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# onsemi EliteSiC M3S Technology for High−Speed Switching Applications

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## Abstract

Silicon carbide (SiC) based power converters are becoming increasingly popular in power electronics due to their high efficiency and power density, which are critical factors for environmental and energy cost considerations. SiC devices possess higher dielectric breakdown strength, energy bandgap, and thermal conductivity than silicon, allowing for the creation of more efficient and compact power converters [1]. Low $R_{DS(on)}$ and body diode reverse recovery charge values are crucial parameters for minimizing switching and conduction losses. SiC devices can switch faster and operate at higher frequencies than Silicon (Si) MOSFETs or IGBTs, resulting in space−saving, reduced heat dissipation, higher efficiencies, and lighter power converters. This article discusses **onsemi**’s current 1200 V SiC MOSFET technology, known as M3S, developed specifically for high−speed switching applications, and compares it with similar parts from competitors under various conditions using characterization tests and simulations on a 3−phase Power Factor Correction (PFC) converter implemented with SiC MOSFETs.

## 1. Introduction

Designers aim to reduce power losses in converters and devices to achieve higher efficiency levels and converters and devices with higher power density. SiC devices are popular in today’s power electronics world as they provide what designers are looking for. SiC’s material properties allow designers to have lower switching and conduction losses compared to Si−based MOSFETs and IGBTs, making them a hot topic. Furthermore, the SiC device industry is expected to grow in the coming years, especially with the expansion of the EV/hybrid−vehicle market. Power losses can be divided into conduction losses and switching losses. Switching losses occur because the current or voltage does not rise or fall instantaneously while the other variable is not zero. For power MOSFETs, the time it takes for the current or voltage to rise or fall is determined by how quickly the parasitic capacitances are charged or discharged. In addition to parasitic capacitances, the reverse recovery charge (Qrr) of the body diode introduces additional switching losses. Conversely, losses due to conduction occur while the device is conducting current. Switching losses depend on the dynamic parameters of the device, while static parameters cause conduction losses.

Since these switching and conduction losses are caused by device parameters, by examining the parameters designers can develop an idea of the device performance relative to losses. The following device parameters can be listed as the main ones that designers should evaluate for switching losses:

- Device capacitances ($C_{oss}$, $C_{iss}$ and $C_{rss}$)
- Reverse recovery behavior ($Q_{rr}$)

Contributors to conduction losses can be listed as the following:

- $R_{DS(on)}$
- $V_{SD}$ (Body diode voltage drop)

## 2. M3S Technology and Portfolio

### Technology Description

EliteSiC MOSFET technology has progressed through three generations at **onsemi** (Figure 1). The M1 is a classic planar DMOS structure with modest critical dimensions to establish **onsemi**'s first generation of SiC MOSFETs. In M2, two major advancements were applied. First, the layout was changed from square to an elongated hexagon, thereby enabling an increase in the unit cell density. Second, the substrate was thinned by more than 70% to reduce its parasitic resistance. The net effect was a 20% reduction in the specific on−resistance ($R_{SP}$). In M3, the geometric unit cells (square and hexagon) were replaced with a stripe design to facilitate an aggressive reduction in the unit cell pitch. This resulted in an additional 30% reduction in the $R_{SP}$ from the previous M2. The M3 technology has been split into two application−specific products: M3S and M3T. The M3T is designed to meet motor control and traction inverter requirements while M3S, which is the topic of this paper, provides an ultra−low $R_{SP}$ along with best in class switching losses ($E_{TOT}$), hence, is well suited for high−speed applications such as on−board chargers (OBCs) and High Voltage DC/DC converters.

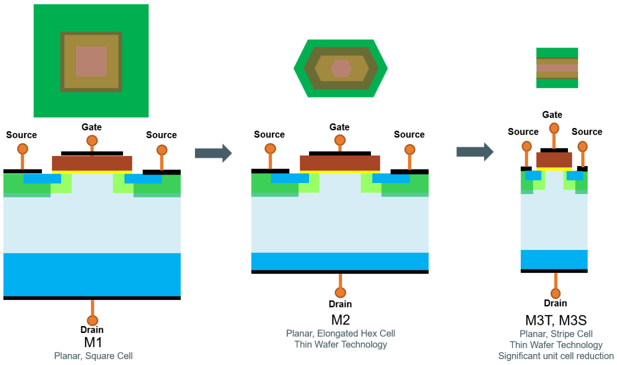


Figure 1. Technology Evolution of EliteSiC MOSFET

## Produce Portfolio

The 1200 V SiC MOSFETs are extensively utilized in 800 V battery automotive applications, such as OBC and High Voltage DC/DC Converter. **onsemi** offers a broad spectrum of products, covering power ranges from 3 kW to 22 kW, with varying $R_{DS(on)}$ values ranging from 20 mΩ to 65 mΩ, complying with the JEDEC Standard TO−247−4 and TO−263−7 (D2PAK 7L high−creepage).

