

## 3.3 kV Full SiC MOSFETs – Towards High-Performance Traction Inverters

*Mitsubishi Electric is developing a new Full SiC device rated for 3.3 kV and 750 A. The device comes in the most recent LV100 package, which is especially suitable for traction application and modular converter designs. This article introduces the new Full SiC device and demonstrates the benefits in traction applications.*

*By Dr. Nils Soltau, Eugen Wiesner, Mitsubishi Electric Europe B.V., Ratingen, Germany and Kenji Hatori, Hitoshi Uemura, Mitsubishi Electric Corporation, Fukuoka, Japan*

### 1. Introduction

Power semiconductor devices made of silicon carbide (SiC) are regarded as the major innovation in modern power electronics. Compared to classical silicon (Si) devices, SiC enables more efficient and more compact converters to save electric energy and valuable materials.

Over the last 20 years, Mitsubishi Electric has developed and commercialized SiC devices for several voltage classes and various applications [1]. Now, after years of in-field experience with different SiC modules in traction application [2], Mitsubishi Electric makes the next big step. With a rated voltage of 3.3 kV and a current of 750 A, the new Full SiC dual module is especially intended for high performance traction converters and flexible converter designs. The type name of this new device is FMF750DC-66A.

Due to the fast switching transients, Full SiC devices require an appropriate package offering low stray inductance. Therefore, the FMF750DC-66A, as shown in Figure 1, comes in the most advanced package for this voltage and power class: the LV100 package. This package offers a stray inductance below 10 nH and simpler parallel connection of several modules. Moreover, the internal package design ensures optimal current sharing among the semiconductor chips inside a module.



Figure 1: The new 3.3 kV Full SiC device is rated for 750 A and comes in the most recent LV100 package

### 2. Comparison with Silicon Devices

The following chapter compares the FMF750DC-66A with two different Si devices that also come in the same LV100 package. These two devices of the same voltage class are rated for 450 A and 600 A. In the following, they are referred to as CM450DA-66X and CM600DA-66X according to their respective type name. Figure 2 shows the static characteristics of all modules and, hence, demonstrates nicely the general difference between bipolar IGBTs and unipolar MOS-

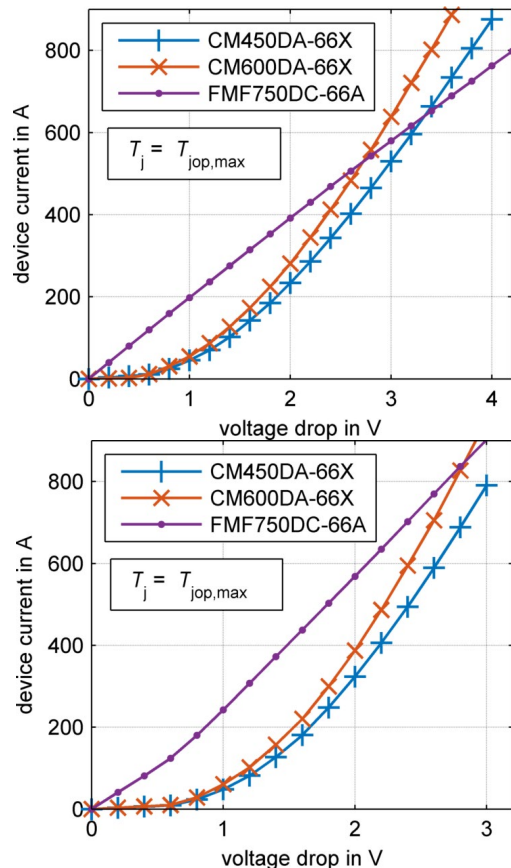


Figure 2: Static characteristic of the Full SiC devices compared to the 450 A and 600 A silicon-based modules

FETs. It should be noted that all device characteristics are given for the respective maximal junction temperature being 150°C for the Si devices and 175°C for the FMF750DC-66A. Due to the linear current-voltage dependency of MOSFETs, the voltage drop at low currents is substantially lower than for bipolar IGBTs (cf. Figure 2 (a)). As shown in Figure 2 (b), also the voltage drop of the FMF750DC-66A in reverse direction is much smaller compared to the freewheeling diodes of the Si modules, if both, diode (SBD) and MOSFET, are conducting the reverse current (synchronous rectifier mode). Consequently, especially at low-load conditions, the use of unipolar devices increases converter efficiency significantly. The subsequent chapter quantifies this for a traction application.

