

PSD ARTICLE SERIES
“Are You SiC of Silicon?” – 2019

Article #3: SiC Applications in Electric Vehicle (EV) Power Conversion

Electric vehicles (EVs) are seeing rapid growth in shipments, with a great deal of acceleration expected in the 2020s. All major car manufacturers have introduced or have firm plans for EV models and are actively engaged with their partners in researching the best power electronics to maximize range and minimize costs. The main applications for SiC devices are shown in Figure 1, and forecasts show the potential for \$10B in SiC shipments by 2030. The highest power element is the EV Traction inverter, which we discuss in a future article. The other main converters are the on-board charger and DC-DC converter. They increasingly involve bi-directional power flow and benefit greatly from fast switches with excellent body diode behavior. SiC FET offerings are now available with AEC-Q101 qualification to meet these needs. We discuss the main topologies, and examine the advantages of using SiC devices, especially in the higher battery voltage systems (500-800V).



Figure 1: The main applications of SiC FETs and Diodes in EV applications. The main advantages of using UnitedSiC FETs in these applications are summarized on the right.

On-Board charger topologies

Since the on-board charger (OBC) is located within the car, it is necessary to save volume and weight by using a converter topology that maximizes both power density and efficiency. The choice of topology can depend on the power range, which can be 6.6KW, 11KW or even 22KW in passenger EVs. In some cases, the

OBC may be bidirectional, which means that not only does the circuit allow the battery to be charged from the grid, your EV can serve as a distributed energy source that feeds energy back to the grid. In that mode, power flow is reversed but the peak operating power may be lower (half) of the battery charging rate.

Figure 2 shows two configurations found in on-board chargers designed for unidirectional power flow. The circuit has two main sections, a frontend rectifier stage, and a DC-DC converter stage. The rectifier stage rectifies the AC mains voltage to provide a DC rail with unity power factor. The DC-DC phase-shifted-full-bridge stage then provides accurately controlled output to charge the battery pack. During Li-ion battery charging, the circuit operates first in a controlled current mode, then a constant power mode for rapid charging, and finally a constant voltage mode until the battery is charged.

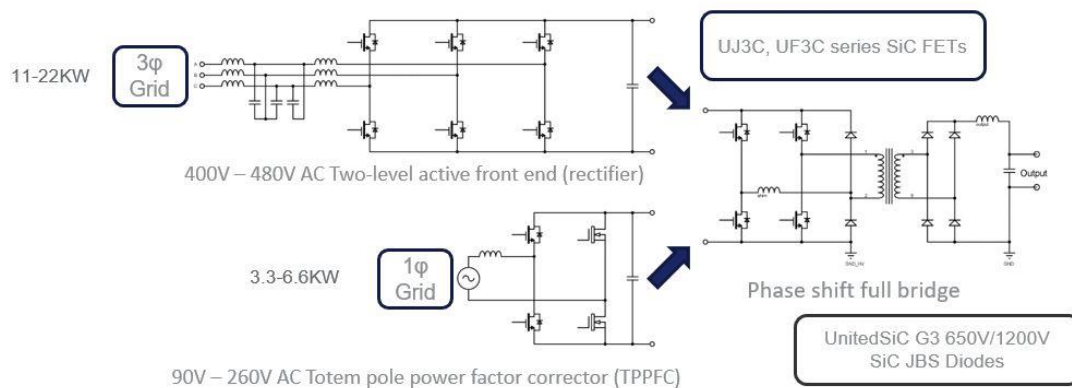


Figure 2: Popular circuit topologies used for the implementation of unidirectional On-board chargers, depending on the power level.

To maximize efficiency in the rectifier stage, bridgeless topologies are increasingly popular, since the conduction losses of the diode rectifier bridge can be avoided. Figure 2 shows the Totem-Pole PFC (TPPFC) circuit that can be used for lower power levels. This circuit involves a fast switching phase leg while the other switches at line frequency. The fast switching leg may be operated in continuous conduction mode (CCM) or Critical Conduction Mode (CRM). In CCM mode, the switch turn-on is hard, and the best option is to use wide bandgap switches with their excellent low Q_{RR} body diodes. Figure 3 shows a comparison of the device parameters, including Q_{RR} of UnitedSiC FETs compared to state of the art Superjunction devices. For switching frequencies above 20kHz, it is necessary to use wide-bandgap switches, and the standard gate drive offered by UnitedSiC FETs makes the transition easier.

