Benefits of CoolSiC MOSFETs in Bi-Directional Inverter Applications

With the move to renewable energy, there is an increased focus not only on generation but also storage, to make the most of the intermittent supply from wind and solar. Batteries are the common solution and costs are dropping, driven by the technology improvements stemming from the EV market. This opens up opportunities for energy storage at any scale, from domestic to utility. **David Meneses Herrera, Senior Staff Application Engineer; and Nico Fontana, Senior Staff Product Definition Engineer, Infineon Technologies**

As the supply paradigm shifts towards renewables, traditional generation from carbon-based fuels reduces, but also interacts to its advantage by using distributed storage to feed AC back into the grid through inverters for 'peak-shaving', to make generation more cost effective and reliable.

To achieve this, batteries need to be able to charge from a cheap or convenient energy source and then discharge to a local load or back into the utility grid as 'feed in'. AC/DC chargers and DC/AC inverters are established products, but if they can be efficiently combined, then there are costs to be saved. As a result, there is intense interest in 'bi-directional converters', with the volume market set to be in households with a local renewable energy source and storage, which may be an EV battery.

Bi-directional converter requirements

A major concern is to maximize the energy from solar or wind sources, therefore any losses in electronic power conversion stages must be kept to a minimum, not least to shorten payback time for the capital costs involved. This has always been true for power processing in any application, so over the years, conversion topologies have evolved towards better efficiency, with 99 % or more now realistic for single stages. For bi-directional converters however, high efficiency has to be maintained with forward and reverse energy flow, which is an added complication. Fortunately, one of the enablers for better efficiency also facilitates bi-directional flow - the use of MOSFETs as synchronous rectifiers in 'third quadrant' operation. A typical bi-directional converter outline that might be used as a battery charger and feed-in inverter is shown in outline in Figure 1. The symmetry of the circuit is evident with bridges of MOSFETs able to act as rectifiers, an inverter or DC/DC converter dependent on drive arrangements.

AC/DC stages must also feature power factor correction (PFC) and this is best achieved at medium power levels by the bi-directional 'totem-pole PFC' topology where MOSFETs double as line AC rectifiers and boost switches in AC/DC mode and inverter switches in DC/AC mode. This characteristic of a MOSFET to change function hinges on its ability to not only conduct through its channel in the 'normal' direction from drain to source but also in reverse from source to drain with low loss, all under the control of the gate drive. MOSFETs also however feature a parasitic body diode from drain to source which can be an advantage; some circuits that require reverse conduction naturally 'commutate' to forward bias this diode to pass energy to the output at the appropriate stage of the switching cycle. The diode is not ideal however and, when conducting, stores significant charge in its junction which is released when reverse biased during each cycle. This results in 'recovery current' which causes losses, reducing efficiency, and increased EMI. The diode also has a high forward voltage drop compared with a Silicon rectifier which causes extra dissipation. Turning on the MOSFET channel bypasses the diode so if this is done with little delay, after the complementary MOSFET in the leg of a