**Table 1. onsemi's 1200 V SiC MOSFET PORTFOLIO**

| $R_{DS(ON)\ typ}$ (mΩ) | TO247−4* | D2PAK−7L |
|---|---|---|
| 20 | NVH4L022N120M3S | NVBG022N120M3S |
| 30 | NVH4L030N120M3S | NVBG030N120M3S |
| 40 | NVH4L040N120M3S | NVBG040N120M3S |
| 65 | NVH4L070N120M3S | NVBG070N120M3S |

* TO247−3L Industrial grade is available

## Advised Topologies

**onsemi**'s M3S technology is specifically designed for well−known high frequency switching applications of electric vehicles, namely OBC and HV DC/DC converter. The M3S MOSFETs are designed to strike an excellent balance between conduction losses and switching losses, making them ideal for hard−switching applications such as Power Factor Correction (PFC). Furthermore, owing to the low $R_{DS(on)}$ values of **onsemi**'s 1200 V SiC MOSFETs, they are strong contenders for soft−switching applications (like LLC, CLLC, Phase Shifted Full Bridge), where switching losses are significantly reduced by virtue of the circuit topology, so that conduction losses become the dominant loss component.

Boost−type PFC and LLC are popular circuit topologies utilized in automotive onboard chargers and HV DC/DC converter designs nowadays. Figure 2 depicts the boost−type 3−phase PFC topology, which incorporates six switching devices, while Figure 3 displays the Full−Bridge LLC topology comprising four switching devices, along with a synchronous rectifier on the secondary side.

