottky diodes are replaced with the 1200V MOSFETs. This allows the configuration to be able to provide bi-directional power. The middle switches are still neutral point clamped (NPC), leading to half of the voltage stress when compared to those seen by the outside switches in a typical 800V bus system.

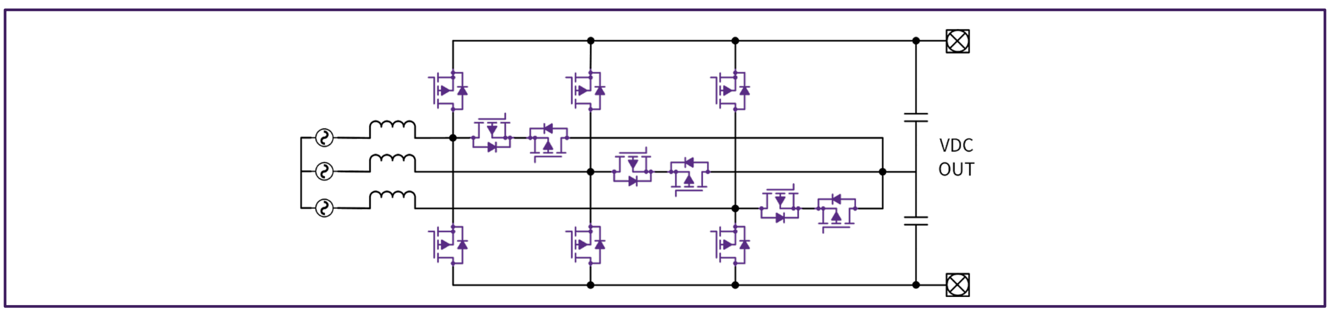


Figure 15: A T-type PFC converter

When building a 25kW power block, the 32mΩ C3M0032120K or E3M0032120K 1200V silicon carbide (SiC) MOSFETs handle the 800V DC bus voltage and 25mΩ C3M0025065K 650V devices can be used for the middle switches, which only see half of the DC bus voltage due to being neutrally clamped.

3 LEVEL – NPC/ANPC PFC

NPC stands for “ Neutral Point Clamped.” As shown with single-phase NPC topology, this topology provides a three-phase system with a neutral point clamp that reduces the voltage stress seen on switches to half of the bus voltage. In a typical EV charging scenario with a bus voltage of 800V, each switch now needs to block only 400V. This implementation allows the customer to use only a (25mΩ C3M0025065K in 25kW block) 650V blocking SiC MOSFETs rather than the typical 1200V blocking SiC MOSFETs that is generally required. In NPC, the active switches are clamped with (20A C3D20065D or E3D20065D in a 25kW block) 650V SiC diodes.

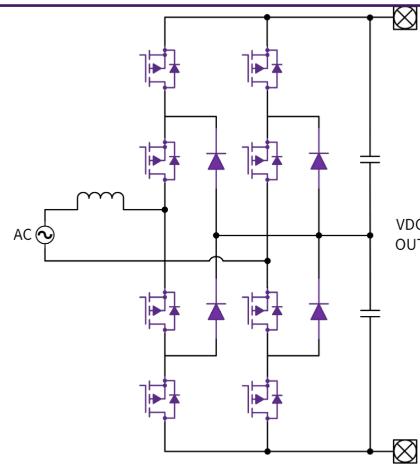


Figure 16: NPC converter

Another version of NPC is known as ANPC (Active neutral point clamped), where all the diodes of the topology are replaced with active switches. This is to avoid unsymmetrical distribution of losses in the system between MOSFETs and diodes, which can cause thermal instability.

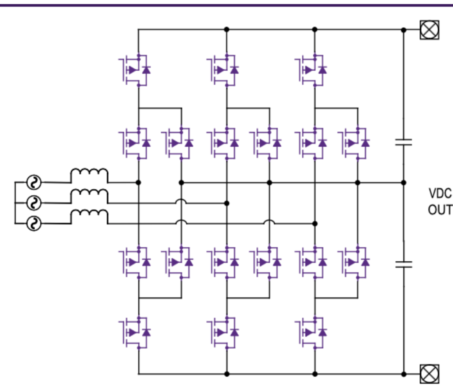


Figure 17: ANPC converter

Main advantages of ANPC:

- Ability to provide bi-directional power transfer.
- Inherent multi-level topology leading to lower dv/dt stress and therefore lower EMI.
- Reduction of the voltage stress across the switches enables the use of 650V rated silicon carbide (SiC) devices, which leads to lower switching losses.
- Operation at higher switching frequencies (greater than 50kHz).
- Higher power density due to lower output ripples and usage of smaller EMC filters.

The main drawback of this topology is the increased part count required.

