Introduction To onsemi M3S SiC MOSFET Technology

Abstract

onsemi introduced its first SiC MOSFET products for the automotive market in 2018 and has since released several improved generations across the voltage range from 650V to 1200V. Since the first releases, tremendous focus has been placed on application-specific technology development to bring the best value to our customers. The latest product family, **M3S,** has best-in-class R_{SP} and offers superior switching performance and low reverse recovery losses, and is particularly well suited to hard switching topologies such as totem pole PFC.

In this article we explore the application of the M3S family of 1200V SiC MOSFETs in high power bridgeless bi-directional PFC designs to help designers exploit its benefits in the power stage to achieve best in class system performance.

Introduction

Electric vehicle (EV) on-board chargers (OBC) are required to have up to 11 or 22 kW power output, bi-directionality for vehicle-to-grid (V2G) functionality, power density approaching 3kW/l to minimize mass and volume, and higher voltage ratings to facilitate 800V batteries. The potential benefits of wide-bandgap semiconductors, particularly SiC, for the OBC application have been known and anticipated for years [1-4]. High level requirements for the SiC MOSFETs include:

- Very low $R_{DS(on)}$ at the 1200V node.
- Low E_{ON}/E_{OFF} values enabling high frequency switching.
- Good 3rd quadrant performance.
- Low thermal resistance junction to case.
- Robust and reliable technology qualified to AEC-Q101 with 175°C capability.

To help designers meet these requirements with automotive qualified SiC MOSFETs, onsemi is introducing the M3S technology node at 1200V.

M3S Technology Features

The 1200V M3S devices from onsemi feature best-in-class $R_{DS(on)}$ in a MOSFET specifically tailored for high switching frequency applications such as the OBC power factor correction stage or any other hard-switched topology. In a comparison of samples openly available on the market, relative figures of merit (FOM) for the PFC application have been determined and are presented in Figure 1. In this figure, each part's value has been mapped on a scale of 1 to 5 for each FOM, with 1 being the best. An ideal switch would have 0 for each FOM. This relative scale is used to highlight differences among available parts. The numeric values of the FOMs are given in Table I. For purposes of comparison, we examine parts that have $R_{DS(on)}$ values in the range of 20 mΩ.

The figures of merit represent the suitability of a given part to the application. As defined here, parts with low figures of merit represent a better fit for the application.

- The specific resistance, R_{SP}, provides an indication of cost, which is important for all applications.

- Parts with low $R_{DS(on)}$ Q_{OSS} facilitate short dead times and affects the resonant current settings, and enables higher frequency operation, leading to higher efficiency.
- The $R_{DS(on)}$ Q_{RR} FOM indicates suitability for repetitive hard commutation.
- $R_{DS(on)}$ E_{OSS} gives an indication of parts that will minimize switching losses in hard-switched applications.
- $R_{ON}Q_{G}$ provides an indication of the relative gate driving losses encountered in the converter and becomes especially important for MHz level switching frequencies.

