APPLICATION NOTE **PRD-05641**

DESIGNING WITH SILICON CARBIDE IN ENERGY STORAGE APPLICATIONS

Silicon Carbide (SiC) technology has transformed the power industry in many applications, including energy harvesting (solar, wind, water) and in turn, Energy Storage Systems (ESSs). Due to the major improvements seen with switching frequencies, thermal management, efficiency, current/voltage capacities, footprint reduction, superior bi-directional flow, and BOM/cost savings, SiC components can benefit just about every power stage of an energy storage system from the energy harvesting mechanism, to the delivery and storage of that energy.

In this app note, we'll find that SiC enables higher system efficiency, higher power density, and a reduction in passive component volume and cost. But it's important to consider the component selection and topology for each power stage to fully benefit from this technology.

What does an ESS consist of? A typical solar application with storage will contain the Photo-Voltaic (PV) panels, power conversion, a battery, power delivery, and then connection to your home or the grid (see **Figure 1**). This system can be scaled depending on the power level and application (residential vs. commercial), and SiC can allow for improved efficiency, size, weight, and cost for each of these main power management blocks.

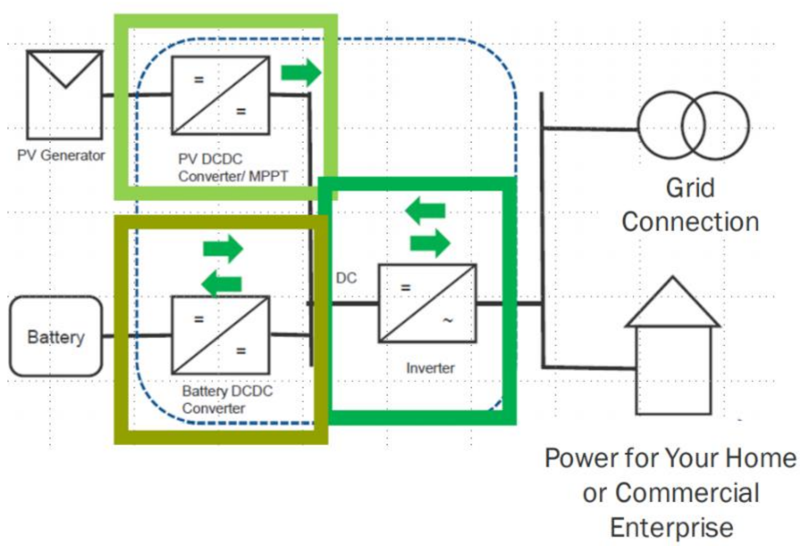


Figure 1. ESS Configuration for Residential or Commercial

Each power stage requires careful consideration for both the topology and the components selected. Let's first look at the DC/DC conversion process.

POWER TOPOLOGY CONSIDERATION – DC/DC BOOST

The DC/DC conversion section of an energy storage system often contains a boost converter which can greatly benefit from SiC technology, particularly with higher efficiencies and power densities. Figure 2 shows a 60kW DC/DC SiC interleaved boost converter, consisting of four paralleled 15kW boost circuits (using C3M0075120K and C4D10120D SiC devices). The input ranges from 470V to 800V and its output can reach 99.5% efficiency at 127W/in^3 power density.