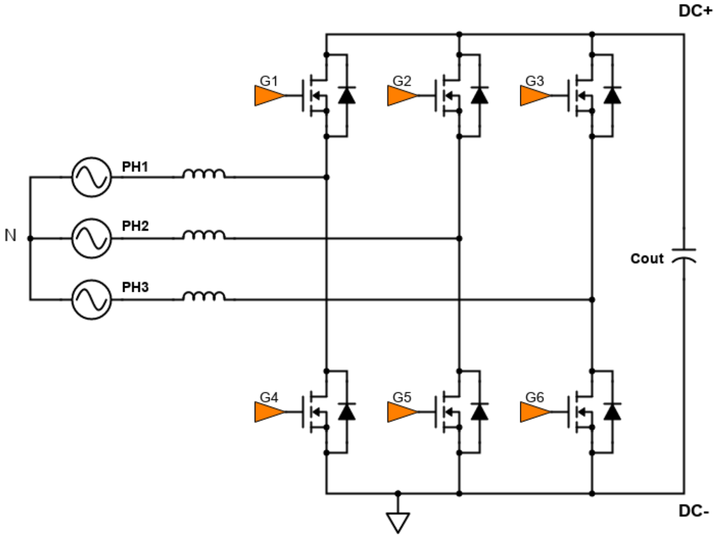


Figure 2. Boost Type 3−Phase PFC

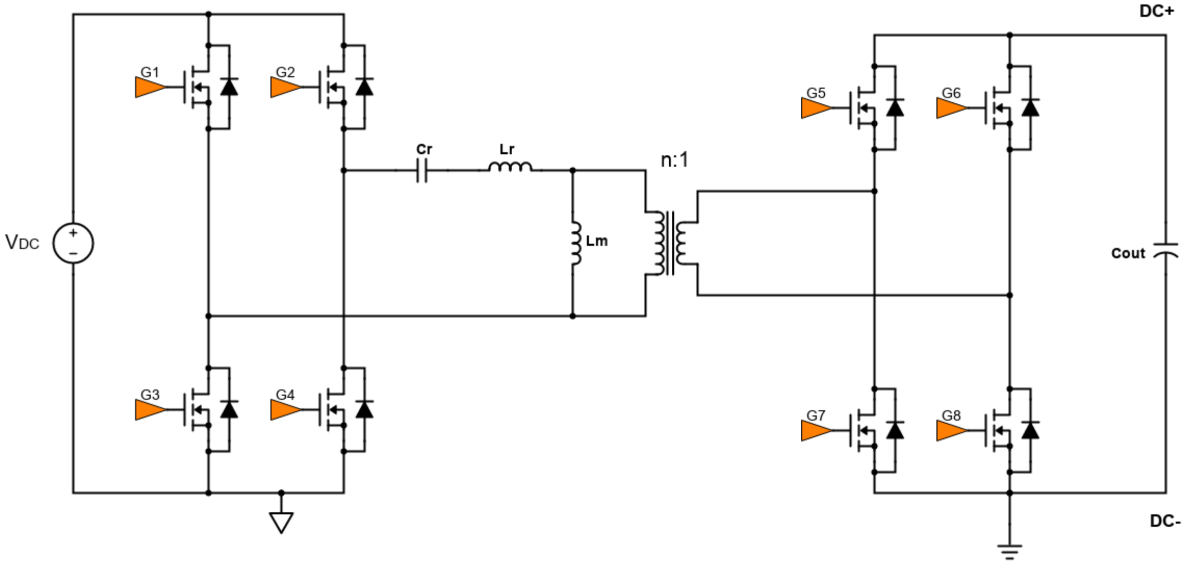


Figure 3. Full−Bridge LLC

## 3. Electrical Characterization, Parameters and Figure of Merit Comparison Results

This section of the paper aims to compare **onsemi**'s M3S family member, NVH4L022N120M3S, with one of its competitors based on Trench technology (referred to as “Competitor A”), with respect to their static and dynamic parameters. Both MOSFETs come in TO247−4L packages. Dynamic characterization tests are carried out under different conditions to compare the key parameters of the two devices, utilizing a double−pulse test setup. Figure 4 depicts a simple diagram of the double−pulse test setup. Finally, a 3−Phase PFC simulation is executed separately for each device to compare system efficiency.

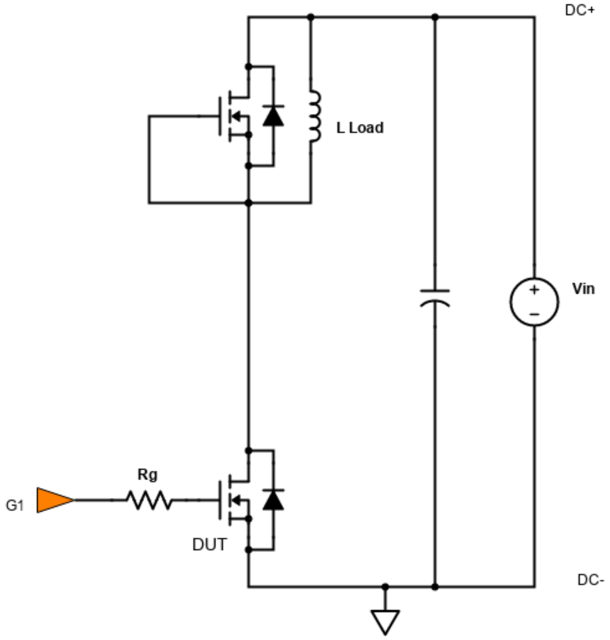


**Figure 4. Simple Diagram of Double−pulse Test Setup**

## Static Parameters (Rdson – Body Diode Conduction)

The important static parameters of SiC are $R_{DS(on)}$ and $V_{SD}$ (Body diode voltage drop). As a result, $R_{DS(on)}$ and $V_{SD}$ parameters are characterized for two devices under various test conditions.

Table 2 shows the body diode voltage drop comparison between NVH4L022N120M3S and Competitor A at −55°C, 25°C and 175°C temperatures. It is seen that NVH4L022N120M3S achieves lower $V_{SD}$ and, hence, conduction loss caused by the body diode will be lower for **onsemi**’s SiC device.

**Table 2. $V_{SD}$ COMPARISON UNDER DIFFERENT TEST CONDITIONS**

| Parameter | Test Conditions | NVH4L022N120M3S | | | Competitor A | | |
|---|---|---|---|---|---|---|---|
| | | −55°C | 25°C | 175°C | −55°C | −25°C | 175°C |
| $V_{SD}$ (V) | ISD = 1 mA, Vgs = 0 | 1.027 | 0.841 | 0.581 | 1.58 | 1.439 | 1.138 |
| $V_{SD}$ (V) | ISD = 10 mA, Vgs = 0 | 1.227 | 1.008 | 0.726 | 1.724 | 1.581 | 1.286 |
| $V_{SD}$ (V) | ISD = 40 A, Vgs = 0 | 3.369 | 3.262 | 3.421 | 3.738 | 3.623 | 3.435 |

$R_{DS(on)}$ is another critical parameter that provides an idea about the conduction loss of the device. Therefore, in the second part of this section, the $R_{DS(on)}$ parameter is characterized for the two devices at 25°C and 175°C junction temperatures. Additionally, measurements are taken under two different gate−source on−state voltages of 15 V and 18 V using a conduction pulse width of 300 μs. Figure 5 displays the measurement data of $R_{DS(on)}$.

