Optimised Integration of PrimePACK™ into Modular IGBT Stacks with Increased Power Density

O. Schilling, M. Wölz, G. Borghoff, J. Schiele, O. Hölbe, P. Luniewski

Infineon Technologies AG, Warstein

Abstract:

The integration of the new PrimePACK™ module into an existing inverter platform is discussed. The modular architecture of the inverter concept is described including the control- and protection mechanism. The mechanic features of the module allow to optimize the thermal management and to reach a high usability of the IGBTs. Different strategies for IGBT driving are analysed and compared. We finally present first results of inverter performance.

I Introduction

When a new power module is integrated into a converter platform thermal, electrical and mechanical constraints have to be considered. The PrimePACK™ housing offers a practical interface between IGBT power switches and the converter surroundings [1]. The first integration of the PrimePACK™ module in a converter is presented here in detail. Experience on ModSTACK™ [2] inverter designs is utilized and will be pointed out.

The modular concept of the ModSTACK™ inverter series is explained. By paralleling of units, higher output currents can be obtained. For each individual unit an optimised cooling concept results in an improved utilization of the available heat sink area and helps to lower the thermal resistance.

The driver and control circuitry can be realised by different approaches. We suggest two possible solutions that differ in the degree of integration. The advantages of each driver architecture are discussed.

The capability of the IGBT module is limiting the power density of the whole inverter. Safe switching under extreme single pulse conditions is analysed. Under periodic operation the limit is set by the maximum junction temperature. The PrimePACK™ package offers the chance to increase the operation temperature up to 150°C. We present first results covering the performance and the increase in converter usability under these harsh conditions.

II Converter architecture: modularity and control functionality

Since basic topologies for power conversion are very similar it makes sense to offer a modular system of power conversion components. It allows manufacturers to take advantage of flexibility and to focus on their own core competence. The approved design kit ModSTACK™ for power converter solutions consists of OEM components for thermal management, electrical and mechanical interconnection and interfaces between power unit and control. Different circuit topologies and expansion of system power range are possible by use of the ModSTACK™ components.

By choosing suitable IGBT halfbridge modules the most common topologies are realised (B6U+B6I, B6I+B6U, etc…). High voltage electrolytic capacitors are used for the DC link circuit of the power unit to ensure safe operation up to 1070V. The monitoring and control unit is supplied with signals supervising four parameters (phase current, DC voltage, on-state voltage, heatsink temperature) and can be employed in a variety of application conditions. It is equipped with integrated IGBT driver cores (EiceDRIVER™). Figure 1 gives an overview about the functional components of a single inverter.

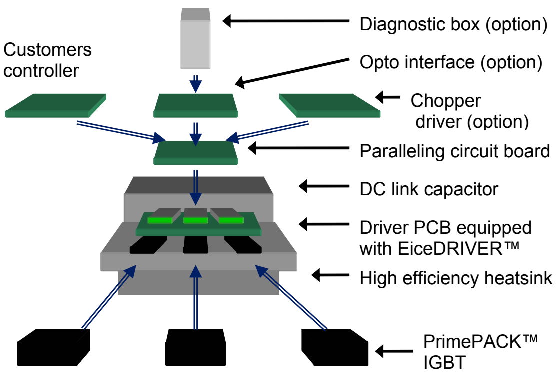

Fig. 1: Modular ModSTACK™ power unit equipped with PrimePACK™ IGBT halfbridge modules

The ModSTACK™ is available in four mechanical platforms. Inside a platform the mechanical design is fixed and variations are possible by use of electrical elements with different ratings but identical mechanical interfaces. To save design and manufacturing costs the modular stack system is designed for industrial approved cabinets. The stacks are available with forced air cooling or water cooling.

By means of the paralleling circuit board in figure 1 up to 4 ModSTACK™ units can be linked in a parallel configuration to reach the maximum extension. The paralleling is done by summing up the phase currents of the individual power units. To achieve the necessary electric balance of the whole system all electric connections, bus bars and mechanical interfaces are symmetrised. Furthermore all inverter units share equal cooling power. In this way the necessary derating factor is kept at a low level. 95% of the rated power of the individual units can be exploited in a parallel configuration.

The ModSTACK™ was originally designed for IHM modules and is now adapted to the PrimePACK™ package (fig. 2). It is compatible with both footprints (PrimePACK2™: 169x86mm² and PrimePACK3™: 247x86mm²) that will be available in the module line-up.

