Converter Power Density Increase using Low Inductive Integrated DC-link Capacitor/Bus

Ionut, Trintis, Aalborg University, Denmark, itr@et.aau.dk
Toke, Franke, Danfoss Silicon Power, Germany, toke.franke@danfoss.com
Bjørn, Rannestad, KK Wind Solutions, Denmark, bjran@kkwindsolutions.com
Stig, Munk-Nielsen, Aalborg University, Denmark, smn@et.aau.dk

Abstract

The power losses in switching devices have a direct effect on the maximum converter power. For a voltage source converter, the DC-link bus has a major influence on the power loss and safe operating area of the power devices. The Power Ring Film Capacitor^{TM} integrated with an optimized bus structure has a measured inductance of around 5 nH. That allows the converter to switch with low turn-off losses, and allows the safe operation at higher dc-link voltages. This paper investigates the power transfer limits of a ShowerPower$^®$ cooled power stack.

1.   Introduction

The increase in the power density of power converters is a continuous power electronics topic always driven by the cost factor. The active and passive components as well as the cooling concepts are improved to enable a doubling of the power density for every decade [1]. Particularly for a voltage source inverter, the DC-link capacitor bank is one of the crucial components that limit the safe operating area of the power electronic devices. Reducing the equivalent series inductance (ESL) in the DC-link can enhance the efficiency and the maximum allowable switched voltage [2]. Moreover, the equivalent series resistance (ESR) of the DC-link bus must be kept low enough to maintain a safe operating temperature of capacitors for the maximum ripple current.

Cooling of power semiconductors is another important factor. The decrease of the equivalent thermal resistance can allow more power to be dissipated and improve the power density. Direct liquid cooling concepts such as ShowerPower$^®$ is a cost effective and efficient solution [3]. The monitoring of the liquid flow is a strict requirement. A feedback to the electrical system in case of reduced flow is trivial for safety.

Traditional power converter design implies a thermal model and a power loss model to estimate the maximum junction temperature. However, an estimation error will lead to increased safety margins. Innovative methods of junction temperature estimation based on electrical parameters such as the on-state voltage drop can provide a valuable feedback [4]. Estimating the junction temperature of the converter during operation can lead to an increase of the operating junction temperature, and therefore allows to increase the power density.

This paper investigates the converter power density increase, when the construction is realized with a high quality DC-link capacitor bank exhibiting low ESR and low ESL. The converter is built with 1700 V IGBT modules. Firstly the characterization of the losses is realized to estimate the power limit by simulation. The converter is equipped with advanced gate drivers that are capable of on-state voltage feedback. The on-state voltage is used together with the measured characteristics to detect the safe operation of the power modules with respect to junction temperature. Finally, the capacitor bank temperature is measured at three typical operating points.

2. Characterization of converter components

2.1. DC-Link Bus Characterization

The converter is built with 1700V, 1400A PrimePACK 3 power modules to operate at DC-link voltages above 1 kV and output the AC voltage at around 690 V. To be able to characterize the DC-link bus inductance, the converter's bus-bar is used with a power module in a double pulse test. The circuit schematic is shown in Fig. 1, where the device under test in this case is the DC-link bus-bar. In this case the inductor is connected to the positive DC terminal.
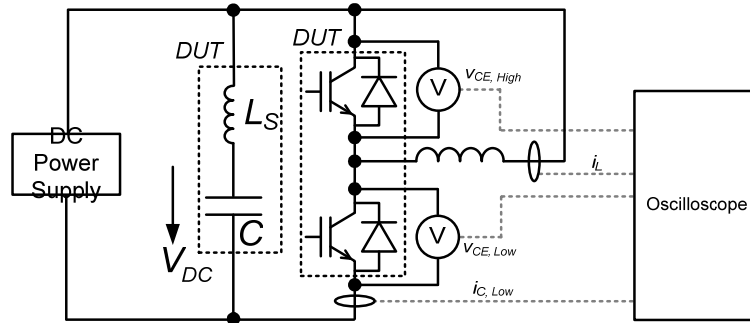

Fig. 1. Test setup for characterization of the DC-Link bus-bar and the IGBT power module