Parameter	Units	UJ3C065040K4S	Superjunction device
Vds	V	650	650
Id 100C	A	40	29
RTHJC	C/W	0.46	0.55
Rds	mohm	42	40
Rds 125	mohm	59	80
Rds 175	mohm	68	
RG	ohm	4.5	0.85
Ciss 400V	pF	1500	4340
Coss 400V	pF	100	70
Coss(er)	pF	146	146
Coss(tr)	pF	325	1630
Eoss(400V)	uJ	12	13.2
Qg (10V)	nC	32	93
Vsd	V	1.4	0.9
Qrr	nC	137	13000

Figure 3: Comparing the device parameters of equivalent SiC FET and Superjunction MOSFETs. Lower conduction losses, gate charge, and especially diode recovery charge make the SiC FET devices excellent choices for all DC-DC circuit topologies, whether hard or soft switched.

If the CRM mode is used, then the peak currents become higher, putting additional constraints on the inductors, and requiring lower on-resistance switches. The absence of hard turn-on allows the use of Silicon Superjunction FETs, at least at lower bus voltages. Even in this situation, using SiC FETs makes sense due to the very low on-resistance options now available, and increasing competitive pricing relative to Superjunction FETs with similar on-resistance. Furthermore, the topology can be extended to higher DC rail voltages with 1200V SiC FETs, to increase power output with minimal switch count.

The 3-phase active frontend rectifier is an excellent option for higher power levels 11-22KW. The bus voltage is typically 600-800V, which requires the use of 1200V devices. Again, the two-level 3-phase circuit of figure 2 requires switches with low switching losses and low Q_{RR} , which shifts the choice towards SiC FETs instead of IGBTs. Figure 4 shows the turn-on and turn-off characteristics of the 35mohm,1200V TO247-4L UF3C120040K4S. These devices are used in parallel to implement the active frontend rectifier with high efficiency, given their very low turn-on and turn-off losses. Using the 4-leded package, users can switch faster with lower losses and cleaner gate waveforms.

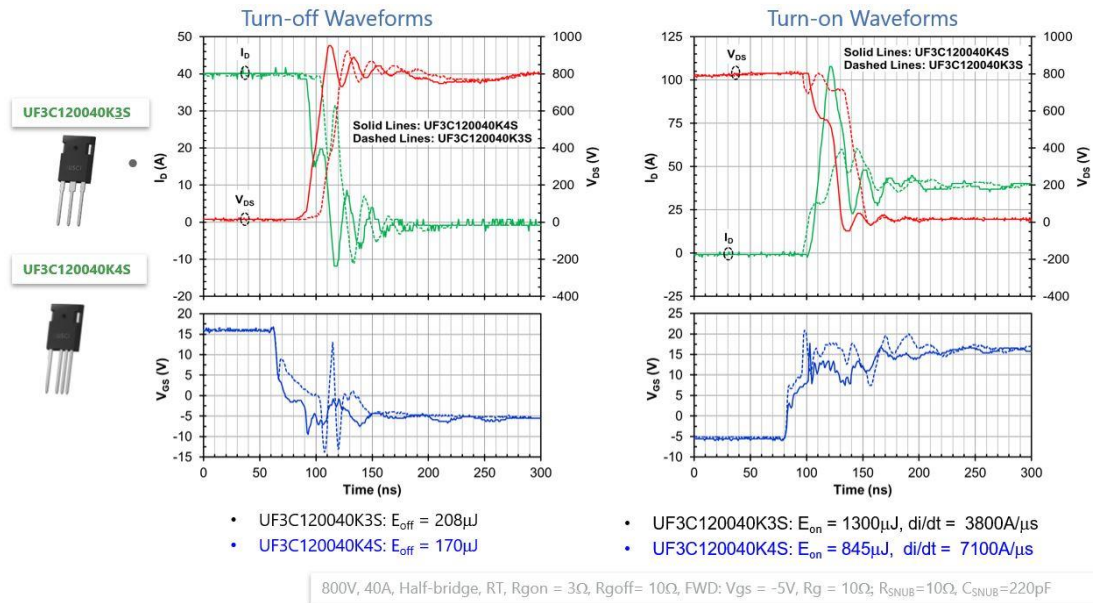


Figure 4: Switching characteristics of fast 1200V SiC FETs in half-bridge configuration using TO247-3L/4L packages. The low switching losses allow designers to increase frequency and drive up power density without loss if efficiency.

An alternate approach to the frontend rectifier is the Vienna rectifier, shown in figure 5, which allows the use of 650V Silicon Superjunction devices along with SiC Schottky diodes to reduce cost. In this circuit, the switches do not undergo hard switching. The number of semiconductors required is higher, and diode drops limit the best achievable efficiency.