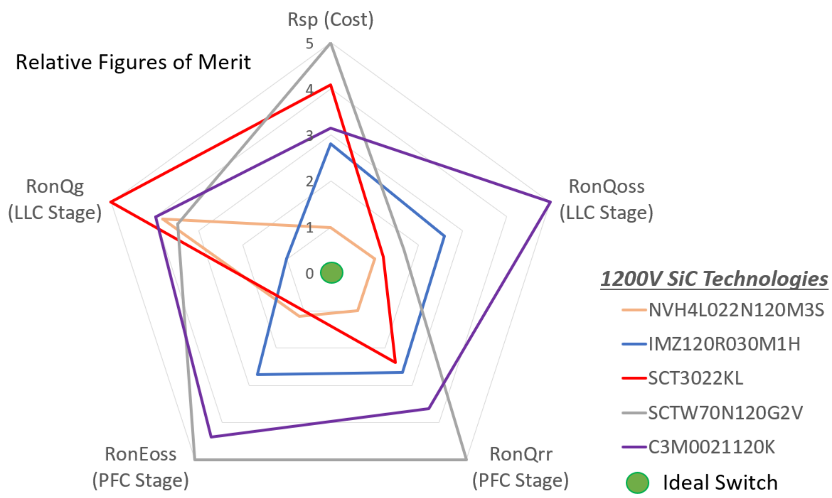


Figure 1. Relative Figures of Merit for Selection of Competitive Parts

1200V Devices	R_{SP} mΩ-cm^2	$R_{DS(on)}$*Q_{OSS} mΩ-µC, 800V	$R_{DS(on)}$*Q_{RR} mΩ-nC	$R_{DS(on)}$*E_{OSS} mΩ-µJ, 800V	$R_{DS(on)}$*Q_{G} mΩ-nC
NVH4L022N120M3S	2.65	2.57	3036	1855	3322
IMZ120R030M1H	3.58	2.79	9600	2043	1890
SCT3022KL	4.23	2.55	3850	2013	3916
SCTW70N120G2V	4.70	3.11	5796	2312	3150
C3M0021120K	3.75	3.02	19488	2155	3402

Table I. Specific FOM Values for Selection of Competitive Parts.

The onsemi M3S product family is expanding and will include the parts with 14 mΩ to 70 mΩ $R_{DS(on)}$ in through hole and surface mount packages.

Device switching characteristics

As with the Figures of Merit discussion, for switching characteristics we are looking at onsemi 22 mΩ part. Later in the article, we will look at PFC performance in a system simulation using the 40mΩ part as appropriate for the 11 kW PFC.

The device under test is NVH4L022N120M3S which has a typ 22mΩ of $R_{DS(on)}$ at 25°C and 1200V voltage rating. To characterize the switching losses, a double pulse test is performed as shown in Figure 2. The free-wheeling current is carried by the MOSFET body diode, as would be the case in the PFC half-bridge and in this case the reverse recovery losses are added to the turn on losses. The test conditions are as follows:

- $R_{G(on/off)}$ = 6.3Ω [total; adjusted to account for different Rg(int)]
- $V_{GS(on/off)}$ = +18V/-5V
- V_{DS} = 800V
- Total Power Loop Inductance = 50nH

Figure 3 shows the total switching losses for onsemi devices M1 (SC1) and M3S compared to a leading competitor. onsemi M3S technology has the lowest switching losses compared to competitors, especially at higher drain currents >40A.

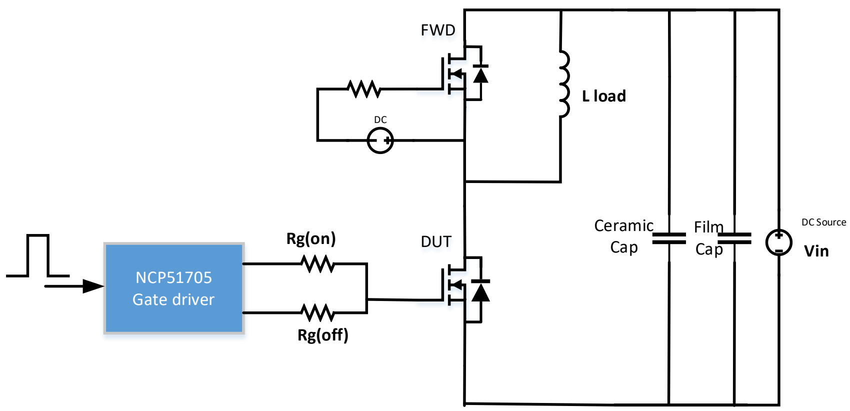


Figure 2. Double-Pulse Test Circuit Diagram

Figure 3: Comparison of Total Switching Losses.

Evaluation using Three-Phase Two Level PWM PFC Simulation

Figure 4 shows the typical OBC system using three phase two level PWM PFC circuit. Other topologies, such as three phase interleaved totem pole PFC or Vienna rectifier, can be also used. The totem pole PFC topology is relatively easy to control but requires a line frequency rectifier leg causing additional conduction loss. As is well known, the Vienna rectifier has the highest power factor and high efficiency, but it has six diodes and a single MOSFET switch per phase to achieve boost mode operation. In this article, the three phase two level PWM rectifier topology (Figure 5) was applied to evaluate the performance of onsemi 1200V 40mΩ M1 and M3S SiC MOSFETs.