The typical insulated-gate bipolar transistor (IGBT) turn-on and turn-off waveforms of the used 1700V power module at 25 °C and 1.1 kV are shown in Fig. 2. It can be noticed the effect of the stray inductance at both turn-off (positive voltage drop) and turn-on (negative voltage drop).
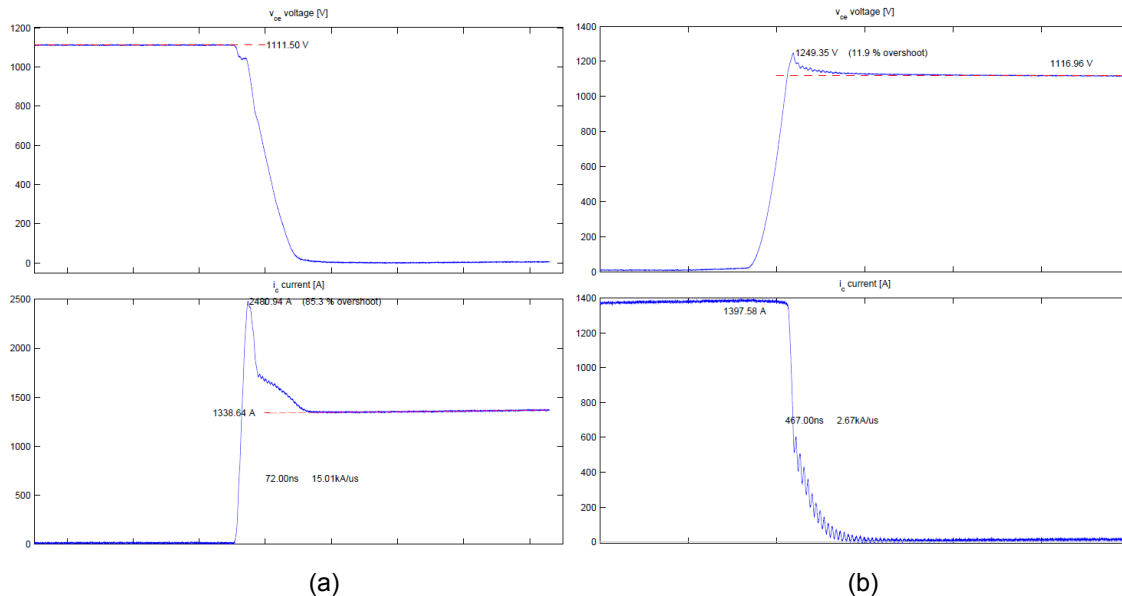

(a)   (b)

Fig. 2. (a) IGBT turn-on transient; (b) IGBT turn-off transient

From the turn-on transient, having the voltage drop on the stray inductance for a given current slope, the DC-bus ESL can be calculated using [5]:

$$L_S = \frac{\Delta V_{L_S}}{di/dt} \cong \frac{70\,V}{15\,kA/\mu s} = 4.66\,nH$$

2.2. IGBT Module Characterization

Switching losses

The test setup presented in Fig. 1 can also be used to characterize the power module under the conditions of the low inductive DC-link and the gate drive settings used. The gate driver in use is based on the Concept 2SC0435T driver core, setup with turn-on gate resistor of R_{ON} = 0.5 Ω and turn-off gate resistor of R_{OFF} = 1.5 Ω. The collector current and collector-emitter voltage are measured with equipment having the minimum bandwidth of 200 MHz.

The junction temperature is adjusted, and the switching losses are measured. Only the IGBT and diode on the low side are measured, while a similar switching performance is assumed for the high side devices. The energy losses are calculated using the notes given in [6], namely:

$$E_{loss,ON/OFF} = \int_{t_{ON/OFF,start}}^{t_{ON/OFF,end}} i_C(t) \cdot v_{CE}(t) \cdot dt$$

