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Thermal Management in Silicon Carbide (SiC) Designs

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As we seek power solutions that are ever more powerful, yet smaller, wide bandgap (WBG) materials such as silicon carbide (SiC) are becoming popular, especially in challenging applications such as automotive drivetrains, DC fast charging, battery energy storage, UPS, and solar power.

These applications are quite similar in that they all require an inverter/switching stages (Figure 1). They also require a lightweight solution that is compact and energy efficient. In the case of vehicles, this is to increase range while in solar applications this is to limit the weight that has to be placed on roofs.

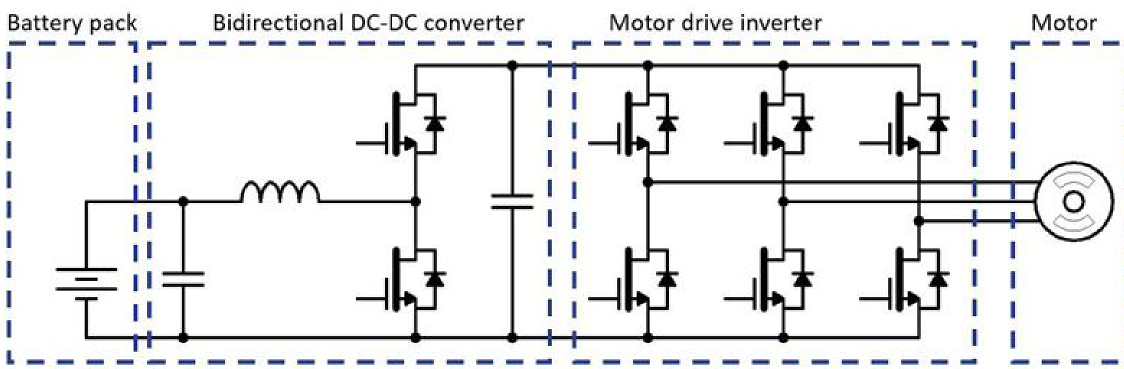

Figure 1. A Typical EV Powertrain Showing the Inverter Stage

Semiconductor Losses

One of the greatest factors in determining the efficiency of an inverter/a power stage is the semiconductor switches (IGBTs / MOSFETs) that are used. These devices exhibit two primary types of losses – conduction and switching. The conduction loss is proportional to the on−resistance ($R_{DS(ON)}$) of the switch and is calculated as the product of the drain current (I_D) and drain−source voltage (V_{DS}).

When comparing the V_{DS} characteristics of a SiC MOSFET against a similar silicon IGBT, it is observed that V_{DS} is generally lower for a given current in the SiC device. It is also worth noting that, unlike IGBTs, V_{DS} in SiC MOSFETs is directly proportional to I_D, meaning that it is significantly lower at lower currents. This is significant in modern high−power applications (such as automotive and solar power) as it means that efficiency is significantly enhanced, with lower losses, even at reduced power levels where inverters in these applications operate for most of their working life.

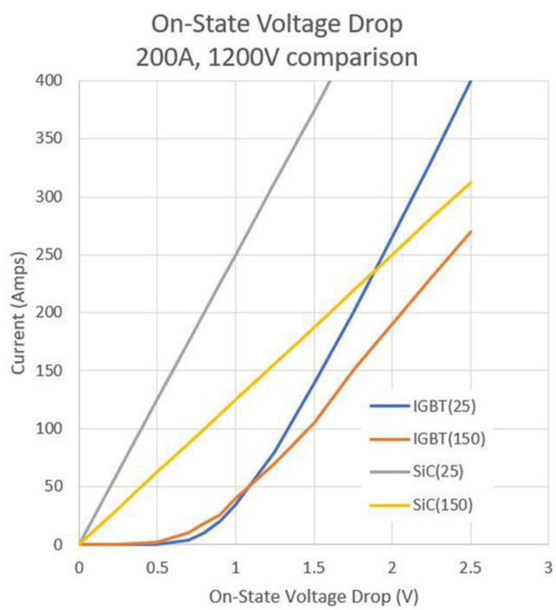

Figure 2. Comparison of VDS for Si IGBTs and SiC MOSFETs

The driving losses are proportional to the gate charge (Qg) required to switch the device. This is required every switching cycle, making it proportional to switching frequency, and is larger for silicon MOSFETs than for SiC devices. Designers are keen to increase switching frequencies to reduce the size, weight and cost of magnetic components, meaning that there becomes a significant benefit in using SiC devices.