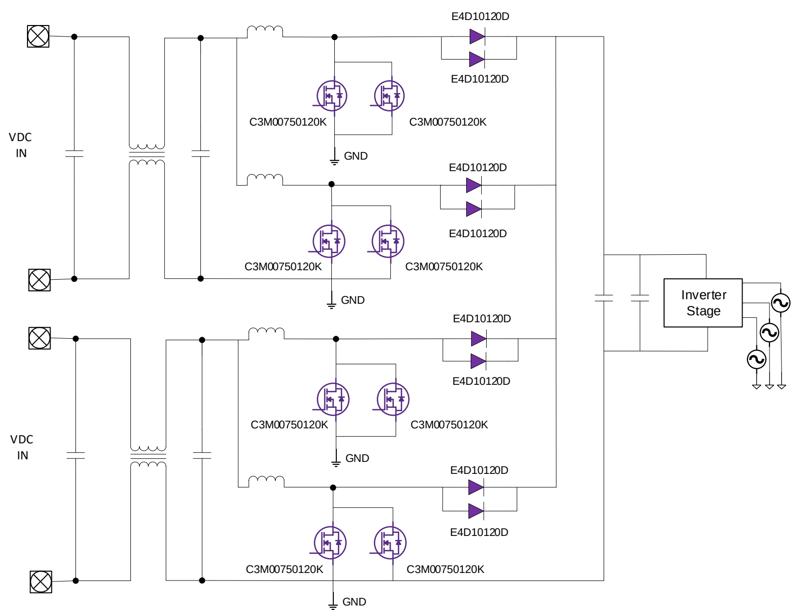


Figure 2. 60 kW SiC-Based Interleaved Boost Converter Reference Design

The boost diode in each of the stages can support 10A (so 20A total) while the SiC MOSFETs provide plenty of head room in thermal performance. The most common configurations for these boost circuits are 2-level and 3-level configurations. **Table 1** describes the differences while **Figure 3** gives a visual of how they are wired.

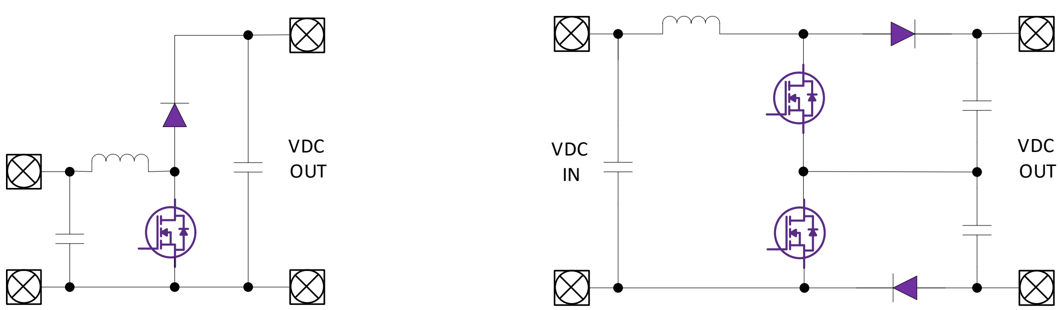


Figure 3. 2-Level Boost Converter (Left) and 3-level Boost Converter (Right)

Topology	Benefits	Drawbacks
2-Level Boost	Simple Structure and Control	Large Inductor
	Lower Cost	Lower Power Density
3-Level Boost	High Power Density	Complex Control
	Slightly Higher Efficiency	Higher Cost

Table 1. 2-Level vs. 3-Level Topology Comparison

A simulation tool "SpeedFIT™" is available to assist in comparing efficiency and temperature of the devices in different topologies. **Figure 4** shows simulations for a 2-level and 3-level boost circuits with an output voltage of 850VDC. This was done using two C3M0075120K MOSFETs and one C4D20120D diode for the 2-level topology, and two C3M0045065K MOSFETs and two C6D20065D diodes for the 3-level topology.

