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On Modern IGBT Modules: Characterization, Reliability and Failure Mechanisms

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Master of Science in Electric Power Engineering
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Problem Description

Description: Power systems containing a high percentage of power electronics loads are known to be complex systems with a lot of uncertainties concerning worst case electrical and thermal stress applied to the individual components, and the component ability to survive specific stress conditions. For remote and inaccessible power electronic conversion systems, like offshore wind applications and subsea oil and gas applications, the reliability issues are of still more concern than for traditional industrial applications. That is why power electronics reliability issues have high priority in two R&D projects at SINTEF Energy Research.

The ability of verifying new design ideas and reducing the demand of laboratory testing, which might be time-consuming and cumbersome, is one salient feature of power electronic converters prototyping using device model. Moreover, better understanding of devices behaviour and related physical phenomena can be gained while developing such a model. Devices based on new emerging materials like SiC and GaN are expected to have better performance. However, being a new technology devices characteristics and behaviour need more investigation. Knowledge about the reliability of these devices is still immature which increase the need to have a model where devices behaviour and stresses can de studied in depth.

In the proposed topic the candidate will be guided by the project team at SINTEF. The candidate will get both theoretical (e.g. literature study) and practical (laboratory work) tasks within one or more of the following subjects:

  General fault mechanisms for power semiconductors
  Fault mechanisms related to type of device, but with special focus on IGBTs
  Fault mechanisms related encapsulation (e.g. press-pack devices, modules etc)
  Fault mechanisms related to materials, and especially new materials like SiC
  Application specific reliability, and especially related to driver characteristics
  Influence from pressure and temperature
  Physics-based modelling for SiC devices
  Combined electro-thermal modelling for reliability studies

The candidate may be offered a summer job at SINTEF Energy Research related to ongoing research projects within this field.

A cluster has applied for an EU project in applications of SiC devices in MW converters for wind energy integration. Parts of this project may be included.

Assignment given: 01. February 2010
Supervisor: Tore Marvin Undeland, ELKRAFT

Faculty of Information Technology, Mathematics and Electrical Engineering

Department of Electric Power Engineering

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On Modern IGBT Modules: Characterization, Reliability and Failure Mechanisms

Master Thesis

By

Di Xiao

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Content

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Foreword

This is a report for the master project in the 2nd year of International Master Degree Program of the department of Electric Power Engineering at NTNU. The project has a weight of 30 ECTS credits.

'Reliable Power Electronics Converters for Offshore Wind Turbines and Subsea Oil Development' is the subject of this project which is a part of an ongoing research launched by SINTEF Energy Research.

As the continue work of summer job and semester project, this thesis investigates switching characteristics and losses of commercially available IGBT modules to be used for this application. It focuses on switching time and switching energy losses depending on gate resistances, current and voltage levels, operation temperatures, and show differences between several devices of the same type. Some tests also show how device dynamic characteristics and energy losses change when the device has been exposed to stress over some time as well as the long-term stability.

I would like to take this opportunity to thank every people who have helped me during this work. Without your help, I could not have accomplished this much. I would like to thank my supervisor Prof. Tore Undeland, co-supervisors Dr. Astrid Petterteig and Ibrahim Abuishmais, and Riccardo Pittini who tireless support throughout the project and thesis. I would like to thank Mr. Heng Xiao and Ms. Meng Wang for their constructive comments which were useful in refining the thesis finally produced. I also want to thank Kjell Ljøkelsøy and Magnar Hernes at SINTEF Energy Research, Trondheim.

I am solely responsible for any errors or shortcomings.

Trondheim, 28.06.2010

Di Xiao

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Abstract

The increased demand of offshore power conversion systems is driven by newly initiated offshore projects for wind farms and oil production. Because of long distances to shore and inaccessibility of the equipment long repair times must be expected. At the same time the offshore environment is extremely harsh. Thus, high reliability is required for the converters and it is important to have good knowledge of the switching devices. This thesis investigates switching characteristics and losses of commercially available IGBT modules to be used for this application. It focuses on switching time and switching energy losses depending on gate resistance, current and voltage levels, operation temperatures, and show differences between several devices of the same type. Some test show how device characteristics and losses when the device has been exposed to stress over a certain period.

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1. Introduction

Power systems containing a high percentage of power electronics loads are known to be complex systems with a lot of uncertainties concerning worst case electrical and thermal stress applied to the individual components, and the component ability to survive specific stress conditions. For remote and inaccessible power electronic conversion systems, like offshore wind applications and subsea oil and gas applications, the reliability issues are of still more concern than for traditional industrial applications.

Insulated Gate Bipolar Transistor (IGBT) is becoming more and more important power electronic device in different industrial field because of the advantage of shorter switching time and lower power loss [1-3]. Understanding device fault mechanisms and assessing its lifetime along with other reliability issues of IGBT modules are very important to understand device limits, and thus optimizing converter design later. This thesis first briefly descried the structure and operation principle of traditional IGBT, compared the difference between BJT and MOSFET, elaborate the turn-on and turn-off process of IGBT, as well as the freewheeling diode performance in IGBT module at chapter 2. Employing new semiconductor structure to increase the safe operating area (SOA) and improve the stability has attracted much attention. The chapter 3, thus, investigated the state-of-the-art of modern IGBT and the new emerging material SiC which is expected to have better performance.

New developed press-pack IGBT can effectively reduce common faults on traditional IGBT module, but the failure mechanisms of press-pack IGBT did not receive much attention. As the traditional bond-wire IGBT module is still the most popular product for industrial application, investigating the failure mechanisms is still very meaningful. Therefore, common failure mechanisms and the countermeasures were summarized at chapter 4, which paved way for the further experimental research. International standard parameter definitions based on IEC 60747-9 international standard, and the standard testing methods were introduced at chapter 5. Those

standards are very important for verification and duplication of the experiments.

Three important experiments were designed and built up to investigate the dynamic characteristics and long-term stability of commercial IGBT modules. Thus chapter 5 also introduced the principles and aims of the experiments theoretically based on the international and industrial standard, and chapter 6 described the build-up processes and operation method of the measurement setups as well as some important tips for mounting the modules, and improving the accuracy of measurements. Finally, chapter 7 analyzed the experimental results, and chapter 8 summarized the thesis and drew some ideas for further research.

2. IGBT Overview

The IGBT represents the most commercially advanced device of a new family of power semiconductor devices combining high-input impedance MOS-gate control with low forward-voltage drop bipolar current conduction [1]. At this chapter, the author briefly introduced the basic structure, operation principles and switching behaviors of IGBT as well as the performance of freewheeling diode (FWD).
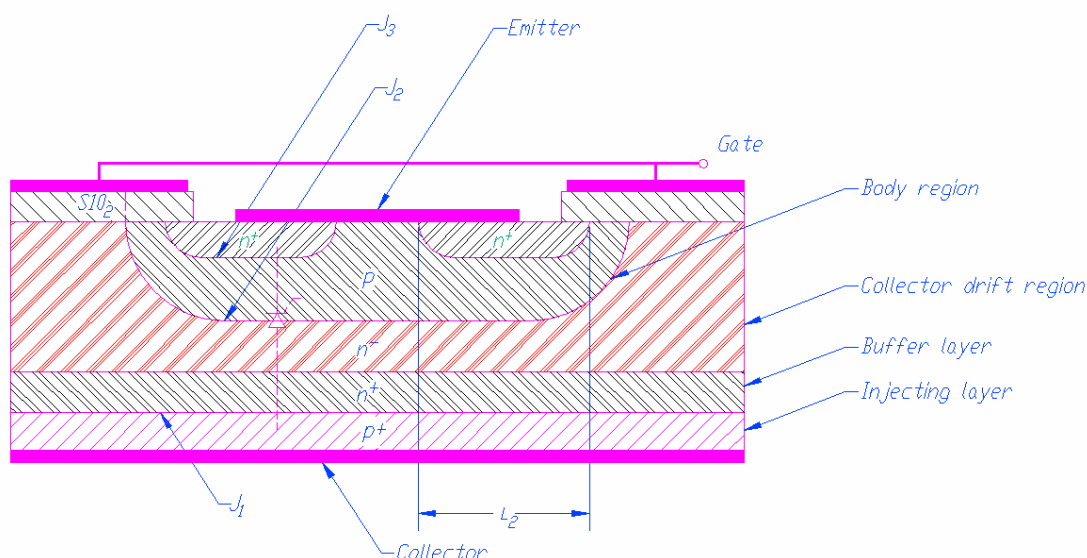
2.1 Operation Principle

Fig. 1 Sketch of IGBT cross section [4]

IGBT is a byproduct of MOSFET technology which can be self-prove by their structures [1-3]. The only difference is the n-type doped area of drain at MOSFET was replaced by p-layer at IGBT. The structure of (PT-) IGBT as shown in Fig. 1, and the n+ buffer layer is not necessary for NPT- IGBT [5]. The equivalent circuit of the IGBT structure is shown in Fig. 2 which shows the main structure cell: a MOSFET, a BJT and a parasitic thyristor. The interaction of MOSFET and BJT made the IGBT has a better performance than MOSFET and BJT device, and the advantages are summed up in Table 1 [1-3, 6]. However the parasitic thyristor is undesired because it

will destroy IGBT if conducted and this phenomenon is called latch-up.

The equivalent circuit of parasitic capacitance which is important to explain the turn-on and turn-off transition and IGBT symbol as shown in Fig. 3. Based on Fig. 2, the operation principle of IGBT can be explained like that: when Gate-Emitter voltage (V_{GE}) excess the gate threshold voltage (V_{th}) of MOSFET which leading electrons flow from emitter to drift region. This electrons current is the base-current of PNP-transistor (T_1). The emitter of T_1 will inject holes into drift region and most of them will recombination with electrons (injected form MOS channel) because of the larger width of drift region. The remaining holes will diffuse to J2 junction (Collector of PNP transistor) because of the slight reverse-bias of J2, and holes captured by electric field and moved into collector region. So far one should also notice that the IGBT terminal labels are confusing because the IGBT can be used as NPN-BJT but the internal structure is PNP-BJT on the contrary. In addition, the JFET effect often mentioned in many technical papers, but in fact, it does not occur at IGBT [2]. The output current-voltage characteristics of IGBT as shown in Fig. 4
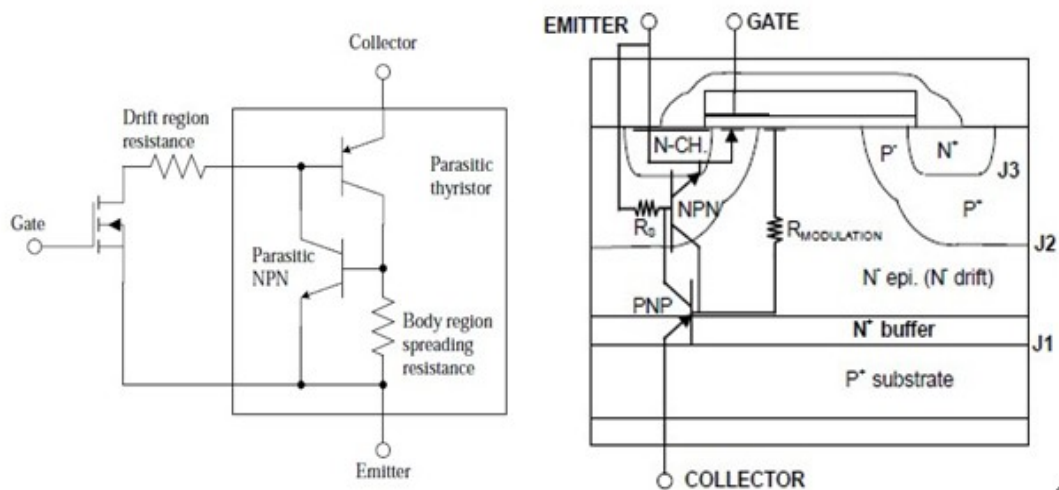

Fig. 2   Equivalent circuit for the IGBT and a cross-section of the IGBT structure (PT & N-Channel)
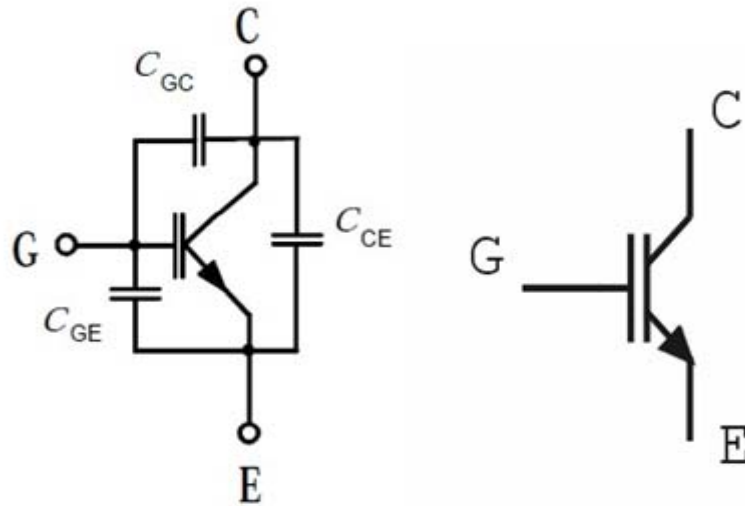
Fig. 3 IGBT Equivalent circuit showing parasitic capacitance (a) and symbol (b) [7]
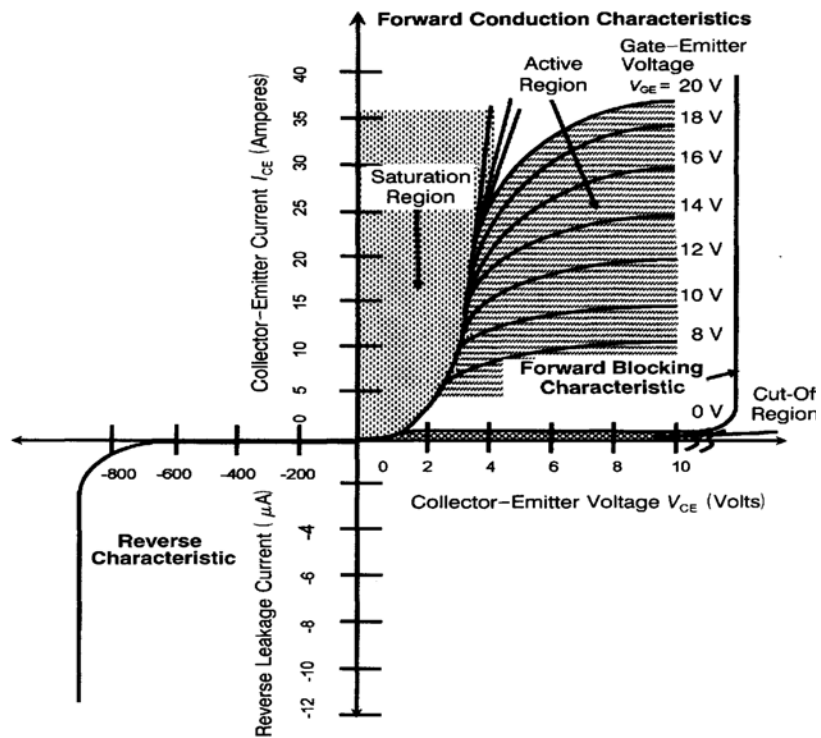

Fig. 4 Output current-voltage characteristic of IGBT [1]

Table 1 The IGBT characteristics vs. BJT & MOSFET

Features	BJT	MOSFET	IGBT
Drive Method	Current	Voltage	Voltage
Drive Circuit	Complex	Simple	Simple
Input impedance	Low	High	High
Drive Power	High	Low	Low
Switching Speed	Slow (µs)	Fast (ns)	Moderate
Operating frequency	Low(<100 kHz)	Wide (>200 kHz)	Moderate
S.O.A	Narrow	Wide	Wide
Saturation Voltage	Low	High	Low