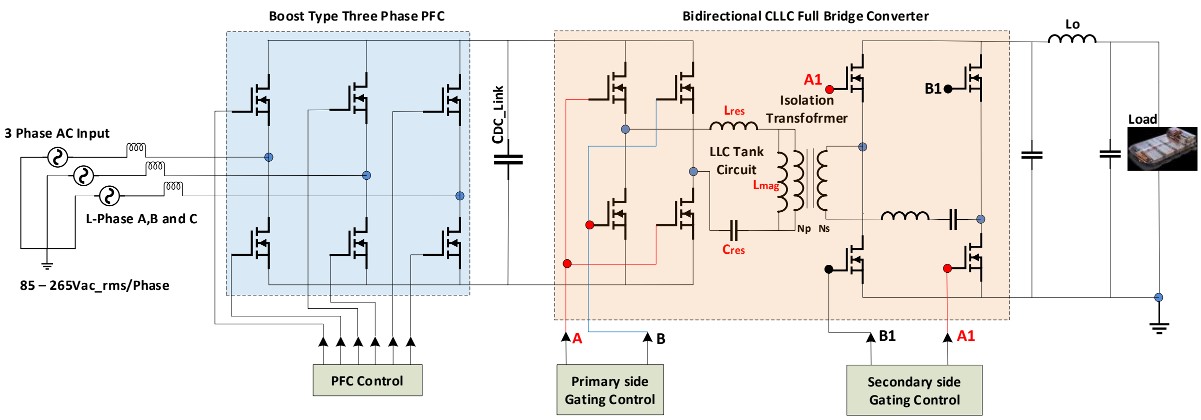


Figure 4. Bi-Directional OBC System Using 3-Phase 2-Level PWM Rectifier PFC.

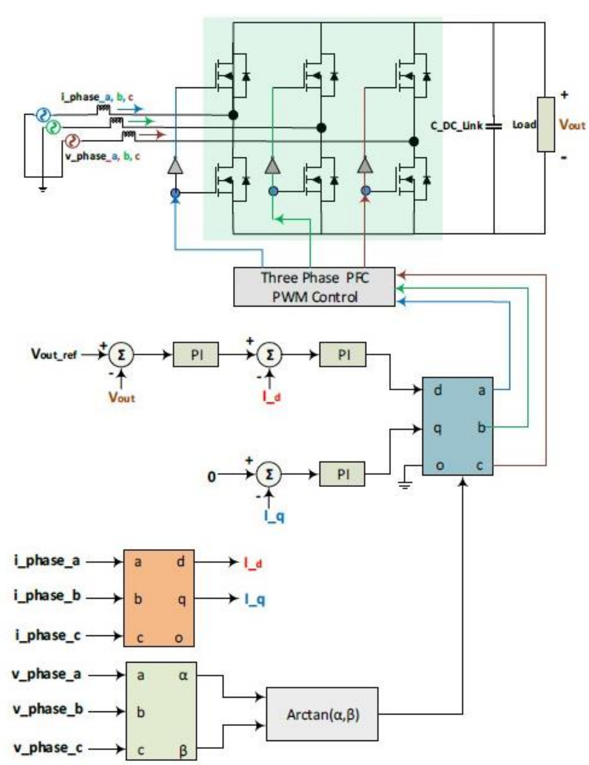


Figure 5. Three Phase Two Level PWM PFC Circuit

Figure 5 represents a three phase, 2-level PWM PFC circuit with control block. The control block is almost identical with a three−phase variable speed motor drive control. The control block consists of:

- abc to dqo transformation (Park transformation)
- abc to αβ transformation (Clarke transformation)
- dqo to abc transformation (Inverse Park transformation)

The abc to αβ transformation block converts the static three−phase reference frame into two−axis orthogonal stationary reference frame, α and β, as given in eq. 1. Using this transformation, the instantaneous phase angle, θ, can be obtained as in eq. 2.