1.6 COMMON DC/DC POWER TOPOLOGIES

After converting the AC power into a typical DC bus voltage of 400V-800V, we can now convert this to the necessary voltage for charging the EV batteries. There are various DC/DC topologies addressed below that can help achieve it.

In some situations, there is a need to charge a broad range of vehicles with battery voltages as low as 200V-250V for a fully discharged 400V vehicle, up to 850V-900V for higher voltage packs when fully charged. This makes using resonant converters challenging. We address this through different control techniques at different operating points. The 60kW LLC Reference design by Wolfspeed user guide explains this fairly well. To fully optimize the system, the AC/DC portion of the converter also needs to be able to adjust its output voltage to provide the most favorable input-to-output voltage ratio for the DC/DC.

This is another example where SpeedFit Design Simulator can be used to evaluate the most common silicon carbide (SiC) power topologies, quickly run simulations to predict conduction and switching losses, evaluate performance variation with Rg, and compare different device and thermal configurations.

DAB – DUAL ACTIVE BRIDGE

As the name suggests, a Dual Active Bridge topology means both the primary and the secondary side switches have active switches. It is a full-bridge topology with a high-frequency transformer providing galvanic isolation. This can be either a single transformer for lower power, or a three-phase topology for higher power as shown below.

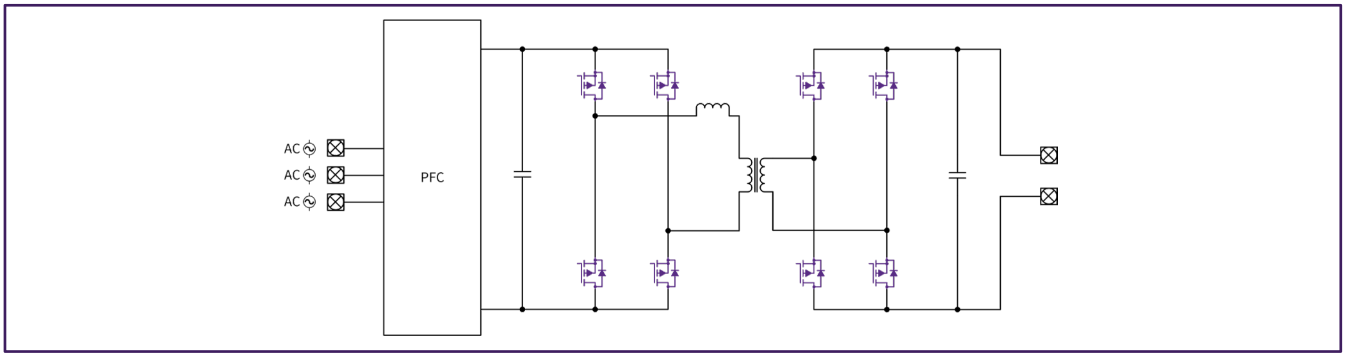


Figure 18: Dual Active Bridge (DAB) converter

Phase-shifted modulation is the most common way to operate the DAB converter with reliable performance at the nominal operating voltage. But in EV charging, the DC bus voltages vary with the different battery voltages from different manufacturers that are connected on the other end. In a typical 800V DC bus for a 25kW power block system, 32mΩ C3M0032120K or E3M0032120K 1200V SiC devices are commonly used on the primary side and 25mΩ C3M0025065K 650V SiC devices on the secondary side to supply the 400V battery. A 10kW DAB reference design is available from Wolfspeed to start building your own EV charger.

The main benefits of this topology are:

- It can provide bi-directional power flow.
- Ability to achieve zero-voltage switching (ZVS) leading to lower switching losses.

At certain predefined operating voltage conditions, the phase-shift modulation technique is the most common way to operate a DAB converter. In the EV charging world, there can be different DC bus voltages depending upon batteries and their connection. This could lead to hard switching in the system and potentially excessive power losses.

To compensate for that, advanced phase-shift modulation techniques need to be implemented. This increases the complexity and control algorithms, making it difficult to design when dealing with high-power charging stations like 50kW-60kW charging blocks used in a typical 600kW charging station.

PSFB – PHASE SHIFTED FULL BRIDGE

Phase-Shifted Full-Bridge topology is similar to the dual active bridge (DAB) topology, the main difference being the secondary side rectification switches are replaced by diodes. The converter operates in ZVS by varying the phase angles of the primary side switches, hence the name.