2.2 IGBT Turn-on and Turn-off

The IGBT turn-on is controlled by voltage rather than current, but the speed of turn-on increase with the magnitude of gate current. To turn on the IGBT, The input capacitance between gate and emitter is charged to a voltage (V_{GE}) greater than the threshold voltage (V_{th}). During turn-off the IGBT, the gate-emitter resistance (R_{GE}) provides a path for the input gate-to-emitter capacitance to discharge. The R_{GE} can alter the IGBT turn-off time and so it is under the control of circuit designer. IGBT usually works as a switcher with a resistive load or an inductive load. In the forward testing the IGBT was working with an inductive load, consequently, the theoretical switching behavior of IGBT will based on the case of inductive load which is shown in Fig. 5.
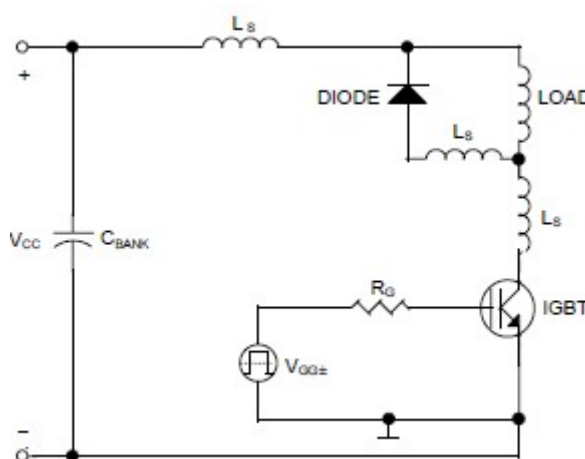

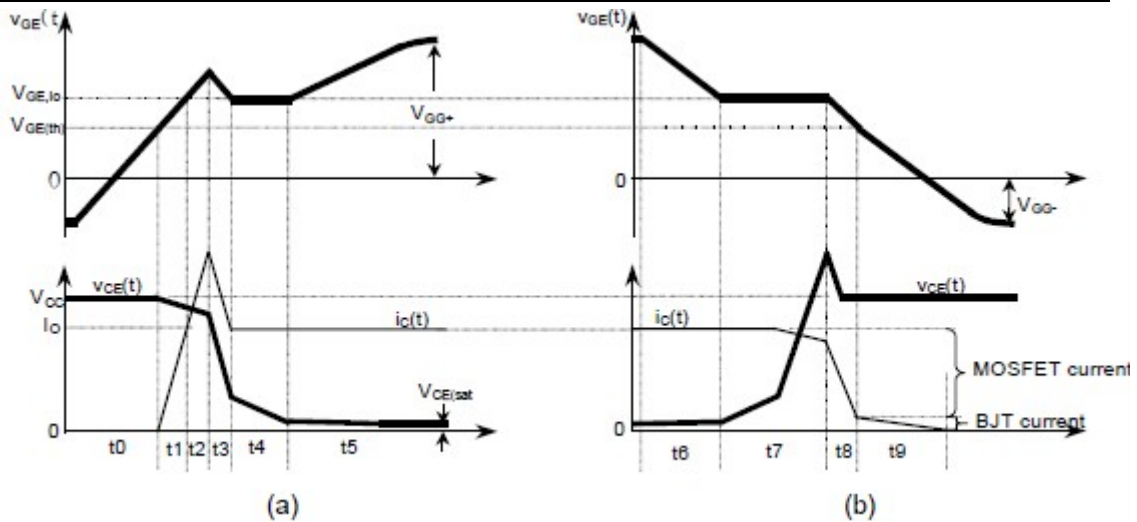Fig. 5 Diode-clamped inductive load circuit [4]

Fig. 6 The waveforms of IGBT turn-on (a) and turn-off (b) process [8]

The waveforms of gate voltage (V_G), Collector-Emitter (V_{CE}) voltage and collector current (I_C) at the IGBT turn-on process as shown in Fig. 6 (a) and at the IGBT turn-off process as shown in Fig. 6 (b). This process can be sum up as following steps [2-3, 9]:

(1) t_0 section: V_G rises to $V_{G(th)}$ while I_G charges the parasitic input capacitance C_{GE} and C_{GC}. The V_{CE} increase pattern is shown to be linear, but it is actually an exponential curve with time $R_G(C_{GE}+C_{GE, miller})$. The V_{CE} is maintained at the V_{CC} value, and I_G remains at zero and most of the turn-on delay falls under this section.

(2) t_1 section: C_{GE} continues to increase exponentially passes $V_{G(th)}$. As V_G increases, I_C begins to increase to reach the full load current (I_0). In the t_1 and t_2 section, V_{CE} appears to be shaved off than V_{CC}. This is due to the inductive voltage ($V_{L_\sigma} = L_\sigma \cdot di_c / dt$) which produced by stray inductor (L_σ).

(3) t_2, t_3 sections: The reverse recovery current of the freewheeling diode is added to i_c caused the overshoot. Meanwhile, the FWD reverses recovery voltage increases, and V_{CE} decreases. It is worth to mention that the decrease speed of V_{CE} depend on C_{GC} and C_{GC} also is the function of V_{CE}. That is why dV_{CE} / dt is large at t_2 section.

Reverse recovery process of the diode stops at the end of t_3 section.

(4) t_4 section: C_{GC} charging, V_{GE} maintains V_{GE,I_0}, and i_c maintains I_o. The V_{CE} falls at a rate of $(V_{CG} - V_{GE,I_0})/(R_G C_{GC})$. Low V_{GE} value caused a large C_{GC} value and this slow discharging produce the voltage tail.

(5) t_5 section: V_{GE} increases exponentially to V_{GG+} with a time constant $R_G(C_{GE} + C_{GC,miller})$ where $C_{GC,miller}$ is C_{GC} that rose form low V_{CE} value due to the Miller Effect. V_{CE} decreases to on-state voltage and becomes fully saturated. This is because the IGBT (PNP) transistor portion is slower than the MOSFET portion in crossing the active region to reach on-state as well as the effect from $C_{GC,miller}$

(6) t_6 section: This is turn-off delay time section. V_{GE} falls from V_{GG+} to V_{GE,I_0} with the same time constant as the (5).

(7) t_7 section: V_{CE} increases at the rate of $\dfrac{dV_{CE}}{dt} = \dfrac{V_{GE,I_0}}{C_{res} \cdot R_G}$ which can be controlled with R_G.

(8) t_8 section: V_{CE} maintains the value of V_{CC}, and i_c decreases at the rate of $\dfrac{di_c}{dt} = g_{fs} \cdot \dfrac{V_{GE,I_0}}{C_{IES} \cdot R_G}$ which also be controlled with R_G. There is an over-voltage $V_{L_\sigma} = L_\sigma \cdot di_c / dt$ due to stray inductance, added to V_{CE} in t_7 and t_8 sections The MOSFET current disappears at t_8, which is the first of the two sections where i_c decreases.

(9) t_9 section: Turn off the PNP transistor (BJT), as shown in Fig. 1, and tail current i_c disappears. It takes place due to the recombination of the minority carrier (hole), which has been injected into the N- drift region during the on-state. Due to the existence of this region, the switching characteristics of IGBT are inferior to that of power MOSFET.

2.3　FWD Performance

The FWD is primarily used to conduct the load current during IGBT turn-off. It must be noticed that in hard switching, turn-on losses increase as the recovery current rises and recovery time is prolonged. To minimized the turn-on losses and withstand surge voltage, as diode having fast, soft recovery characteristic is desirable. The diode with a snappy reverse characteristic and hence high recovery di/dt is problematic with transient voltage. Therefore, the turn-off current should be diverted through the FDW. When the IGBT is off, the current is carried by the FWD, and due to the conduction of FWD, the voltage across the load terminal is zero. The performance of snappy diode and fast diode is shown in Fig. 7 . To improve the FWD performance, three important design techniques are often used: (1) emitter efficiency control, (2) axial lifetime killing, and (3) deep diffusion control. More information related to those technique can refer to [1, 10-14], and some failure mechanisms related to the FWD will be introduced at chapter 4, more details has given at the summer job report [15].
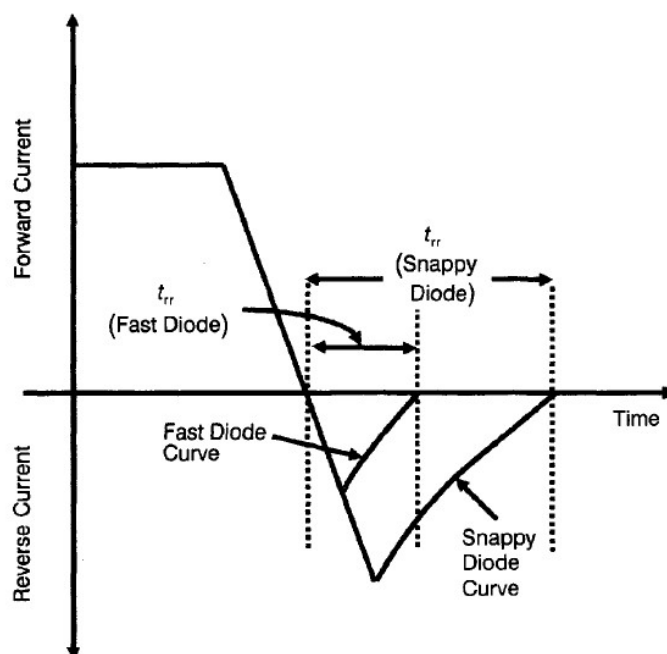
Fig. 7 Reverse recovery waveforms of snappy and fast diodes[1]

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3. State-of-the-art Technology of IGBT Module

With the development of new technique, more and more new IGBT concepts appeared. The performance also greatly improved. Present IGBT modules are divided into two categories: (a) the conventional module package derived form low-power technology and (b) the new press-pack IGBT based on the classical high-power diode or thyristor technology [1]. This chapter would briefly compare some of the new IGBT concepts like SPT-, FS- and SPT+- IGBT which developed by ABB^{TM} with the traditional IGBT concepts like PT-, NPT- IGBT. The difference between Planar- and Trench- IGBT technology [16-18], the advantages of press-pack IGBT module [19-23], and the application of promising semiconductor material SiC [24-29] also covered at this chapter.

3.1   Planar- vs. Trench- IGBT

The IGBT's gate structure has an important influence on its performance. Iwamoto H., et al. in [30] have evaluated and compared the performance of Planar- and Trench- IGBT under hard- and soft- switching found that trench- IGBT maintains clear advantages: (1) Enhanced electron injection effect, (2) Reduced channel resistance i.e. improved conduction [31], (3) One dimension current flow, (4) No parasitic JFET which can avoid the current crowding occurs, (5) Reduced latch-up effect because the n+ source regions can be make smaller as they are self aligned to the trench, and (6) Better gate contact because the poly-silicon thickness is greater than in the planar case and the reduced gate resistance means the turn-on can be faster. However, a new developed planar- IGBT by ABB^{TM} seems challenged this fact [32] . The planar- and trench- IGBT structure are shown in Fig. 8. More details can be found at the semester project report [33].
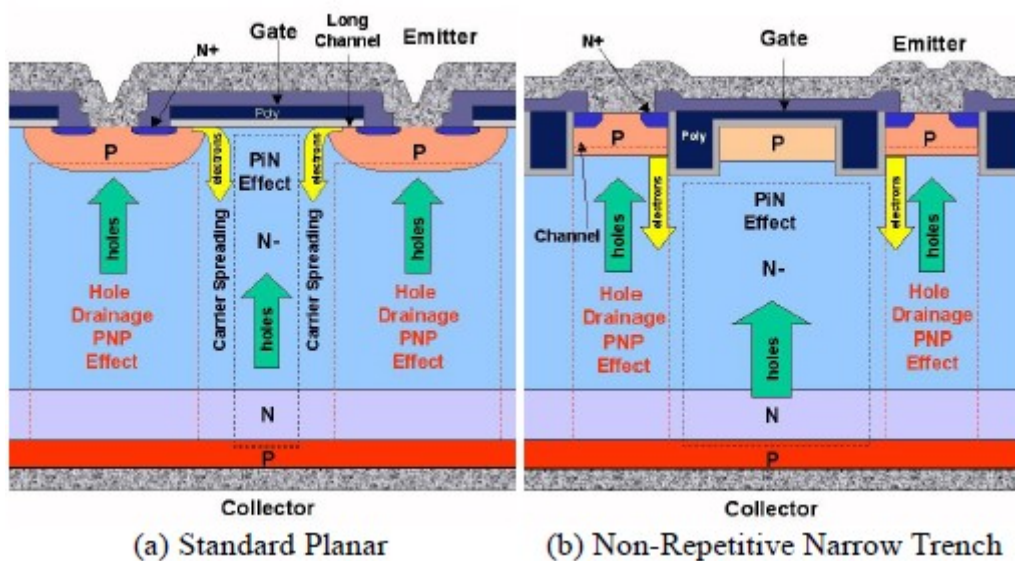
Fig. 8 Planar- (a) and Trench- (b) structures of IGBT [32]

3.2 PT-, NPT-, FS-, vs. SPT- IGBT

The traditional PT- as shown in Fig. 9.a , and NPT- IGBT as shown in Fig. 9.b concept has introduce at [3, 33], thus will not pleonastic cover at here. Several manufactures like ABB[TM], Semikron[TM], and Westcode[TM] have developed technologies which located between PT and NPT like FS-, and SPT- IGBT. The FS-technology is based on NPT technology. The field stop zone is injected on the shallow p-emitter as shown in Fig. 9.c, and the SPT-technology basically consists of a low-doped n-base and SPT [16-17, 19, 32, 34-36] n-buffer as shown in Fig. 9.d, and makes the switching behavior of normal PT devices softer. In other words, di/dt during switching (especially turnoff) becomes lower than that of a PT device. Anyway, FS- and SPT- IGBT more or less have the same structure and performance; Udrea F. [37] has investigate the new technology elaborately.
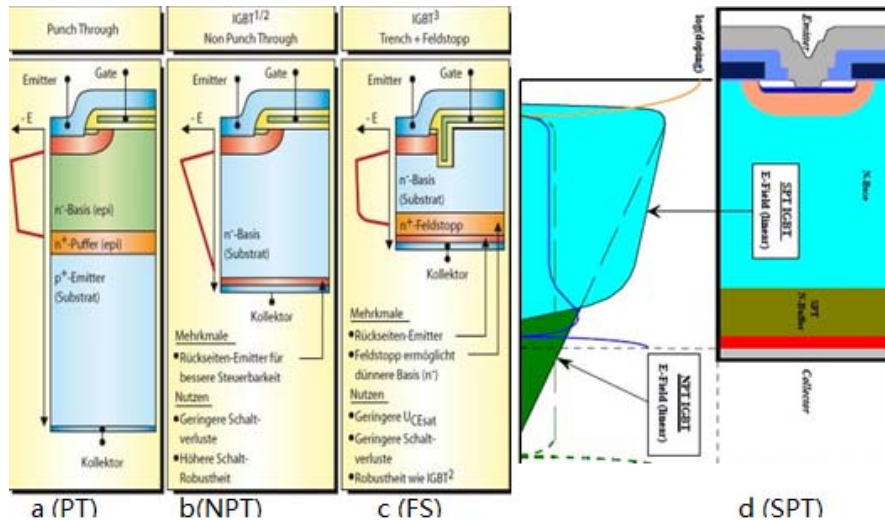
Fig. 9 Chip structure of different IGBT technologies and field distribution [34, 36]

3.3 SPT$^+$ IGBT

The newly developed SPT$^+$ IGBT from ABB^{TM} [16-17, 32, 34] offers significantly lower on-state losses while still maintaining low turn-off losses, and achieve extreme ruggedness during switching and under short circuit conditions and offers the same low EMI levels as for the current SPT platform. Fig. 10 shows a cross-section of the SPT$^+$ diode. The new technology utilizes a double local lifetime-control technique to optimize the shape of the stored electron-hole plasma. Due to the improved plasma distribution, the overall energy losses could be reduced, while maintaining the soft recovery characteristics of the standard SPT diode technology.
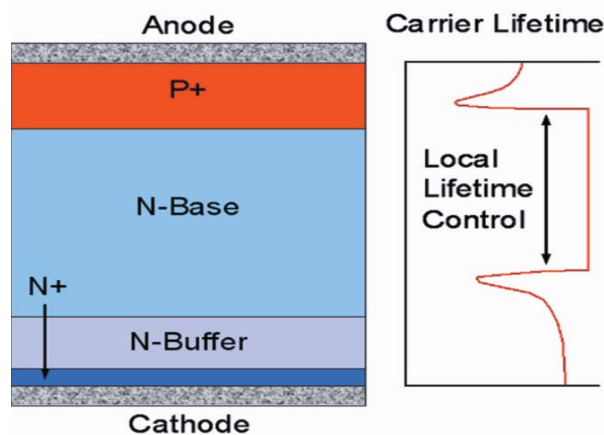
Fig. 10 SPT$^+$ diode technology [16]