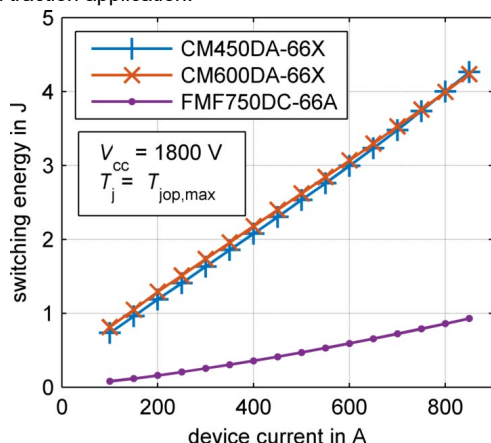


Figure 3: Switching losses of the Full SiC module compared to Si-based modules

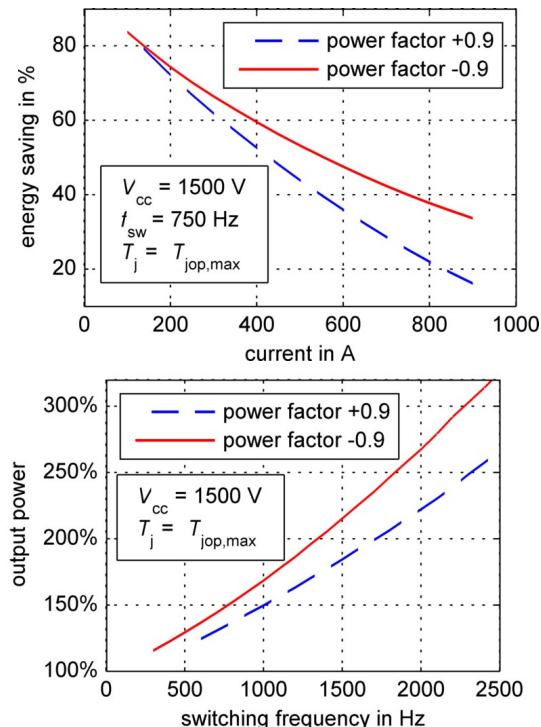


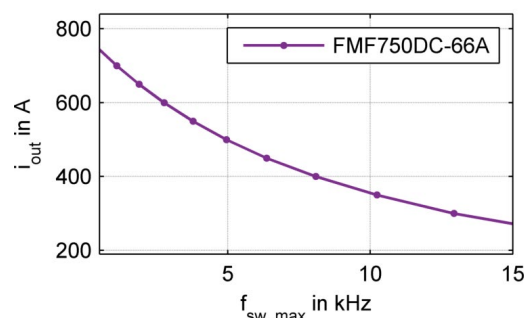
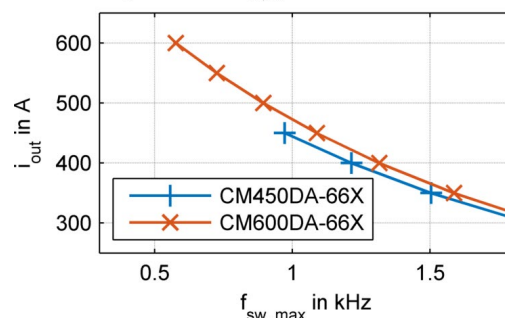
Figure 4: Comparison of FMF750DC-66A with CM600DA-66X

Another very prominent advantage of Full SiC devices is the reduction of switching losses. Again, this effect results from the unipolar nature of the devices. The lack of reverse recovery and tail currents decreases switching energy and allows higher switching frequencies compared to Si devices. Figure 3 shows the sum of energy loss during turn-on, turn-off and reverse recovery. Compared to the Si-based

IGBTs, the switching losses in the Full SiC module are reduced by 80 – 90 %.

The following chapter quantifies and discusses advantages for the converter design and intended applications.

$$V_{cc} = 1500 \text{ V}, m = 1, \cos \phi = 0.9, T_j = T_{jop,max}, \\ T_w = 40^\circ \text{C}, R_{th,cw} = 20 \text{ K/kW per module}$$



$$V_{cc} = 1500 \text{ V}, m = 1, \cos \phi = -0.9, T_j = T_{jop,max}, \\ T_w = 40^\circ \text{C}, R_{th,cw} = 20 \text{ K/kW per module}$$

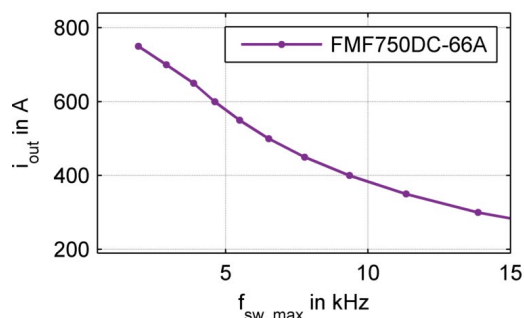
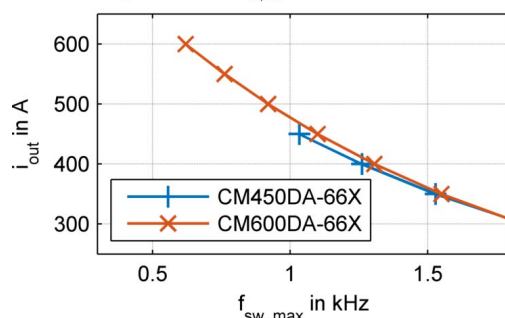