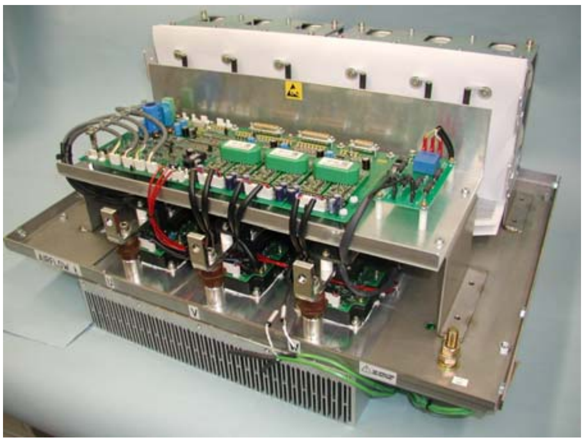

Fig. 2: photo of ModSTACK™ power unit equipped with PrimePACK2™ according to the scheme in fig. 1

The modular power electronic design is assisted by an appropriate monitoring and control architecture. Up to 4 identical units can be connected in parallel. Each unit generates and processes various monitoring signals according to the scheme in figure 3. When set limits for a power unit are exceeded a shut down of the unit is initiated and accompanied by the relevant fault signal. The electrical interface to the system control is equipped with filters and sophisticated grounding. To suppress noise level at the controller an optical interface unit is available, too (see figure 1).

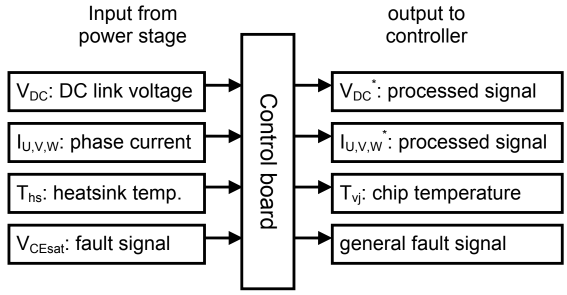

Fig. 3: flow of monitoring signals and function of control board

To accelerate the reaction to over-temperature faults the virtual chip temperature is calculated by a fast analogue circuitry. It takes into account the heat sink temperature, output current, DC link voltage and switching frequency which are combined by the logic array shown in figure 4.

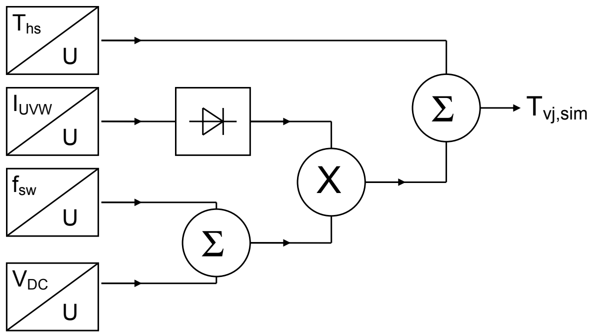

Fig. 4: logic array of the fast analogue circuit that combines T_{hs}, I_{UVW}, f_{sw} and V_{DC} to calculate chip temperature $T_{vj,sim}$ by a simplified model.

Different root causes for a fault are taken into consideration by the overload protection logic. Table 1 presents an overview of 3 possible overload scenarios that can lead to a system shut down in 4 different time scales respectively.

Signal	root cause	time scale
V_{CEsat} detection	bridge or low inductive short circuit (SC)	1…10µs
$I_{U,V,W}$ - monitoring	SC at stack terminal or within some meters	>10µs
T_{vj} (simula-tion) or $I_{U,V,W}$	overload in ms time scale	> 2ms

Table 1: principle of overload protection

An example for active over-current protection by V_{CEsat} protection is shown in figure 5. PrimePACK2™ IGBTs FF600R17IE3 are subjected to a short circuit with a remaining inductance of 1.3µH. The DC-link voltage is 900V. It is divided by the off-state IGBTs in the upper and lower leg of a phase. At t_1, the IGBT is turned on. V_{CE} (Ch4) falls and the current I_C across the short circuit (Ch2) rises. At t_2, I_C reaches the desaturation level and is stabilized by the IGBT at 2kA. Now the full DC-link voltage is across the IGBT. This is registered by the V_{CEsat} detection and within 2,8µs the short circuit is turned off at t_3.

