Innovative Measuring System for Wear-out Indication of High Power IGBT Modules

Rasmus Ørndrup Nielsen, Jens Due, Stig Munk-Nielsen
Department of Energy Technology
Aalborg University
Denmark
adlertropf@gmail.com, jensdue@gmail.com, smn@et.aau.dk

***Abstract*—Power converter failures are a major issue in modern Wind turbines. One of the key elements of power converters for high power application is the IGBT modules. A test bench capable of performing an accelerated wear-out test through power cycling of IGBT modules has been made. In the test bench it is possible to stress the IGBT module in a real life working point, controlling the voltage, current and phase of the device under test. An analysis of failure mechanisms has been carried out, indicating that V_{CE} can be used as an sign of wear out of the IGBT module. Therefore an innovative measuring system for V_{CE} monitoring with an accuracy as low as a few mV has been implemented. The measurements on the IGBT in the test bench show that it is possible to monitor V_{CE} and use this as an indicator of wear-out.**

I. Introduction

By the year 2020 the Member States of the European Union have made a commitment to reduce consumption of primary energy by 20 %, introducing 20 % renewable energy and reducing carbon emissions with 20%. The research in and usage of renewable energy sources needs to grow fast in order to be able to fulfill this goal. One of the most applicable renewable energy sources is wind power. Through analysis of failures in wind turbines it was discovered that approximately 15% of all failures is due to the frequency converter [1]. This article will deal with the design of a test bench capable of stressing the IGBTs in an accelerated real life wind turbine working point, and the design of an innovative measuring system that is capable of predicting the wear-out of high power IGBTs.

II. Objectives

The objectives of the work done, described in this article:

1. To build a test bench for benchmarking IGBT modules.
2. To build a measuring system capable of measuring wear-out of the high power IGBT modules.
3. To show that it is possible using the measuring system to predict IGBT failure.

A major reason for failures in IGBT modules is mismatched coefficients of expansion (CTE) of the layers an IGBT consists of. This mismatch causes strains to both the bondwires and the soldering of the IGBT modules thus causing the IGBT modules to fail over time [2].

The Doubly-Fed Induction Generator (DFIG) is a widely used generator in the wind turbine industry. This is used as it is possible to have a variable rotor speed without using a full-scale power converter. The power converter of a DFIG is connected to the rotor and is only supplying the difference regarding frequency between the rotor field and the stator field so that these are synchronized. This causes that the operating point of the converter typically is a few Hz [3]. This low frequency operation causes high temperature changes in the junctions of the IGBT modules. Therefore the stress of the IGBT modules in a DFIG application is severe. It could be advantageous to be able to predict in advance, as this could decrease the downtime of the wind turbine, and that it could be possible to schedule changes of the IGBT modules in the wind turbine based on wear out indication.

III. Design of IGBT Test Bench

In order to be able to stress test the IGBT modules in a manner close to the real life application a test bench has been designed. With this it is possible to choose an arbitrary voltage from the Device Under Test (DUT) and an arbitrary current through both in amplitude and phase angle. The principle of the of the test setup can be seen in Figure 1.

In order to realize a system capable of testing the DUT in such a manner another IGBT module (Control module) is used and connected to the DUT through an inductor. Together the Control module and the inductor can be interpreted as a current source. Thus the principle in Figure 1 is realized. The diagram of the test bench is shown in Figure 2. The inductor used for this setup is a 350 µH inductor, rated for 1100 A.