In Fig. 3 the calculated switching energy losses based on measurements are shown for different temperatures, blocking voltages and currents.
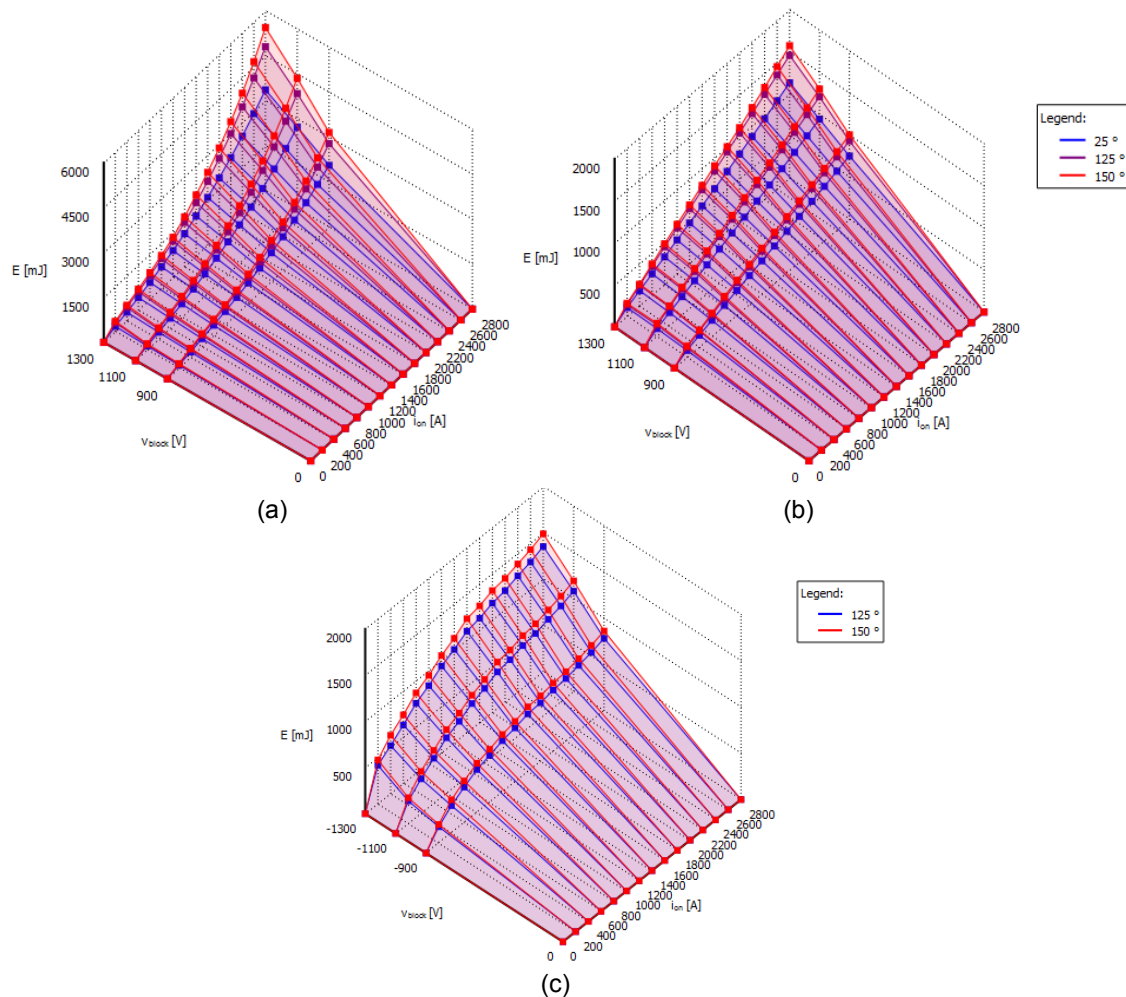

(a)

(b)

(c)

Fig. 3.   (a) Measured IGBT turn-on energy loss; (b) Measured IGBT turn-off energy loss; (c) Measured diode recovery energy loss

Conduction losses

The conduction losses are measured at a higher temperature resolution, using a curve tracer, all the power devices can be characterized. The measured I-V curves are shown in Fig. 4, measured in millivolts [mV].
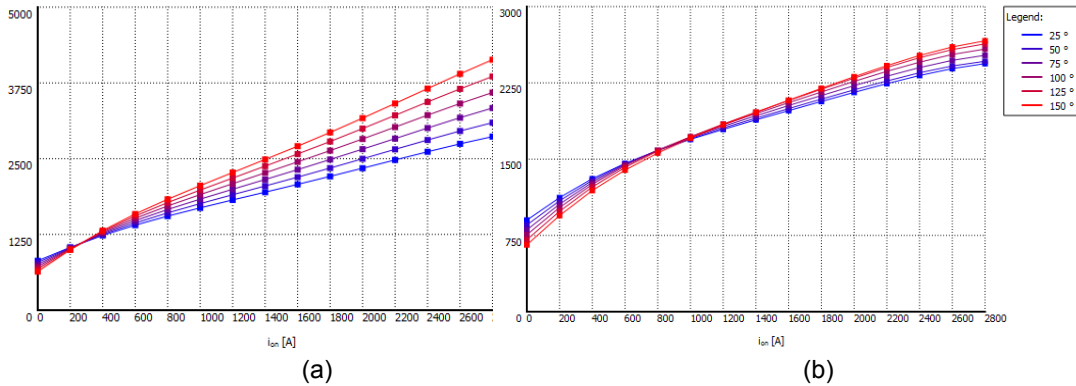