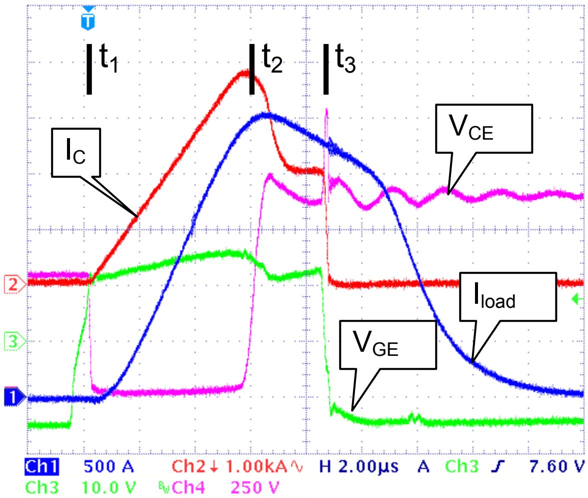

Fig. 5: Turn-off by V_{CEsat} detection after IGBT desaturation, Ch1=Load current, Ch2=IGBT collector current, Ch3=IGBT Gate voltage, Ch4=IGBT collector voltage

III Thermal properties and layout optimization for an air cooled heatsink

The PrimePACK™ offers a practical solution to improve the thermal management by lowering the thermal resistance R_{thch} between baseplate and heat sink. Due to the rectangular footprint of the PrimePACK™ a small distance between the screws that tighten the baseplate to the heatsink is realised even for a large overall contact area between both components. The thickness of thermal grease d_g can thus be kept in a very low regime d_g<50µm. The copper baseplate furthermore ensures effective heat spreading through its high thermal conductivity λ=385W/mK. In an experimental setup R_{thch} is measured on a water cooled heatsink. From the point of view of R_{thch} it will represent a worst case situation because water cooled systems are characterised by less thermal spreading in comparison to their air cooled counterparts.

The heatsink is equipped with a set of thermocouples that allows measuring both the temperature at the module baseplate (T_c) and inside the heatsink close to the surface (T_{hs}). The thermocouples are positioned underneath the devices that generate power in the way shown in figure 6 (TC1 and TC2).

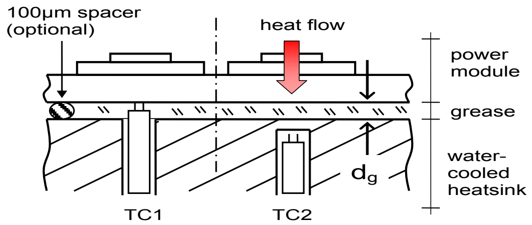

Fig. 6: Schematic cross section of measurement setup including position of thermocouples.

The overall geometry of the setup is symmetric with respect to the dashed line in Fig. 5. If the total electrical power dissipated in the power module (P_{el}) is known, the following formula can thus be applied to evaluate R_{thch}:

$$R_{thch} = \frac{T_c - T_{hs}}{P_{el}} = \frac{T_{TC1} - T_{TC2}}{P_{el}}$$

The influence of the amount of thermal grease that is dispensed on the surface of the module baseplate prior to mounting it onto the heatsink is investigated. A thermal grease with λ=1W/mK is used. The measurement is done for the PrimePACK2™ package subsequently for IGBTs and diodes and R_{thch} is calculated by paralleling both values. The result is given in figure 7, where R_{thch} is plotted as a function of the *dispensed* thickness d_g*.

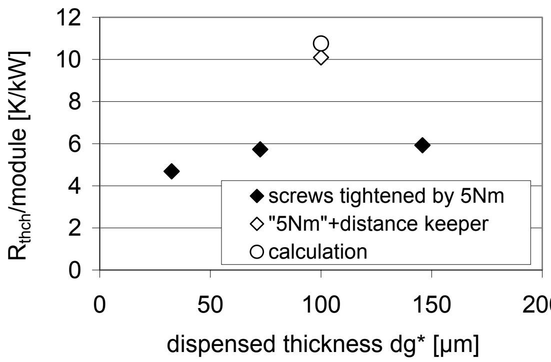

Fig. 7: Correlation between R_{thch} and grease thickness d_g*, which is measured prior to mounting.

The following conclusions are drawn:

- If a 100µm spacer is applied to guarantee that d_g=100µm after mounting, the measured value is R_{thch}~10K/kW. This is close to the calculated value which is reached if we make the simplified assumption that only the area below the substrates is taking part in the heat exchange and not the total baseplate.