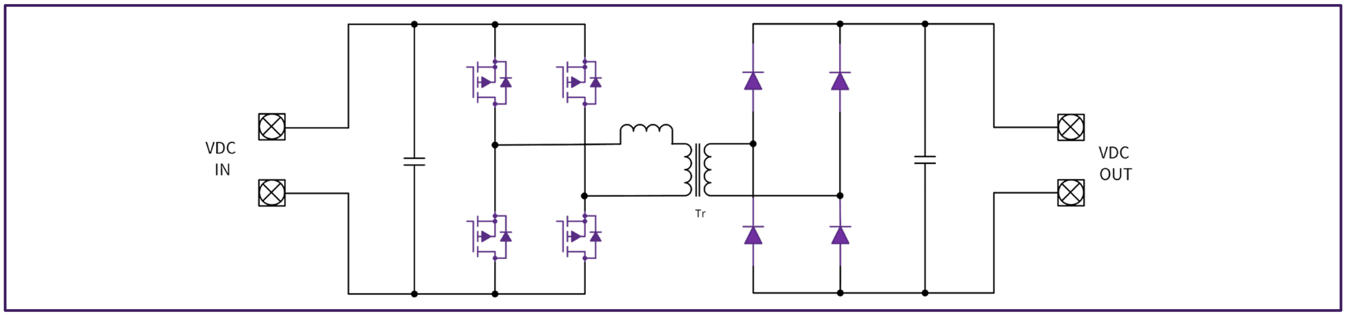


Figure 19: Phase Shifted Full Bridge (PSFB) Converter

PSFB is a common topology being used for both on-board and off-board EV charging. The main benefits of using PSFB converter are the same as DAB with one significant difference:

- Lower system cost by using half the number of active switches, thus making it only suitable for uni-directional power flow.
- Ability to achieve zero-voltage switching (ZVS) leading to lower switching losses.
- Able to operate at higher switching frequency leading to smaller passive components and increased power density.

When this topology is being used for a 12kW power block, the 75mΩ C3M0075120K or E3M0075120K 1200V SiC MOSFETs are suitable candidates for an 800V DC bus system on primary side and 25mΩ C3M0025065K 650V SiC MOSFET on the secondary side (for higher efficiency) to supply power to the 400V battery.

LLC CONVERTER

As the name suggests, an LLC converter has a resonant tank in addition to an isolated full-bridge DC-DC converter. The primary side contains the active silicon carbide switches and secondary side rectification has silicon carbide Schottky diodes. A typical LLC topology is shown below.

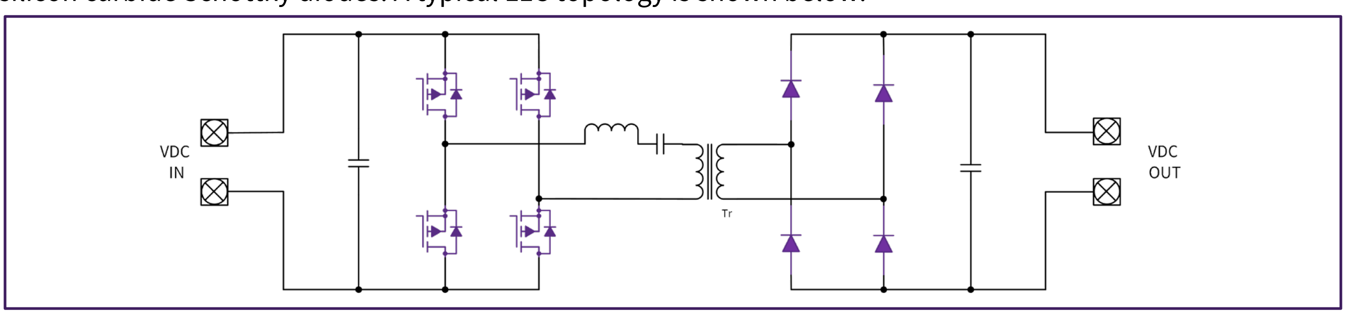


Figure 20: LLC converter

The modulation of an LLC converter is done by varying the switching frequency as compared to a PWM control by varying the duty cycle. There are three modes of operation: the switching frequency is resonant, below resonant frequency, and above resonant frequency. The desired mode of operation is to operate as close to resonance as the converter can in order to achieve both zero-voltage turn on (ZVS) and zero-current turn off (ZCS).

The main drawback of this converter is that it can provide power in only one direction.

In a 12kW power block, the 75mΩ C3M0075120K or E3M0075120K 1200V SiC MOSFETs are viable candidates for 800V DC bus system on the primary side and 25mΩ C3M0025065K 650V SiC MOSFET on the secondary side, for higher efficiency, to supply power to the 400V battery. Wolfspeed has developed a 30kW Interleaved LLC and a 60kW Interleaved LLC reference design to provide a detailed design guide for customers looking for a starting point to building their own EV chargers.

CLLC CONVERTER

The major difference between CLLC topology and LLC topology is that the secondary side diode switches are replaced with active silicon carbide switches. The biggest advantage of this converter is the ability to provide bi-directional power. The desired mode of operation remains the same to be able to achieve zero-voltage turn on (ZVS) and zero-current turn off (ZCS).

