SOLVING THE CHALLENGES OF EV CHARGER DESIGNS

WITH SiC POWER MODULES

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EMPOWERING YOUR IDEAS
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1  Introduction

Automotive industry is going electric. With automakers rolling out more and more models, all those e-vehicles will need EV chargers with key requirements of power density, overall system efficiency and capability for fast battery charging. Diverse industries and markets have to adapt to this mega trend towards electrification. But regardless of the line of business, every stakeholder expects the same things from the Power Electronics that drive these systems – highly efficient performance from a package with a small footprint and a competitive system level price. This trade-off between performance and cost brings several challenges in the system design and implementation for companies that build EV chargers. The adoption of SiC power electronics devices in EV chargers is an interesting approach due their outstanding intrinsic electrical and thermal benefits compared to standard Si devices. This paper reviews EV charger implementations and presents Vincotech solutions designed for these use cases – power modules that strike the right balance between size, performance, efficiency and price.

![Figure 1: Block diagram of an electric vehicle (EV) battery charging system and the key power electronics stages](image)

2  EV charger architectures – the DC charger

The basic and generic structure of EV DC chargers is represented in the block diagram in Figure 2. The system draws power from the grid for the charger to process and convert. It then delivers regulated DC voltage and current to the battery in a proper shape and behavior. The power flow of the most common types of chargers on the market is unidirectional, in which energy flows one way, from the grid to the battery. However, some use cases require...
bidirectional power flows: EV chargers send power from the grid to the battery and from the battery to the grid. This paper focuses on solutions for designs with unidirectional power flows.

The global specifications for EV charging systems are high efficiency, high power density, modular architecture and fast-charging capability. In the generic architecture of DC charger system, the following blocks can be identified:

**First stage:** The AC/DC stage provides the interface between the grid and the other segments of the EV charger. PFC converters are often selected because of their inherent function and benefits they provide – specifically, sinusoidal main currents with low harmonic distortion and regulated DC link voltage. Several power electronics topologies have been used to this function.

**Second stage:** An isolated DC/DC converter provides the interface between the PFC stage and the EV battery. This intermediate block generally is implemented by resonant DC/DC converters that operate under soft switching techniques in order to maximize the overall system efficiency. There are several topologies addressed for this segment, such as DAB, LCC. This power conversion stage is generally isolated for the safety reasons.
The EV charger versions can be classified differently as seen in Table 1. The most common approach is to follow the maximum power that a charger can process, which defines, basically, its capability for the charging time. Nowadays, the most significative trend are the Level 2 and Level 3 implementations due to fast charging time capability.

<table>
<thead>
<tr>
<th>Power Level Types</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage</td>
<td>120 V (US)</td>
<td>240 V (US)</td>
<td>208 V up to 600 V in AC or DC</td>
</tr>
<tr>
<td></td>
<td>230 V (Europe)</td>
<td>400 V (Europe)</td>
<td></td>
</tr>
<tr>
<td>Power range</td>
<td>Lower than 3.7 kW</td>
<td>3.7 kW up to 22 kW</td>
<td>More than 50 kW</td>
</tr>
<tr>
<td>Charging time</td>
<td>11-36 hours</td>
<td>1 – 6 hours</td>
<td>20 min up to 60 min</td>
</tr>
<tr>
<td>(approx)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charger Concept</td>
<td>ON-board</td>
<td>ON-board</td>
<td>OFF-board</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF-board</td>
<td></td>
</tr>
<tr>
<td>Grid Supply</td>
<td>1 phase</td>
<td>1 phase or 3 phase</td>
<td>3 phase</td>
</tr>
<tr>
<td>Charging Type</td>
<td>Slow charging</td>
<td>Semi-fast charging</td>
<td>Fast charging</td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>15-50 kW</td>
<td>15-50 kW</td>
<td>15-50 kW</td>
</tr>
</tbody>
</table>

Table 1: Basic definitions for categorizing charger systems

3 SiC-based power electronics devices

Silicon Carbide (SiC) material gives the flexibility to implement power electronic devices with superior performance compared to standard material such as Silicon (Si). The literature shows many documented instances of SiC-based power semiconductor devices’ benefits over standard Si-based devices. For one, SiC devices’ higher breakdown field characteristic and higher electro-saturation velocity gives lower conduction losses. For the other, higher bandgap energy levels and better thermal performance mean SiC-based devices can operate at a higher temperature and with a smaller chip area. These are some of the reasons why SiC is a better choice of material for power electronics devices that provide converters that demand higher efficiency and power density.

