XHP™ 2 – The low-inductive, multi-package housing for the next generation of high-power applications

Waleri Brekel[1], Wilhelm Rusche[1], Alexander Höhn[1], Wolfgang Bücker[1]

[1] Infineon Technologies AG, Germany

Corresponding author: Waleri Brekel, waleri.brekel@infineon.com

The Power Point Presentation will be available after the conference.

Abstract

The harmonization of power electronic platforms for various urban transportation and their different operation voltages is one of the major requirements for future-oriented developments. In addition, new and upcoming technologies in switching devices like IGBT5/.XT or SiC MOSFETs in high-power applications make the increase of current density possible. As a result, size and volume have been reduced, advantages that support such harmonized platforms. A low-inductive, high-current and symmetrical power-module design fulfilling the requirements for both low and high operation voltages at the same time is needed.

In this work we discuss the low-inductive concept of XHP^{TM} 2 for high-power applications, switching characteristics, and the extended module lifetime with IGBT5/.XT technology.

1 Multi-package design XHP™ 2 for high-current, low parasitic inductance and various voltage classes

The implementation of a low-inductive strip line concept offers many opportunities to use new and upcoming switching devices in terms of clean switching [1], but at the same time also presents many challenges that need to be solved. The new multi-package XHP^{TM} 2 module addresses voltage classes from 1.2 kV, 1.7 kV up to 3.3 kV. In low-voltage applications, the package needs to be capable of withstanding the elevated operation temperature of the IGBT5/.XT with its $T_{vj,max}$=175°C. At the same time, a high-current capability for I_{Cnom}=1800 A and a low parasitic inductance of the module power connections are needed as well. This high-current capability for the connection to an external bus bar can be done by screws. The arrangement of the DC(+) and DC(-) terminals in two rows as a strip line will significantly reduce the module inductance. A sidewise-located interface connection between DC(+/-) terminals and the bus bar presents the opportunity to design a low-inductive DC link as well [2]. The auxiliary connections are located in the middle of the module with appropriate height and space to enable the usage of a double-sided printed circuit board mounted on top of the module (Figure 1).

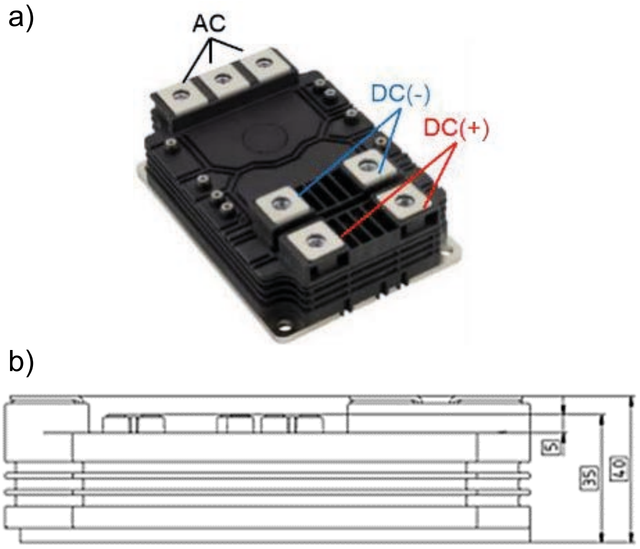

Fig. 1: a) Typical appearance of XHP™ 2, and b) Aux terminal height for usage of a double-sided printed circuit board mounted on top of the module

However, the low-inductive module bus bar design is in conflict with the creepage and clearance distances for high-voltage designs (3.3 kV). The smaller the distance between the DC terminals, the lower the module inductance [3]. Due to these conflicting requirements, the XHP™ 2 DC(+/-) main terminals have been designed as depicted in Fig. 2 resulting in a low module inductance of Ls<10 nH and creepage distance of 34 mm (red arrows). Furthermore, the gap between DC(+) and DC(-) terminals enables the use of an insulation to increase the clearance distance, if necessary. With a thin insulation layer between the DC(-) and DC(+) layer of the DC link bus bar, it is also possible to implement a low-inductive system, which is more important for fast switching devices like SiC MOSFETs to take full advantage of its benefits.