Thermal Management Implications

All losses in a power system become heat, which has an impact on component density, thereby increasing the size of the end application. Heat-generating components do not only raise their own internal temperature, but they also raise the ambient temperature of the entire application. Ensuring that the temperature rise does not restrict operation or even lead to component failure requires thermal management within the design.

SiC MOSFETs are able to operate at higher frequencies and temperatures than silicon devices. As they can tolerate higher working temperatures, the need for thermal management is reduced as it is permissible to allow a greater thermal rise in the devices themselves. This means that when comparing a silicon-based design with the equivalent SiC-based design, there is a significantly lower thermal management requirement, as a SiC system generates lower losses and can operate at a higher temperature.

By way of comparison, a typical SiC diode exhibits 73% lower losses than the equivalent silicon diode when operating at 80kHz. As a result, in the high-power inverters found in solar applications and EV, the efficiency benefits of SiC devices will have a very significant impact in reducing the thermal management needs of power systems, potentially by 80% or more.

Total Cost of SiC-based Power Systems

Although SiC devices have been shipping to customers for some time, the perception that SiC-based designs will ultimately cost more than a Si-based design has slowed the adoption in some quarters. However, a direct comparison of the relative cost of Si and SiC devices without considering the impact of each technology on the overall system cost can lead designers to the wrong conclusion.

If we consider a Si-based power solution at around 30 kW, the semiconductor devices used for switching add up to about 10% of the BOM cost. The primary passive components (inductors and capacitors) account for the majority of the remaining cost at 60% and 30% respectively.

While it is true that SiC devices have a unit cost that is greater that their Si equivalents, the performance of the SiC devices allows the values of the inductors and capacitors to decrease by 75%, significantly reducing the size, weight and cost. This alone can reduce the total cost of the SiC-based BOM to appoint that is lower than the equivalent Si-based solution. However, as we have seen, the cost of thermal management in a SiC-based solution is also significantly lower. So, adding in this cost saving means that the SiC design is more efficient, smaller, lighter and lower cost – by some margin.

The latest 1200 V and 900 V N−channel EliteSiC MOSFETs from **onsemi** has a body diode with low reverse recovery charge to significantly reduce losses, even when operating at higher frequencies. The small chip size helps with high frequency operation as does the reduced gate charge, reduced Miller (Crss) and output (Coss) parasitic capacitor charge which lessens switching losses.

Available with I_D ratings up to 118 A, these new devices improve overall system efficiency and improve EMI while allowing designers to use fewer (and smaller) passive components. Where higher current handling is required, the devices can also be configured to operate in parallel, due to their positive temperature coefficient / temperature independence.

Primarily there are two approaches to thermal management, active or passive. The passive approach uses heatsinks or other similar devices such as heatpipes to move excess heat from the heat generating device to the housing where it can dissipate into its surroundings. The capacity of a heatsink increases with size and heat dissipate capabilities are proportional to the available surface area, often leading to complex designs to achieve the greatest surface area in the smallest volume.

Active cooling usually involves some form of air−moving device such as a fan or coolant fluid in e−mobility applications. As these generate forced airflow, they can deliver more cooling within a constrained space. However, there are some significant drawbacks including fan reliability and the requirement for an opening in the inverter housing to allow airflow (which can also allow the ingress of dirt or liquids). Also, fans require electrical energy to operate which has an impact on overall system efficiency.

Summary

With power designers being challenged to deliver solutions that are more efficient, reliable and smaller, they are looking to new technologies such as SiC to help them meet these challenges and also achieve a lower total cost.

SiC based switching devices offer designers the ability to operate at higher temperatures and frequencies with lower losses which are all key in meeting these challenges. Furthermore, these electrical performance benefits mean that the thermal management requirements and component values of passive devices are significantly reduced, thereby delivering further cost and size/weight reductions. As a result, SiC designs are able to achieve higher levels of performance than Si at a reduced size and cost.

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