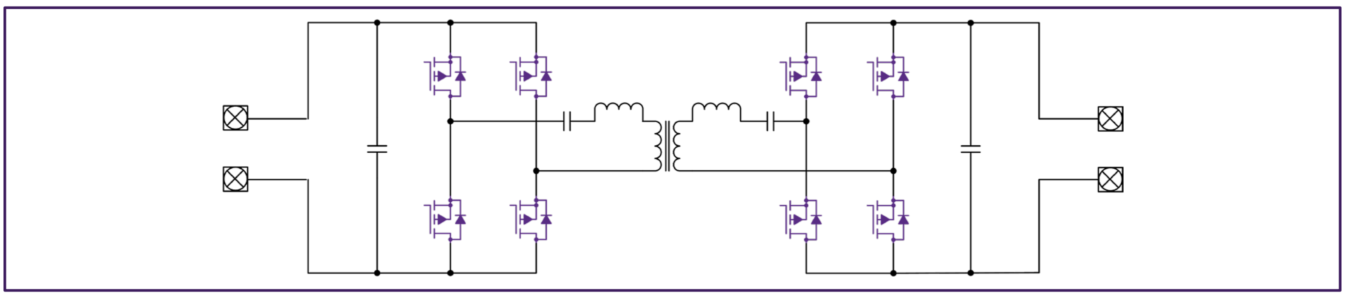


Figure 21: CLLC converter

This converter can provide remarkably high efficiency for a wide variety of battery voltages and is quite common for on-board charger applications. With the addition of capacitors on either side of the transformers, the topology becomes symmetrical and could have similar power losses depending upon input & output voltage.

Wolfspeed's 6.6 kW Bi-Directional Totem-Pole PFC and CLLC, High Power Density reference design guide along with a 22kW Bi-directional CLLC are available to support customer designs along with recommended products.

When building a 12kW power block, the 75mΩ C3M0075120K or E3M0075120K 1200V SiC MOSFETs are a good candidate for a 800V DC bus system on the primary side and 25mΩ C3M0025065K 650V SiC MOSFET on the secondary side to supply power to the 400V battery or one can replace all the sockets with the 32mΩ C3M0032120K 1200V SiC MOSFET on both the primary and secondary side to support 800V battery systems for high efficiency.

1.7 SUMMARY

In this ever-evolving EV charging landscape, there is a big push for higher power and higher density solutions to reduce the charging downtime for an EV when compared to a typical ICE vehicle, which remains the biggest bottleneck to widespread adoption. This leads to more adoption of innovative multi-level topologies to address these power demands until there is a breakthrough in battery technology.

As EVs are effectively batteries on wheels, there is an enormous potential that these batteries can support power grids during peak demand times when not in operation. This will also require the topologies to support bi-directional power.

Both requirements further strengthen the need to have more efficient power semiconductor switches. Wolfspeed's silicon carbide devices are perfectly suited to support these next-generation requirements. Visit www.wolfspeed.com to find product offerings, reference designs, and design support tools that you need to start your own EV charger design journey.

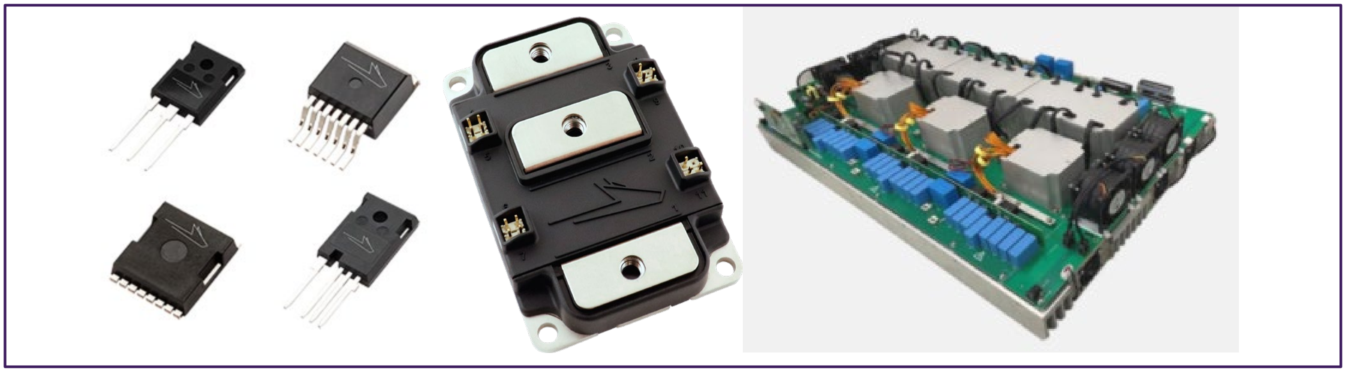


Figure 23: (a) Wolfspeed® Discretes, (b) Modules & (c) A 60kW LLC Reference design

1.8 REVISION HISTORY

Date	Revision	Changes
Jan 2024	1	Initial Release

REFERENCES

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