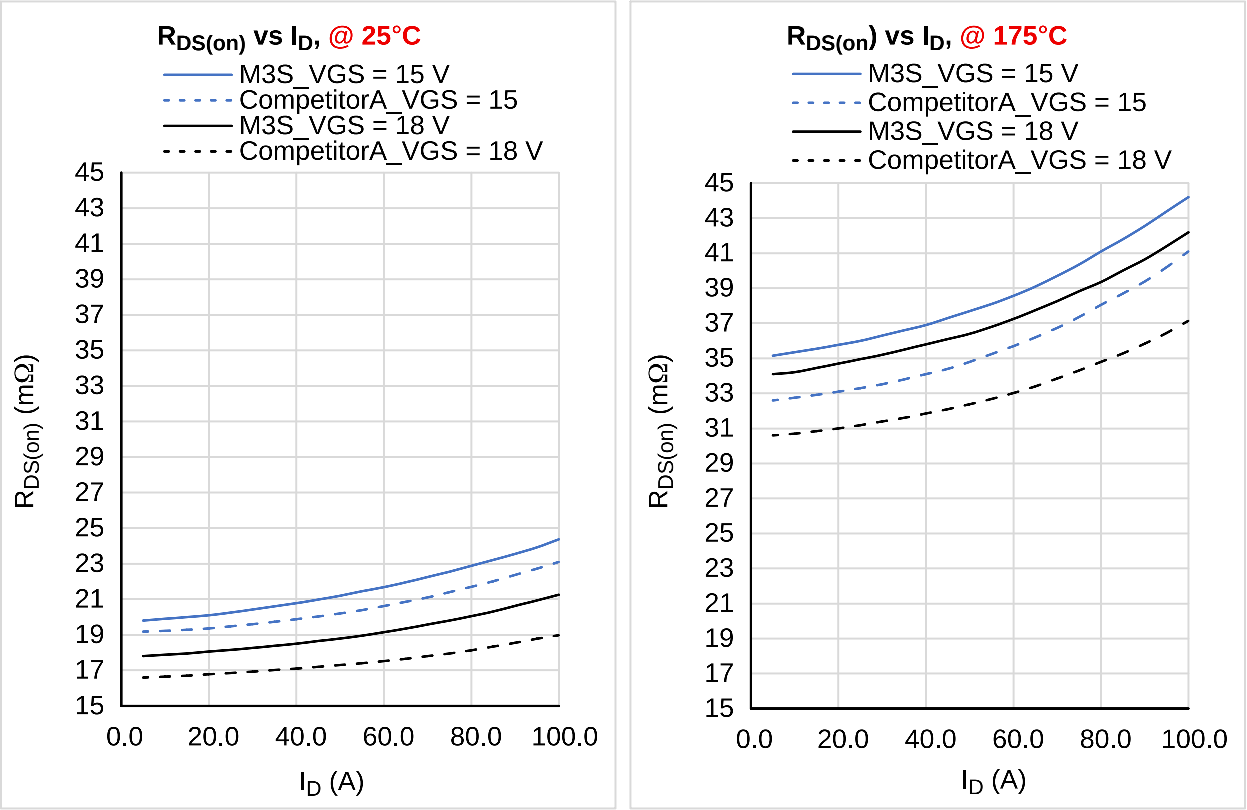


**Figure 5. $R_{DS(on)}$ Comparison for Two Devices under 25°C (Left) and 175°C (Right)**

Table 3 summarizes the $R_{DS(on)}$ comparison results for 40 A drain current at 25°C and 175°C junction temperature and with 15 V and 18 V gate−source voltage.

**Table 3. $R_{DS(on)}$ COMPARISON UNDER DIFFERENT TEST CONDITIONS**

| $I_D$ = 40 A | NVH4L022N120M3S | | Competitor A | |
|---|---|---|---|---|
| Temperature (°C) | $R_{DS(on)}$ (mΩ) with $V_{GS}$ = 15 V | $R_{DS(on)}$ (mΩ) with $V_{GS}$ = 18 V | $R_{DS(on)}$ (mΩ) with $V_{GS}$ = 15 V | $R_{DS(on)}$ (mΩ) with $V_{GS}$ = 18 V |
| 25 | 20.78 | 18.50 | 19.80 | 16.50 |
| 175 | 37.30 | 36.02 | 34.60 | 32.40 |

Based on Figure 5 and Table 3, Competitor A has slightly lower $R_{DS(on)}$ value for each test condition. This indicates that Competitor A will experience lower conduction losses than NVH4L022N120M3S at the same junction temperature.

## Dynamic Parameters

SiC MOSFETs do not suffer from tail current as Si IGBTs do, due to the absence of minority carriers. This absence results in a drastic reduction in turn−off switching loss [4]. Additionally, SiC devices exhibit lower reverse recovery charge than Si MOSFETs, leading to smaller turn−on peak currents and a reduction in turn−on switching loss [5]. To investigate switching losses, input capacitance (Ciss), output capacitance (Coss), reverse transfer capacitance (Crss), and reverse recovery charge (Qrr) are important parameters. Figure 6 presents a comparison of these capacitances for NVH4L022N120M3S and Competitor A. In switching applications, drain−source voltage is much higher than 6 V most of the time during a switching transient; hence the important portion of the curves in Figure 6 is the high voltage range. Lower capacitances generally result in lower switching losses. As shown in the figure, NVH4L022N120M3S exhibits lower capacitance values for Ciss, Coss, and Crss for $V_{DS} \geq 6$ V, thereby producing lower losses for both turn−on and turn−off in comparison to Competitor A [6].