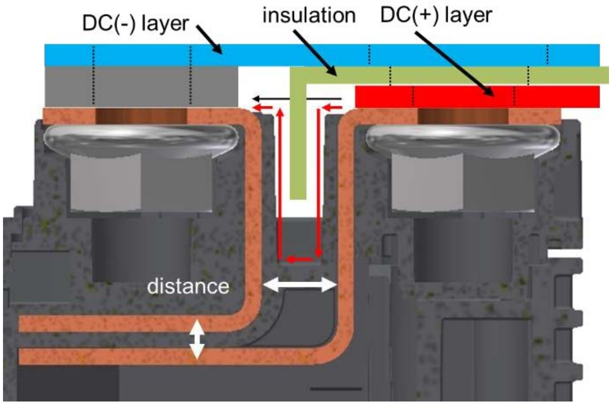

Fig. 2: Cross-section through the part of the module with DC(-) and DC(+) terminals, it illustrates the distance between DC terminals, bus bar and insulation

1.1 Thermal aspects of module main terminals

1.1.1 Simulation of dissipation losses

With respect to a future-oriented platform development and upcoming new semiconductor technologies, such as SiC-MOSFETs, the further increased current density needs to be considered. For this increased current range, the terminal power losses, the heat dissipation and the resulting terminal temperatures are investigated. As the ohmic loss is squared to the current, the heat dissipation becomes an important issue for both module and system development, with increasing current density.

The XHP™ 2 power terminal design deals with this application-relevant interface. According to application note from Infineon [4], the power loss simulations under various boundary conditions have been calculated. Figure 3 provides an overview of the defined parameter.

Input parameter:

- $T_{terminal}$: Temperature at the top of terminals
- T_{foot}: Temperature of main terminal foot, connection to substrate
- T_c: Base-plate temperature underneath the chip
- I_{DC}: DC current as RMS value through the terminal

Output parameter:

- $P_{out,terminal}$: Thermal power dissipation out of the module
- T_{max}: Maximum temperature in the terminal

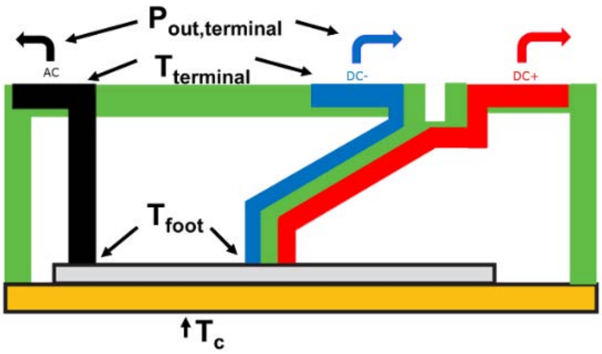

Fig. 3: Defined parameter for thermal simulation of main terminals

Figure 4 shows the results of a calculation using the selected conditions: T_c~T_{foot}=100°C, $T_{terminal}$=125°C with the power dissipation out of the module per terminal, and maximum terminal temperature as a function of the RMS phase-leg current. At this point it should be taken into account that the RMS current in a DC terminal ($I_{DC,RMS}$) is in relation to AC phase-leg current by a factor of √2.

$$I_{DC,RMS} = \frac{I_{phase,leg}}{\sqrt{2}} \tag{1}$$

That means the appropriate current of the DC terminal in Fig. 4 has been considered by Eq. (1). With an increasing phase-leg current, the $P_{out,terminal}$ behaves over-proportionally. Thus for higher output current densities, it becomes essential to dissipate terminal generated losses to the ambient at the system level. The direction of thermal heat flow is determined by the temperature gradient along the main terminal. That means that for positive values of $P_{out,terminal}$, there is a higher temperature on the main terminal inside the module, as defined by $T_{terminal}$.