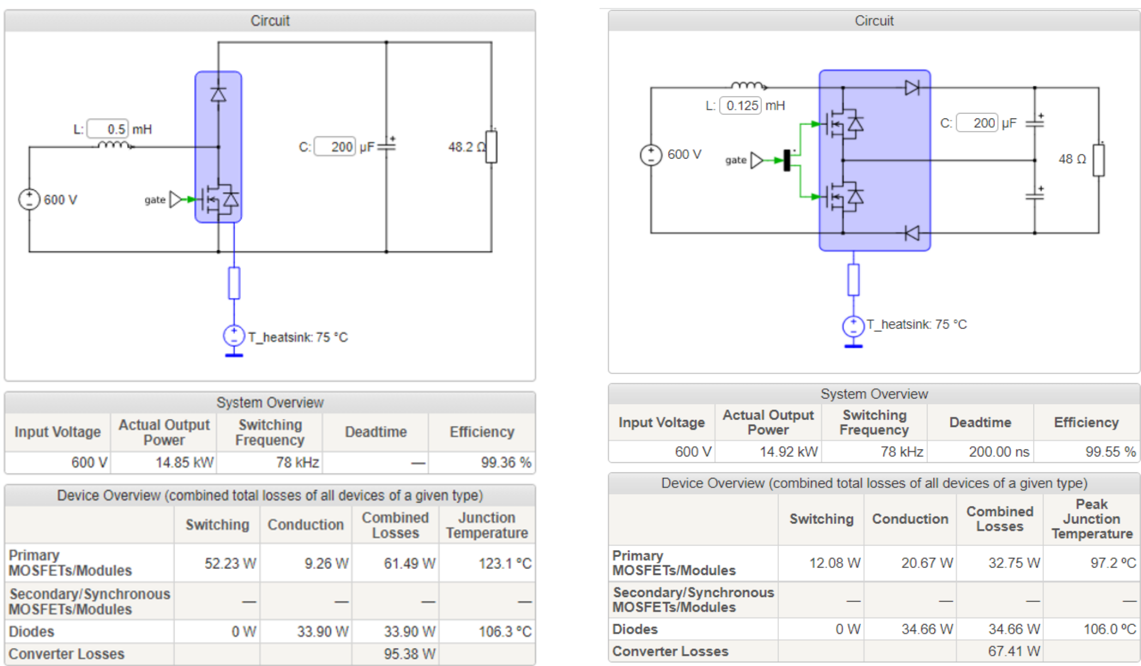


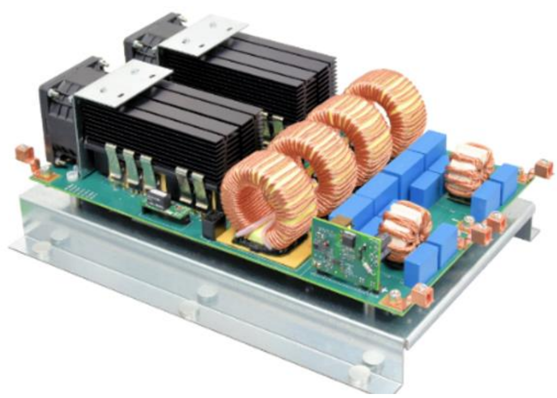
Figure 4. SpeedFIT Simulations for 2-Level (left) and 3-Level (Right) Boost Topologies

Another design approach to consider for boost converters, particularly for Photo-Voltaic (PV) applications, is a Maximum Power Point Tracking (MPPT) algorithm that modifies the operating voltage or manipulates the load impedance to maximize power output. This is useful for solar panels with internal resistances that vary with output power. Wolfspeed's 60kW Interleaved Boost Converter reference design (CRD-60DD12N shown in **Figure 5**) can take a variable PV output and convert it to an intermediate 850V bus voltage at a low power loss and high-power density, while maintaining 99.5% efficiency. This design utilizes two C3M0075120K MOSFETs in parallel per channel, as well as two C4D10120D boost diodes.

In general, using SiC MOSFETs and diodes for this DC/DC boost converter allow for the following advantages over Silicon-based components:

- 1-2% higher efficiency due to faster switching and zero reverse recovery
- 3X power density thanks to higher switching frequency
- Lighter weight due to smaller magnetic components
- Lower system cost

Please note the actual performance varies with operating conditions and parts used in the system.