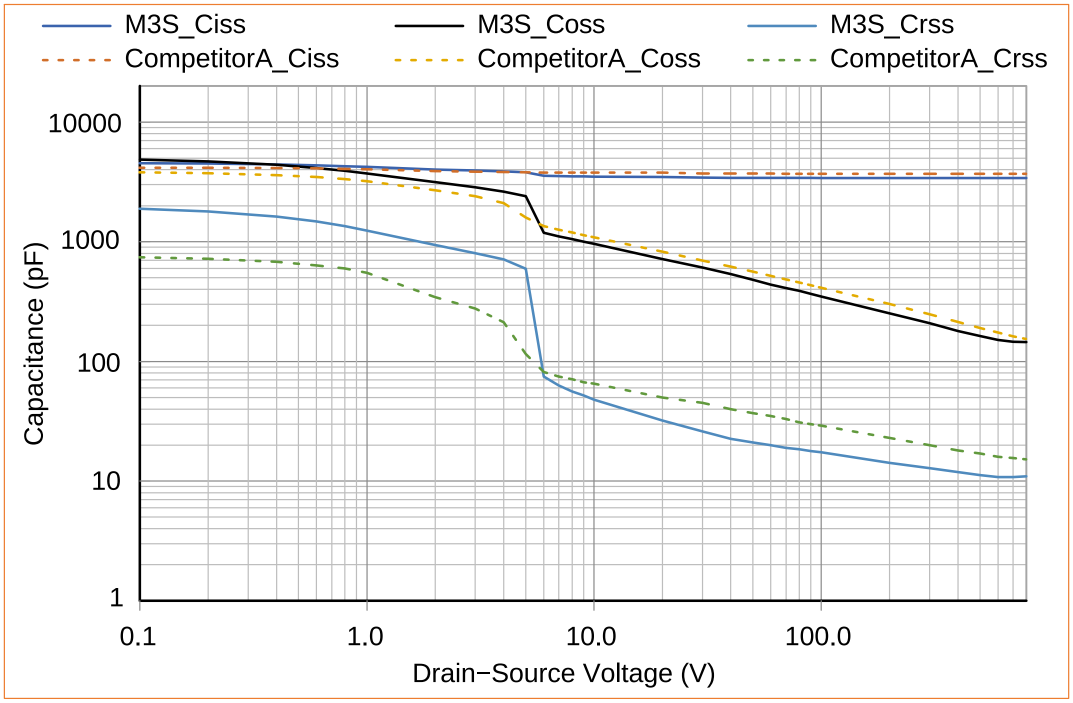


**Figure 6. Input, Output and Reverse Transfer Capacitances Comparison**

The switching energy losses of both devices are measured at several load current conditions for both 25°C and 175°C. The measurements are carried out using the double−pulse test setup depicted in Figure 4. The test conditions are set as follows:

- Vin = 800 V
- Rg = 4.7 Ω
- Vgs_on = +18 V
- Vgs_off = −3 V
- Load current = 5 − 100 A

Figures 7 and 8 illustrate the comparison of switching energy losses. Specifically, Figure 7 depicts the turn−on, turn−off, and total switching energy losses for 25°C, while Figure 8 shows the corresponding results for 175°C.