As an example, for the above-mentioned conditions at I_{RMS}=1200 A, the thermal power of 12 W for AC and 15 W for one DC terminal need to dissipate to keep the $T_{terminal}$ at 125°C. At the same condition, the maximum temperature in terminals with $T_{max,DC\ terminal}$~140°C and $T_{max,AC\ terminal}$~131°C behaves quite moderately (Fig. 4).

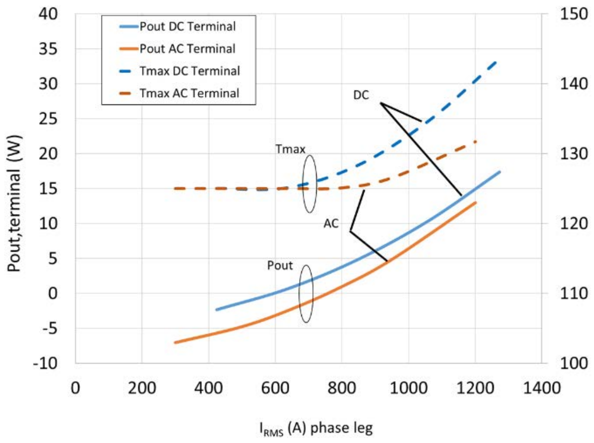

Fig. 4: Output power dissipation for AC and DC terminal as a function of output phase-leg current at T_{foot}=100°C and $T_{terminal}$=125°C, $P_{out,terminal}$>0 W means thermal dissipation out of the module, $P_{out,terminal}$<0 W means thermal dissipation into the module

Those simulation results are the basis for mechanical design and the thermal verification of the temperature by infrared (IR) measurements on the hardware.

1.1.2 IR measurements with DC load

Besides thermal simulation of the main terminals, an IR measurement for the first estimation under DC-current load are performed. For this case, an opened and black-coated XHP^{TM} 2 module with mounted DC link bus bar on the DC terminals and copper block on AC terminal has been tested.

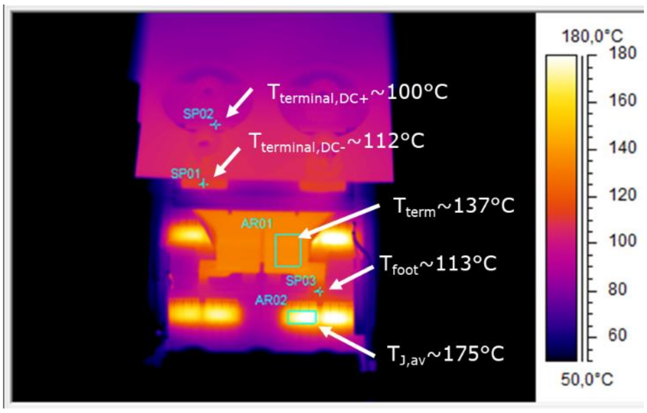

Fig. 5: IR measurement and temperature of an opened and black coated-module, DC terminals under DC-load condition I_{DC}=876 A, average junction temperature FWD $T_{J,av}$~175°C, foot temperature of DC(-) terminal T_{foot}~113°C, DC(-) terminal temperature T_{term} ~137°C, temperature at screw position $T_{terminal,DC(+/-)}$~110°C

Figure 5 shows an IR photo of DC terminals under the following conditions: water-cooled system, T_C~120°C, I_{DC}=876 A. The current is impressed from the DC(-) via the series connection of the freewheeling diodes (FWD) of the low-side and high-side system to the DC(+) terminal. This current value is equivalent to the phase-leg current $I_{phase,leg}$=1238 A. The temperature in the interconnection screw area between module DC terminal and DC bus bar is below 125°C. Measured temperatures do not show any critical value on the DC terminals of the power module.