3.4   Press-Pack IGBT Module vs. Standard IGBT Module

Press-pack encapsulation IGBT offers several advantages over the traditional wire bond package, as point out in Table 2. For press-pack IGBT, the electrical contact is established by pressing the IGBT chips between two high-planarity conducting disks as shown in Fig. 11. An adequate stress relief layer is included to forebear the compression. The chips are housed in a compact both-side cooled hermetic, square flat-packaged ceramic structure is pressure contacts. Low inductance is achieved inside the package because of the absence of Al wire bonding. For compactness, the unused area in the assembly is minimized [1].
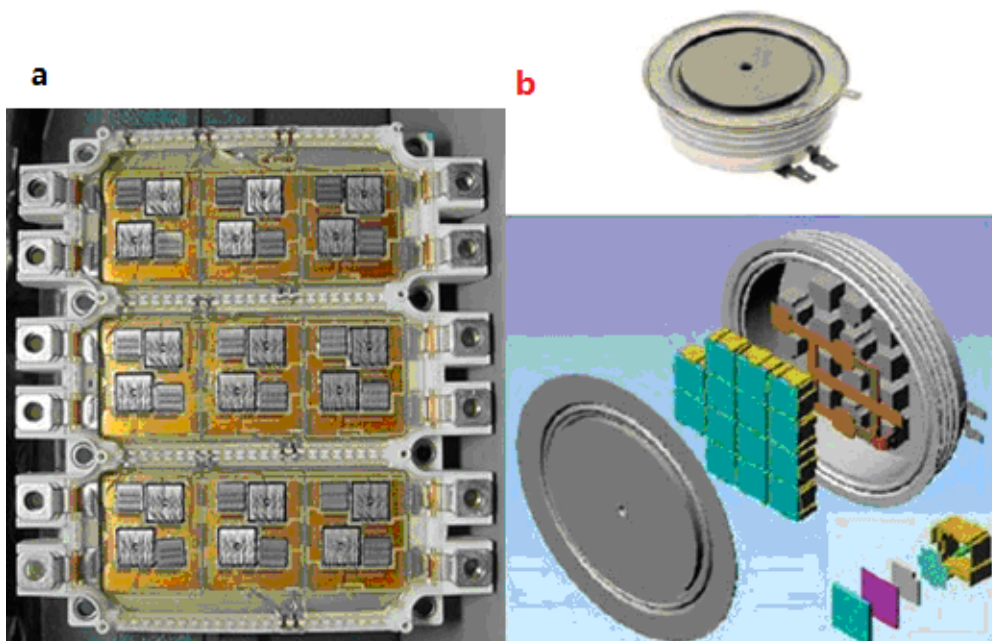
Fig. 11 Bond Package IGBT (a) and Press-pack IGBT (b) (Internet)

Table 2 Comparison of bond pack with press-pack IGBT module [1]

Bond Package	Press-pack Package
High inductance	Low inductance
For good bonded joints, the wire should be small in diameter. The thin wire is also unable to conduct the heat away. So, the wire introduces significant electrical and thermal resistance.	Absence of wires overcomes this limitation
Nonhermetic and one-side cooling structure	Hermetic and both-side cooling structure
The base plate is completely isolated making the cooling simple and lowering the cost	Insulation of the IGBT and cooling are necessary, increasing the cost
Poor power cycling capability	Superior power cycling ability
Possibility of explosion during failure	Explosions are avoided
Less reliable	More reliable

3.5   SiC Overview

Silicon Carbide (SiC) has many favorable properties making it interesting for high temperature, high frequency and high-power applications. More specifically,

these properties are: wide band gap, high thermal conductivity (better than for example, copper at room temperature), high breakdown electric field strength (approximately 10 times that of Si), one magnitude order higher saturation drift velocity than Si and high thermal stability and chemical inertness [38]. While the smaller on-resistance and faster switching of SiC helps minimize energy loss and heat generation. The higher thermal conductivity of SiC enables more efficient removal of waste heat energy from the active device. Because heat energy radiation efficiency increases greatly with increasing temperature difference between the device and the cooling ambient, operating SiC at high junction temperatures permits much more efficient cooling to take place, so that heat sinks and other device-cooling hardware (i.e., fan cooling, liquid cooling, air conditioning, etc.) typically needed to keep high power devices from overheating can be made much smaller or even eliminated [39-40].

A. SiC Diodes

Power diodes made with SiC are expected to show great performance advantage as compared to those made with other semiconductors. A high breakdown electric field allows the design of SiC power diodes with thinner and higher voltage blocking layers. The 4H polytypic of SiC diode is particularly suited for vertical power devices because of higher radiation hardness. The thermal conductivity of SiC is about three times higher than Si. The PiN diodes made using conventional semiconductor materials are restricted to less than 50 kHz and 125 $^\circ$C. The main features of 4H-SiC PiN diodes are: (1) a voltage drop in the on state comparable to stacked Si diodes at sufficiently high current densities; (2) switching speeds that are at least 30 times faster than any of their Si counterparts because of the use of thinner epitaxial layer; and (3) good high-temperature operating characteristics [27]. SiC Schottky diode, the commercial available power device, has achieved great progress those years and the advantages compare to Si PiN diode is shown in Table 3

Table 3 expect performance for high voltage SiC Schottky diode and Si PiN diode[41]

Static Characteristics	SiC Schottky Diode	Si PiN diode
On state Voltage @ 25 $^{\circ}$C	1 V @ 250 A/cm^2	2 V @ 100 A/cm^2
Temperature coefficient	+Ve	+Ve or –Ve
Leakage current @ 125 $^{\circ}$C	10 mA/cm^2	0.5 mA/cm^2
Max Junction Temp.	250 $^{\circ}$C	150 $^{\circ}$C
Dynamic Characteristics	SiC Schottky Diode	Si PIN diode
Reverse Recovery loss	Small capacitive effect	High
IGBT switching losses	Low	High
EMI	Low	High@ high di/dt
Stray inductance dependence	Low	High
Forward current dependence	Low	High
Temperature Dependence	None	High
Dynamic avalanching	None	Yes at high di/dt
Snappy recovery	None	Yes at high di/dt

B. SiC- IGBT

The availability of SiC IGBT will be delayed because of technical problems, i.e. function density limited and high cost, as previously described by Brown [42]. However some testing has shown that replace the FWD by SiC Schottky diode can greatly improve the IGBT module performance. In addition to providing low switching losses, low voltage and current stress; SiC devices can operate at much higher temperatures. The low switching losses and reverse recovery current will allow power converters to operate with high efficiency and low EMI [43]. Simulation experiment results by J. Wang and BW. Williams [29] also shows that 4H-SiC IGBT exhibit lower on-state voltages at typical operating current and slightly higher on-state voltage at higher current level [29, 41]. This reduces the on-state power losses at typical operating current and ensures current sharing between parallel connected IGBTs [1, 28-29].

C. Si-SiC inverter and Full-SiC inverter

Although there is no SiC inverter commercially available now, there are some experiments have proved the advantages of SiC inverters. Schafmeister F. [44] has evaluated the performance of SiC-JFET three-phase inverter shows that SiC JFET inverters have relatively high efficiency at all powers, switching frequency, and temperature ranges. Compared to Si inverters, the advantage is more obvious at high frequency and high temperature. Motion control, solar energy, wind generation, and vehicle systems might benefit from these SiC inverters in the near future [45]. Replacing Si PiN diodes with their SiC Schottky diode counterparts will decrease the losses of an inverter considerably because the high reverse-recovery losses of Si PiN diodes are negligible at SiC Schottky diodes [45-46]. Thus full-SiC inverter will be an attractive field to explore for researchers and industry applications.

4. Failure Mechanisms Summary

Failure mechanisms are physical, chemical, or other processes resulting into a failure. For practical purposes they can be divided in two categories. The first includes mechanisms which result from poorly controlled or poorly designed manufacturing processes. The second category includes those failures, which occur during the normal operation of the device [47-48]. As there is no any literature study involved in the press-pack IGBT (already commercially available), this chapter will just summarize the main failure mechanisms of wire bond IGBT but not cover too much details because those faults and related countermeasures have been discussed in the summer job report [15] and semester project report [33].

4.1 Package-related Failure Mechanisms

Multichip modules for high-power IGBT devices are complex multilayered structures consisting of different materials, which have to provide a good mechanical stability, good electrical insulation properties, and good thermal conduction capabilities. The IGBT and diode chips are soldered on AlN or Al_2O_3 ceramic substrates (Direct Copper Bonding or Active Metal Braze technologies), which provide high voltage insulation. The substrates are then soldered to a copper or AlSiC base plate, acting as a mechanical support and providing a thermal interface to the cooler. The modules are encapsulated in plastic housings and filled with Silicone gel. The crosses section as shown in Fig. 12 and Fig. 13 [47, 49-51].
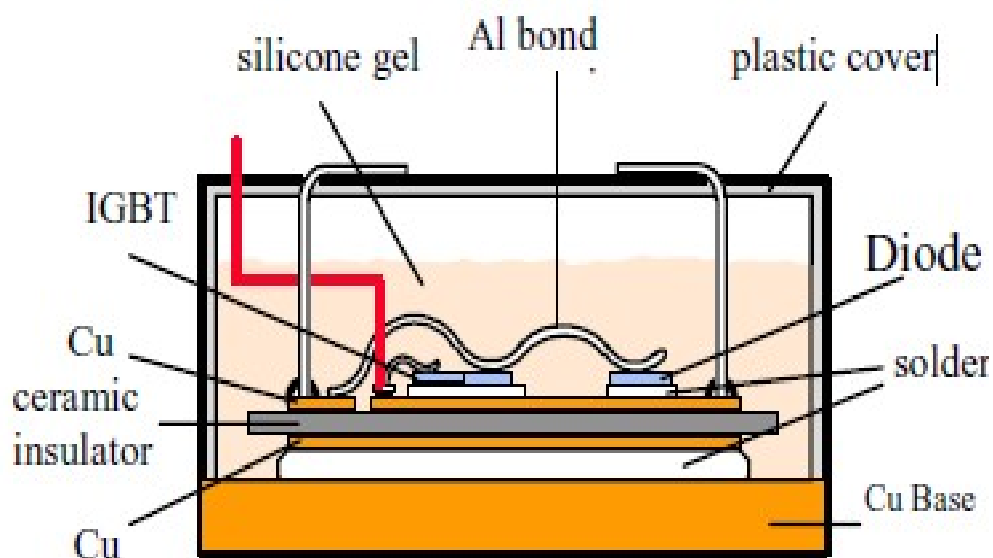
Fig. 12 Cross sectional of a classical IGBT module [48]

Fig. 13 IXYS IGBT inside (without gel)

Due to the different thermal expansion coefficient (CTE) between different materials, wire bonds lift off as shown in Fig. 14 is the most common fault, the mismatch CTE between ceramic and the base-plate also cause the solder interface fatigue as shown in Fig. 15. The faults like fatigue and creep interaction of power terminals as shown in Fig. 16 a, gel related faults [52-53], partial discharge as shown in Fig. 16 b and interconnection corrosion as shown in Fig. 17 are also very common at stressful environment or testing conditions like thermal cycling.
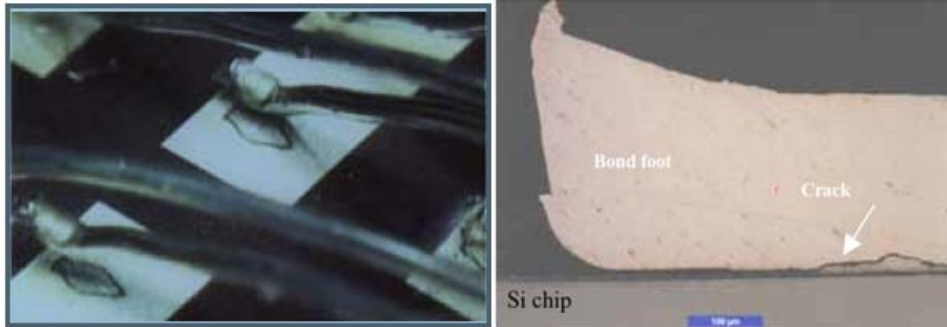
Fig. 14 Wire bonds lift-off (a) and wire bond after a crack has propagated under the bond foot (b) [47]
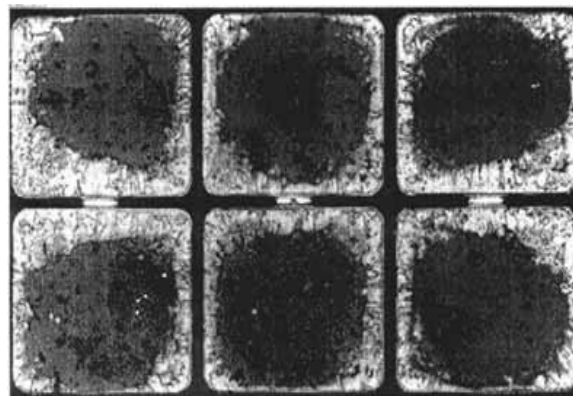
Fig. 15 Delimitation of the solder (white areas) due to thermal fatigue [47]
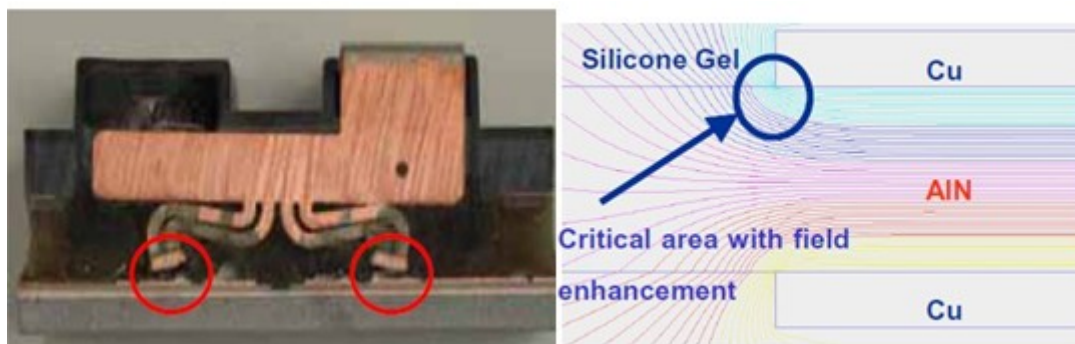
Fig. 16 a. Pull-out of the terminal feet on the ceramic substrate b. E-field simulation of AlN substrate [47]
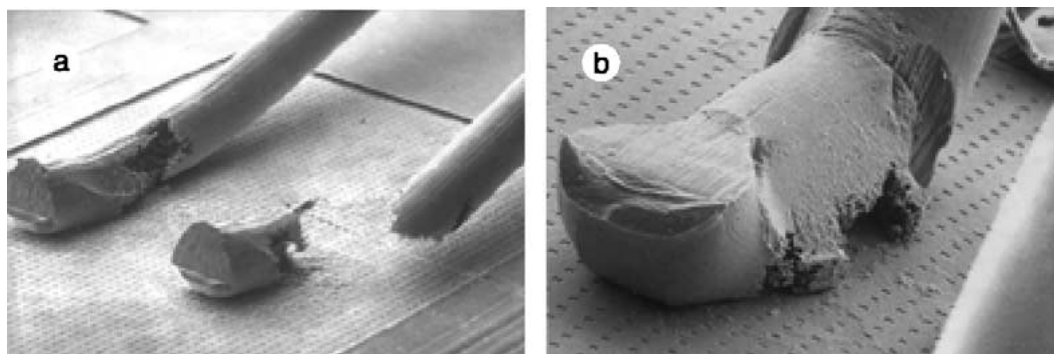
Fig. 17 Rupture of emitter bond wire due to stress corrosion (a), Enlarged picture (b) [52]

4.2 Failure Mechanisms during Application

Fault operation or under stressful operation condition can result in faults. Faults caused by short circuit or switching under clamped inductive is very common in real application, the semester project report [33] and summer job report [15] have discussed them deeply. Dynamic avalanche occurs on IGBT [54] and/or FWD [55-56] also can destroy IGBT module if it out of control. In addition, faults caused by cosmic ray and irradiation are not just very important especially in the outer space applications, but also in deep ocean, high temperature, and high power applications. The factor is shown in following formula. However, it did not received enough attention [57].

$$\lambda(V_{DC}, T_{Vj}, h) = C_3 \cdot \exp(\frac{C_2}{C_1 - V_{DC}}) \cdot \exp(\frac{25 - T_{Vj}}{47.6}) \cdot \left(\frac{1 - (1 - \frac{h}{44300})^{5.26}}{0.143} \right)$$

5. Experimental Standards and Principles

This chapter will focus on the important parameter definitions according to the IEC 60747-9 International Standard [7], and the industrial standard measurement methods which were used in this project. Three different testing principles, that is double pulse switch testing, repetitive switch testing, and power cycling testing, were introduced in this chapter.