978-1-4577-0541-0/11/$26.00 ©2011 IEEE

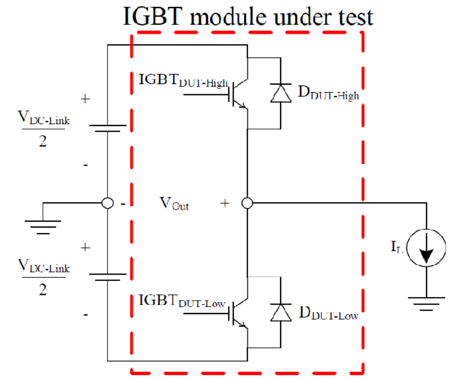


Figure 1: Basic test setup for testing IGBT modules

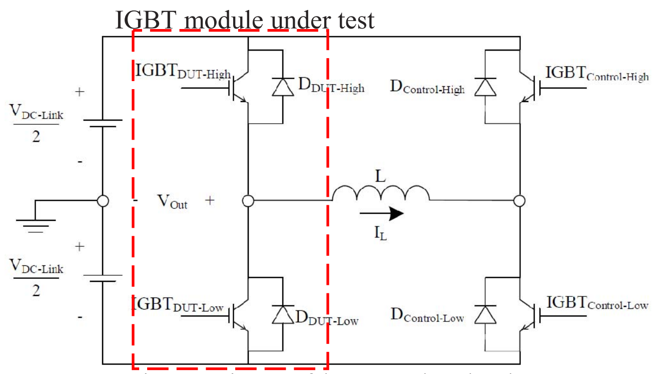


Figure 2: Diagram of the proposed test bench

A. Specification of operating point

In order to select a working point for the test bench a lifetime model for the modules is used together with a real life working point. The lifetime model used is based on the Coffin-Manson law for plastic fatigue fractures [4,5]. The Coffin-Manson law gives a number of cycles as output as function of the delta temperature and the medium temperature. The equation is shown below:

$$N_f = A \cdot (\Delta T_J)^{\alpha} \cdot e^{\frac{E_a}{\kappa_B \cdot T_M}} \tag{1}$$

N_f is the lifetime in number of cycles, (ΔT_J) is the difference between the minimum and the maximum temperature of the junction, A is a constant [$K^{-\alpha}$], Ea=9.89e-20 J, α=-5.039, κ_B=1.38066 JK^{-1} and $T_M = T_{J\text{-}min} + \Delta T_J$[K].

The coefficients in the Coffin-Manson law was found by adapting the equation to lifetime data give by Infineon. The lifetime data was found by pulsed power cycling tests by Infineon. The device tested in this article was the Infineon FF1000R17IE4D. The device is rated at 1000 A, 1700 V. The module consists of 6 IGBT chips in parallel for each IGBT and 6 diode chips in parallel for each diode. To each IGBT chip there is 8 bondwires connected. In total this gives 48 bondwires to all the diodes and IGBTs. One of the 6 sections in an FF1000R17IE4D is shown in Figure 3.

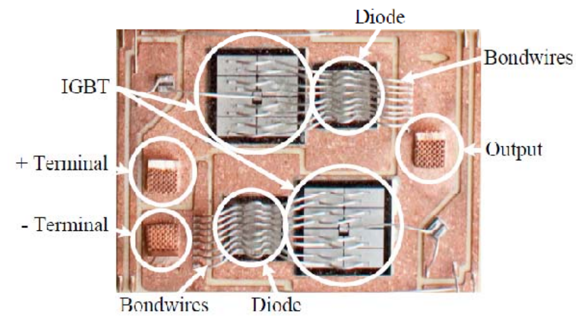


Figure 3: Picture of one section out of 6 of the used IGBT modules

After the lifetime model was completed a loss model and a thermal model was made in order to be able to input the temperatures to the lifetime model. The models were made from the data give in the datasheet. The thermal model and the loss model was verified by comparison with results from Infineon IPOSIM6-2g, and showing results within 4% of selected representative working points. This resulted in the accelerated working point in Table I.

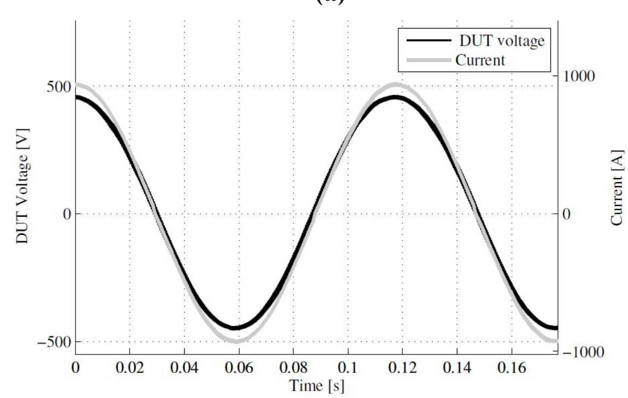
TABLE I: ACCELERATED DFIG OPERATING POINT

Parameter	Value
$V_{DC\text{-}Link}$	1000 V
V_{out}	315 V
I_L	640 A
f_{out}	6 Hz
f_{SW}	2.5 kHz
Phase (voltage to current)	2.7 rad
$T_{Baseplate}$	80 °C

B. Verification of Test Bench

In order to determine that the test bench is capable of testing the IGBT modules as described in the previous section a verification of the test bench was made. The test result is shown in Figure 5. It can be seen that the voltage, current and phase can be controlled to the desired levels.