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} \qquad \text{(eq. 1)}$$

$$\theta = arctan\left(\frac{\beta}{\alpha}\right) \qquad \text{(eq. 2)}$$

Then, the rotating reference components, i_d and i_q are calculated using abc to dqo transformation as equation eq. 3.

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{phase\_a} \\ i_{phase\_b} \\ i_{phase\_c} \end{bmatrix} \qquad \text{(eq. 3)}$$

Using i_d and i_q from eq. 2 and eq. 3, rotating reference voltages, v_d and v_q are obtained through the PI regulator and finally, inverse Park transformation (dqo to abc) generates the instantaneous phase voltage vector, v_a*, v_b* and v_c* as eq. 4.

$$\begin{bmatrix} v_a^* \\ v_b^* \\ v_c^* \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix} \qquad \text{(eq. 4)}$$

Finally, these three voltage vectors are input to the PWM circuit to generate the gating signals for each of the six MOSFETs.

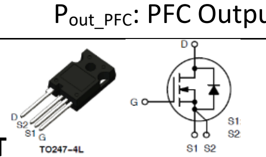
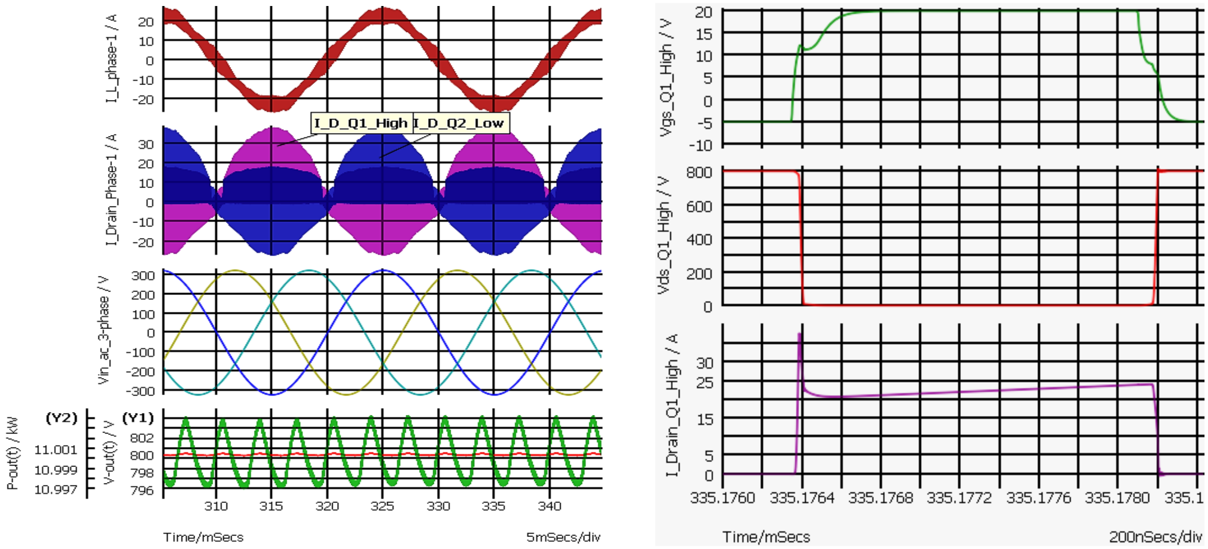
V_{in_phase}: Phase Input Voltage		220V_50Hz
V_{out_PFC}: PFC Output Voltage		800V
P_{out_PFC}: PFC Output Power		11kW
DUT 	M1	NVH4L040N120SC1
	M3S	NVH4L040N120M3S
f_{pwm}: PWM Frequency		100kHz
T_{CASE} (assumes Tcoolant ~85°C)		100°C

Table III. Simulation Conditions

A coupled electro-thermal simulation was carried out using SIMetrix [6] v.8.5, a Spice model-based simulation tool, and the simulation conditions are as given in Table III. In the simulation of the 11kW three-phase two-level PWM PFC circuit, NVH4L040N120SC1 and NVH4L040N120M3S were used for the M1 and M3S 1200V 40mΩ SiC MOSFETs, respectively.