The measurement of the AC terminal was performed on a similar water-cooled setup. Figure 6 shows the equivalent IR photo of the AC terminals under the conditions T_C~120°C and I_{DC}=1100 A. In this case, the current is impressed from the AC via low-side IGBT and high-side FWD to the DC terminals. The resulting temperature in the interconnection screw area between module AC terminals and the external AC bus bar is low at approximately 85°C.

The absolute conditions used in the simulation and the conditions in the experiment differ and cannot be directly compared. However, the terminal simulation as a starting point supports the terminal design at the beginning of the mechanical development. The overall target for all those efforts is to reduce the power losses that need to be dissipated in the converter design.

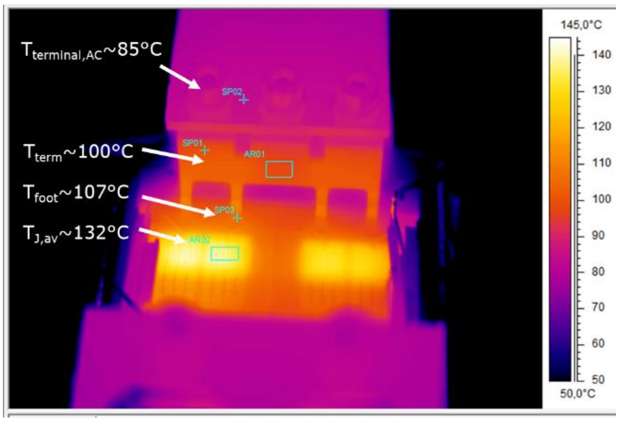

Fig. 6: IR measurement and temperature of an opened, black-coated module, DC terminals under DC load condition I_{DC}=1100 A, low-side IGBT $T_{J,av}$=132°C, foot temperature of AC terminal T_{foot}=107°C, AC terminal temperature T_{temp}~100°C, temperature on screw position $T_{terminal,AC}$~85°C

1.2 Dynamic switching characteristics of the XHP™ 2

For all voltage classes, the main module circuit is the most often used and flexible half-bridge configuration. In Fig. 7, the module's equivalent circuit diagram and the top view with all terminals, is presented. If a more sophisticated gate-control design is required, the module offers the possibility to use the leakage inductance via additional emitter main connectors 8 and 12, marked in red in Fig. 7. These additional emitter mains are connected to the half-bridge circuit inside the module. The leakage inductance between the Aux emitter and the emitter mains will provide a voltage drop in the di/dt phase, which can be used to control the transient behavior of the IGBT [5].

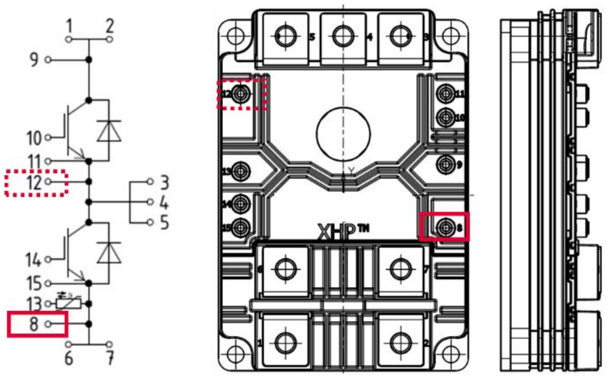

Fig. 7: Circuit diagram of the XHP™ 2 power module

Due to the internal connection of the high-side and low-side system, the commutation between IGBT and diode takes place within the module. Compared to the previous IHM/IHV generation in single-switch topology, the internal connection of the XHP™ 2 is a significant advantage because of the reduced leakage inductance. Employing the new 5th generation IGBT and diode technologies from Infineon Technologies, the maximum module current for the 1700 V XHP™ 2 is now further increased up to 1800 A with the continuous operating junction temperature $T_{vj,max}$ of 175°C.