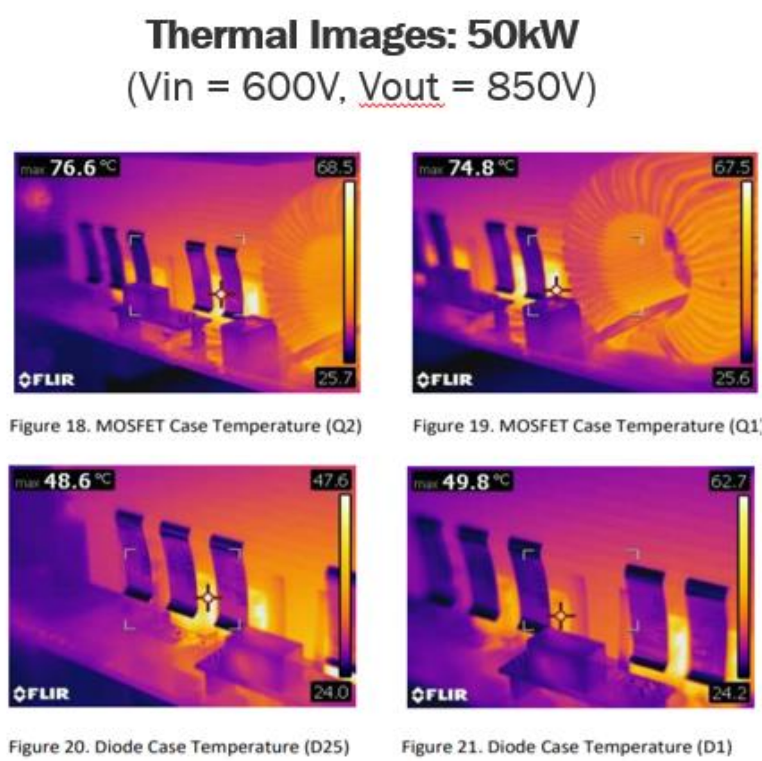


Figure 5. Wolfspeed's 60kW Interleaved Boost Converter Reference Design - CRD-60DD12N and Thermal Images Indicating Case Temperature

POWER TOPOLOGY CONSIDERATION – DC/AC INVERTER/AFE CIRCUITS

While DC/DC boost converters cover most solar ESS applications, DC/AC or AC/DC conversion is necessary for fuel-cell-based or other alternative-based energy systems where power entry comes in at 850V bus level and is used to either charge batteries or to be put onto a grid system. SiC can help improve these conversions as well.

Active front-end/inverters for three-phase systems are traditionally designed with IGBT components, but as seen in the boost converter topologies, SiC can offer higher efficiency and power density at higher switching frequencies. And as with most conversion types, there are many topologies to choose from. **Table 2** describes the differences between a 2-level inverter, NPC 3-level inverter, and T-type inverter.

	2-Level Inverter	3-Level Inverter	T-Type Inverter
Number of MOSFETs	6	12	12
MOSFET PNs	6*C3M0040120K	6*C3M0025065K(HF) + 6*C3M0025065K(LF) + 6*C6D16065D	6*C3M0025065K (HF) + 6*C3M0025065K (LF)
Device Cost	X	2X	1.8X
Gate Driver Cost	X	2X	2X
Inductor Volume	X	0.55X	0.55X
Inductor Cost	X	0.69X	0.69X
Efficiency	X	X+0.1%	X+0.5%
Total Cost	X	1.56X	1.50X
Benefits	Simple Control Low Cost	Higher Efficiency Lower Harmonics	Higher Efficiency Lower Harmonics
Drawbacks	Lower Efficiency Higher Harmonics	Complex Control Higher Cost	Complex Control Higher Cost

Table 2. 22kW Inverter/AFE Comparison

The Wolfspeed 22kW bi-directional charger reference design (CRD-22AD12N shown in Figure 6) showcases an inverter/AFE with a six-switch configuration that can operate in single or three-phase mode during both charging and discharging. The high efficiency paired with the very wide range of voltages makes it ideal for various battery systems and fast chargers for EVs. **Table 3** shows the specifications for this design.