5.1 Parameter Definitions

The parameters used at the report and measurement were refer to the IEC 60747-9 standard. The definition of turn-on time is the time between gate voltage reaches 10 % of its nominal value and the collector current rise up to 90 % of its desired value. That includes the delay time and rise time. While turn-off time is the time interval between gate voltage decrease to 90 % and the collector current fall down to 10 %. This is also includes turn-off delay time and fall time. Both of the definitions are base on the IEC 60747-9 standard [7]. Some important parameters for this project such as switching time, switching power loss as shown in Table 4, and Fig. 18 and Fig. 19 make it straight. and the full list can refer to [7]. As the power and energy can not be obtained directly form the scope, but the power can be calculated by

$$P = V(t) \times I(t) \tag{1}$$

And the turn-on (turn-off) energy is the energy dissipated inside the IGBT during the turn-on (turn-off) of a single collector current pulse which can be calculated by

$$E_{on} = \int_{t_{on}} V(t) \times I(t)\, dt \tag{2.1}$$

and

$$E_{off} = \int_{t_{off}} V(t) \times I(t)\, dt + \int_{t_z} P_{tail}\, dt \tag{2.2}$$
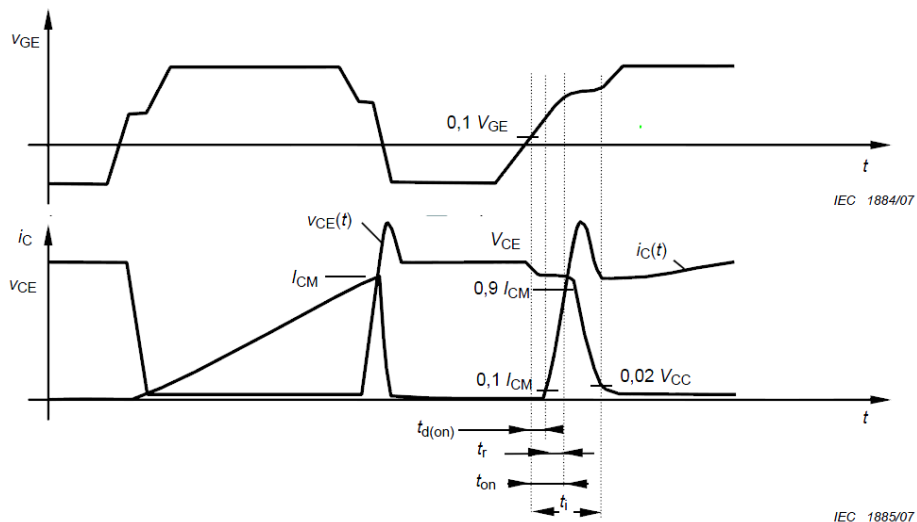
Fig. 18 Waveforms during turn-on times [7]
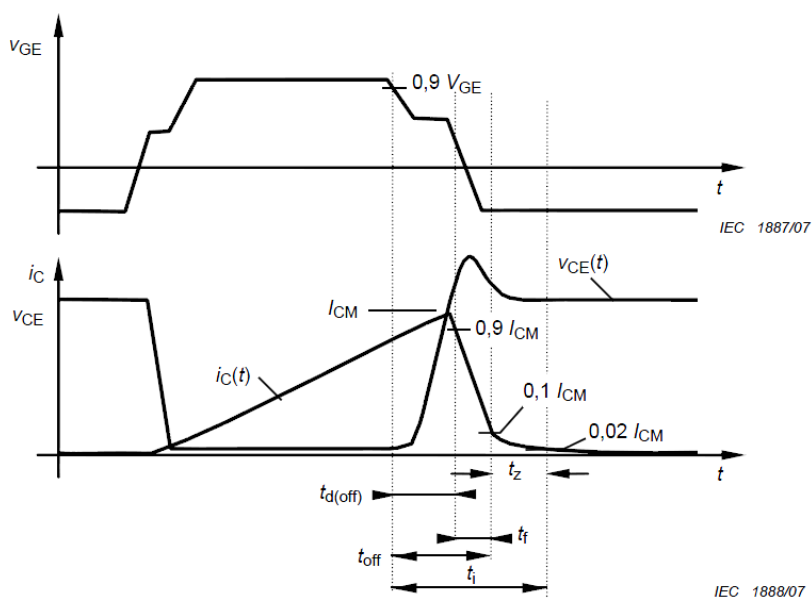
Fig. 19 Waveforms during turn-off times [7]

Table 4: Important Parameters Definition

Term	Abbr.	Definition
Turn-on delay time	t_d	time interval between the beginning of a voltage pulse across the input terminals which switches the IGBT from the off-state to the on-state and the beginning of the rise of the collector current
Rise time	t_r	time interval between the instants at which the rise of the collector current reaches specified lower and upper limits, respectively, when the IGBT is being switched from the off-state to the on-state
Turn-on time	t_{on}	sum of the turn-on delay time and the rise time
Turn-off delay time	t_s	time interval between the end of the voltage pulse across the input terminals which has held the IGBT in its on-state and the beginning of the fall of the collector current when the IGBT is switched from the on-state to the off-state
Fall time	t_f	time interval between the instants at which the fall of the collector current reaches specified upper and lower limits, respectively, when the IGBT is switched from the on-state to the off-state
Turn-off time	t_{off}	sum of the turn-off delay time and the fall time
Tail time	t_z	time interval from the end of the turn-off time to the instant at which the collector current has fallen to 2 % or lower specified value
Turn-on energy	E_{on}	energy dissipated inside the IGBT during the turn-on of a single collector current pulse
Turn-off energy	E_{off}	energy dissipated inside the IGBT during the turn-off time plus the tail time of a single collector current pulse

5.2 Testing Standard

Investigating the reliability and failure mechanisms of power electronic component (IGBT), experiment should be conducted under much stressful situation such as high temperature, short circuit and vibration. Power cycling and thermal cycling as the strongest challenge in respect to high junction temperatures often employed to evaluated the stability and investigate the failure mechanisms [58-60] is shown Table 5.

Table 5 Stressful testing standard [61]

Name	Condition	Standard
Thermal Cycling (Infineon)	External heating and cooling $2min<t_{cyc1}<6min$; $\Delta Tc=80K$, $Tcmin=25^oC$ High power standard:2000 cycles Medium power: 5000 cycles	IEC 60747-2/6 IEC 60747-9
Thermal Cycling(Semikron)	external heating and cooling tstgmin-tstgmax 100cycles conventional device (IGBT, diode) modules:25 cycles	IEC 60068-2-14
Power Cycling(Infineon)	internal heating and external cooling $0.5<tcyc1<10sec$ $\Delta Tj=60K$, $Tjmax=125^oC$ 130,000cycles	IEC 60747-9
Power Cycling (Semikron)	internal heating and extremal cooling $\Delta Tj=100K$, 20000 cycles	IEC 60747-9

5.3 Double Pulse Switch Testing

Double pulse switch testing [62] (DPS) as shown in Fig. 20 is a standard and efficient method to investigate the switching energies, turn-on and turn-off power loss, turn-on and turn-off time, and conduction loss of power electronic devices (transistor and FWD) at different voltage and current levels. The gate drive circuit is attached to transistors gate, and a double-pulse is applied. The two pulses are composed by one long pulse and followed by a shorter pulse. This allows for turning on and turning off at full current i.e. 400 A in this case. The typical current and voltage waveforms can be seen in Fig. 21.a - Fig. 21.e, the power dissipation and energy loss of transistor can be calculated by formula (1). Energy loss is the integral of power dissipation. The power and energy losses waveforms are shown in Fig. 21.f - Fig. 21.g . Because of the diode reverse recovery, practically observed transistor and diode current waveforms are shown in Fig. 21.h and Fig. 21.i. The more specific details can be found at semester project report [33].
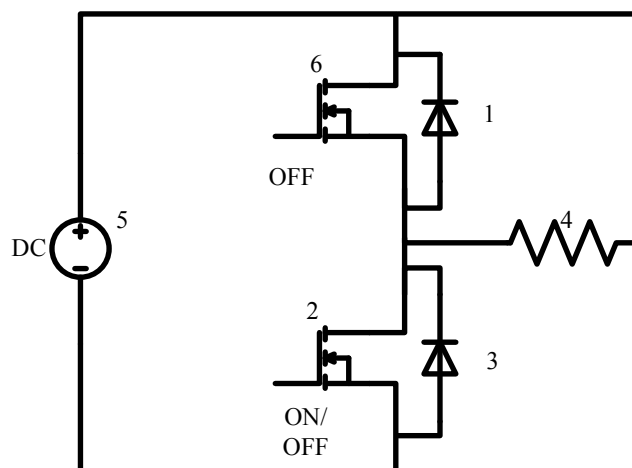
Fig. 20   Schematic of DPS testing circuit
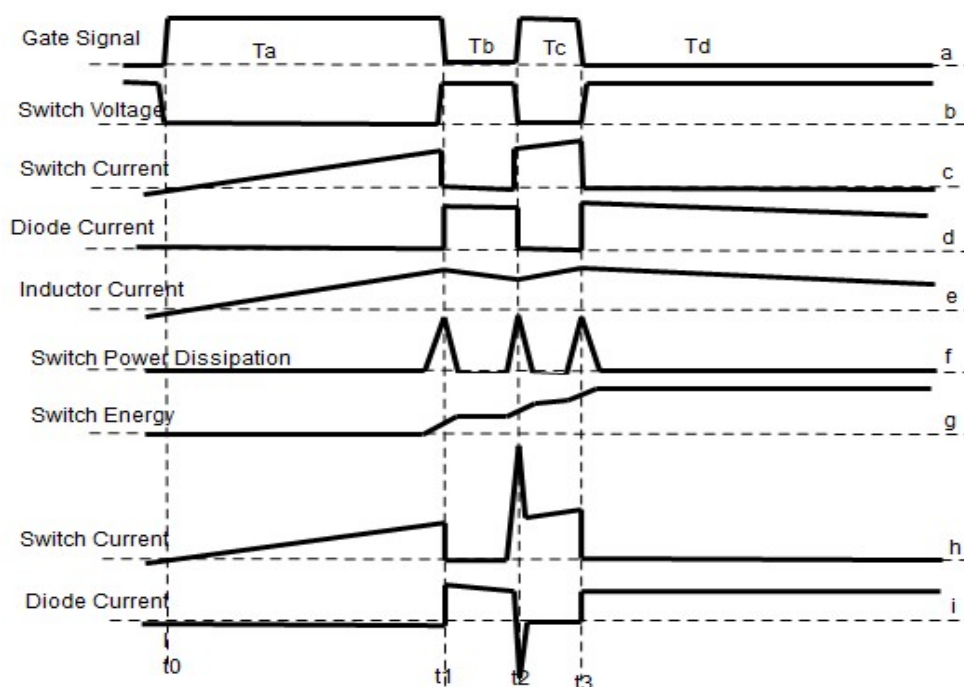
Fig. 21 Principle waveforms at DPS (a～i)

5.4 Repetitive Switch Testing

The long term stability of IGBT modules can be experimentally under multiple switching tests. Two IGBT modules were used to build a full bridge inverter as shown in Fig. 22. The inverter was controlled by PWM switching scheme as shown in Fig. 23 with carrier signal switching at 10 kHz. The system was controlled to keep a constant junction temperature of IGBT chips i.e. 80 ^{o}C, for a certain power level (600 V and 105 A in this case). Ambient temperature was 20 ^{o}C and test lasted for 90 days.

Then the same double pulse switch testing method was employed to measure the IGBT switching performance, and compared the result with that previously taken. It is wroth to mention that this test is not a life time test, but rather an evaluation of module performance in order to gain an optimized inverter design.
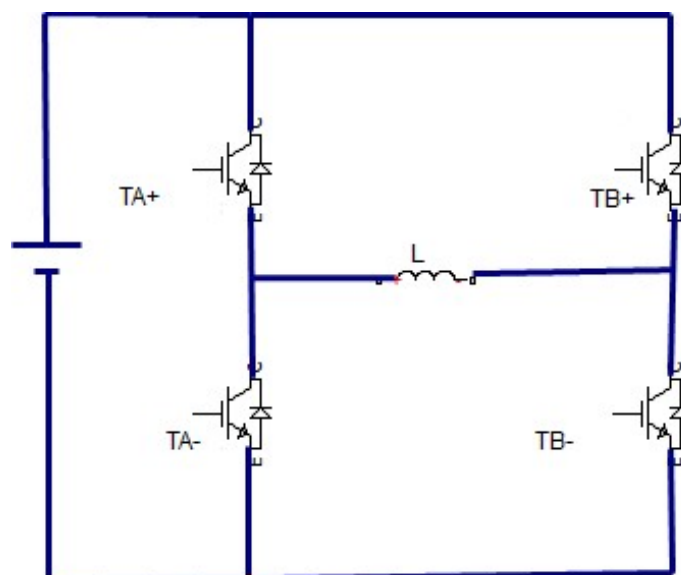
Fig. 22 Principle of repetitive switching test
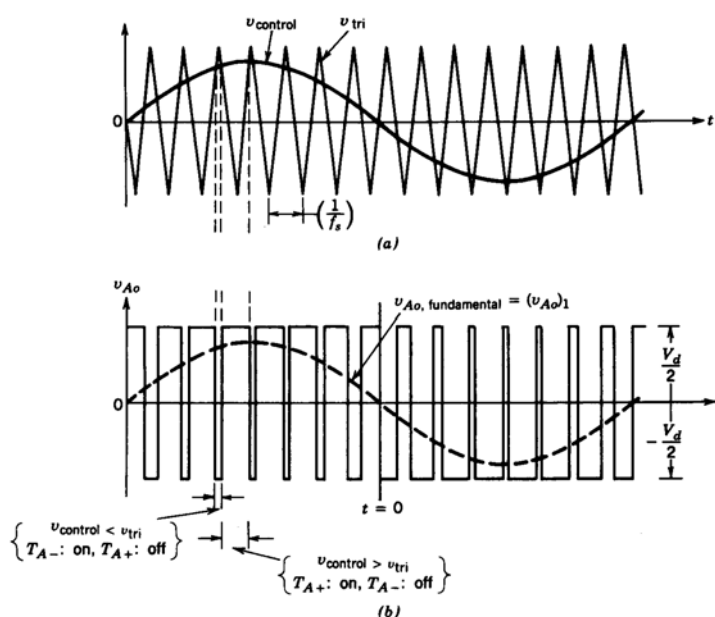
Fig. 23 Scheme of IGBT control signal [3]

5.5 Power Cycling Testing

To assess their reliability in these applications and lifetime, power cycling is the most suitable stress test, because the devices are operated in conditions similar to

those encountered in the field. In effect, the main cause of failure is the repetitive thermal cycling, which occurs when power cycling is applied. In spite of the fact that reliability is a key factor for the development of the IGBT technology, only few data are available and no standard test methods have been defined to evaluate the power cycling reliability and the effective impact of the various stress parameters is not yet established [60, 63-64]. The power dissipation losses of the IGBT chip are calculated by I_C and V_{CE}. Basically, I_C is fixed to the rated current value of the chip, and V_{CE} is adjusted to produce a specified temperature difference between T_{jmax} and T_{jmin} (ΔT_j) as shown in Fig. 24.b, and the scheme of setup is shown in Fig. 24.a.
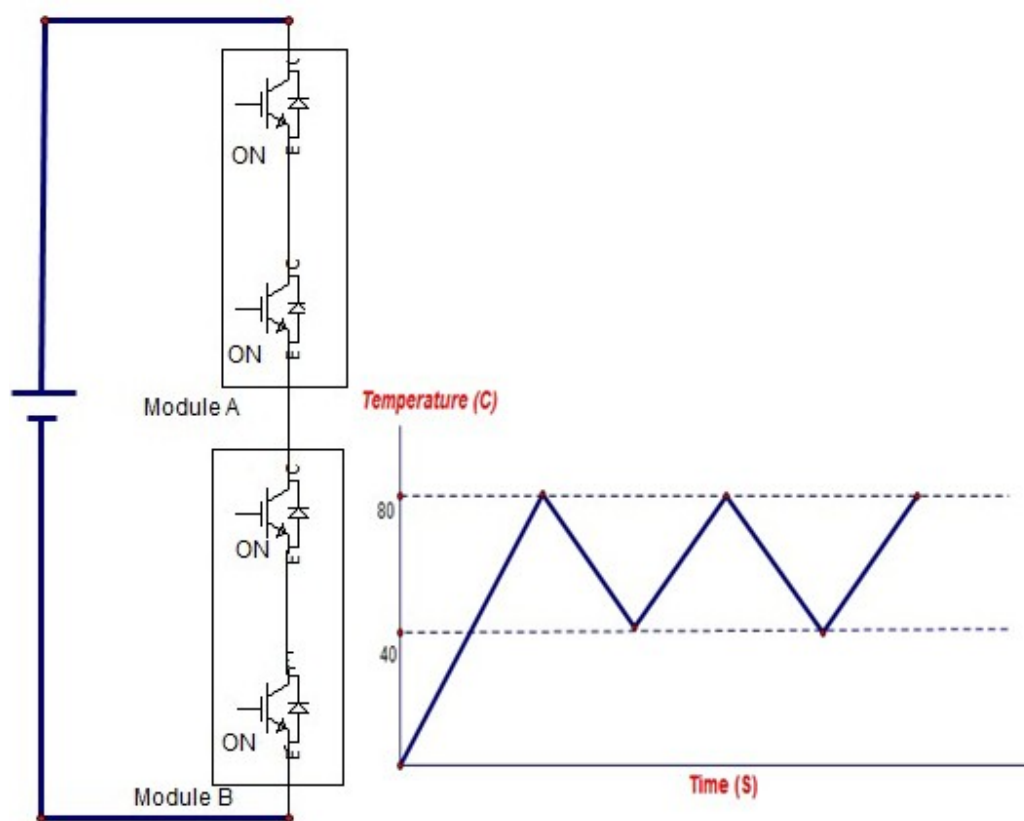
Fig. 24 Scheme of power cycling set and working temperature waveform

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6. Setup and Measurement Description

This chapter first described two type commercial standard IGBT modules which have been tested at this project, then introduced some of the experimental instruments and mounting tips, finally present the structure and operation method of different setups.