- If mounting is done without spacers keepers lower R_{thch} values are reached (4…6K/kW) that depend little on the amount of dispensed grease in the range d_g*>50µm. The reason for the observed independence is that excessive grease is squeezed out during the mounting process very effectively due to the aforementioned small distance of mounting screws. Besides, the heat transfer at the metallic contact between baseplate and heatsink in the vicinity of the mounting screws plays an important role and does not depend on grease thickness at all. In general the R_{thch} of a PrimePACK™ module in a converter is rather insensitive towards the method by which heat conductive grease is dispensed at the mounting procedure. Thermal management is made more reliable by means of the footprint geometry.

- In the range d_g*<50µm an R_{thch} of ~4…5K/kW can be reached. The thermal resistance is not going down to 0 as d_g* is decreasing. There is a remaining thermal resistance even for neglectable thickness of grease that can be explained as a contact resistance between both metal surfaces.

The thermal resistance between the heatsink and ambient air is qualified by the value R_{thha}. It depends on how IGBT modules are positioned on the heatsink surface. In order to find an optimised geometry R_{thha} is determined by measurements using resistors as well-defined heat sources. Square shaped resistor modules are fixed to the baseplate of the PrimePACK™ (e.g. 4 resistors on the baseplate with 247mm length in figure 8) thus creating a reference-module. The use of a reference-module has the following advantages:

- exact determination of dissipated heat,
- high reproducibility of the measurement,
- simple setup allows fast evaluation of different layouts (e.g. no bus bar necessary).

R_{thha} is calculated by the formula

$$R_{thha} = \frac{T_{hs} - T_a}{P_{el}}$$

The ambient temperature T_a is measured at the entrance of the air flow. In order to determine the heatsink temperature T_{hs}, small grooves are milled into the surface of the heatsink to place thermocouples close to the module baseplates. The hottest point (highest T_{hs}), which is always close to the centre of the baseplates, is used in the formula for R_{thha}. P_{el} is the resistive energy dissipation for each PrimePACK™ prototype.

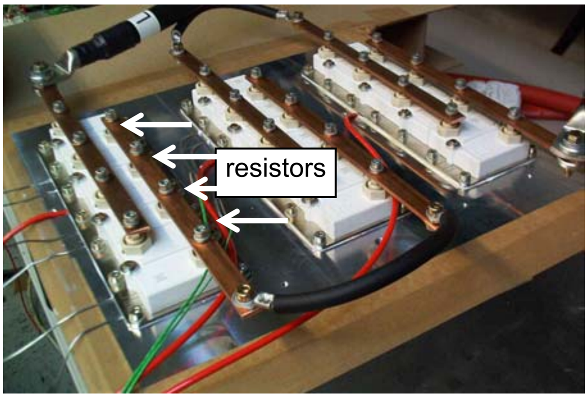

Fig. 8: Experimental setup for R_{thha} measurement. A DC current is fed into reference resistors fixed to a PrimePACK™ baseplate that is mounted on a aluminium air cooled heatsink

The simple handling of the described reference-modules allows varying the arrangement in order to find an optimised geometry. Generally the distance between the modules themselves and between the modules and the edge of the heatsink should be as large as possible. It turns out that less thermal stacking and lower R_{thha} values are obtained if the longitudinal axes of the rectangular modules are aligned in parallel to the heatsink fins in comparison to the geometry with perpendicular orientation of modules and fins. Figure 9 shows a comparison for different footprints. The lowest values are obtained for the PrimePACK3™ footprint (247x86mm²), because it offers the largest interface area to the heatsink (right axis in fig. 9).

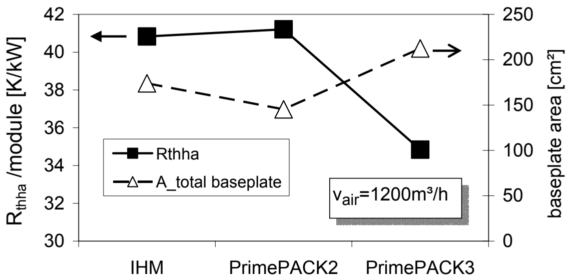

Fig. 9: Experimental R_{thha}-values for different reference-modules on an air cooled heatsink with surface=400x400mm² and height=88mm.

V Design and Functionality of driver core interface to power system level

The driver system used in the modular IGBT stacks consists of well known EiceDRIVER™-boards 2ED300C17-S or 2ED300C17-ST which supports power supply, isolates the control signal and provides short circuit protection [3]. To increase stack-modularity and flexibility for different converter topologies and varied output power, every IGBT module is equipped with a dedicated adaptor board. Both a passive and an active version of the adaptor board is developed and investigated in combination with the PrimePACK2™ IGBT halfbridge FF800R12IE4.

