Wolfspeed 1200 V SiC MOSFETs enable bidirectional charging for 200 V to 800 V EV batteries

The electric vehicle (EV) industry has struggled to reduce EV charging times while keeping hardware economical and compact. With silicon carbide (SiC) MOSFETs, it has been proven that a higher efficiency and power density coupled with improved ruggedness and reliability help to keep system designs low-profile, lighter and lower-cost in terms of maintenance and component longevity.

The same applies to EV charging systems, and Wolfspeed’s 1,200V SiC MOSFETs not only meet up to these performance enhancements but also allow for bidirectional charging/discharging, thereby replacing IBGT topologies and allowing for simple two-level implementations.

On-board charging (OBC) systems for EVs typically require four-hour–plus charging time when connected to utility AC power. DC fast chargers, on the other hand, can charge battery systems as fast as 30 minutes. OBC systems are meant for battery systems that are specific to the vehicle and typically operate at lower power levels. Fast charging systems are higher in power and can support a wide variety of vehicle battery voltages.

EV battery systems can have voltages as low as 200 V and as high as 800 V, which reduces the overall current, making hardware smaller, lighter, and less costly. Though these two charging methodologies (shown in Figure 1) have significantly different power ratings and specifications, they can both benefit from SiC’s advantages. This article will review how SiC MOSFETs can be employed to meet the wide range of battery voltages and reduce losses as much as 40%, increase power density by 50%, use as many as 50% fewer active components, and lower overall system cost.

Figure 1: OBC and fast-charging system comparison
SiC enables a simple, two-level AFE AC/DC block

Wolfspeed has developed a unique approach to meet the challenges of a wide battery voltage range and bidirectional power management and includes a 22-kW active front end (AFE) block along with a flexible DC/DC converter that can be applied to either OBC or DC fast charger power blocks. The goal here is to provide a higher power density and efficiency at lower cost, support bidirectional and three-phase operation, and meet the variable 200 to 800V requirements of fast charging systems.

*Figure 2a* demonstrates the simplicity of a two-level SiC AFE. Unlike other AC/DC systems such as a six switch IGBT based design which is simple but much less efficient and power dense and T-type converters (*Figure 2b*), which perform well but are much more complex and costly, the SiC AFE can provide bidirectional operation with a lower part count and a simpler control/driver interface. The C3M0032120K 1,200V 32-mΩ SiC MOSFET has been selected for this configuration based on electrical stress and thermal design, and its new Kelvin-Source package helps to reduce switching loss and crosstalk while allowing for an easy driving voltage of 0-15V $V_{gs}$.

![Two-Level AFE AC/DC converter utilizing a Wolfspeed 1,200V 32-mΩ SiC MOSFET](image1)

![Typical 3-phase T-type converter](image2)

The AFE includes design optimizations for magnetics, resulting in higher-frequency operation and lower power loss on both the core and winding. A parameter/performance comparison was conducted for the power inductor, and several families of components were closely evaluated to match the operating conditions. It was found that the KAM series (by KDM) provides a decent tradeoff between core loss and DC bias while operating at a frequency range of up to 300 kHz.

Additionally, an advanced digital control scheme exists to accommodate both three-phase and single-phase PWM schemes. This control scheme helps to balance switching loss in all devices while optimizing thermal performance, efficiency, and reliability. Furthermore, variable DC link voltage control enables high system efficiency by varying the output based on sensed battery voltage and ensuring the CLLC runs close to resonant frequency.

Lastly, careful considerations must be made when laying out the PCB. Examples of this are keeping the ground shielding layer right below the signal layer while minimizing loop traces to reduce parasitic capacitance and inductance and not overlapping sensitive signals with the power loop.

A test was conducted at single-phase AC; *Figure 3a* displays waveforms for both charging and discharging modes. For charging mode, totem-pole operation was used to achieve the best efficiency, and for discharging mode, interleaved operation achieved the best balance for thermal conditions. *Figure 3b* shows test results for three-phase AC, whereupon the system sustained excellent power factor with a clean, stable, and well-balanced three-phase current and had an overall total harmonic distortion of less than 5%.

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When analyzing efficiency for both single- and three-phase configurations, it is found that SiC achieves a total of 98.5% efficiency with 38% lower losses when compared with IGBT topology, which typically tops out at about 96%. While T-type topology can hit similar performance to SiC, it is more complex and costly to implement. Additionally, SiC’s thermal advantages allow for much cooler temperatures all around, including case, junction, and baseplate temperatures. At max power (22 kW), it was measured 89.4°C at the case, 112.4°C (calculated) at the junction, and 65°C for the baseplate. Figure 4 displays efficiency plots for all test results.