6.1 Testing Object Description

Five standard IGBT modules were tested in this project and four of them were manufactured by IXYS, and one of them was produced by Tyco. The tested IXYS IGBT module in this experiment is IXYS^{TM} MII 400-12E4 as shown in Fig. 25 which is half bridge structure. Each phase leg contains three NPT IGBT chips and three HiperFRED^{TM} diode chips anti-parallel connected. The maximum collector-emitter voltage (V_{CE}) and current rating is 1200 V and 420 A, respectively, where the maximum junction temperature defined by the datasheet is 125 ^{o}C for this standard module. The Tyco IGBT is V23990-P660-F02-PM as shown in Fig. 26 which is also half bridge structure. The maximum V_{CE} and I_C rating is 1200 V and 450 A, and the maximum junction temperature is 150 ^{o}C.
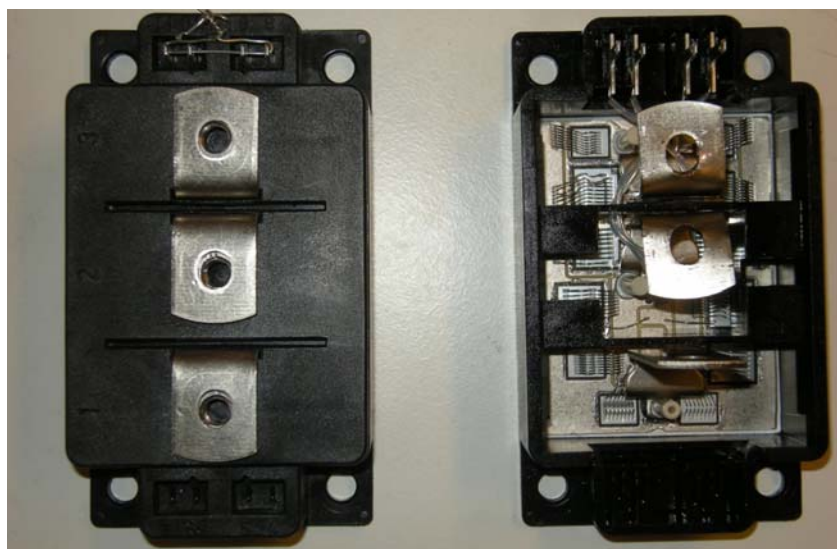
Fig. 25 IXYS MII400-12E4 IGBT
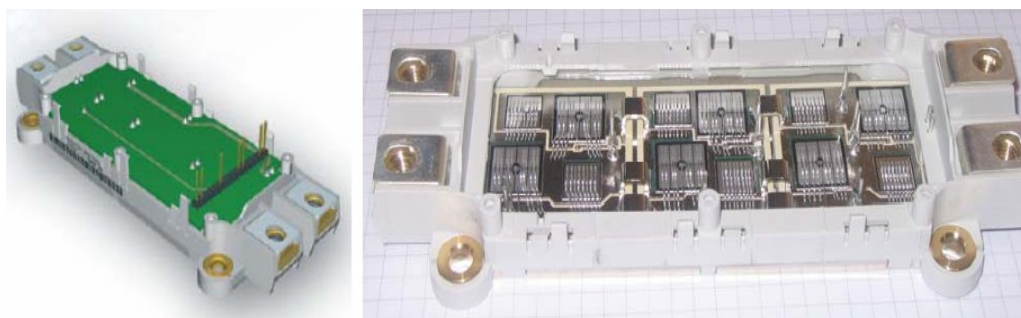
Fig. 26 Tyco IGBT module V23990-P669-F02 [65]

6.2   Measurements and Instruments

The main principle of testing is shown in Fig. 27, although different experiments have some different parts which will discuss later. For all of the experiments, the converter, transformer, voltage regulator are the same. In the experiments, the Agilent 74970A was used to acquiring the data of the temperature, voltage and current. Tektronix DPO4050 Digital Phopher Oscilloscope was used to collecting the testing waveforms and the data of waveform. For the sake of convenient comparison, keep the probe at the same channel and testing the same parameter as shown in Table 6.

Table 6 Probe position vs. channel

Probe name	Chanel	Parameter	Comment
DPO106-0481	CH1	V_{FWD}	50X
DPO106-0485	CH2	V_{IGBT}	50X, current probe when measure I_{FWD}
DPO106-0484	CH3	V_G	50X
Current Probe	CH4	I_C	20mA/div

Keep the switching waveform at same reference time for each test at the oscilloscope (ie. 200 ns/div and reference time is 600 ns for turn on waveform, and 400 ns/div and reference time fixed to 1.2 μs for turn-off wave form). All of the data were recorded in excel which is easy to analysis and compare with different experiments.

At the starting of the experiments of repetitive switch and power cycling test,

some faults observed because of the bad thermal grease contacting as shown in Fig. 29 (a) result in the generated heat can not dissipate quickly. As high temperature is the most important reason to cause the IGBT faults, the thermal grease should cover the IGBT module base plant carefully. By trial and error, the method as shown in Fig. 29 (b), with strong vertical force and bit more thermal grease proves to be the best method. In addition, gate driver signal noise also may fail the measurement. Twist is around a coil as show in Fig. 30 is a good method to reduce it. This method applied to both repetitive switch and double pulse switch testing. In addition, stray inductance as shown in Fig. 28 is another important factor to influence the accuracy of the measurement. Moving the DC-capacitor close to the IGBT module and keeping cables as short as possible are effective methods to reduce the inductance [33].
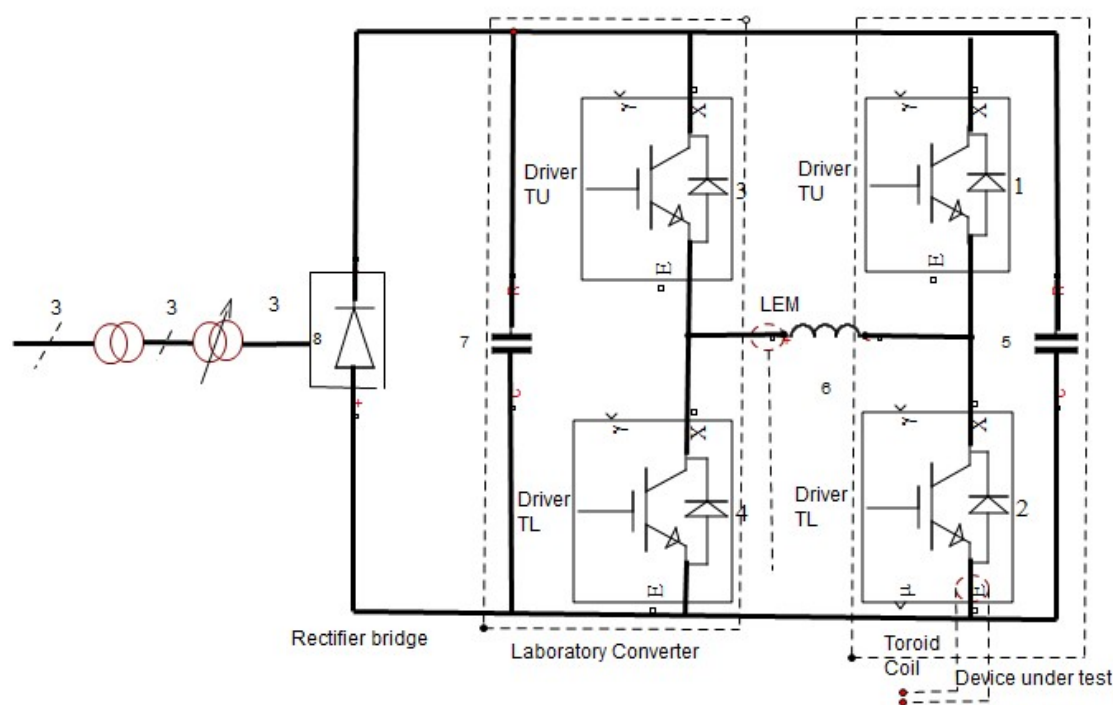
Fig. 27 Principle of measurement setup [66]
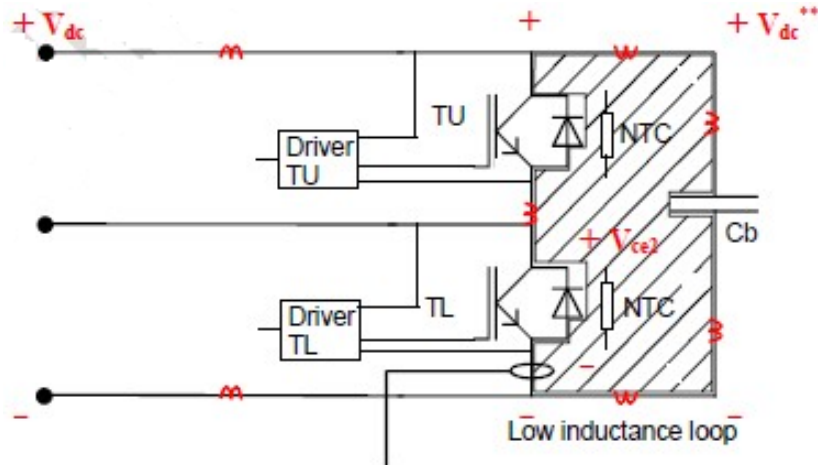
Fig. 28 Area which contributes to stray inductance in the loop between the capacitor and the transistor (From SINTEF Memo) [65]
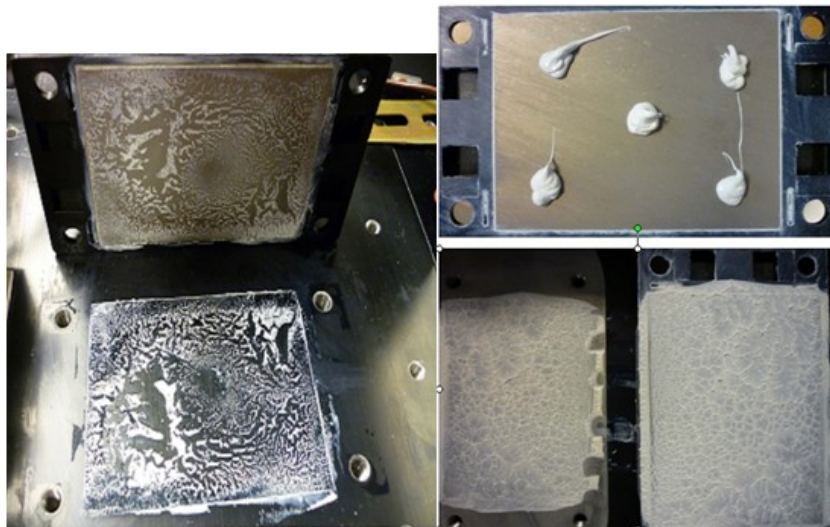
Fig. 29 The break IGBT footprint (a) and the best covering method (b)
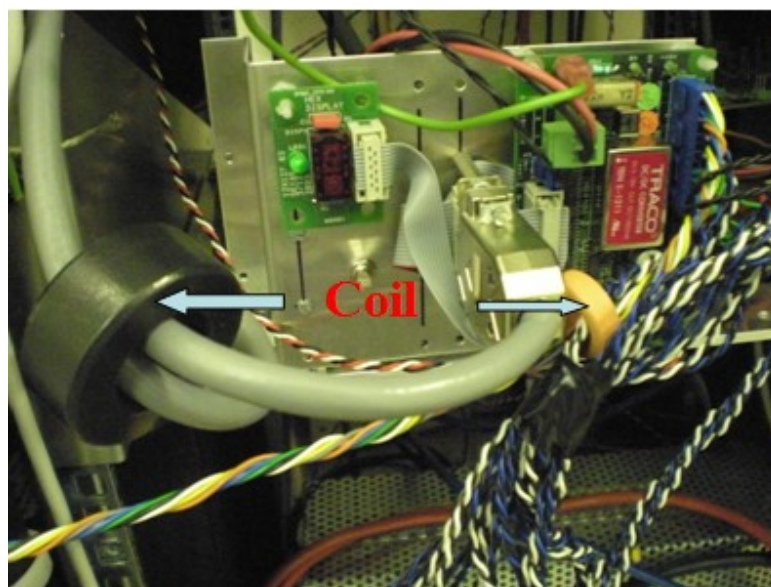
Fig. 30 Coil for filter noise

6.3 Double Pulse Switch Testing Setup

Base on the principle of double pulse switch testing (Chapter 5.3), and Fig. 27, two double pulse switch testing were built before and after stressful test conducted (ie. repetitive switch and power cycling test). The first setup as shown in Fig. 32 was used to investigate the dynamic performance of IGBT including the turn-on and turn-off energy losing, turn-on and turn-off time at different temperatures and power levels. The second setup was used to testing the dynamic performance of Tyco IGBT and IXYS IGBT after expose stressful condition for some time. Keeping two setups have the same external condition (ie. inductor, stray inductor, and converter) is very important for testing results comparison. Two new IGBT modules tested at the same voltage, current and juncture temperature on different setups repetitively. The comparison result is shown in Fig. 31 which proves that two setups have exactly the same performance. Both IXYS IGBT modules and Tyco IGBT module tested at different conditions is shown in Table 7. The gate resistance for the IXYS IGBT module test was 4.125 Ω, and Tyco IGBT module tested at three different gate resistances, that is 2.2 Ω, 3.9 Ω, and 4.7 Ω. All of the double pulse switch testing, the first turn-off waveforms and second turn-on waveforms were captured and the gate voltage was $\pm 15V$.