(a)   (b)

Fig. 4. (a) Measured V_{ON} for IGBT; (b) Measured V_f for Diode

It is important to measure the conduction loss characteristics at higher resolution, since the power limitation due to power module maximum operating junction temperature is to be determined using the online measured on-state voltage drop. The intermediate temperatures from the minimum to the maximum temperature can be used to make a preliminary verification of the estimation error.

3. IGBT virtual junction temperature estimation

It has been shown that the junction temperature over a transistor or diode die area varies significantly, the temperature distribution presenting a high degree of uniformity [7]. Therefore a virtual junction temperature must be determined, being the weighted average temperature over the whole die. In case of power module packages, a device comprises of paralleling of multiple dies. The virtual junction temperature of that device is the weighted average of the virtual junction temperatures of the paralleled dies. The device virtual junction temperature is to be estimated.

3.1. IGBT gate driver with integrated on-state voltage feedback

The online feedback of the on-state voltage drop will require an upgrade of a state of the art gate driver. For that reason, a standard gate driver core is used together with an online on-state voltage measurement circuit. In Fig. 5, such a gate driver was built, where the analog to digital converter that measures the on-state voltages can transfer data over fiber optics.
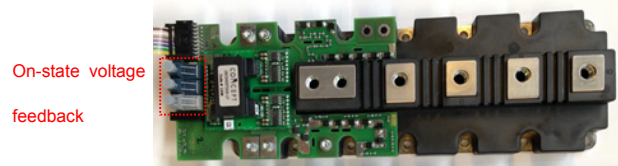

Fig. 5. IGBT gate driver with on-state voltage feedback

3.2. On-state voltage feedback usage for temperature monitoring

Assuming that the measured on-state voltage drop measured on the low impedance terminals of the characterized power devices is the weighted average of the voltage drop on the paralleled dies in the power module, the data from the conduction loss characterization

can be used to estimate the virtual junction temperature. Polynomial representation of the characterized data can be used for two temperatures, and the temperature can be estimated using linear interpolation. Considering the two temperatures being 25 °C and 150 °C, the temperature can be estimated using:

$$T_{vj,estim} = 25 + \frac{V_{ON,meas} - V_{ON,25}}{V_{ON,150} - V_{ON,25}} \cdot 125$$

4. Power limit detection

The absolute power limit detection will be limited by the device reaching the highest temperature. Some components however may present significant decrease in reliability due to higher operating junction temperature, a fact that is not investigated in this paper. It is however of a high interest for the power converter user to ensure that the converter can safely operate for a limited amount of time at high power.

To be able to test the converter power limits, a test setup for circulating the power is to be used to operate the converter under different conditions with the following variables: output voltage, output frequency, output current, power factor, dc-link voltage, and coolant liquid temperature. The main components that are to be investigated to detect the power transfer limit is the IGBT power module and the DC-link capacitor bank, described in the following paragraphs.

4.1. Cooling of IGBT power modules and power transfer limit

The IGBT modules are direct liquid-cooled using a ShowerPower® cooling system [3]. The flow of the coolant was set to 45 l/min, and the temperature of the outlet was controlled to 60 °C. The DC-link voltage was controlled to 1070 V, output voltages controlled at 650 V (line-to-line) modulated with continuous space vector pulse width modulation and switching at 2.5 kHz. The test results at unity power factor when operating in the inverting mode (power flow from DC to AC) are shown in Fig. 6. Data snapshots were saved in the digital signal processor (DSP) and transferred to a computer for analysis.