(a)



(b)

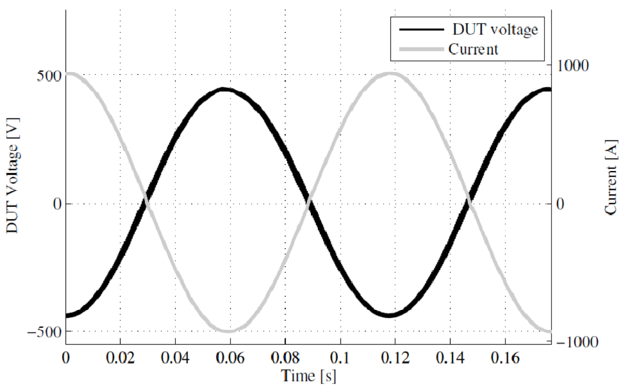


Figure 5: Verification of the test bench, measured DUT voltage and current, where the DUT voltage is the filtered PWM voltage. (a) Voltage and current in phase. (b) 180 º phase angle.

IV. Design of V_{CE} Measuring system

A. Specification of V_{CE} measuring system

A number of different companies have been working with lifetime estimation based on a physical measurable parameter e.g. Semikron GmbH where the voltage V_{CE} across the IGBT was monitored during the test period. A change of up to 10 % was detected before the IGBT was destroyed [6]. However this number is highly dependent on the type and rating of the module. Other authors suggest that the change in the forward voltage drop depends on the rated current of the module. A general rule is stated below [4][7]:

$$\Delta V_{CE}[\%] = \frac{1500}{I_{Rated}} \qquad (2)$$

For the used Infineon FF1000R17IE4 modules the change in V_{CE} will be 1.5 % since the rated current equals 1000 A. This corresponds to approximately 30 mV. This means that the measuring system must be capable of detecting a change of 30 mV, hence high accuracy is demanded. The aim of the measuring circuit should be to measure with a resolution less than 10 % of this, 2-3 mV.

As the temperature of the water cooling during the test is constant, it is mainly the junction and therefore the bondwires there are subject to stress. Therefore it is expected that the main failure mechanism in this test setup is bondwire lift off. This would result in discrete steps in V_{CE} when a bondwire lifts off.

B. Design of V_{CE} measuring system

A circuit for measuring V_{CE} in situ must be developed if a reasonable resolution (with regard to the time) shall be obtained. The system must be able to measure both the voltage drop of the IGBT and of the diode as the diodes on the DUT side is actually the components that are most stressed on the DUT side and the IGBTs on the Control side is most stressed.