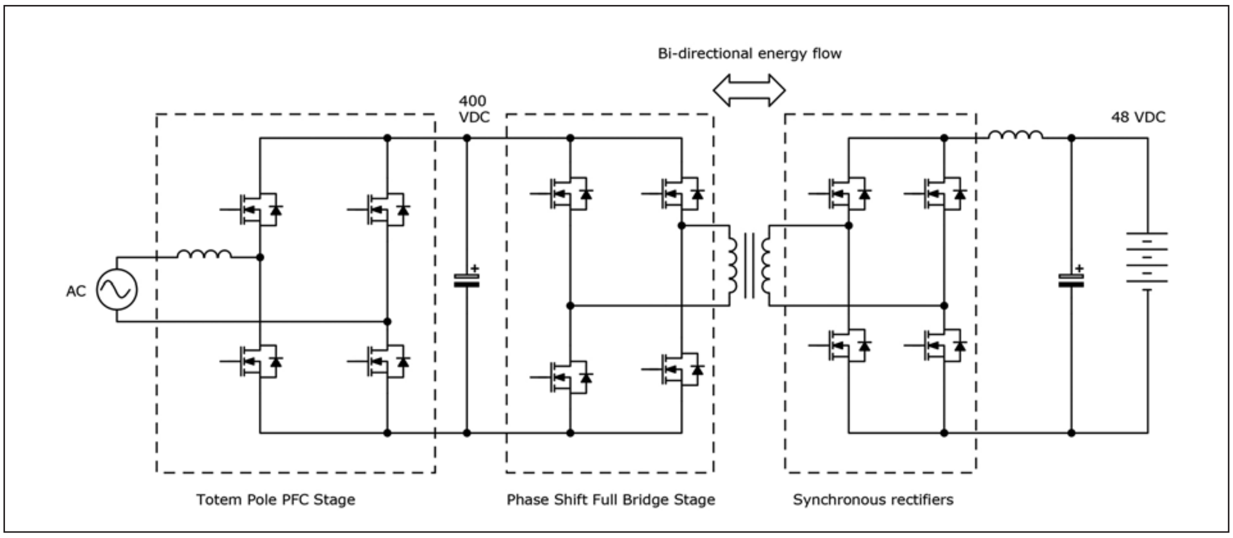

Figure 1: MOSFETs in bridge arrangements suit bi-directional power converters

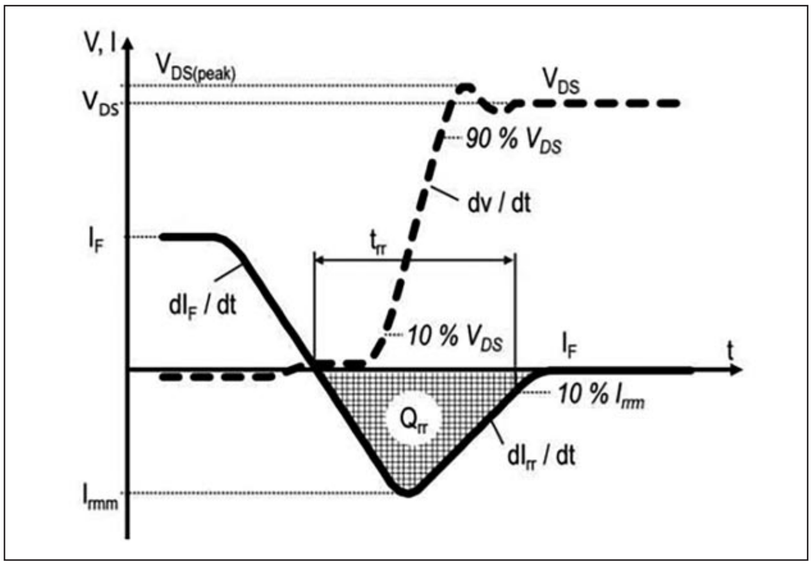

Figure 2: **MOSFET body diode reverse recovery waveform. SiC exhibits QRR of about 20 % the value of Si MOSFETs**

bridge is turned off, the additional dissipation from the forward conduction of the diode can be minimized.

Bi-directional converters such as the PSFB or versions of the 'LLC' arrangement operate with zero voltage switching (ZVS) for highest efficiency, in which mode the reverse recovery of the body diodes is not critical, as the applied reverse voltage rises resonantly. However, there are situations where the converter may transiently enter a 'hard' switching mode such as on start-up, shut-down or with load steps, during which periods high voltage is present during recovery, leading to possibly damaging stress. Device failure can also result if recovery is not complete during the on-period of the associated MOSFET channel.

Problems can also occur if the MOSFET switch in a bi-directional converter has too high output charge, Q_{OSS}. In a hard-switched converter, the current resulting during switching transitions circulates within the primary circuit of a converter causing losses. The output capacitance C_{oss} also varies strongly with drain-source voltage resulting in high Q_{oss}. If it is the dominant charge to be removed in a soft-switched resonant converter, then it can be difficult to maintain ZVS and high efficiency under worst case conditions. Minimum dead time between high- and low-side switches must also be increased as a function of Q_{oss}, resulting in a significant duty cycle loss at high switching frequencies. With lower Q_{oss}, the circuit can be 'tuned' for better efficiency.

For all these reasons therefore, stable and low output capacitance, low Q_{OSS} and minimum body diode reverse recovery energy and time are vital for high efficiency and reliability. In some topologies such as the totem-pole PFC, which is hard-switching, current Silicon superjunction MOSFET technology yields body diodes which are simply not good enough for a viable circuit.

SiC MOSFETs are a better solution

Wide bandgap silicon carbide (SiC) MOSFETs are now mainstream and are used for their better figures-of-merit (FOMs) for efficiency at high frequency, compared with Silicon. They have a range of additional advantages as well, such as inherent high temperature operation, low gate charge, lower increase of on-resistance with temperature, or robustness. Importantly for this discussion, their body diodes have much lower recovery charge, along with output capacitance that varies much less than that of Silicon MOSFETs with drain-source voltage. Additionally, for the same RDSON, a SiC MOSFET has around one sixth of the Q_{OSS} of a Silicon superjunction MOSFET.

As a comparison, we can take a Si-based 600 V CoolMOS™ CFD7 superjunction MOSFET (IPW60R070CFD7) and a CoolSiC™ SiC MOSFET 650 V (IMZA65R048M1H) from Infineon. These are both TO-247 packaged devices with similar voltage and on-resistance ratings at 25°C. The general body diode reverse recovery waveform for both is shown in Figure 2, with total reverse recovery charge noted as Q_{RR}. For the CoolMOS™ device, the figure is typically 570 nC and for the CoolSiC™ MOSFET just 125 nC at twice the forward current and 10x the rate of change of current dIF/dt.

Figure 3 shows the variation in output capacitance of the two MOSFET technologies, with a range of CoolSiC devices shown compared with the CoolMOS CFD7 superjunction MOSFET. SiC devices show lower C_{oss} at low voltages, with both types low at high voltages. Note however that the IMZA65R048M1H CoolSiC MOSFET changes by a factor of around ten between saturation and full blocking voltage whereas the superjunction MOSFET changes by a factor of about 8000. Although low C_{oss} is good for low loss from charge and discharge currents, a non-zero value for C_{oss} at high voltages with SiC is helpful – it reduces the need to slow switching speed with a gate resistor, to keep drain-source voltage within recommended derating from its maximum value. Otherwise with Si devices, a higher value resistor is needed to limit peak drain voltage, resulting in less controllability.