(a) (b)

Figure 6. (a) Waveforms in major components and (b) MOSFET Voltage and Current Waveforms at Peak Power Point in Three-Phase Two-Level PFC Simulation.

Vin_phase = 220V_{rms_60Hz}, Vout = 800V, Pout = 11kW and fsw = 100kHz: Tcase = 100°C

Device		Current [Arms/unit]	Psw [W/unit]	Pcon [W/unit]	Ptotal/unit [W/unit]	Ptotal [W]
Phase Inductor (2 x 170µH)		14.6Arms	$14.6A^2 * 0.025\Omega + 2W = 7.3W$			21.9W
SiC MOSFET	SC1 (M1)	10.3 Arms	25.2W	5.2W	30.4W	182.4W
	M3S	10.4 Arms	20.1W	7.6W	27.7W	**166.2W**
Control and misc.		5W				5W
Total PFC Loss and Efficiency Tcase = 100°C	SC1 (M1)	Total Converter Power Dissipation = 209.3W $\varepsilon = \frac{11000W}{(11000 + 209.3)W} \times 100\% = 98.1\%$				
	M3S	Total Converter Power Dissipation = **193.1W** $\varepsilon = \frac{11000W}{(11000 + 193.1)W} \times 100\% = \mathbf{98.3\%}$				
Tj Estimation Tcase =100°C	SC1 (M1)	Tj = 114.1°C Max				
	M3S	**Tj = 112.5°C** Max				

Table IV. 11kW Three-Phase Two-Level PFC Simulation: NVH4L040N120SC1 and NVH4L040N120M3S

The simulation conditions and results are summarized in Table III and Table IV, respectively. At steady state operation the switching loss was reduced by 5.1W in M3 comparing to M1. With M3S, the smaller and thinner die size enables C_{OSS} reduction. Total gate charge, $Q_{G(TOT)}$ was also reduced in M3S by 17%. As expected, lower C_{OSS} and lower gate charge resulted in reduced switching loss in M3 1200V SiC MOSFET. The efficiency of the PFC function block is 98.1% with M1 MOSFET and 98.3% with M3 MOSFET.

Conclusions

onsemi M3S technology has been compared to M1 (SC1) and competitor devices based on figures of merit and device characteristics, followed by system level evaluation in simulation of PFC stage of OBC. Results show a clear improvement in performance in the PFC stage of the on-board charger, with increased efficiency, reduced losses, and reduced operating temperature. Compared to onsemi's prior generation, improvements included:

- RSP reduction by 35.4%
- Switching loss reduction of 20.2% at 11 kW PFC operation according to simulation
- Total losses reduced by 8.9% at 11 kW PFC operation according to simulation

The product family provides SiC MOSFETs with $R_{DS(on)}$ from 14 to 70 mΩ in through hole and SMD packages providing designers with a wide range of parts suitable for high frequency switching in the OBC application from 7 kW up to 22 kW.

References

[1] J. Millan, P. Godignon, X. Perpina, A. Perez-Tomas, and J.Rebollo, "A Survey of Wide Bandgap Power semiconductor Devices," IEEE Transactions on Power Electronics, vol. 29, no. 5, pp. 2155-2163, 2014.

[2] Application Note AND90103/D; "ON Semiconductor Gen 1 1200 V SiC MOSFETs & Modules: Characteristics and Driving Recommendations". March, 2021 − Rev. 0.

[3] Paula Diaz Reigosa, Thomas Keller, Tobisas Strittmatter, Ishan Pendharkar, Nicola Schulz, "A Framework for Reliability Analysis of a SiC Converter for Automotive On-Board Charger Applications," PCIM Europe Digital Days 2021, 3-7 May 2021, pp. 964-971.

[4] Chen Wei, Haitao Xie, Ying Liu, Zongzeng Hu, Jianwen Shao, "A SiC Based High Efficiency 22 kW Bi-Directional EV On-Board Charger," PCIM Europe Digital Days 2021, 3-7 May 2021, pp. 1022-1028.

[5] SIMetrix is the product of SIMetrix Technologies, www.simetrix.co.uk.