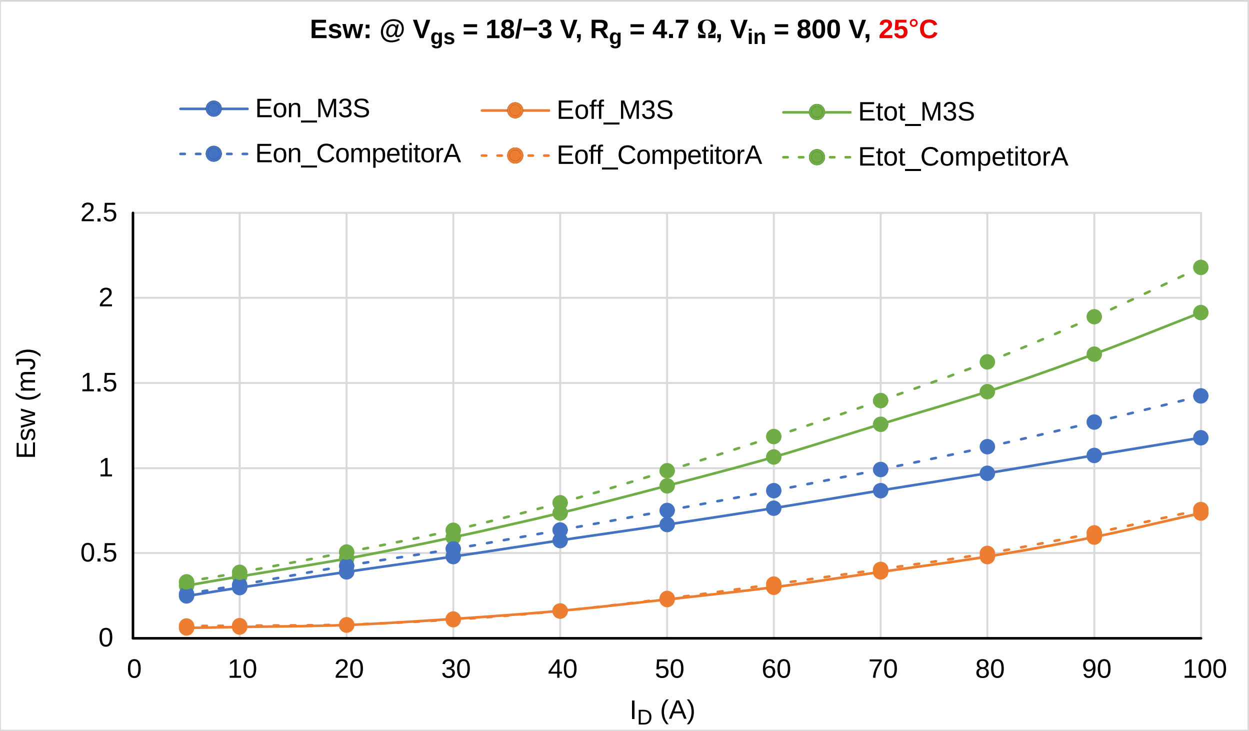


Figure 7. Switching Energy Losses Comparison at 25°C

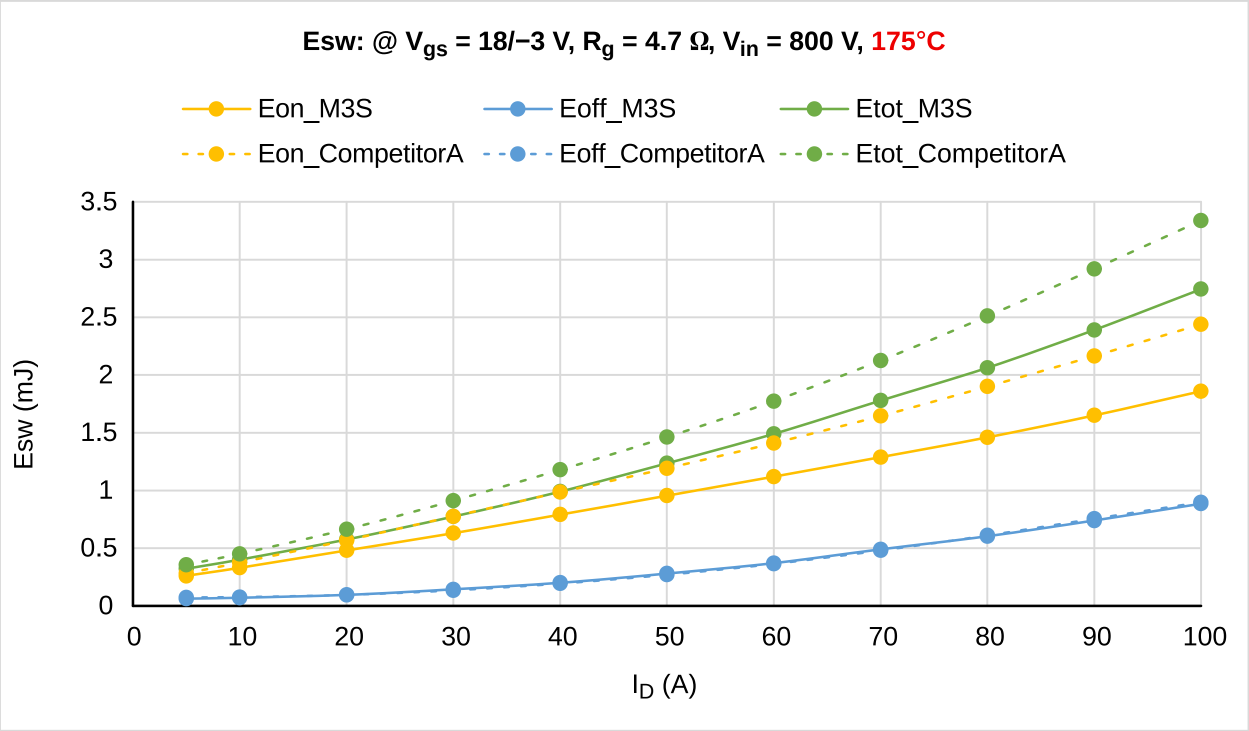
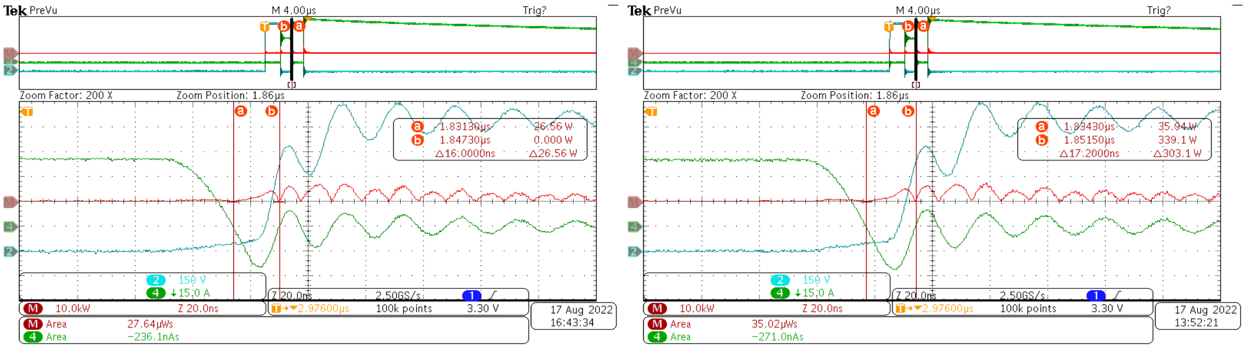