The main task of the adaptor boards is to ensure an easy and reliable connection between driver and controlled IGBT. In addition the adaptor board enables to implement extended functions like gate resistors, saturation diodes and GE-voltage suppressor diode as close to the IGBT gate as possible and to apply an active clamping system with low inductance in the collector–gate path. The layout of the auxiliary terminals of the PrimePACK™ package facilitates an easy layout of driver boards that can be mounted on top of the module. By use of an active adaptor board the parasitic gate emitter inductance is reduced significantly by implementing the booster stage as driver output stage close to the gate. The low inductive and fast booster stage design not only make it possible to amplify the main gate control signal of the driver but also allows mixing it with a feedback current coming from the active voltage clamping system and extends the possible usage of sophisticated strategies like DVRC [4] [5] which guarantee fast over-voltage protection during IGBT turn off.

The junction temperature T_{vj} of the silicon inside the module is influenced by the generated power losses. The inverter concept has to guarantee that loss dissipation is homogenously distributed across all modules operating in the inverter. This can be influenced by the way the driver is connected to the IGBT module. As can be seen in Fig. 10a the turn-on energy E_{on} strongly depends on the cable length between driver and IGBT module when the passive adaptor is used. E_{on} decreases roughly by 32% when the connector length is extended from 7cm up to 50cm. The disadvantage is especially severe in large inverters when the construction does not allow for having the same driver – module distance in every case. Decreased turn-on energy seems to be beneficial for the IGBT but faster switching slightly increases peak current due to the recovery of the diode (Fig. 10b). Therefore higher peak power losses, that are generated in the free wheeling diode, have to be taken into account which may lead to local overheating of the diode. When the passive adaptor board is replaced by the active version, E_{on} and the peak current I_{MAX} don't depend on gate inductance. It may be adjusted by the gate resistor alone.

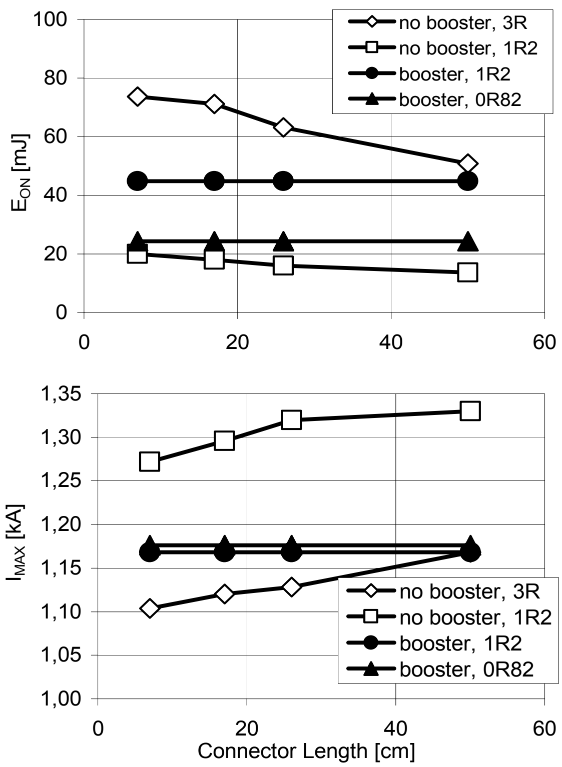

Fig. 10a/b (top/bottom): Dependence of switching parameters E_{on} (top) and I_{max} (bottom) on length of cable connecting the IGBT to the driver board for FF800R12IE4. U_{DC}=600V, I_C=800A, T_{vj}=25°C

IGBTs in the PrimePACK™ can be driven either by the passive or active version of the adaptor board. Both approaches have their merits and drawbacks. The summary is presented in table 2.

	version of adaptor	
function / properties	active	passive
independence of switching speed on GE-cable lenght	++	-
over-voltage protection possible ("boosted clamp)	++	-
number of parts needed	-	+
required PCB area	-	+

Table 2: adaptor board comparison

VI Inverter performance

Measurements have been carried out on the ModSTACK™ inverter equipped with FF600R17IE3 PrimePACK2™ modules under laboratory conditions (V_{CC}=900V, f_{sw}=2,5kHz, f_0=50Hz, cos(ϕ)=0, T_a=24°C). Thermal measurements show that R_{thha} of the air cooled heatsink is slightly enhanced by ~15% in comparison to the results presented in chapter III if real IGBT modules are acting as heat sources resulting in R_{thha}=47K/kW per module. This is because the distribution of heat across the baseplate area is more even if flat resistors are generating power instead of real IGBTs and diodes. The maximum RMS current is calculated as a function of the junction temperature T_{vj}. For $T_{vj,max}$=125°C (150°C) we obtain I_{rms}=380A (440A). At 440A_{rms}, the IGBT operates up to its nominal current I_C=600A. The operation point is successfully mastered which is proved by the turn off waveform in figure 11, that is recorded at the running inverter