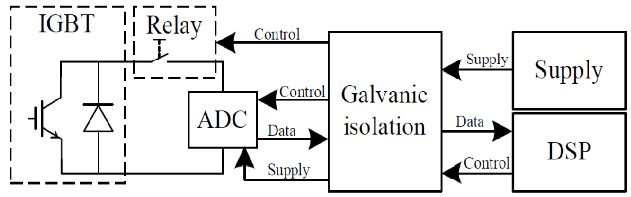


Figure 4: Proposed system for measuring V_{CE}

Therefore the system shown in Figure 4 is proposed for measuring V_{CE}. The system works by utilizing a reed relay (Cynergy3 DAT70515) to connect an ADC directly to the IGBT. When the converter is operating in normal mode the voltage V_{CE} will not be measured since the relay has to disable the connection between the ADC and IGBT. The reason for not being able to measure online is that the response time of the reed relay, which is around 3 ms, is longer than a switching period of 0.4 ms at 2500 Hz. When the converter enters the V_{CE} measuring routine a control signal to the relay enables it and thereby creating a connection between the IGBT and ADC. The advantages of the system are that by use of the reed relay V_{CE} will be measured directly on the Kelvin terminals of the module, hence the noise immunity is high. Furthermore the relay will not influence on the dynamic performance of the system. The drawbacks are that extra advanced control is needed in order to operate the system. When V_{CE} of an IGBT is measured the IGBT must first be turned on, thereafter the relay must be enabled. Next the opposite IGBT on the other half bridge must be turned on in order for a current to run through both the inductor and IGBT. A measuring routine that stops the sinusoidal current and starts the measurements has been implemented in the DSP. This allows for measuring all diodes and IGBT's every 5 minutes with high accuracy, 12 bit ± 5 V corresponding to a resolution of 2-3 mV. The rise time when the measurement takes place is approximately 300 µs long, thus the change in temperature during the measurement is very small. The waveform during the measurement is shown in Figure 6. The measurement system is described in further detail in a previous article [8].

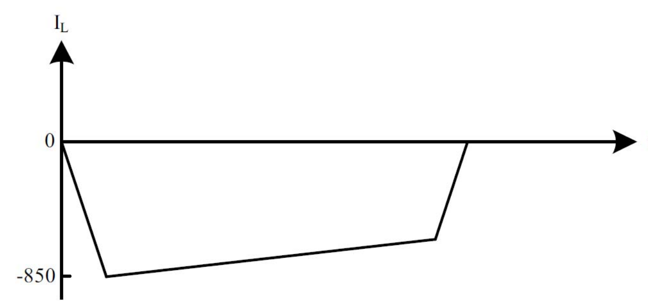


Figure 6: The current waveform during the V_{CE} measurement, during the first slope the DUT-low IGBT is measured; during the second slope the low control diode is measured.

C. Verification of the measurement system

One measurement system as shown in Figure 4 is implemented for each IGBT and diode pair. Thus in all 4 measuring systems are implemented. In Figure 7 ten measurements of 26 points of the voltage during the turn on slope of the IGBT DUT-Low. As can be seen the measurements are very consistent and is therefore concluded that the measurement system is sufficient.

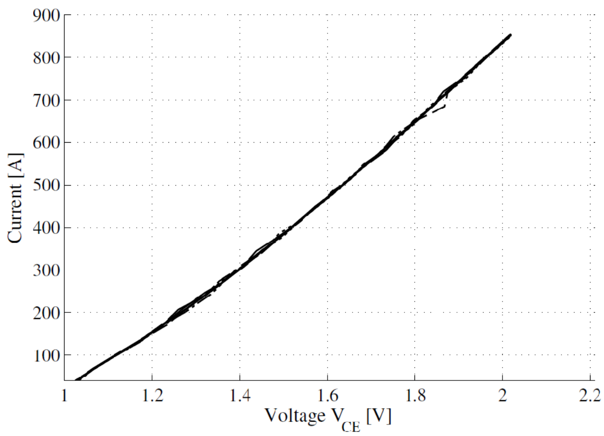


Figure 7: 10 measurements of 26 points of the V_{CE} voltage of the IGBT DUT-Low

V. Results and Measurements

The measurements were done with test setup running in the working point described in Table I. Measurements were done every 5 minutes and each component was measured 3 times. First outliers were sorted out, from the measured data. Thereafter a third order polynomial is fitted to the measured curve (as in Figure 7) and the average of V_{CE} for the IGBT or V_D was taken at 800 A for the IGBT or 600 A for the Diode.

The first test done showed an increase in V_{CE} of 40 mV, before complete failure of the module, close to the expected 30 mV. The second test was therefore stopped after an increase of approximately 35 mV in order to be able to examine the module afterwards. Also this was done in order to be able to run with the same DUT module thus running the DUT module to failure. In both the first and the second test it was the IGBTs in the control side that showed to be the weakest components. The test result for the second test is shown in Figure 8. This figure shows a linear increase of V_{CE} before in the end the expected discrete steps are seen. This linear increase could be explained by Aluminum reconstruction of the aluminum metallization of the chips or an increase in junction temperature over time [2]. The post failure analysis will reveal if this is the case.