Figure 6. Wolfspeed 22kW Bi-Directional Charger Reference Design CRD-22AD12N

	3Phase AC Charging	1Phase AC Charging	Discharging Mode
Input Voltage	304Vac~456Vac	90Vac~277Vac	300Vdc-800Vdc
Output Voltage	200-800Vdc	200-800Vdc	220Vac
Rated Power	22kW 36A max	6.6kW	6.6kW
Overall Peak Efficiency	>96%	>96%	>96%
DCDC Peak Efficiency	>98.5%	>98.5%	>98.5%
DC Bus Voltage	650V-900V	380V-900V	360V-760V

Table 3. CRD-22AD12N Reference Design Specifications and Performance

Selecting power components is critical for this kind of application. C3M0032120K (1200V/32mΩ) SiC MOSFET was selected due to its high voltage rating (1200V) and low conduction loss. Kelvin source package of this device allows optimization of the driver circuit and increase of the switching speed to get the highest efficiency and higher frequency that drives cost down. **Table 4** shows the thermal performance of this reference design operating in different modes.

	Calculated Power Loss	Case Temperature	Calculated Junction Temperature
Input 3-phase 380VAC, Output = 900VDC 22kW			
PFC MOSFET	52W	89.4°C	112.4°C
Input Single Phase 215VAC, Output = 900VDC 6.6kW			
PFC MOSFET HF	42W	84.9°C	103.9°C
PFC MOSFET LF	20W	69.1°C	78.1°C
Input 760VDC, Output = 220VAC Single Phase 6.6kW			
PFC MOSFET	36W	79.8°C	96.1°C

Table 4. AFE Thermal Performance with C3M0032120K

POWER TOPOLOGY CONSIDERATION – DC/DC BATTERY CHARGERS

For bus voltage up to 900VDC, in general a cascaded multilevel topology is what 650V silicon MOSFETs can do as shown on the left in Figure 7. However, this multilevel topology has higher part count of gate drivers associated with all the switches, higher conduction losses, with more complex control and current sharing problem. In the end, this results in higher overall system cost as compared to the two level topology shown on the right in Figure 7 even given the higher prices of the 1200V SiC devices. With 1200V silicon carbide MOSFETs, there is a lower part count, higher efficiency, and simpler control. Wolfspeed's CRD-22DD12N reference design is a two-level bi-directional DCDC converter that can replace a more complicated silicon-based cascade converter. Furthermore, the CLLS topology has zero-voltage turn on and very low current turn off, which makes combating EMI a relatively easier task. **Table 5** demonstrates why the two-level converter solution is preferred.

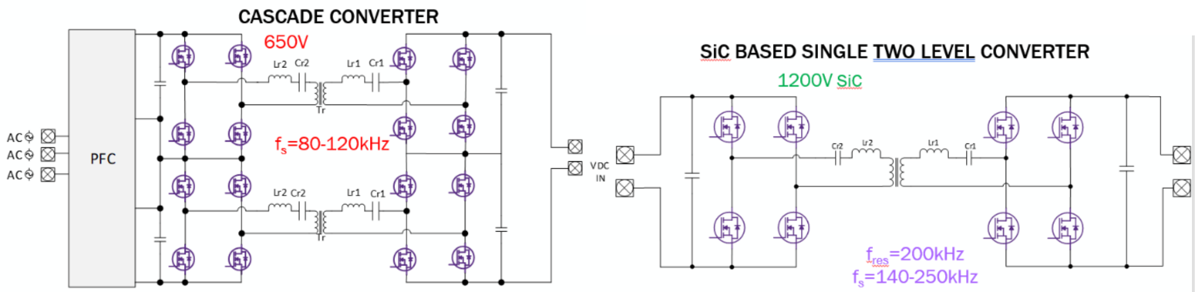


Figure 7. DC/DC Converter Topologies for Battery Charging Systems

Cascade Converter Drawbacks	Single Two-Level Converter Advantages
Higher parts count (16 MOSFETs)	Lower parts count (8 MOSFETs)
Higher conduction loss	Higher efficiency
Higher control complexity	Simpler control
Higher system cost	Lower system cost
	Zero voltage turn-on
	Low current turn-off and lower switching loss