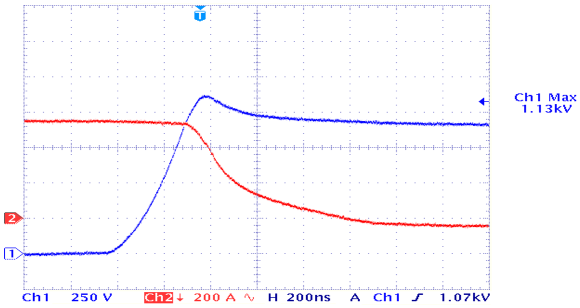

Fig. 11: IGBT turn-off at V_{CE}=900V, I_C=600A, T_{vj}=145°C, I_{rms}=440A, R_G=1,6Ω recorded during inverter operation at 2,5kHz.

The usabilitiy of PrimePACK™ and IHM dual IGBT modules is compared based on measured R_{th} values and application conditions that allow driving a 690V_{rms} motor. The implemented safety margin for over-current capability is 20% for 10s time duration. Since the PrimePACK™ package is designed for operation up to T_{vj}=150°C, the calculation is also done for this extended temperature. The result is given in figure 12.

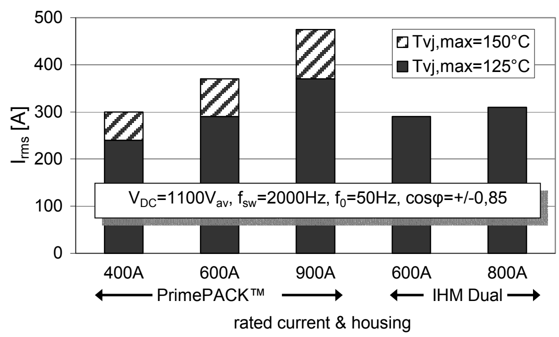

Fig. 12: usable rms current in a ModSTACK™ inverter for different 1700V IGBT modules and rated currents.

Apparently the PrimePACK™ package offers the chance to reach a higher power density even if the maximum junction temperature is kept at 125°C. Assuming that T_{vj} can be raised up to 150°C, I_{rms} can be increased further by roughly 25%. The future work will focus on qualifying products in the new package for this extended temperature range.

To ensure safe operation not only temperature but also over-voltage has to be limited. To operate at high V_{DC} and fast switching, a low stray inductance L_σ of both the module and the inverter assembly is essential. The PrimePACK™ is characterised by low internal inductance [1]. In the ModSTACK™ environment a total L_σ=42nH is reached, which is proven by measurements of the inductive voltage drop during current commutation at IGBT turn-on. In terms of over-voltage, operation at low temperature is most critical because of faster switching. Fig. 13 shows the over-voltage reached for a range of V_{CE} and I_C. The system guarantees that even for highest currents I_C the voltage stays safely below 1700V.

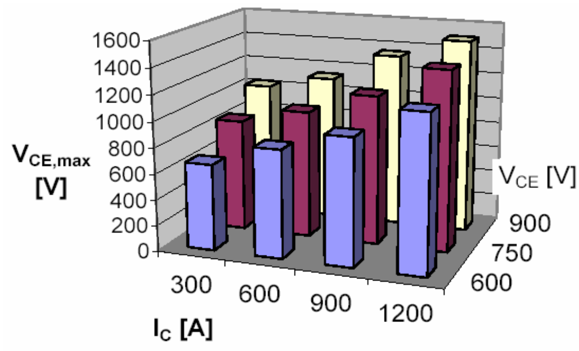

Fig. 13: $V_{CE,max}$ for turn-off at room temperature, L_σ=42nH, no V_{CE} clamping is applied.

VI Conclusion

The first integration of PrimePACK™ IGBT module into an existing converter proved to work safely. The optimisation of important issues like thermal management or driving of the IGBT are well supported by the new power module. The potential for higher inverter power density is shown and proved by experimental runs of a laboratory inverter. The most striking benefit will come into play when first products are qualified for operation up to T_{vj}=150°C.

References:

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