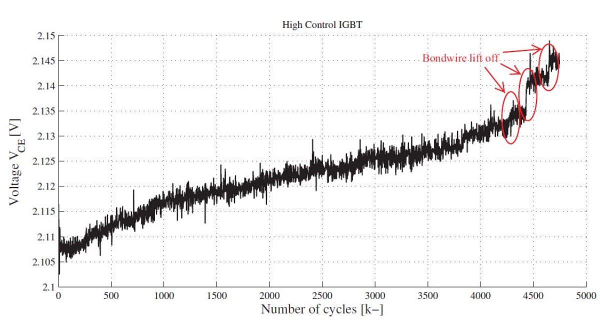


Figure 8: Measurement of V_{CE} of control IGBTs during power cycling. The experiment was stopped after 4,748 kcycles.

After the control module was exchanged the test was continued. The next components that showed an increase in there forward voltage drop were the DUT diodes. The result of this test can be seen in Figure 9. The first discrete step in V_D was due to the change of the control module. This is considered due to changed thermal properties as the test setup must be drained of water every time a module is exchanged as the Danfoss Shower Power technology is used for cooling. No linear increase is shown in V_D this is concluded to be due to that V_D for 600 A for this module is almost constant with temperature. Again discrete step in the voltage is seen in the end which could be explained by bondwire lift off. The noise in the measurement could be due to small temperature variations in the cooling water. This is also an issue that should be addressed if such a system should be installed in a real life application, such as a wind turbine.

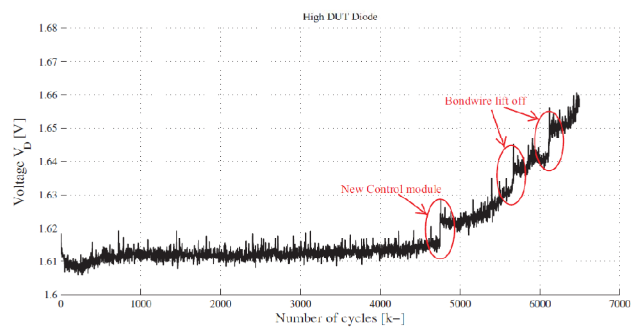


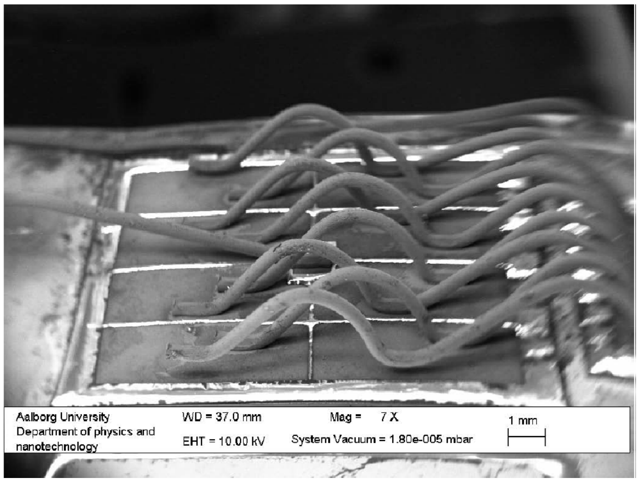
Figure 9: Measurement of V_D of DUT diodes during power cycling. The experiment was stopped after approximately 6,500 kcycles.

VI. Post Failure Analysis

Both tests were stopped prior to complete failure of the modules. This was done in order to be able to examine the modules in order to determine whether the failure mechanism in fact was bondwire lift off. After the test the modules was disassemble and the silicone gel was removed. This was done using a solvent (Digesil NC Liquid concentrate). The first thing noticed after removing the silicone gel was that in all 5 bondwires had lifted off in the control IGBT. If comparing this with Figure 8 only three steps can be seen, but each step can conceal more than one lifted bondwire. Especially the second step seems to have a larger magnitude. Thereafter the module was taken for analysis in a SEM (Scanning Electron Microscope). The result of this analysis can be seen in Figure 10. This clearly shows bondwires no longer attached to the IGBT chips. However what is also clear from the figure is that the aluminum metallization is no longer smooth as in a new module. Thus the module has also suffered from aluminum reconstruction which could explain the linear increase in V_{CE}.