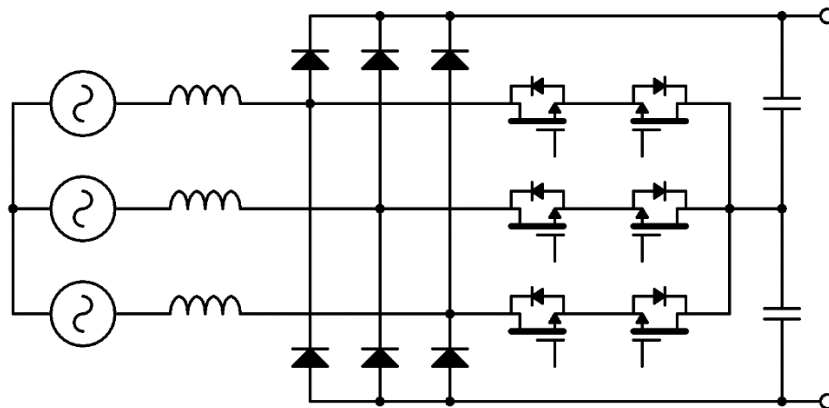


Figure 5: The Vienna rectifier topology is used with Superjunction MOSFETs since it does not allow hard body diode recovery. The SiC diodes needed in this circuit ultimately limit efficiency and power density due to their conduction loss.

DC-DC converters

As shown in figure 2, the workhorse DC-DC converter for both battery charging and supplying 12V/24V power is the phase shift full bridge. At full load, this circuit operates with zero-voltage-switched (ZVS) turn-on of the FETs, and turn-off loss is minimized with a snubber capacitor across the device. The circuit can be operated at high frequencies (100-300kHz) with good efficiency. The low conduction and turn-off losses of SiC FETs make them ideal, especially since their gate drive requirements are also simple. This is the case with UnitedSiC FETs that can be driven with 0 to 12V, or from a simple pulse transformer that outputs -12/0/12V. In light load conditions, hard switching might occur, which makes the Superjunction FETs problematic and more prone to diode recovery induced failure, and IGBT circuits prone to elevated losses.

The LLC topology shown in figure 6 is an excellent choice, especially when the output voltage is fixed. This topology is found most often in the fixed output DC-DC converter stage, while the phase-shift full-bridge is considered more suitable for dealing with variable output voltage. At lower bus voltages, Superjunction FETs with fast diodes are used in LLC circuits. At higher voltages, IGBT losses become excessive and the choice shifts to SiC FETs.

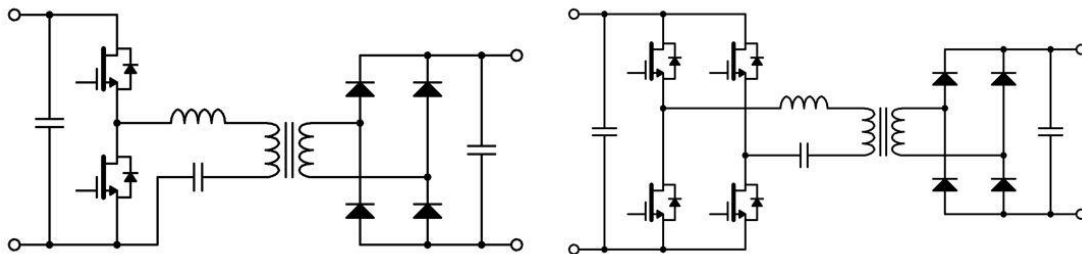


Figure 6: The half-bridge (left) and full-bridge (LLC) topology is an excellent choice for DC-DC conversion circuits when output voltage range is limited. Switching losses are minimized, and the low conduction losses of the low gate charge SiC FET devices is useful to drive up frequency while retaining high efficiency.

Even at lower bus voltages, UnitedSiC 650V SiC FETs offer very low gate charge, low time to charge the output capacitance and low body diode conduction loss, that can be used to drive up LLC operating frequencies from 100kHz to 500kHz. On-resistances as low as 7m, 650V are now available in the TO247-4L package. For low profile space constrained applications, a 27m, 650V device is available in the industry standard DFN88.

For Bi-directional DC-DC conversion, figure 7 shows the Dual active bridge (DAB) and CLLC circuits, where the output side has active switches. For battery charging, since the output voltage varies widely, the DAB can be controlled from a fixed DC bus by varying the gate PWM waveforms. If the CLLC topology is applied, then to maintain operation near resonance for the DC-DC stage, the bus voltage must be varied by changing the control scheme on the active rectifier stage (Totem pole PFC or 3-phase active frontend). In either case, it becomes necessary to use SiC FETs on the secondary side to efficiently hard-switch in the inversion mode. These may be 650V to 1200V FETs for EV battery charging, or lower voltage Silicon FETs in the 100-150V class for 12V/24V outputs.