Figure 5: Maximal output current in dependence on switching frequency

### 3. System Level Advantages

The first example regards traction inverters with 750 Hz switching frequency at 1500 V dc-link voltage. The losses generated by the Si-based CM600DA-66X and the SiC-based FMF750DC-66A are compared. Figure 4 (a) shows the energy savings using the FMF750DC-66A instead of a CM600DA-66X. Especially at vehicle's part-load condition, saving potential is enormous. Below 400 A output current, the Full SiC devices saves more than 50 % - 80 % of the energy loss by semiconductors (at the same device footprint).

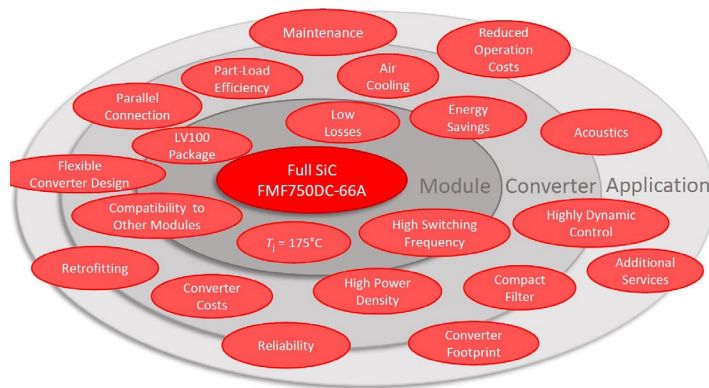


Figure 6: Opportunities enabled by the Full SiC FMF750DC-66A

Especially at part load, operational energy costs can be reduced. Moreover, due to higher efficiency and the higher operational junction temperature of the FMF750DC-66A, the maximal power in rectifier operation increases. As illustrated in Figure 4 (b), maximal output power increases by roughly 60 % at exemplary switching frequency of 750 Hz. Since the rectifier mode serves the recovery of energy when the vehicle slows down, potentially more energy can be recycled and fed back into the electricity network. Moreover, this reduces stress on the conventional braking system.

The second example considers a grid-connected converter operating at a power factor of 0.9. The maximal switching frequency in dependence on the output current is calculated. Figure 5 shows the results considering

cooling water temperature of 40°C. Consequently, the maximal switching frequency for the FMF750DC-66A increases by a factor of 5 to 9 compared to the CM600DA-66X at same current level.

The higher switching frequency allows converter manufacturers a grid-filter design for higher resonance frequencies. Consequently, the required inductance and capacitance values for an LCL filter decrease. This in turn decreases filter's size, cost and losses. Moreover, the converter achieves a more dynamic control. Furthermore, for machine-

side inverters or dc-dc converters, the higher switching frequency enables the design of more compact high-speed drives and medium-frequency converters [3,4].

Besides the switching frequency increase, Figure 4 (b) has already demonstrated that keeping the switching frequency constant, the converter achieves significantly higher output power. The fact that the FMF750DC-66A comes in the same package as the CM450DA-66X and CM600DA-66X allows more flexible converter designs and fast development (having a similar inverter configuration as Si-based inverter).

Beyond the discussed benefits in traction and grid applications, the FMF750DC-66A make further benefits accessible. Figure 6 tries to illustrate the advantages of the

FMF750DC-66A at different system levels: at module level, at converter level and at application level. In general the use of new FMF750DC-66A makes sense in those applications where these system-level advantages potentially over-compensate the higher costs of today's SiC-modules compared to established silicon devices.

### 4. Conclusion

Mitsubishi Electric offers an extensive line up in the state-of-the-art LV100 package. Now, a 750 A Full SiC module is added to the 3.3 kV line up.

The FMF750DC-66A Full SiC module increases the converter's power density by increased switching frequency and higher maximal junction temperature of 175 °C. Moreover, the module achieves higher system efficiency. Especially at part load conditions or rectifier operation, the FMF750DC-66A reduces the inverter losses by 50 – 80 %. The FMF750DC-66A comes in the same low-inductive LV100 package as its Si counterparts. For converter manufacturers, this simplifies the transition from Si to SiC and gives tremendous flexibility.

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