In conclusion, the 22-kW AFE incorporating C3M0032120K SiC MOSFETs and a flexible control scheme enables high efficiency (>98.5%), high power density (4.6 kW/L), and a bidirectional charging/discharging scheme that can support single- and three-phase inputs, and it supports a very wide range of battery voltages (200 to 800 VDC).

Full-bridge CLLC DC/DC Converter with 1,200V SiC MOSFETs

Another comparison can be made with the 1,200V SiC MOSFETs in a full-bridge CLLC DC/DC converter. Traditionally, cascade converters incorporating 650V silicon result in higher part count, higher conduction loss and control complexity, and a higher overall system cost. Because the SiC MOSFETs can be used in a single, two-level converter scheme (seen in Figure 5), lower part counts and higher efficiency can be achieved, along with simpler control and a lower system cost.
In this configuration, we again use the C3M0032120K 1,200V 32-mΩ SiC MOSFET for both the primary and secondary of the CLLC converters because of the electrical and thermal stress. Operating currents on the DC link side (900 V) are as high as 22.6 Arms, while the battery side (800 V) sees up to 28.5 Arms. After a comparison for Tx core material was made, it was found that the 3C97 series (by Ferroxcube) was selected due to its optimized temperature range, magnetic flux density, and power ratings resulting in lower losses.

Benefitting from the SiC AFE design, the full-bridge DC/DC design takes advantage of the variable DC bus voltage provided by the AFE based upon the sensed battery voltage to be charged. This enables highest system efficiency, achieved by a CLLC running close to resonant frequency. Additionally, when battery voltage becomes low, control will switch to phase-shift mode, which reduces circuit gain without running inefficiently outside of the resonant frequency range. This method incorporates the same hardware as before and results in high efficiency even with lower output voltages. Finally, at lower output voltages (just above 400 V), CLLC primary is run as a half-bridge, which further reduces system gain and maintains the resonant converter in an efficient zone of operation. The half-bridge mode is limited in total power range but provides a strong peak efficiency of 98% even for low voltage batteries.

Figure 6 demonstrates the DC/DC waveforms associated with the full-bridge configuration for both charging and discharging modes. It can be observed that not only does the switching appear clean with a very low overshoot, but there is essentially zero voltage turn-on and a low current turn-off, resulting in high efficiency.

The efficiency for the DC/DC converter DC link for charging mode (Figure 7) is observed to peak at about 98.5% and sustained above 97% across the load until it enters half-bridge mode. Note that for lower output voltages (during charging), half-bridge mode limits both efficiency and delivered power capability. Similar peak efficiencies can be seen in discharging mode.

Thermal results were recorded for both 611 VDC @ 22 kW and 480 VDC @ 17.28 kW and, as with the AFE design, were observed to be well within the SiC device operating range. The highest loss/temperatures recorded were with the CLLC MOSFET in the 17.28-kW test, with a calculated power loss of 42 W, case temperature of 97.8˚C, and calculated junction temperature of 116.7˚C. Thus, the 22-kW CLLC DC/DC converter incorporating the C3M0032120K SiC MOSFETs along with its flexible control scheme enable high-efficiency (>98.5%) and high-power-density (8 kW/L) bidirectional charging systems.
Conclusion

To summarize, Wolfspeed's 22-kW AC/DC and DC/DC converters demonstrate high performance of Gen3™ SiC MOSFETs for automotive on-board chargers, fast chargers, and energy storage applications. These reference designs demonstrate how the benefits of innovative control methods such as variable DC bus control, combination of frequency modulation and phase shift, and topology can altogether combine to achieve the highest system efficiency and power density. In addition, reference designs provide guidance on key component selection for power components, magnetics, and gate drivers.

Wolfspeed offers many other reference designs and additional support tools, including design schematic and layout files, BOMs, info on preferred magnetics, application notes, training presentations, and some firmware upon request. Additionally, the SpeedFit simulator program helps to quickly calculate losses and estimate junction temperature for power devices based on lab data for common topologies ranging from simple buck and boost converters to a fully bidirectional totem-pole PFC with a resonant DC/DC converter.

Finally, a 1,200V SiC MOSFET demonstration kit exists in an evaluation board and can be evaluated/optimized at steady-state and high-speed switching conditions, giving the designer confidence and allowing for a quicker time to market.