Table 5. SiC Two-Level Converter Advantages Over Traditional Cascade Converter Solution

The Wolfspeed 1200V SiC MOSFETs C3M0032120K provides a good solution to the 2-level CLLC topology. It has low conduction loss as well as low switching loss thanks to the Kevin source package for the gate drive. Another unique feature of this reference design is that the DC bus voltage, i.e, the AFE output (link voltage), can be adjusted based upon the sensed battery voltage. A variable DC link voltage allows the switching frequency to be as close to the resonant frequency as possible, and enables the best system efficiency.

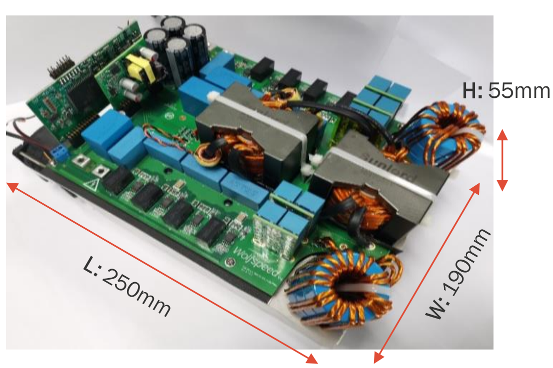


Figure 8. CRD-22DD12N Reference Design

Table 6 highlights the thermal performance of this reference design.

	Calculated Power Loss	Case Temp	Calculated Junction Temp
		Output = 611VDC Input = 772VDC 22kW	
CLLC MOSFET	32.5W	87.6°C	102.2°C
CLLC SR MOSFET	38W	91.7°C	108.8°C
		Output = 480VDC Input = 650VDC 17.28kW	
CLLC MOSFET	42W	97.8°C	116.7°C
CLLC SR MOSFET	38W	92.1°C	109.2°C

Table 6. Thermal Performance of CRD-22DD12N

The 22kW CLLC DC/DC converter reference design with C3M0032120K SiC MOSFETs allows for a flexible control scheme, high efficiency, and high-power density, bi-directional charging systems. **Table 7** describes some of these characteristics.

Attribute	System Performance
Power Density	8kW/L compared to 5.5kW/L seen with silicon
Efficiency	> 98.5% for both charging and discharging
DC Link	Single-phase and three-phase AC Input
Battery Voltage Range	200VDC-800VDC
Cost	0.18X lower than Silicon-based system

Table 7. Characteristics of the CLLC DC/DC on the CRD-22DD12N Reference Design

For residential ESS systems, the new C3M0060065D 650V MOSFETs and C6D10065A diodes can be used for a 400V bus voltage and switched at high frequency. This enables low power loss while also shrinking the footprint and BOM costs due to smaller and lighter magnetics. Another reference design consisting of a unidirectional 500kHz LLC converter has the electrical specifications shown in **Table 8** and a comparison of the magnetics in **Table 9**.

Parameter	Value
Input Voltage	380 – 420VDC
Output Voltage	400VDC (Closed-Loop)

	390 – 440VDC (Open Loop)
Output Power	6.6kW Max
Peak Efficiency	98.5%
Switching Frequency	400kHz – 1.5MHz

Table 8. 500kHz LLC Converter Reference Electrical Specifications

Silicon Solution	SiC Solution	SiC Advantage
fs = 150kHz	fs = 500kHz	233% Faster
Transformer/inductor volume = 48 cm^3	Transformer/inductor volume = 25 cm^3	40% Smaller
Weight = 416 g	Weight = 200 g	52% Lighter

Table 9. Comparison of Magnetics Used for Si- and SiC-based LLC

With high switching frequency, the leakage inductance can be used as a resonant inductor in LLC. The above table shows the advantage in doing this. Furthermore, high switching frequency can lead to a smaller size of filter and EMI filter, as well as faster transient response.