(a)   (b)
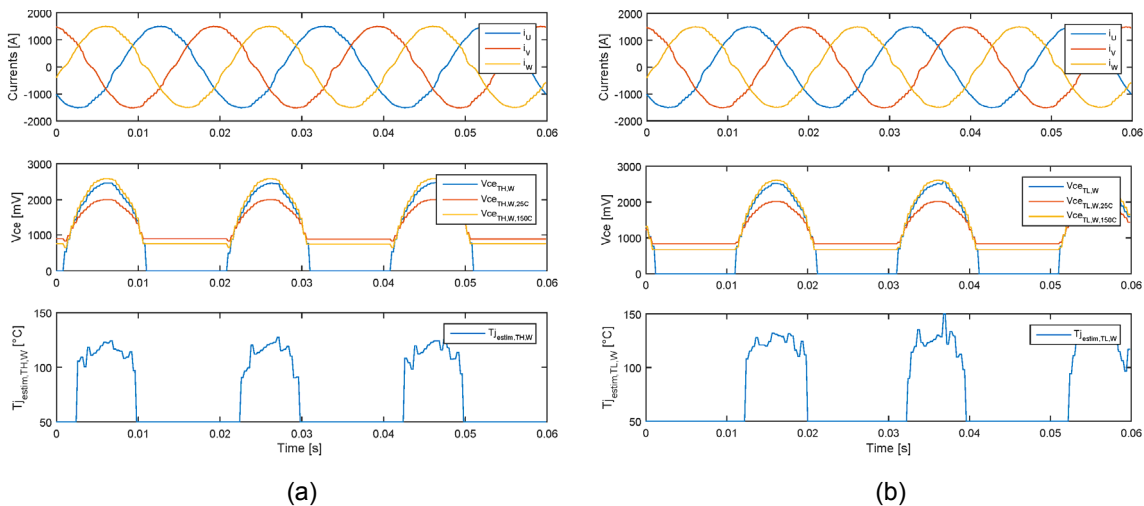
Fig. 6. The on-state voltages and virtual junction temperature estimation of IGBTs in a power module: (a) high side; (b) low side.

Fig. 6 shows the data that is measured and calculated in the DSP, namely the output three phase currents, the model based calculated on-state voltage drops for 25 °C and 150 °C as

well as the online measured on-state voltage drop (in blue). The estimated temperature is shown in the last subplot, only in the positive temperature coefficient region.

Unity power factor operation in the inverting mode is the worst test case for the IGBTs. However, it can be seen that the temperature is well below the maximum junction temperature.

The RMS current at this operating point was 1080 A, resulting in an output power of 1.2 MW.

A simulation model was made using the experimentally characterized switching and conduction losses, while the thermal model was built using the datasheet of the power module and of the cooling system. Fig. 7 shows the simulated and experimentally tested operating points, in the same conditions with the maximum operating junction temperature of 150 °C. Only three operating points were experimentally verified, namely: unity power factor, 0.8 inductive and 0.8 capacitive.
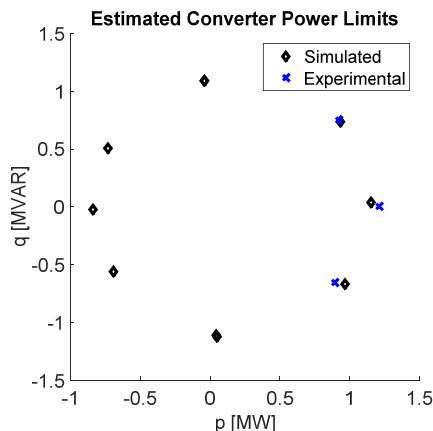

Fig. 7. Simulated and measured power limits of the IGBT converter

It can be noted that in case of unity power factor operation the measured power limit is higher compared with the simulated limit, which in one way can be explained by a difference in the modeled thermal resistance compared with the resistance in real life.

The limitation in Fig. 7 is in the case when only the IGBT modules are considered as the limiting factor, but in fact also the capacitors will limit the power – which is seen in the 0.8 capacitive power factor operation.

4.2.   Cooling of DC-Link capacitors and power transfer limit

Air cooling is usually implemented for DC-link capacitors, due to the low power loss. In case of natural convection, the output power will be limited by the temperature of the capacitors mounted on the warm side of the converter which is usually on the top side for a vertical construction.   Forced cooling will result in a better temperature distribution among the capacitors used in the bus-bar.