Figure 8. Switching Energy Losses Comparison at 175°C

It can be concluded that for load currents ranging from 10 A to 100 A, the M3S device exhibits an average of 5% lower switching losses (at 25°C) and 9% lower switching losses (at 175°C) compared to Competitor A, mainly due to $E_{ON}$ losses resulting from **onsemi**'s M3S technology. Another important parameter affecting switching losses is the reverse recovery behavior of the device.

Reverse recovery tests were conducted under the following conditions: ID = 40 A, di/dt = 3 A/ns (with Rg values adjusted to have the same di/dt), and 25°C. Based on the results presented in Figure 9, it can be observed that M3S has a better reverse recovery performance compared to Competitor A, as it exhibits a shorter reverse recovery time, less reverse recovery charge, and less reverse recovery energy.



Trr=16ns,Qrr=236nQ,Err=27.64uJ

Trr=17.2ns,Qrr=271nQ,Err=35uJ

**Figure 9. Comparison of Reverse Recovery Losses, M3S Technology (Left) and Competitor A (Right)**

## PFC System Efficiency Comparison

Having evaluated conduction and switching losses, we now present a comparison of system efficiency using the PSIM simulation program [7].

The 3−Phase Boost−type PFC converter is chosen as the topology, and the following test conditions are used in all the following discussion.

- $V_{aLL} = V_{bLL} = V_{cLL} = 400$ V
- $f_{line} = 50$ Hz, Rg = 4.7 Ω
- $V_{Out} = 800$ V
- $f_{SW} = 100$ kHz
- $P_{out} = 11$ kW maximum

Figure 10 shows the simulation circuit schematic used for efficiency estimation, along with simulation waveforms of input voltages, input currents, and output voltage.

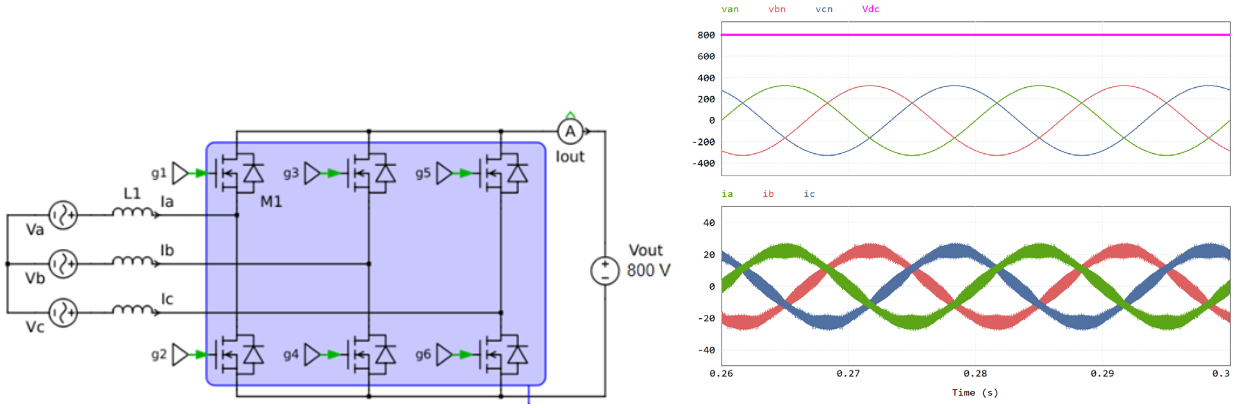


**Figure 10. PSIM Simulation Circuit (Left) and Simulation Waveforms (Right)**

Table 4 presents a comparison of losses and efficiencies at the 11 kW power level for constant heatsink temperatures of 25°C and 65°C, based on simulation results.