It is also noted that bondwires that was lifted all were the ones furthest from the center of the IGBT chip, even though the IGBT chip would get warmest in the middle. However the bondwires that lifted were those that spanned the longest distance. This could suggest that the bondwire lift-off may be linked to some sort of self-heating of the bondwire.

(a)



(b)

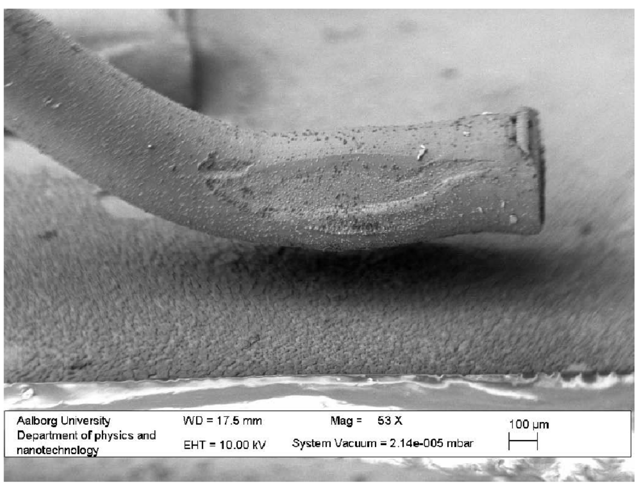
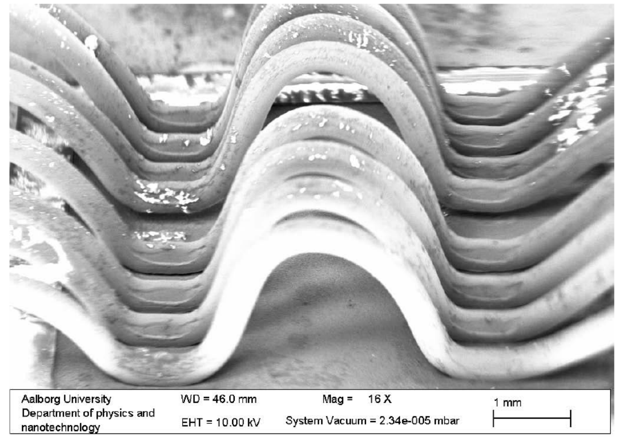


Figure 10: Results from SEM investigation of Control IGBT. (a) Overview of IGBT, (b) Zoom on a bondwire lift off

The DUT module was also disassembled after the test, and in total 11 loose bondwire were found. So again bondwire liftoff seems to be the main failure mechanism of the DUT device. Also the DUT module was investigated in a SEM. The result from the test can be seen in Figure 11. Again bondwire lift off is clear. It can also be seen that surface of the chips show some sort of aluminum reconstruction.

(a)



(b)

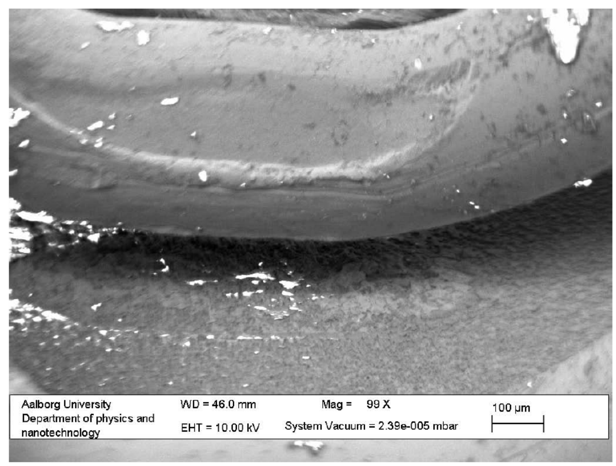


Figure 11: Results from SEM investigation of DUT-High element. (a) Overview of diode (b) Zoom on a bondwire lift off

After the SEM analysis was done the module a 3D CT scan of the modules was performed. This was done in order to determine whether the power cycling had damaged the soldering in any way. The result of this scan for one of the chips with bondwire lift off is shown in Figure 12. The figure shows the soldering between the chip and the DCB. As can be seen no cracks or voids are found in the soldering. Therefore it is concluded that the soldering cannot account for the linear increase in V_{CE}. Also the soldering between the DCB and the baseplate was checked, this was also found to be good. Both the IGBT and the diode were checked and no faults were found in either soldering.