The ambient temperature (test room) must be also measured, since it presents variations given by the air temperature control which in this test case is not optimal due to the high dissipated power in the components of the test setup. Having the absolute ambient temperature, synchronously measured, the relative capacitors temperature can be calculated and is presented in Fig. 8.

The temperature of the capacitor bank was measured in the three operating points (PF=1, 0.8ind., 0.8cap.). The temperature is measured in three points in the bus-bar using thermocouples. A fan is used to provide forced air cooling for the capacitors, ensuring a better temperature distribution among the discrete parts that form the DC-link. It is however noticed that still the capacitors on the top of the converter are warmer (sensor B1-2, blue line), while the ones on the bottom remain cooler (sensor B5-6, orange line).

After each operating point is tested, a system stop is required to save the test data logs and to cool the capacitors – therefore the temperature in the beginning drops because the capacitors are cooled. After the system is restarted at full power, the temperature starts to increase. The stop of the test is after the temperature increase is less than 0.1 K/min.
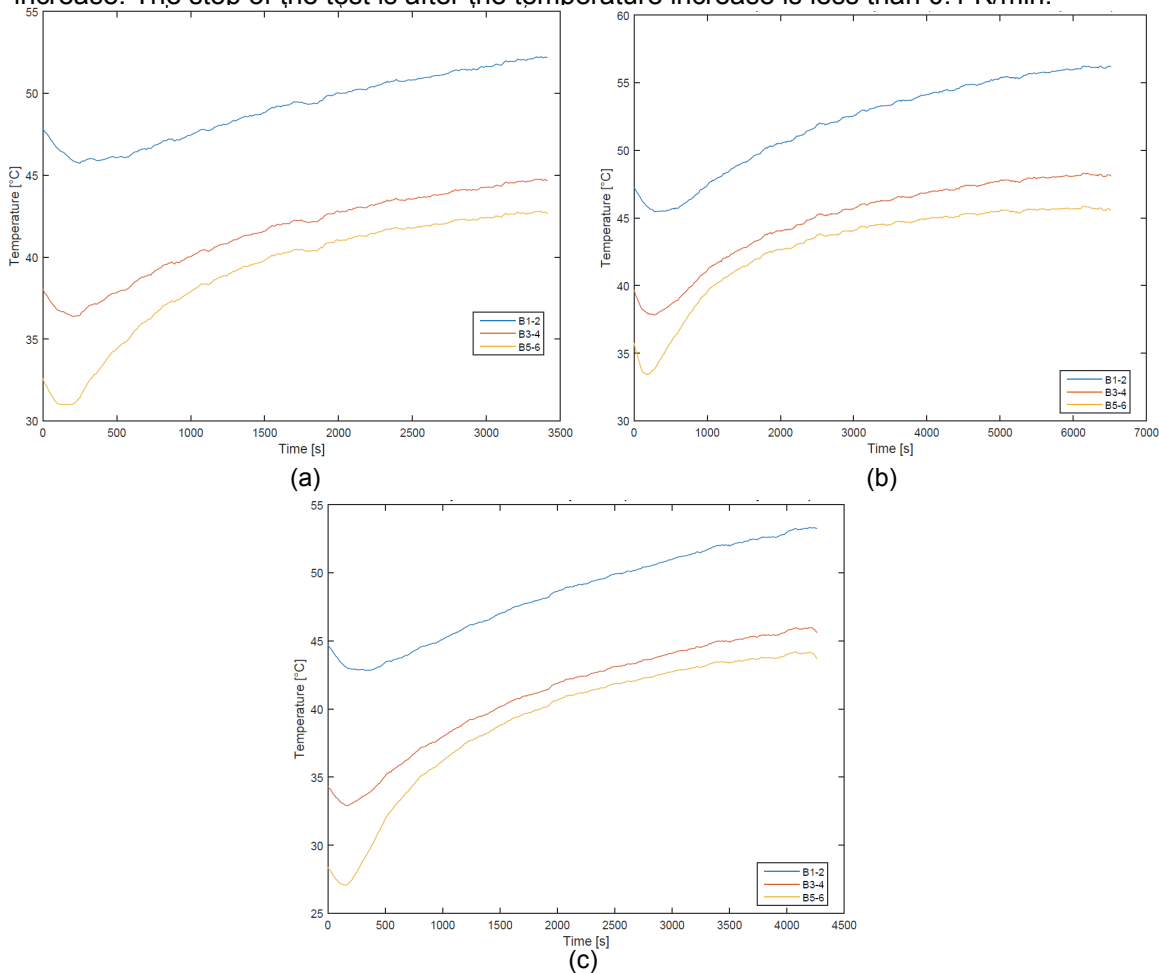