Reference design shows high efficiency

As a demonstration of the advantages of SiC MOSFETs in a bi-directional converter,

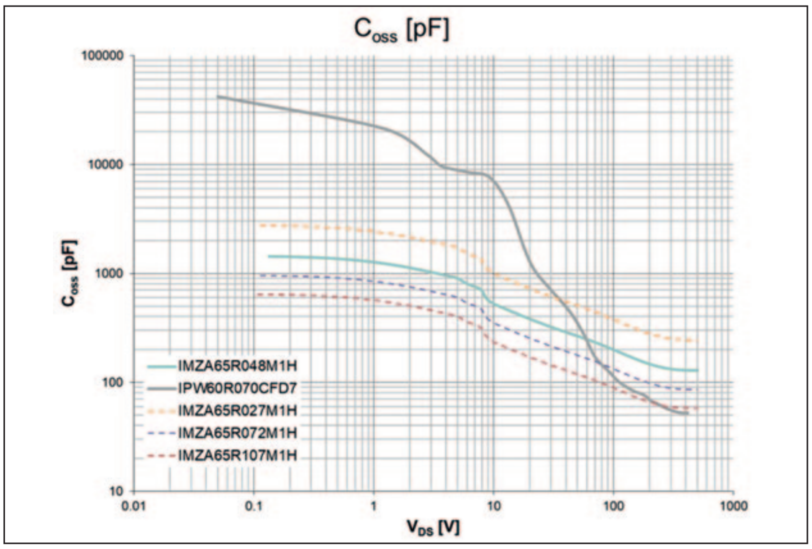

Figure 3: SiC devices show far less variation in output capacitance with drain voltage

Infineon has showcased a 3.3 kW totem-pole PFC stage (EVAL_3K3W_TP_PFC_SIC) [1] which achieves 73 W/in^3 (4.7 W/cm^3) power density with a peak efficiency of 99.1 % at 230 VAC input and 400 VDC output (Figure 4). Efficiency also peaks at over 98.8 % when operating in inverter mode, generating 230 VAC at 50 Hz. The evaluation board features full digital control, implemented with the Infineon XMCTM series microcontroller.

Conclusion

SiC MOSFETs are a natural evolution from Si superjunction MOSFETs for applications at medium to high power with high switching frequency. Here there are significant efficiency gains to be had, along with a reduction in size and cost of associated components, particularly magnetics. This can result in significant end-product savings in cost, size and weight, as well as lower energy bills. In bi-directional converters, SiC devices can perform all high voltage switching functions with higher efficiency than traditional solutions and with their superior body diode characteristics, can make hard switching topologies such as the totem-pole PFC viable and cost effective.

Infineon offers a range of CoolSiC™ MOSFETs in discrete and module formats in ratings from 650 V to 1700 V and with on-resistance down to 2 milliohms. The devices are further complemented by a range of EiceDRIVERTM gate drivers in non-isolated and isolated variants for low- and high-side drives, using Infineon's coreless transformer technology. For a complete solution, current sensing ICs and microcontrollers for digital control are also available.

Literature

[1] 3300 W CCM bi-directional totem pole with 650 V CoolSiC™ and XMC™ Infineon application note AN_1911_PL52_1912_141352

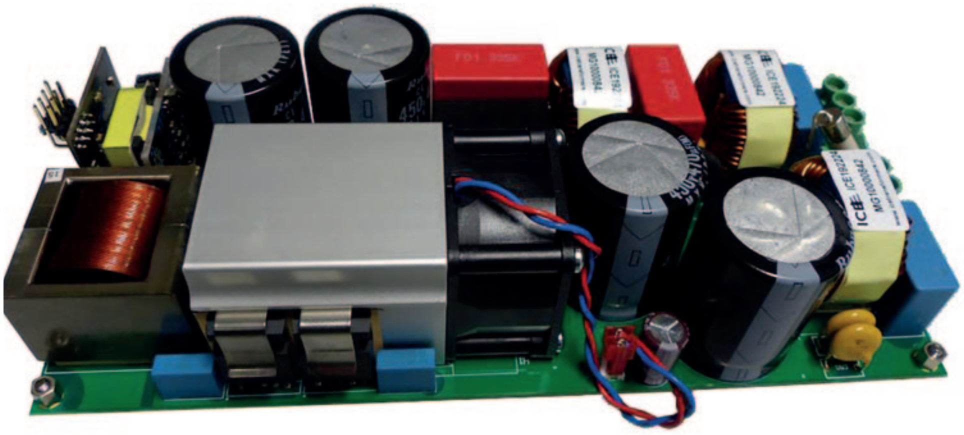

Figure 4: A high-efficiency bi-directional AC/DC-DC/AC converter using CoolSiC MOSFET technology