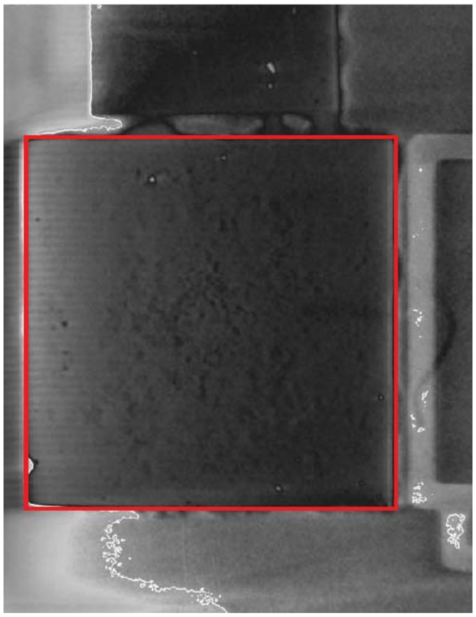


Figure 12: 3D CT-scan of the control IGBT, showing the solder layer between the chip and the DCB.

VII. CONCLUSION

A test setup capable of testing IGBT modules in an desired operating point has been designed. This test setup is capable of stressing the modules in a manner similar to that of a real life application, thus eliminating the uncertainty of relying on pulsed test. This test setup is capable of stress testing the modules to such a degree that they fail within 14 days.

A measuring system capable of measuring V_{CE} and V_D in situ was designed. This system can measures the voltages with a resolution of 2.44 mV, thus enabling it to measure the small changes caused by degradation of the module. The measurement system was installed and tests were run. These tests show that the measuring system is able to measure V_{CE} and V_D with such a resolution that both linear increases and discrete increases are measured. The relay used in the measuring system should be changed in order to be able to measure online, as it is now too slow to switch with the speed of PWM signal.

Through post failure analysis it was found that the main failure mechanism of the used modules was bondwire lift off. This result was expected as the baseplate was kept at a constant temperature and the junction was subject to changes in temperature due to power cycling.

ACKNOWLEDGEMENT

The authors would like to thank KK-Electronic A/S for components and valuable counseling. Also thanks to Siemens Wind Power A/S for supplying modules and the inductor.

REFERENCES

[1] M. Wilkinson, G. Hassan Partners Ltd, and Reliwind EU Project. "Reliability data field study in the reliawind project". Wind Turbine Reliability Workshop Albuquerque, NM USA, 2009.

[2] Mauro Ciappa, "Selected failure mechanisms of modern power modules" Microelectronics Reliability 42, pp. 653–667, April-May 2002

[3] M. Bartram, J von Bloh, and Rik W. De Doncker, "Doubly-fed-machines in wind-turbine systems: Is this application limiting the lifetime of igbt frequency-converters?", Proc. Power electronics specialists conference 35, Aachen, pp. 2583–2587, 2004

[4] M. Held, P. Jacob, G. Nicoletti, P. Scacco, and M Poech, Fast power cycling test of igbt modules in traction application", Proc. International Conference on Power Electronics and Drive Systems, pages 425–430, 1997

[5] U.Scheuermann and U.Hecht, "Power cycling lifetime of advanced power modules for different temperature swings", PCIM Nürnberg, pages 59–64, 2002

[6] Uwe Scheuermann. "Module packages and reliability." The 21st International Symposium on Power Semiconductor Devices and ICs, 2009. Short Course Presentation.

[7] Raed A. Amro. "Packaging and interconnection technologies of power devices, challenges and future trends." World Academy of Science, Engineering and Technology 49, pp. 691–694, 2009.

[8] J. Due, S. Munk-Nielsen, R. Nielsen, "Lifetime investigation of High Power IGBT modules", Proc. EPE, Birmingham, September 2011.