**Table 4. ESTIMATED EFFICIENCY BASED ON PSIM SIMULATION RESULTS**

| **$P_{in}$ = 11 kW** | | **I_MOS [$A_{rms}$]** | **$P_{SW}$ [W] per Device** | **$P_{con}$ [W] per Device** | **$P_{\_total}$ [W] per Device** | **$P_{\_total}$ [W] per Device** | **Estimated Magnetic Loss and Internal Bias Loss (W)** | **Total Losses (W)** | **Estimated Efficiency [%]** |
|---|---|---|---|---|---|---|---|---|---|
| **25°C** | NVH4L022N120M3S | 11.3 | 18.84 | 4.47 | 23.31 | 139.86 | 20 | 159.86 | 98.55 |
| | Competitor A | 11.3 | 25.59 | 4.92 | 30.51 | 183.06 | 20 | 203.06 | 98.15 |
| **65°C** | NVH4L022N120M3S | 11.3 | 18.87 | 5.22 | 24.01 | 144.06 | 20 | 164.06 | 98.51 |
| | Competitor A | 11.3 | 27.81 | 4.99 | 32.8 | 196.8 | 20 | 216.8 | 98.03 |

Figure 11 shows the resulting efficiency versus power level plot from 2 kW to 11 kW. The data presented in Figure 11 indicates that the 3−Phase Boost PFC system constructed using NVH4L022N120M3S exhibits higher efficiency at all operating points compared to a system constructed using Competitor A devices.

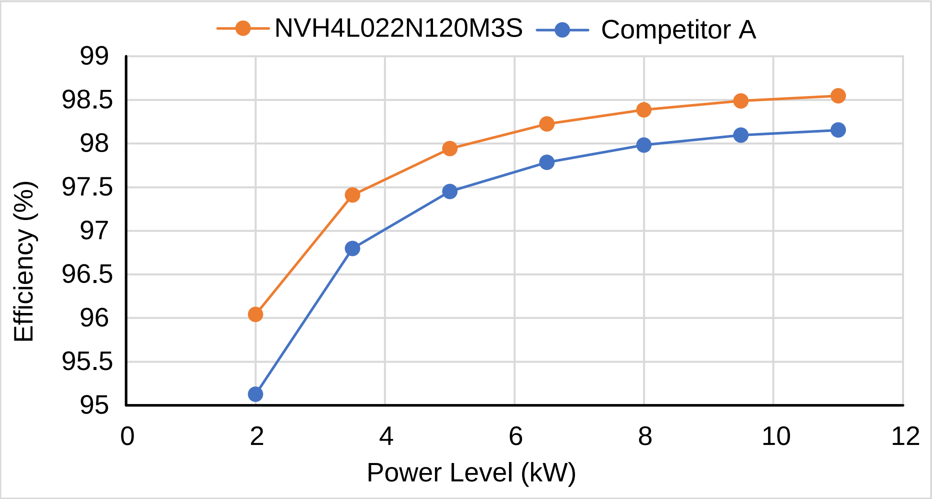


**Figure 11. Efficiency versus Power Level**

### Parameters and Figure of Merits Comparison

Based on the results of parts a, b, and c, Table 5 is presented to show the normalized values of some important figures of merit: total switching energy loss, reverse recovery charge, body voltage drop, $R_{DS(on)}$, and efficiency.

**Table 5. PARAMETERS COMPARISON**

| Parameter | NVH4L022N120M3S | Competitor A |
|---|---|---|
| $E_{TOT}$ (mJ) | 100% | 118% |
| $Q_{rr}$ (nC) | 100% | 114% |
| $V_{sd}$ (V) | 100% | 113% |
| $R_{DS(on)}$ (mΩ)<br>@ 175°C and $V_{gs}$ = 18 V | 112% | 100% |
| Efficiency @ 11 kW | 98.48% | 98.13% |

## 4. Conclusion

**onsemi**'s SiC MOSFETs are highly robust and exceed the reliability tests set forth by ACQ101 requirements. In comparison with industry offerings, they provide superior performance in total losses for high frequency switching applications such as the EV on−board charger and HV to LV DC−DC. The planar design ensures no drift in $R_{DS(on)}$, $V_{GS(th)}$, or body diode voltage drop over their lifetime, and they can operate with negative gate drive voltages. The recommended on−state gate voltage for these MOSFETs is 18 V, but they can still work down to 15 V to remain compatible with gate drive circuitry designed for older generation SiC MOSFETs [8].

**onsemi** distinguishes itself from most competitors by offering end−to−end production of SiC, from the substrate to the packaged discrete device or module. With a fully integrated supply chain and highly efficient SiC products, **onsemi** is a top choice for customers who need a reliable supply to meet the demands of the rapidly growing market [8].

SiC devices offer several advantages over traditional silicon devices in power electronics, including higher efficiency and power density, lower switching and conduction losses, and the ability to operate at higher frequencies. The M3S technology from **onsemi** is a promising development in this field, as demonstrated within this paper when compared to a competitor under a range of operating conditions. Thanks to **onsemi**'s wide portfolio of SiC MOSFETs, designers can choose the optimal switching device according to their needs.

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