Table 7 Available switching waveforms of IXYS and Tyco IGBT at 23 $^{\circ}$C, 80 $^{\circ}$C, 125 $^{\circ}$C

V_{DC}/I_{CE}	10 A	25 A	50 A	100 A	200 A	300 A	400 A
50 V	ON/OFF						N/A
100 V				ON/OFF	ON/OFF		N/A
200 V			ON/OFF				ON/OFF
400 V				ON/OFF	ON/OFF		ON/OFF
600 V		ON/OFF	ON/OFF	ON/OFF	ON/OFF	ON/OFF	ON/OFF
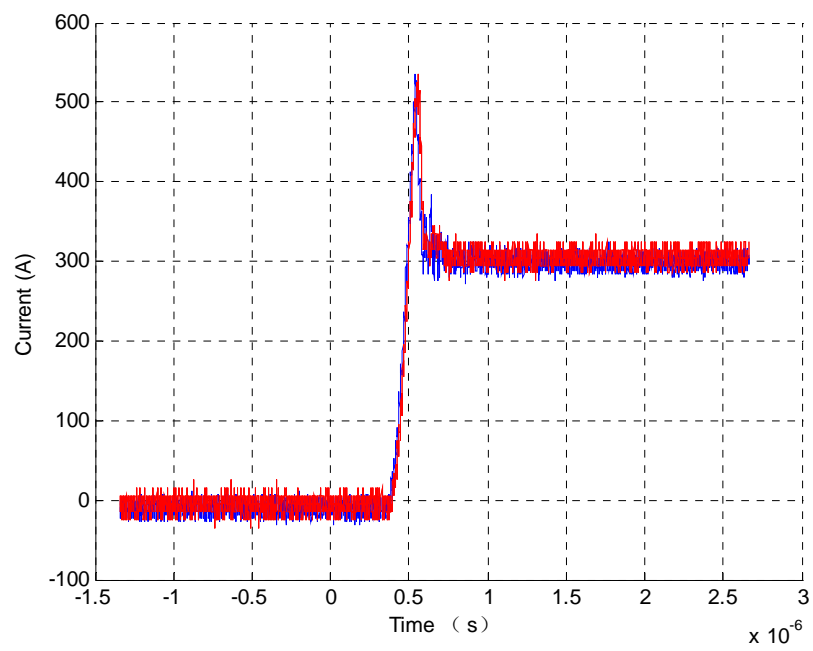
Fig. 31 Compare First setup (red) and Second setup (blue) at 600 V, 300 A, and 25 $^{\circ}$C
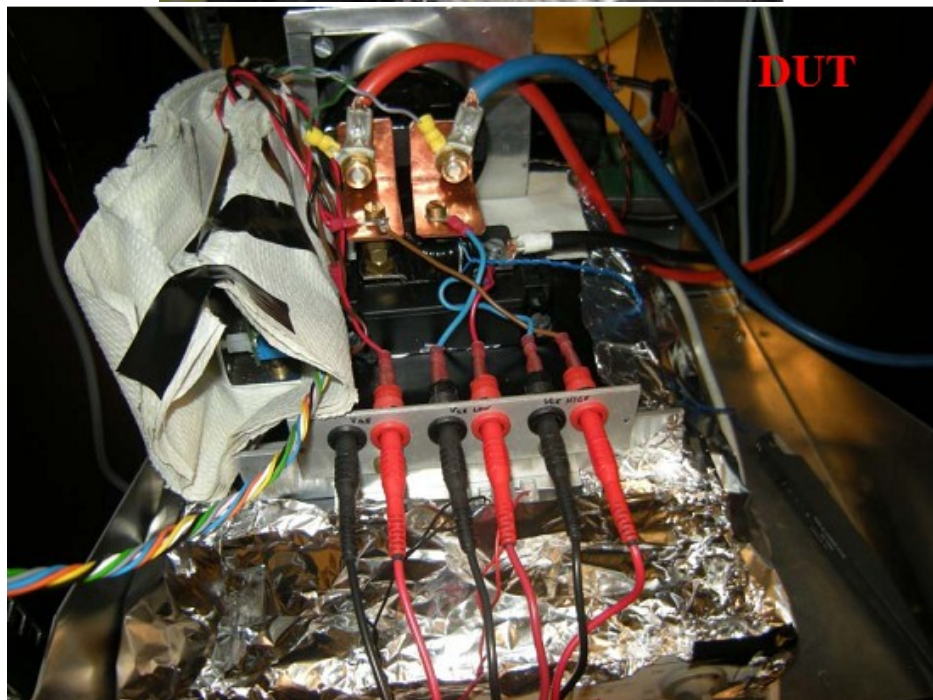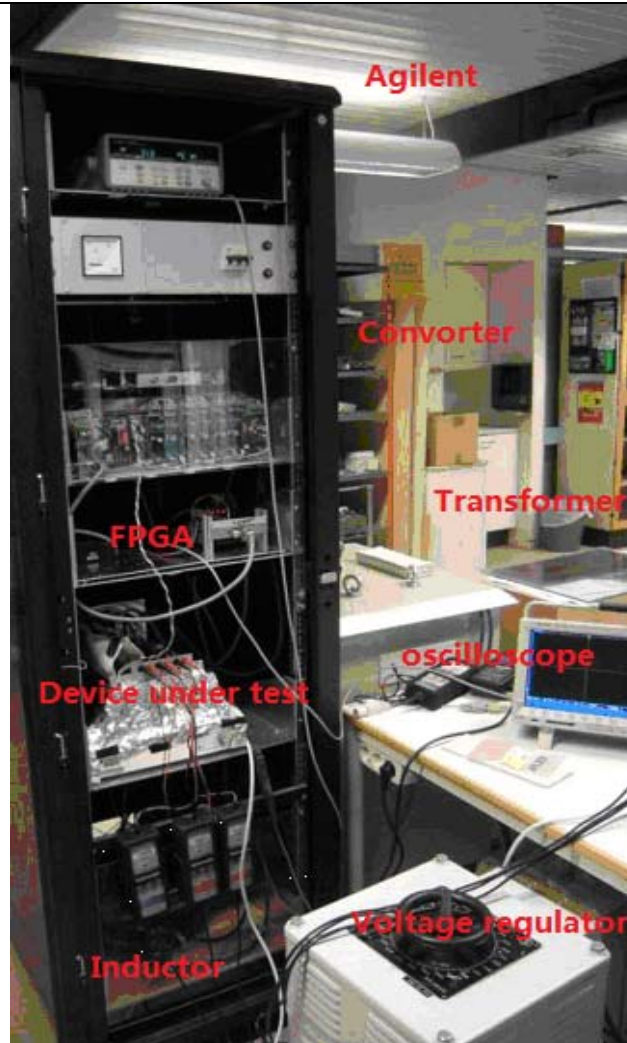
Fig. 32 Double Pulse Switch Testing setup

6.4 Repetitive Switch Testing Setup

Repetitive switch test setup was built up base on chapter 5.4 and chapter 6.2, as shown in Fig. 33. The signal generator produced 10 kHz square waveform signal to control the 50 Hz sinuous waveform (PWM control). The air conditioner keeps the ambient temperature at 20 ^{o}C. The heat sink can get the thermal balance temperature at 80 ^{o}C when set the voltage at 600 V and current at 105 A with fan cools it down constantly. The Agilent recorded different parameters as shown in Table 8, and the sampling frequency is 5 s. After three month repetitive switching, employing the double pulse switch testing again to measure the dynamic characteristics.

Table 8 Agilent channel and parameter

Channel	101	102	103	104	106	107
Parameter	IGBT A Temp.	Diode A Temp.	Ambient Temp.	Current	IGBT B Temp.	Diode B Temp.
Channel	108	109		105	110	111
Parameter	101 alarm 2	102 alarm 2		Voltage	106 alarm 2	107 alarm 2
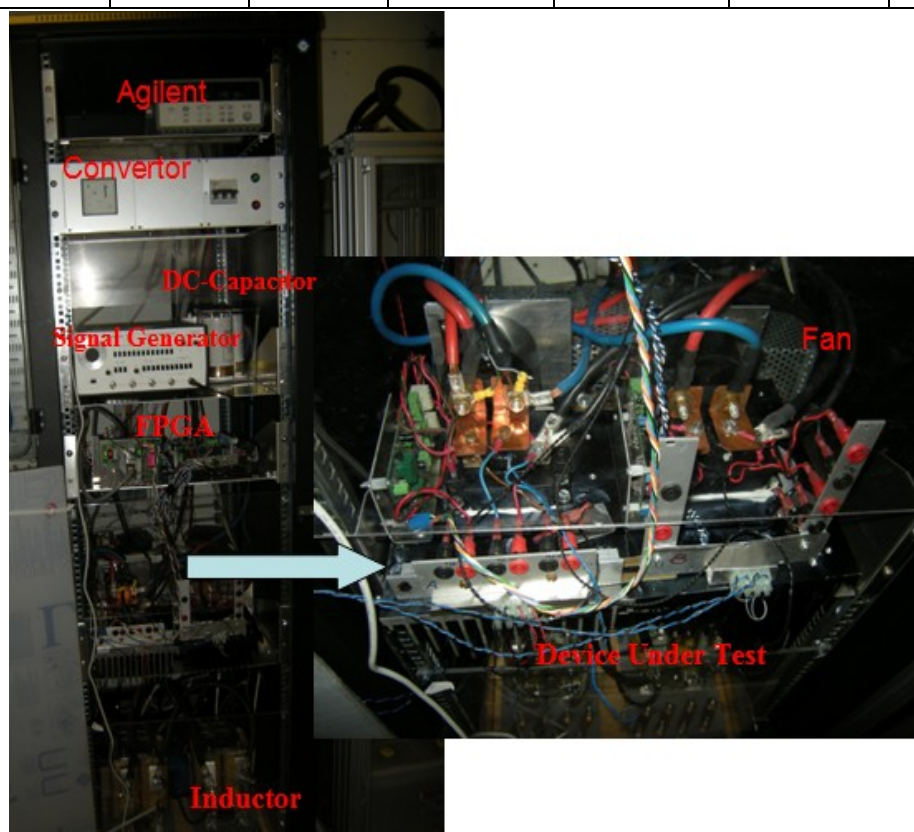
Fig. 33 Repetitive Switch Testing setup

6.5 Power Cycling Testing Setup

The power cycling testing setup is shown in Fig. 34. The power supply with 105 A and 20 V heating the IGBT module up to 80 ^{o}C, and the fan cools it down to 40 ^{o}C, the cycle waveform as shown in Fig. 35, power supply and fan are interlocked. This cycling process controlled by Agilent. The recoded parameters as show in Table 9, and the sampling frequency is 5 s.

Because of some bugs at the Agilent software and computer, made the IGBT module temperature out of control (the fan can not start again) result in the failure of the experiment and one of the IGBT modules broken. The high temperature caused the outside package plastic softy as shown in Fig. 36, some documents has shown that the temperature must higher than 230 ^{o}C to melt the plastic. The two tested IGBT module connected in series, and the energy produced by IGBT chips which means IGBT modules work at extremely high temperature (higher than 125 ^{o}C) for quite a while (longer than 250 s) based on the temperature increase rate. This 'happy accident' proves that measure the dynamic characteristic of IGBT module at higher temperature, ie. 180 ^{o}C, is possible.

Table 9 Channel and parameter of power cycling

Channel	101	102	103	104	105	106
Parameter	Up Diode A Temp.	Low IGBT A Temp.	Up IGBT A Temp.	Low Diode A Temp.	Up Diode B Temp.	Low IGBT B Temp.
Channel	107	108	109	110	111	112
Parameter	Low IGBT B Temp.	Low Diode B Temp.	Heat sink output Temp.	Ambient Temp.	102 alarm 2	Current
Channel	113	114	115	116		
Parameter	Low IGBT A voltage	Up IGBT A voltage	Low IGBT B voltage	Up IGBT B voltage		

Fig. 34 Power cycling testing setup
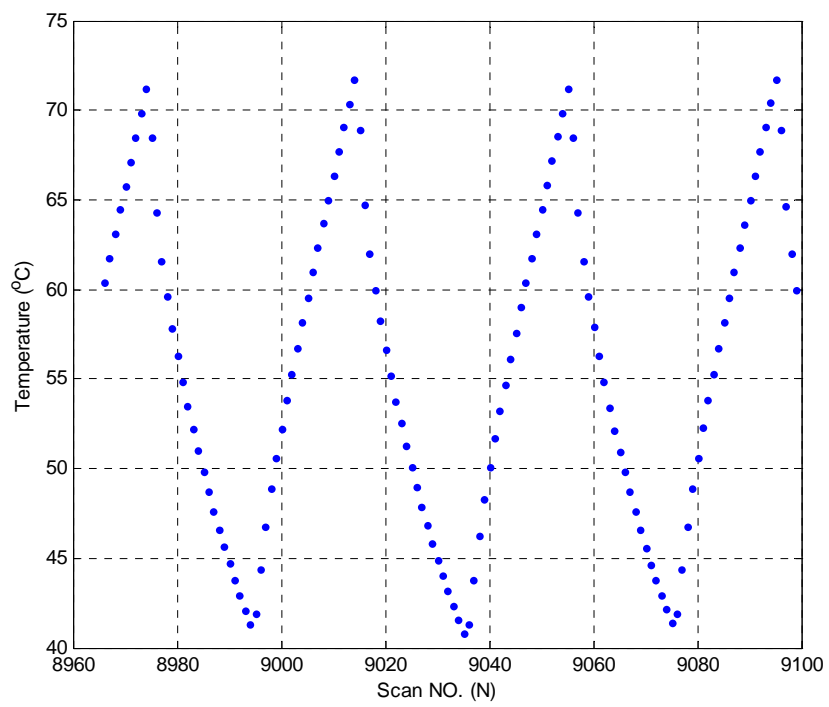
Fig. 35 Power cycles

Fig. 36 melted plastic due to temperature out of control

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7. Results and Analysis

The parameters of turn-on and turn-off time, and turn-on and turn-off energies decide the performance of IGBT module, and thus the converter design. Those parameters under different voltage and current levels and different temperatures were investigated in this project by employing the double pulse switch testing. Repetitive switch test and power cycling test as the stress testing investigated the long-term stability of IGBT module which is very important at the industrial application. This chapter analyzed the results of both before and after stressful testing, and explored the influence of gate resistance, temperature, voltage and current level on both IGBT chips and the FWD chips. This chapter also compared the IXYS and Tyco IGBT module performance, verified the credibility of the testing methodology and gained the short-term and long-term stability information. The influence of snubber and stray inductance have been investigated at semester project report [33] thus will not cover at here.

7.1 Conduction Voltage

Conduction voltage is an important factor to decide the power loss of IGBT. The relation between conducting voltage of IGBT and temperature is shown in Fig. 37. The conducting voltage increased only 0.15 V when temperature increased from 40 ^{o}C to 80 ^{o}C, which means that conducting voltage only slightly influenced by temperature for this IXYS IGBT module. Therefore, increase the temperature will not result in lager additional power loss at the IXYS IGBT module. The testing results show that the conducting voltage is about 6 V which match the datasheet data (4.5 V ∼ 6.5 V). If IGBT working at rated current, the power losses were 2.4 kW.
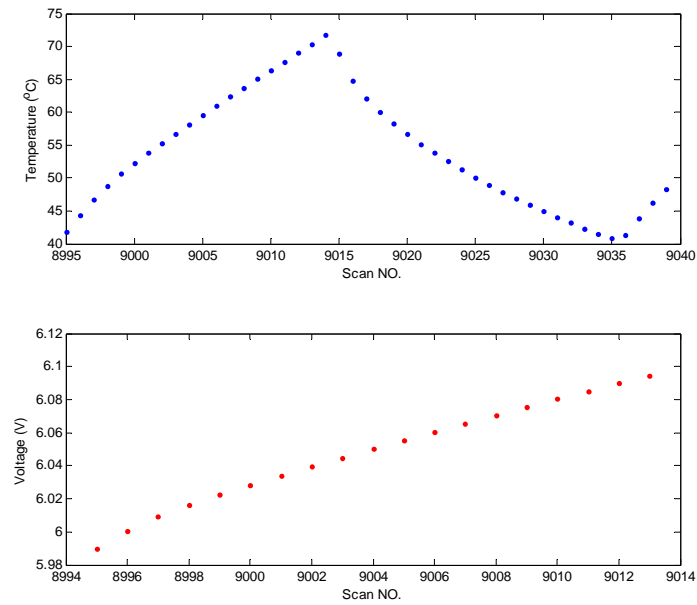
Fig. 37 Conducting Voltage vs. Temperature

7.2 Gate Resistance Influence

The Tyco IGBT was tested at two different gate resistances ie.2.2 Ω and 4.7 Ω, and the results is shown in Fig. 38. Decrease the gate resistance can decrease the turn-on delay time, but increased the overshoot and fluctuation of the current waveform, thus a trade-off between them always should be made. In addition, decrease the gate resistance will increase the FWD stress [3, 33], and the influence on turn-off process was less than that of on turn-on process.
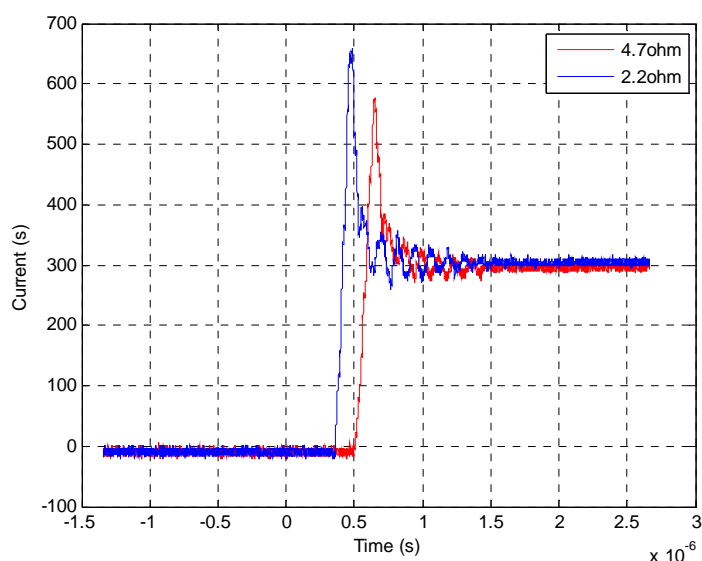
Fig. 38 Influence of gate resistances (Tyco IGBT module at 600 V 300 A and 25 $^{\circ}$C)