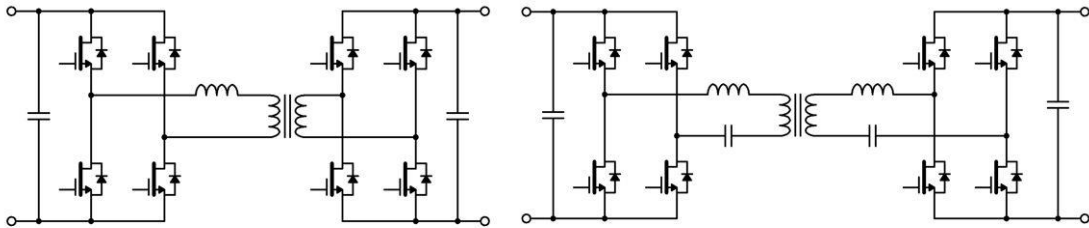


Figure 7: The Dual active bridge (left) and CLLC (right) circuit topologies are used for bi-directional DC-DC power conversion, so the EV battery can be used to return power to the grid when needed.

Easing the transition

Wide bandgap SiC FETs enable the use of improved topologies and higher frequencies to achieve the targets of high-power density and efficiency. The higher cost of the switches is easily offset by the system level gains in the EV space. UnitedSiC FETs provide a key benefit of being compatible with all types of gate drive voltages, so they can be dropped into Silicon based designs, as well as SiC MOSFET designs. This eases the transition for designers around the world as they increasingly deploy SiC, sometimes just to upgrade existing Silicon based designs.

What's on the horizon

The next stage is likely to involve integrated driver and FET stages, such as the SIP half-bridge with driver shown in figure 8, using 35mohm,1200V stack cascode switches. The switching waveforms show the very fast and clean switching enabled by such a device, which can be used as a building block for all the circuit options described in this article.

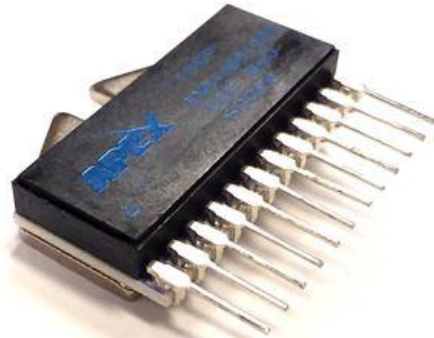
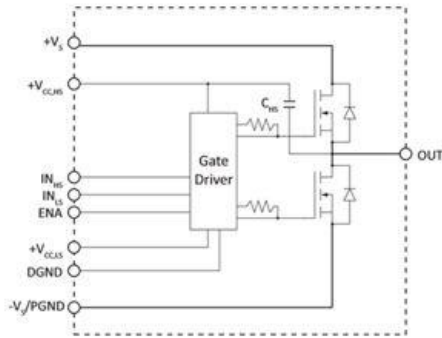
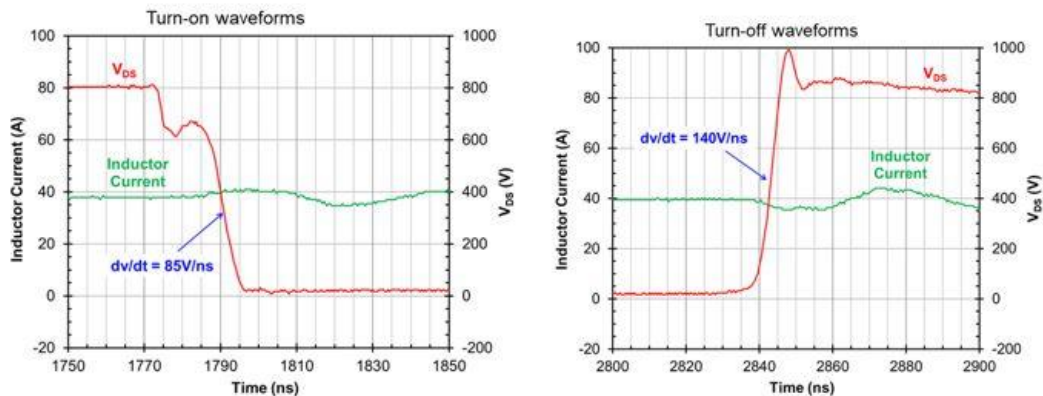


Image of 12-Pin SIP IPM Half-Bridge module with UnitedSiC 35mOhm/1200V Stack-Cascode technology (31mm x 29.5mm).



Switching performance of SiC Stack-Cascode SIP IPM

Figure 8: A SIP Module with a built-in half-bridge driver and the high/low side SiC FETs allows for much faster switching without the problems of large power loop or gate drive loop inductances. Arrangements such as these can serve as building blocks for a whole range of DC-DC circuits.

Conclusion

SiC FET technology improves rapidly, with 2X improvements in switching figures of merits under development for 2020 release. Coupled with discrete package improvements and the introduction of SiC based intelligent power modules, these advances will help push power density further as EV deployment continues to ratchet up.