The most common SiC-based devices available on the market currently are diodes and MOSFETs. Various suppliers offer both types of devices for different voltage levels and current.
ratings. This is the reason why the SiC devices are nowadays so successful in power electronics applications across several sectors. Nearly all suppliers have SiC devices in the range of 650 V up to 1700 V for different current ratings and manufacturing technologies.

SiC devices are used frequently in EV chargers because of the benefits and characteristics they bring to these applications. SiC-based devices are valued above all for their role in maximizing efficiency and power density.

Vincotech offers an independent chipset supplier chain. It gives the flexibility to design and build power modules with the chipset that provides the best technology, features and characteristics for each use case from different suppliers. This freedom of choice also allows the designers to calibrate the best balance between cost and performance.

4 Three-phase active front-end converters

The active front-end converters are the first stage inside an EV charger. They provide the interface between the grid and the DC-DC converter. For 22 kW EV chargers (Level 2, see Table 1), the most common approach is to use three-phase active front-end topologies. The following section describes the three-phase PFC converters most commonly found in EV charger systems.

4.1 Two- and three-level PFC converters

Literature often classifies power electronics converters according to the number of levels they can synthesize. Two- and three voltage-level topologies are very popular choices for active front-end converters. In this context, the two-level converters mean that a converter synthesizes just two distinct voltage values during the nominal operation in steady-state. Three-level converters do the same for three distinct voltage levels. A generic description of this operation can be observed for the equivalent circuits depicted in Figure 3. The two-level converter can apply the levels P or N; the three-level converter does the same for the states P, O and N.
Figure 3: The ideal topologies for the two-level three-phase converter (a) equipped with SPDT devices and a three-level converter (b) equipped with SPTT devices

Figure 3 demonstrates the ideal implementation of two-voltage-level and three-voltage-level converters. The two-level converter, in the ideal implementation, features three units of SPDT (Single Pole Double Throw). The three-level converter contains three SPTT (single pole triple throw) units. This ideal implementation is useful, in order to investigate several aspects for the power converter operation. Based on that, the ripple current in the AC input inductor can be properly analyzed.

Figure 4 depicts the results of simulated steady-state operations for both types of PFC converters. These simulations clearly indicate the voltages synthesized by each converter, with the local average value shown as $\langle u_x(t) \rangle$ and the instantaneous voltage as $u_x(t)$ – where $x \in \{1,2,3\}$.

Two level converters have some performance limitations. First, the two-level output voltage waveform and second, they require semiconductor components with high voltage rating. Both aspects impact negatively on the converter losses and the grid-side filter size. Even though SiC MOSFETs can increase the two-level converters’ performance by reducing losses and allowing for higher switching frequencies, the three level converter solutions have demonstrated higher achievable performance, both in terms of efficiency and power density. Actually, these topologies simultaneously reduce the stress on the AC-side filter components and allow the implementation of semiconductor devices with lower voltage rating, consequently lower cost.
Since the three-level PFC converters provide the volume reduction of passive filters, the focus of this paper is on implementing three-phase / three-level PFC converters.

Figure 5 depicts the basic cell for the most popular three-level PFC converters; the Symmetric Boost PFC (SPFC), Neutral Boost PFC (NPFC) and Advanced Neutral Boost PFC (ANPFC). These topologies have unidirectional power flow and they have reduced number of power semiconductor devices.
Figure 6 demonstrates the efficiency and cost benchmarks for these three-level PFC converters. The NPFC power converter has the highest efficiency compared to all other three-level converters, but also the highest cost. The ANPFC converter is next – its second highest efficiency comes at lower cost. This option demonstrably gives the best balance between performance and price, which is why the ANPFC converter is highly recommended as the topology of choice for EV chargers.

![Graph and chart benchmarking 3L-PFC converters’ efficiency](image)

Figure 6: A graph and a chart benchmarking 3-level PFC converters’ efficiency

### Conclusion

The market for EV chargers demands power electronics solutions that provide a balanced trade-off of high performance and competitive pricing. Vincotech power modules meet this demand. The company’s solutions cover these use cases well and support efforts to design chargers that are more efficient yet cost less to build.

The SiC-based power electronics devices have been used successfully in EV charger systems. SiC diodes and MOSFETs’ inherent thermal and electrical properties bring several benefits to power electronics designs. For one, they provide the flexibility necessary to improve the switching frequency. For the other, a system equipped with these devices and the proper power electronics circuit has smaller passive components. This saves overall system volume and cuts costs. In this context, three-level converters are much more interesting topologies compared to the standard two-level converters. The right SiC technology paired with the proper power electronics circuits is a tremendously beneficial combination that boosts the overall system’s performance and cuts its overall cost. The three-phase, active front-end converter described in this paper features this combination and delivers both of these benefits. The ANPFC three-level power converter with a SiC-based power module design is available from Vincotech.