7.3   Influence of Temperature

Based on the double pulse switch testing, the turn-on and turn-off time at 600 V was measured at different temperatures and different current levels. Both of the turn-on and turn-off time definitions are base on the IEC 60747-9 standard [7]. Turn-on time at different collector currents and three different temperatures are shown in Fig. 39. Turn-off time at same current levels and temperatures are shown in Fig. 40 and the 2-D figure of IGBT switching at 600 V and 400 A but different temperatures are shown in Fig. 41, and more figures please refer to Appendix. Setting V_{CE} and I_C to 600 V and 300 A, respectively, and junction temperature heated to 125 $^{\circ}$C. Measured turn-on and turn-off time were $211.4\ n\sec$ and $683.2\ n\sec$ respectively. Module datasheet [67] stated $230\ n\sec$ and $730\ n\sec$. The gate resistance used during this measurement was 4.125 Ω compared to 4.7 Ω in the datasheet, which cause this slight difference.
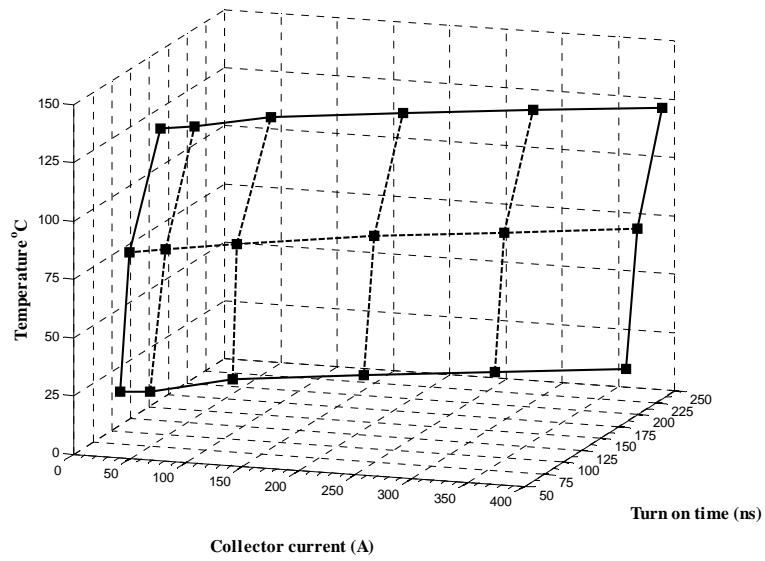
Fig. 39 Turn-on time at different currents and temperatures (V_{CE} = 600 V)
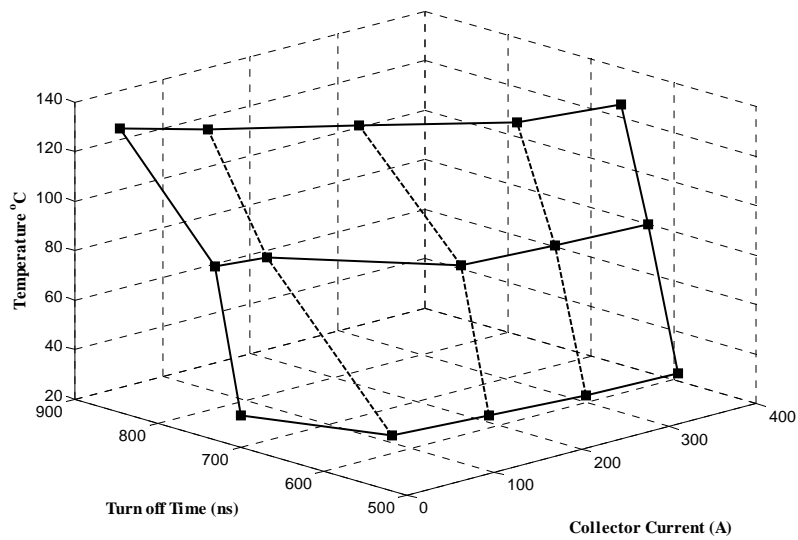
Fig. 40 Turn-off time at different currents and temperatures (V_{CE} = 600 V)
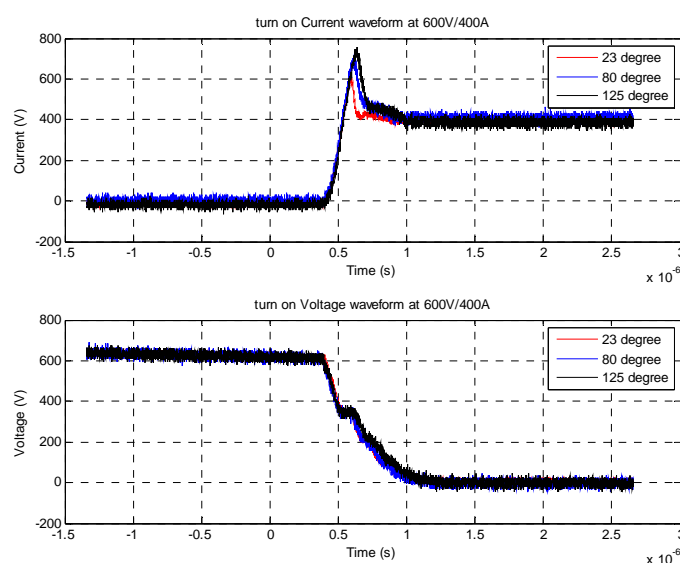
Fig. 41 Turn-on current and voltage waveforms at different temperature (600 V, 400 A)

Turn-on and Turn-off energy losses decided the reliability and lifetime [63, 68-69] of IGBT modules. According the IEC standard, the turn-on (turn-off) energy is the energy dissipated inside the IGBT during the turn-on (turn-off) of a single collector current pulse which can be calculated by formula (2.1) and (2.2). The power dissipations inside the IGBT chip during the turn-on period is shown in Fig. 42 and the turn-off period is shown in Fig. 43. This power pulse commences when the collector current start rising up and continues as far as the device is not fully on i.e. V_{CE} is higher than $V_{CE(on)}$. The turn-on and turn-off energy losses at different current levels and temperatures are displayed in 3-D plot as shown in Fig. 44 and Fig. 45. At the conditions of 600 V, 300 A, and 125 ^{o}C ambient temperature, the calculated turn-on and turn-off energy dissipation based on the experimental results and Eq. (2.1) and Eq. (2.2) are $40.0\,mJ$ and $34.3\,mJ$, respectively. Datasheet given values are $44.0\,mJ$ and $30.0\,mJ$ respectively. The slightly lower gate resistance leads to a faster turn-on and turn-off transients and thus a lower energy loss.
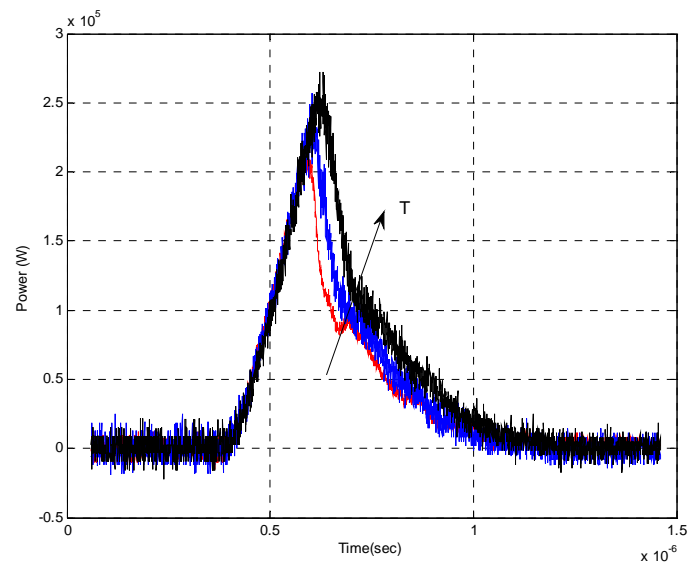
Fig. 42 Turn-on power dissipation at 600 V/400 A/ (23 ^{o}C, 80 ^{o}C and 125 ^{o}C)
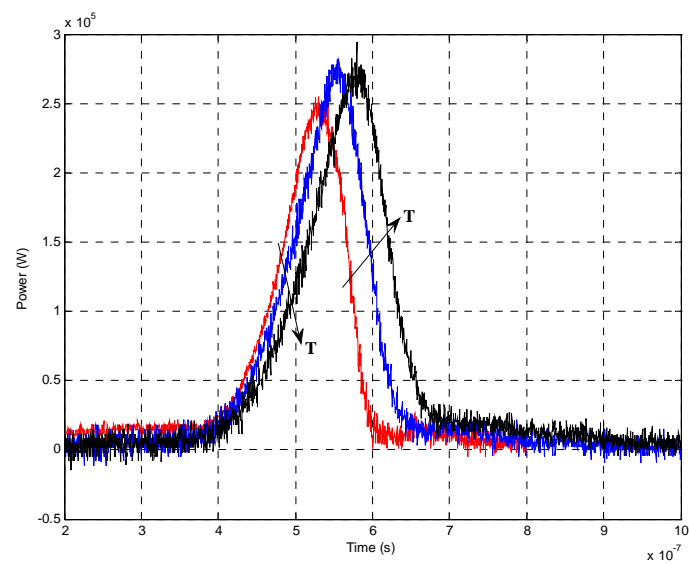
Fig. 43 Turn-off power dissipation at 600 V/400 A/ (23 ^{o}C, 80 ^{o}C and 125 ^{o}C)
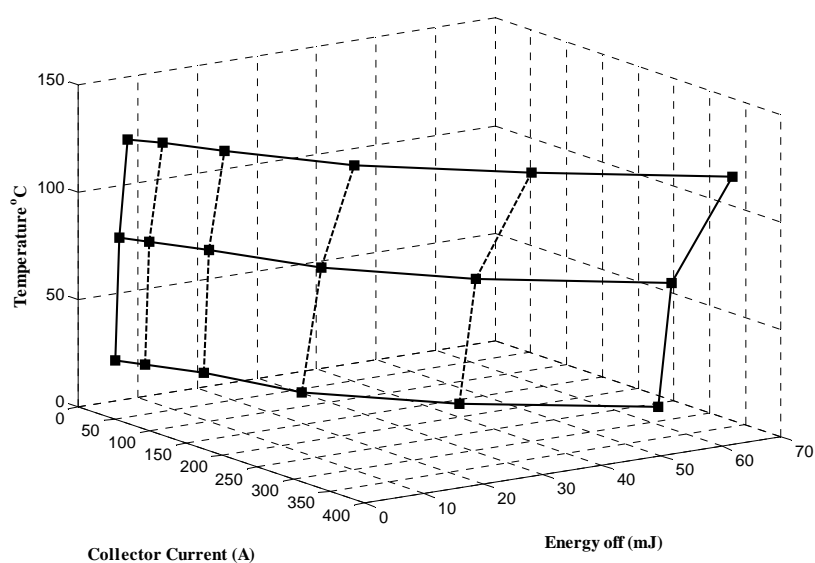
Fig. 44 Turn-on energy loss at different current and temperatures (V_{CE} = 600 V)
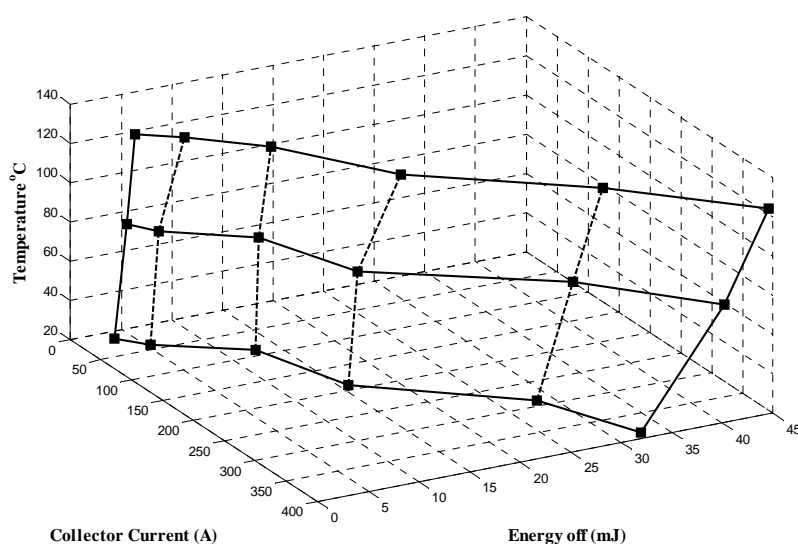
Fig. 45 Turn-off energy loss at different current and temperatures (V_{CE} = 600 V)

7.4 Influence of Power

The turn-on time increase with the increasing of voltage and current levels on the IGBT module. Thus the energy dissipation at IGBT module also increases with the temperature. However, the turn-off time decrease with the increasing temperature as shown in Fig. 46 and the turn-off power losses increase with temperature is shown in Fig. 47. Table 10 shows the relation between turn-off time and turn-off energy

dissipation.   More waveforms can refer to Appendix. This is because most of the energy loss occurs at the rise time not at the delay time. The delay time is decreasing as current increase.

Table 10 Turn-off time and energy loss at 600 V and 125 °C

I_C	400 A	300 A	200 A	100 A	50 A
t_{off} (ns)	663.8	683.2	768.8	845.2	898.8
E_{off} (mJ)	44.5	34.3	20.4	13.7	8.2
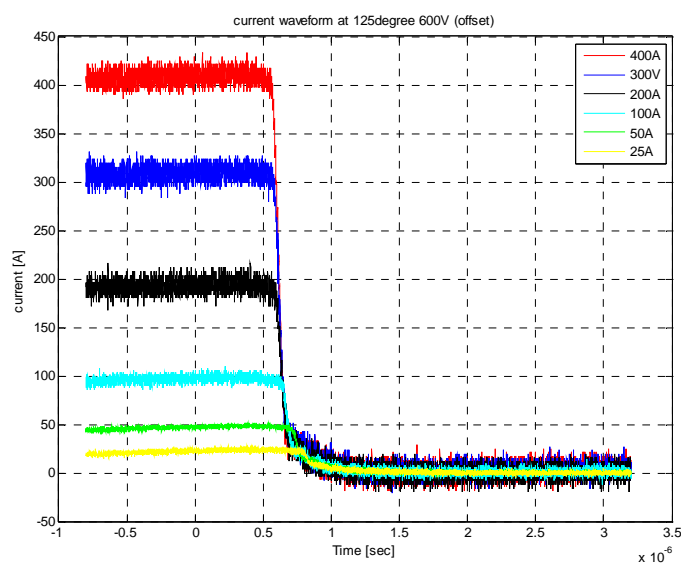
Fig. 46 IGBT turn-off current waveforms at 600 V and 125 °C
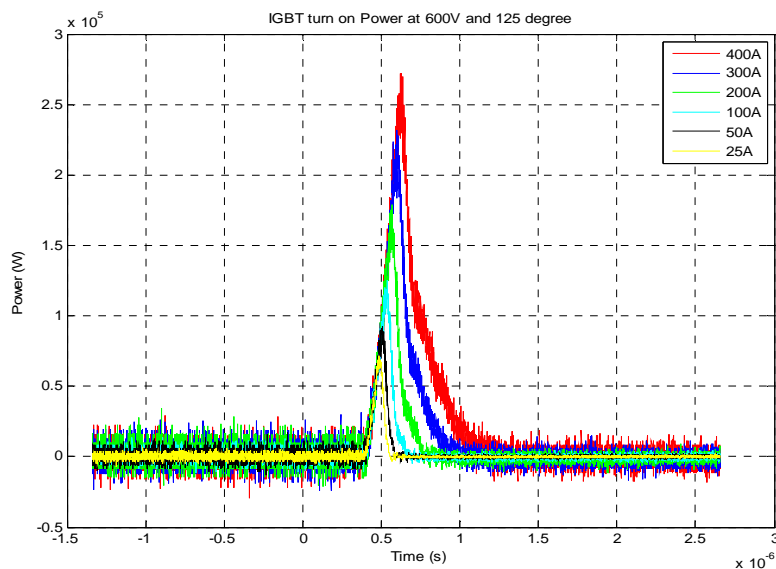
Fig. 47 turn-on power loss at different current