Figure 8 illustrates the IGBT turn-on, turn-off and diode recovery at T_{vj}=175°C and 25°C of an FF1800XTR17T2P5 power module with IGBT5/.XT under the nominal conditions U_{DC}=900 V, $I_{C\ nom}$=1800 A. In the turn-off example, with a total stray inductance of L_S~30 nH, the overvoltage shoot at ΔU_{CE}~300 V is small, a further benefit of the mechanical design efforts. To prevent the use of an external collector-emitter clamping, the overall system commutation inductance must also be low with respect to the external DC bus bar to have a turn-off overvoltage shoot within the specified limits.

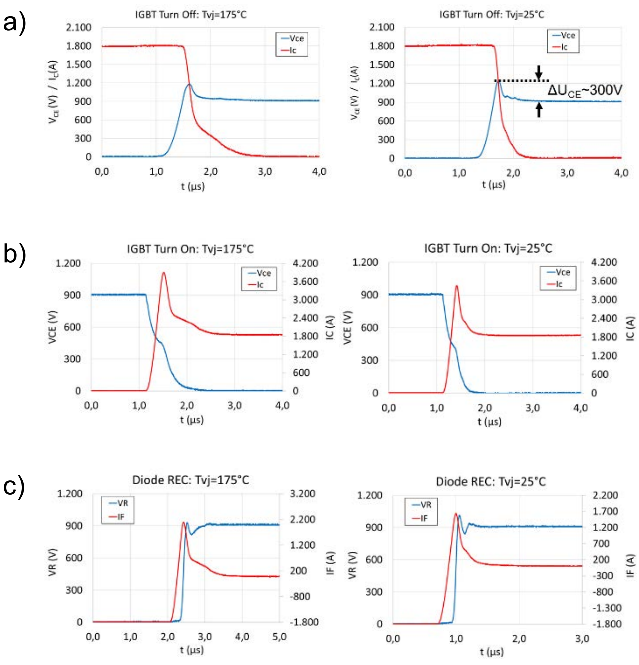

Fig. 8: IGBT turn-on a), turn-off b) and diode recovery c) at nominal conditions of an FF1800XTR17T2P5 at T_{vj}=175°C and 25°C power module

All depicted switching events show a smooth waveform and characteristics without any snap-off or oscillation effects.

Due to the mechanical arrangement of the power terminals of DC(+) and DC(-), refer to Fig. 1, the XHP™ 2 module is optimized for paralleling. As shown in Fig. 9, the IGBT turn-on switching behavior of two modules in parallel, and the current sharing of each device is very similar. There is no current mismatch affected by the DC bus bar design described in [6], [7].

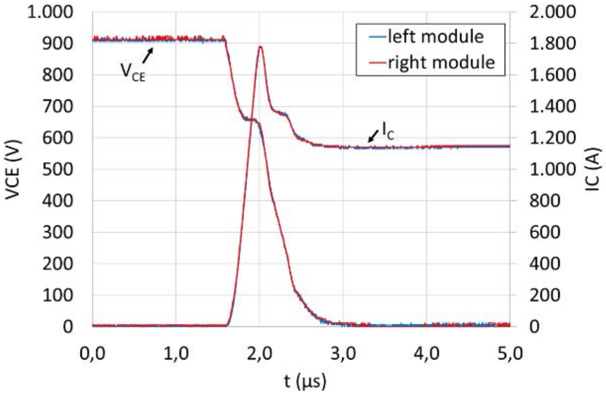

Fig. 9: IGBT turn-on of two modules in parallel. Blue represents the left module, and red the right module

If the layout of high-side and low-side systems are not optimized, and result in unequal impedances, the IGBT turn-on will react with asymmetrical switching. Due to the characteristic arrangement of chips and commutation loop inside a XHP^{TM} 2, it was possible to balance the impedances for symmetrical switching. Figure 10 shows IGBT turn-on waveforms of the high-side and low-side switch. As can be seen, the switching behavior is very similar.