Lastly, a non-isolated buck converter can be used as a battery charger for PV applications, offering simplicity without isolation transformers and high efficiency. The battery voltage can be boosted to the desired DC bus voltage and then converted to AC for either the grid or household use. **Figure 9** shows an example of this kind of circuit, utilizing 9 total MOSFETs.

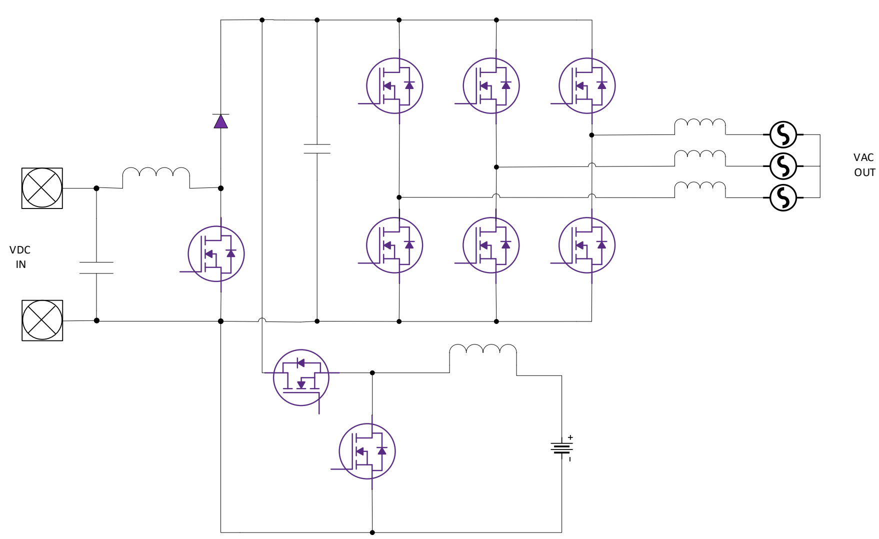


Figure 9. Circuit Diagram of Non-Isolated Buck Converter for Battery Charging Application

For this particular application, it was found that for a simple buck converter with 5kW power output (VIN = 800V, VOUT = 400V), a peak efficiency of 98.6% can be attained with C3M0075120D SiC MOSFETs and switching frequency of 100kHz. For even higher power and efficiency, C3M0032120K can be used thanks to its lower switching loss and lower turn-on resistance.

SUMMARY

To conclude, there are many sections in a battery charging, energy storing system that can benefit from SiC technology, primarily due to superior thermal properties, faster switching with lower power loss, smaller footprints, and lower BOM costs. **Table 10** highlights a broad comparison of some of these topologies (which are listed below) and their main features.

Topology 1 – DC/DC 60kW Interleaved Boost Converter

Topology 2 – DC/AC 22kW Bi-directional Two-Level Inverter

Topology 3 – DC/DC 22kW Battery Charger (Isolated)

Topology 4 – DC/DC 5kW Battery Charger (Non-Isolated Buck)

	Topology 1	Topology 2	Topology 3	Topology 4
SiC MOSFET Count	8	6	8	2
Efficiency	99.55%	> 96% single phase > 97.5 three phase	98%	98.6%
Main Features	Easy Control Low Cost High Power Density	Easy Control Low Cost High Power Density	Flexible Control High Efficiency High Power Density	High Efficiency Simple Control

Table 10. Topology Summary for Different Converter Systems for ESS Applications