Fig. 8. Temperature measurement of DC-link capacitors, relative to the ambient temperature:
(a) for PF=1; (b) PF=0.8ind.; (c) PF=0.8cap.

The maximum operating temperature of the DC-link capacitors is specified at 85 °C when the operating voltage is in the range of the rated voltage. Therefore, from the above test results, either the maximum ambient temperature must be set or the maximum power transfer will be de-rated according to the operating ambient temperature.

5. Conclusions

This paper has investigated the operating power limits of a new power converter unit. The converter is built with high quality DC-link capacitors, that have low ESR and low ESL, as well as with advanced gate drivers that can measure the on-state voltage drop on the power devices and a highly efficient direct liquid cooling system. From the on-state voltage drop measured online, it was seen that it is possible to increase the converter power density. The power limit was detected using both simulation, calculating the power losses in the semiconductor devices, as well as by experimental testing and monitoring of the on-state voltages to ensure a safe operation. For the increased power transfer, the temperature of the DC-link capacitor bank was measured. It can be concluded that at the tested operating

points, the maximum ambient temperature will be limited by the capacitor with the highest temperature in the worst case operating scenario (inductive power factor). If the maximum temperature of 85 °C is considered, results that the maximum ambient temperature without converter de-rating must be lower than 30 °C. For higher ambient temperature, de-rating power will follow accordingly.

However, one must also measure or estimate the reliability of the converter components (power modules and capacitors) to ensure that the operating at the newly increased power rating offers enough life time for the given application. Here new advances in the bonding and joining technologies such as Bond Buffer [8] will offer further potential.

6.   References

[1] Kolar, J.W.; Drofenik, U.; Biela, J.; Heldwein, M.L.; Ertl, H.; Friedli, T.; Round, S.D., "PWM Converter Power Density Barriers," Power Conversion Conference - Nagoya, 2007. PCC '07 , vol., no., pp.P-9,P-29, 2-5 April 2007.

[2] Brubaker, Michael; Hage, Dayana El; Hosking, Terry; Sawyer, Edward; Franke, W.-Toke, "Integrated DC link capacitor/bus enables a 20% increase in inverter efficiency,"; Proceedings of PCIM Europe 2014, vol., no., pp.1,8, 20-22 May 2014.

[3] Olesen, K.; Bredtmann, R.; Elisele, R., ""ShowerPower" New Cooling Concept for Automotive Applications", Automotive Power Electronics, Paris, 21-22 June 2006.

[4] Ghimire, P.; Pedersen, K.B.; de Vega, A.R.; Rannestad, B.; Munk-Nielsen, S.; Thogersen, P.B., "A real time measurement of junction temperature variation in high power IGBT modules for wind power converter application," Proceeding of CIPS, pp.1-6, 25-27 Feb. 2014.

[5] M. A. Brubaker, T. A. Hosking, and E. D. Sawyer, "Characterization of Equivalent Series Inductance for DC Link Capacitors and Bus Structures", Proceedings of PCIM, Nuremberg, Germany, May 2012.

[6] Infineon AN 2011-05, "Industrial IGBT Modules – Explanation of Technical Information", V.1.1 May 2013.

[7] Schmidt, R.; Scheuermann, U., "Using the chip as a temperature sensor — The influence of steep lateral temperature gradients on the Vce(T)-measurement," Power Electronics and Applications, 2009. EPE '09. 13th European Conference on , vol., no., pp.1,9, 8-10 Sept. 2009.

[8] Rudzki, Jacek; Becker, Martin; Eisele, Ronald; Poech, Max; Osterwald, Frank, "Power Modules with Increased Power Density and Reliability Using Cu Wire Bonds on Sintered Metal Buffer Layers," Integrated Power Systems (CIPS), 2014 8th International Conference on , vol., no., pp.1,6, 25-27 Feb. 2014.