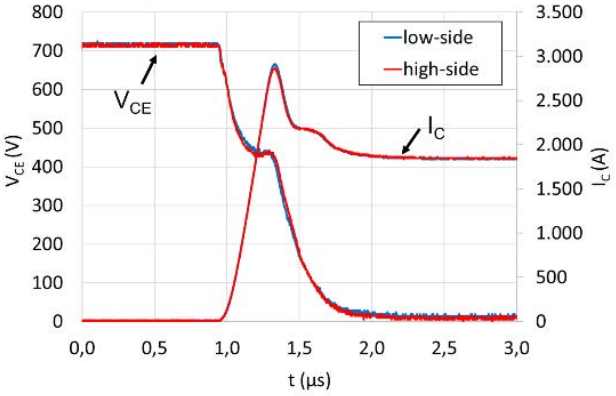

Fig. 10: Comparison of IGBT turn-on switching behavior of high-side and low-side at V_{CE}=700 V, I_C=1800 A, T_{vj}=25°C

2 Application-oriented design requirements

The combination of features such as package platform and latest IGBT technology with its highest power density allows the increase of current density at the system level. As a result, size and volume can be reduced. Beside these needs, the dominating criteria for the propulsion converter is the resulting lifetime. For example, urban transportation vehicles are used to transport people for short distances and some minutes of driving within the city. While driving or accelerating the vehicle, the energy in the converter is conducted mainly by the IGBTs. When the vehicle brakes, the FWD of the converter have to conduct the generated reverse energy.

Figure 11 shows a simplified example of the deployment profile of an electric drive system of a subway [8].

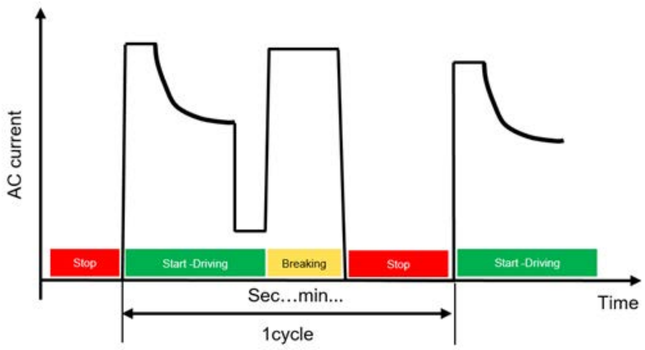

Fig. 11: Generic metro mission profile

Those short-distance, day-to-day operations, result in an enormous stress, especially for the power modules used in the electronics of the converter. Hence, the long-term reliability for required lifetime is one of the major criteria.

The dominant end-of-life (EOL) mechanisms for standard joining technologies in such demanding applications include solder degradation and the aluminum bond wire lift-off. Those die interconnections are highly stressed by the relative temperature swing ΔT at the resulting junction operating temperature T_{vj} as well as by the duration of the thermal stress (t_{on}). Owing to these challenging requirements, the power modules used nowadays are typically oversized. The modules are either bigger than required, or smaller ones are used in parallel to reduce the thermal loads and fulfill the high lifetime demands. Consequently, IGBT modules in typical traction inverters are operated with junction temperatures significantly lower than the specified maximum temperatures, thus the full potential in terms of current density is not utilized.

To achieve smarter, tailor-made solutions in the power converter, the typical end of life mechanisms must be significantly improved for extended running times, or if possible eliminated. If the EOL can be extended, the current de-rating due to lifetime constraints can be reduced, and the RMS current can be increased. The 1700 V XHP™ 2 module generation makes use of the latest and most rugged 5th generation IGBT and emitter-controlled diode with its .XT joining technology from Infineon Technologies. This combination makes the power device extremely robust against cycling loads [9]. To quantify this effect, an XHP™ 2 with IGBT5 and .XT has been compared to an IHM module with IGBT4 and standard joining technologies. The typical lifetime target for such a propulsion converter can be assumed with 25 years, which results in less than 4% lifetime consumption per year. In Fig. 12, the junction temperature of the IGBT (red), the FWD (green) and the base plate temperature (blue) are depicted, which are based on an exemplary deployment profile of an electric drive system of a subway (Fig. 11). The 1200 A, 1700 V IHM IGBT4 technology shows in this example a lifetime consumption of approximately 6% per year. This results in a total lifetime that is significantly shorter than the required lifetime of 25 years for this application. Further power-module oversizing, e.g. by paralleled modules, is needed to meet the lifetime requirement. For the XHP™ 2, the absolute temperature and the temperature swing are slightly higher as compared to the IHM, but the resulting lifetime consumption with 2.8% per year is significantly lower due to the .XT joining technology.

Based on this exemplary application profile, the 1200 A, 1700 V XHP™ 2 fits perfectly in this design and application requirement. Since the resulting lifetime consumption of the power modules depends on the circumstances within the target applications and conditions, the resulting lifetime may differ under varying conditions. Therefore, the lifetime consumption needs to be investigated for each individual module and for each individual condition.

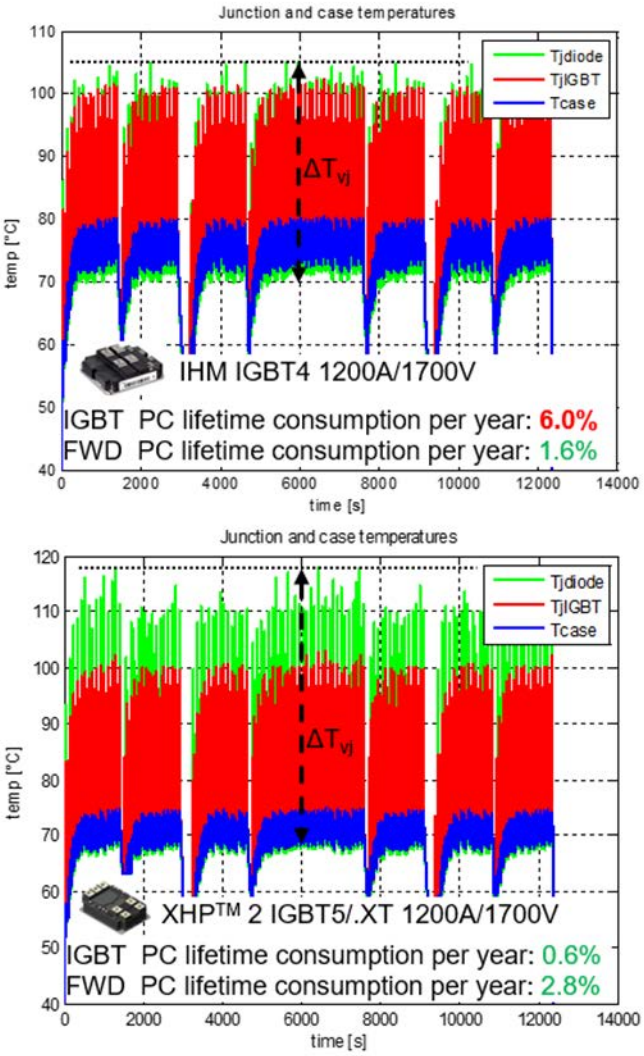

Fig. 12: Junction temperatures of the IHM (top) and XHP™ (bottom) based on a standard urban transportation mission profile

3 Summary

In this work, we introduced the XHP™ 2 multi-package housing for the next generation of high-power applications. As a low-inductive and symmetrical design, it enables the utilization of future-oriented fast switching devices like SiC-MOSFETs. With the increasing of current density, the terminal power loss becomes an important issue. A low-ohmic terminal design reduces the terminal losses, but cannot eliminate them, this should be considered on system level. The IGBT5 and .XT technology from Infineon Technologies enables extremely robust power device module against cycling loads for the required lifetime. Furthermore, it has been shown, how Infineon XHP™ 2 can support the needs of the application and the requirement for harmonizing propulsion converters for various urban applications using different operation voltages from 1.2 kV and 1.7 kV up to 3.3 kV.

4 References:

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