7.5 FWD Performance

Medium and high voltage level modules employ PiN freewheeling diodes. With necessary high injection level of free carrier to reduce on-state resistance, PiN exhibits a recovery of this storage charge at turn-off. This leads to reduction in switching speed and increase in the turn-on energy losses of the nearby IGBT, thus the performance of FWD impacts IGBT module performance. The reverse recovery charge can be calculated by;

$$Q_{rr} = I_{rr} t_{rr} / 2 \qquad (3)$$

With minority carrier lifetime increases with temperature [3], peak reverse recovery current and energy loss during recovery also increase. The waveforms of voltage and current when turn-on the IGBT at different temperatures but the same voltage and current i.e. 600 V and 300 A are shown in Fig. 48 and Fig. 49, the experiment results show that the reverse recovery time t_{rr} are 0.9 *ns* ns at 23 ^{o}C and 1.8 ns at 125 ^{o}C, where peak reverse recovery current are 225 A and 405 A, respectively. Again power loss can be calculated using Eq. (2.1). The calculated energies dissipation in FWD are 21.6 *mJ* and 10.2 *mJ* when the IGBT is turned on at 23 ^{o}C and 125 ^{o}C, respectively. Calculated energies are 5.1 *mJ* and 3.8 *mJ* during IGBT turn off at 23 ^{o}C and 125 ^{o}C, respectively.
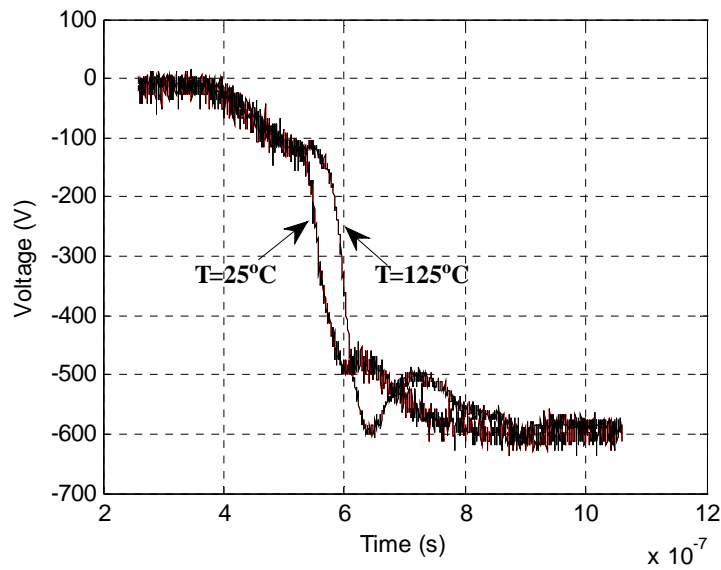
Fig. 48. FWD Voltage waveforms at (23 $^{\circ}$C and125 $^{\circ}$C)
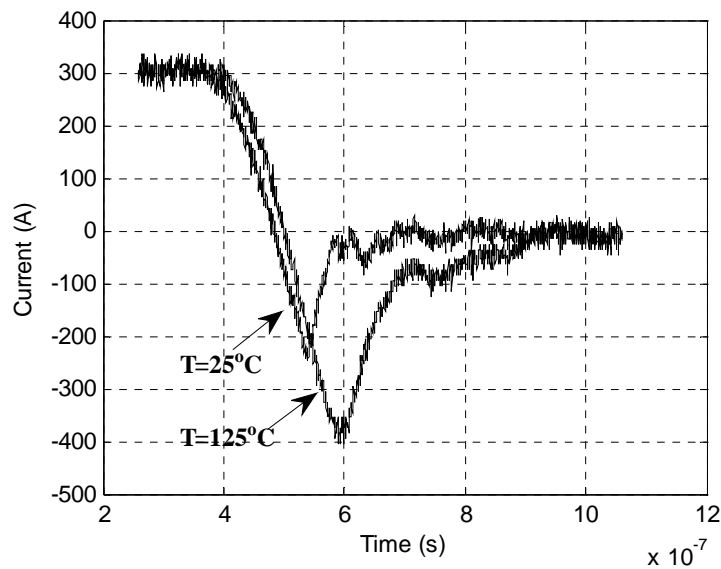
Fig. 49. FWD Current waveforms at (23 $^{\circ}$C and125 $^{\circ}$C)

7.6 Long-term Stability

The double pulse switch testing results of turn-on waveforms before and after the repetitive test is shown in Fig. 50. The results show that after 90 days of stressful switching, the IGBT modules still exactly exhibit the same performance as before. No sign of degradation is noticed. Moreover, the IGBT modules worked under power cycling (refer to chapter 6.5) until one of the IGBT modules were destroyed by

over-temperature. Testing the survived IGBT again after it undergo 21,073 cycles and extremely high temperature for a while. The compared result is shown in Fig. 51. It is very impressive that after undergoing such strong stress the dynamic characterizes and performances not show degradation. Therefore, it is quite safe to conclude that IGBT modules have very good long-term stability.
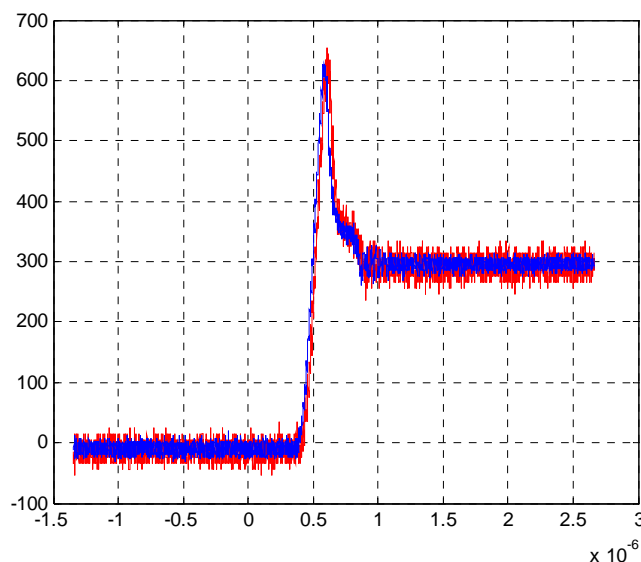
Fig. 50. Turn-on current before and after repetitive switching test
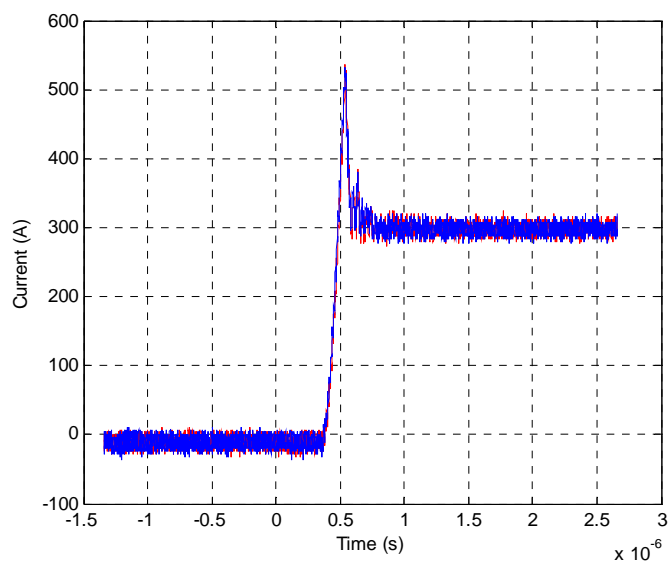
Fig. 51. Turn-on waveforms before and after power cycling test

7.7　Tyco-IGBT Performance

The turn-on and turn-off waveforms of Tyco IGBT are shown in Fig. 52, and the turn-off waveform tested by SINTEF [65] as shown in Fig. 53. The rise time are much faster at the new testing than the old one (tested by SINTEF), but due to the two experiments tested at different external conditions, it is hard to judge the accuracy of the Tyco IGBT testing, thus more measurements need to conduct.
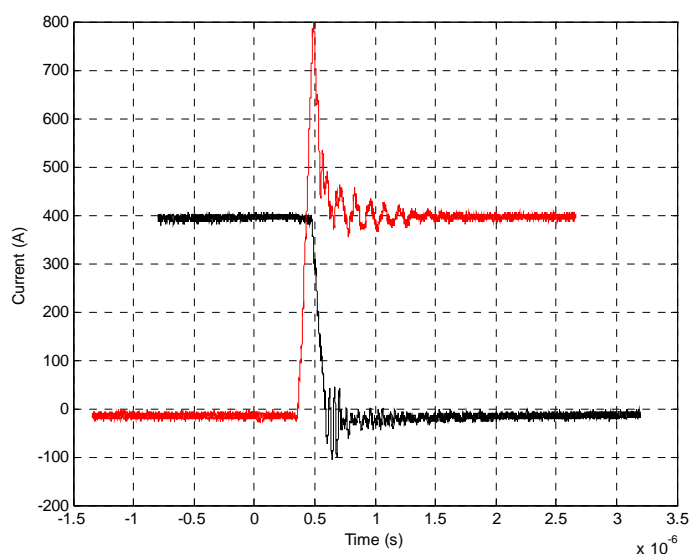
Fig. 52 Tyco IGBT turn-on (red) and turn-off current waveforms
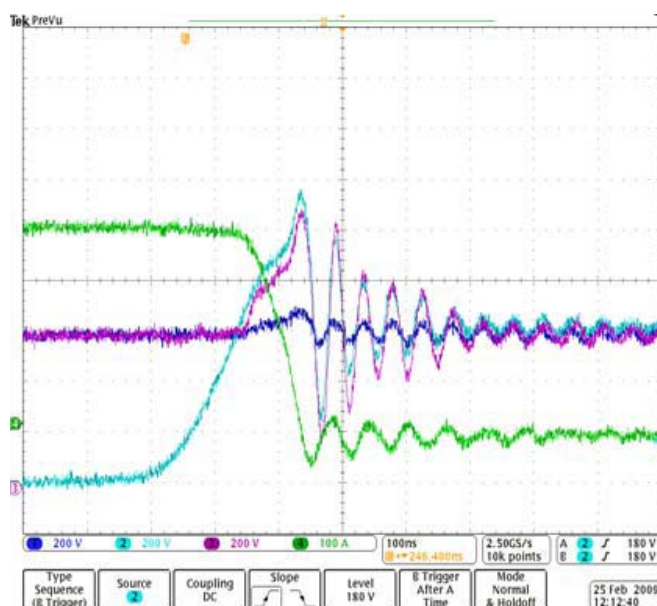
Fig. 53 Tyco turn-off waveform at 600 V and 400 A (from SINTEF memo)

7.8 Tyco vs. IXYS IGBT Module

The Tyco IGBT module and IXYS IGBT module were tested at the same conditions, and the results are shown in Fig. 54. The Tyco IGBT has short turn-on time but higher overshoot. The Tyco IGBT should have less energy loss, but the FWD will undergo heavier stress than IXYS IGBT. Observing the faults of IXYS IGBT module repetitive switch test setup due to the bad contact with the heat-sink, the Tyco IGBT module should has better long-term stability because the baseplate has a certain curve which makes the contact much well when screw it up to heatsink.
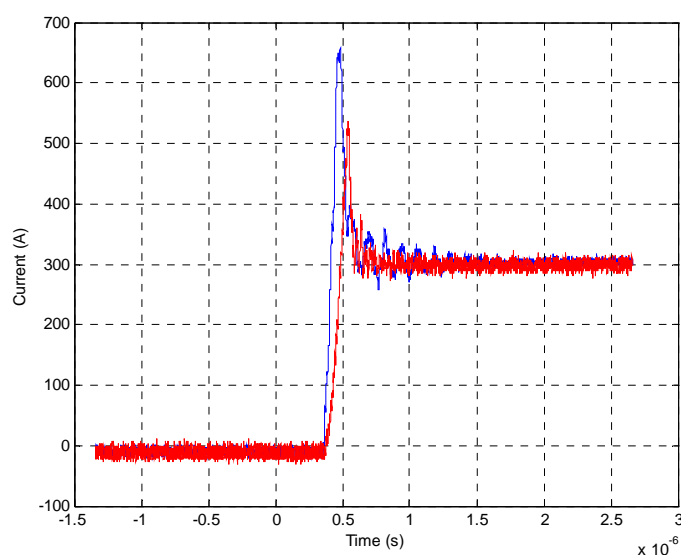
Fig. 54 IXYS (red) vs. Tyco (blue) IGBT at 600 V, 400 A and 25 $^{\circ}$C

7.9   Verification of Test Results and Error Evaluation

To ensure results soundness and accuracy, four identical IGBT modules in total were measured at the same test conditions and results were compared. Fig. 55 shows the turn-on and turn-off waveforms for the four modules result at V_{CE}= 600 V, I_C= 300 A, and 125 ^{o}C. Turn-on and turn-off time were the same, with same switching power losses. This shows measurements accuracy and credibility of the used methodology.   Errors exist in every experiment, but the acceptance of error rang were proved at semester project report [33].
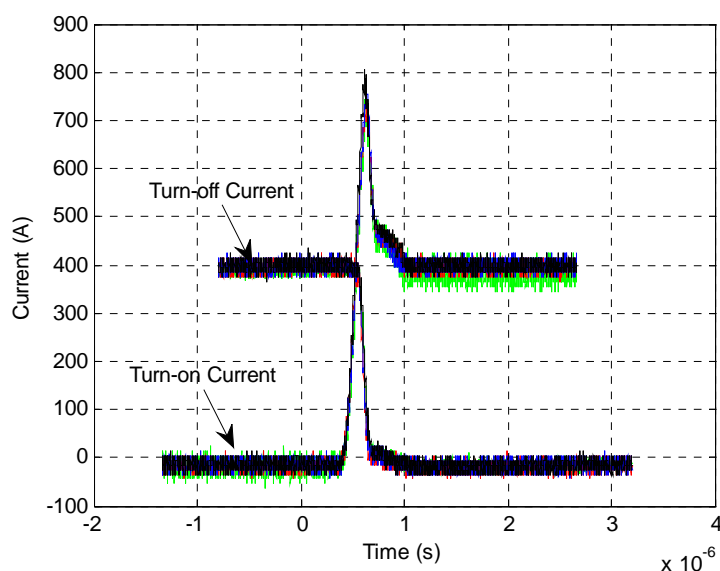
Fig. 55. Four IGBT modules Turn-on and turn-off waveform at 600 V/400 A /125 ^{o}C

8. Conclusion and Outlook

The chip and module technology will be extended to cover higher insulation levels and lower power dissipations. Employing new materials, especially the SiC, is another new development trend for high temperature conditions.

As the traditional wire-bond IGBT module is still the most popular component for industrial applications, three types of experiment setups were designed and build up to explore the dynamic performance and long-term stability of the IXYS^{TM} IGBT module. The double pulse switch tests were conducted to investigate the dynamic characteristics. The repetitive switching tests and power cycling tests were conducted to explore the long-term stability by exposing the module to stress over certain period.

The experiments demonstrate that the turn-on and turn-off time and energy losses depend on the IGBT operation conditions including gate resistance, device voltage and current level, and junction temperature. Reducing the gate resistance value would reduce switching time and switching loss but increase the reverse recovery peak current, which would put heavy stresses on the FWD. Therefore, the gate resistance value should be chosen carefully. Under the same V_{CE} and junction temperature, increasing the collector current increases the turn-on time while the decrease the turn-off time. However, the turn-off energy loss increases. The higher energy losses can be explained by the higher charge recovery of the FWD and the longer tail current. Generally, energy loss increases as the temperature increases. During the turn-on, the delay time is almost constant for different temperatures, while the I_C rise time increases. This leads to higher loss during the turn-on. For example, turn-on energy was increased by 25.4%, when the temperature rises from 25 ^{o}C to 125 ^{o}C for same V_{CE} and I_C. During the turn-off, energy losses increase with temperature. A 39.5% increase in E_{off} was recorded when the temperature rises from 25 ^{o}C to 125 ^{o}C. The reverse recovery loss doubles when temperature increases from 25 ^{o}C to 125 ^{o}C, while turn-on loss increases by 34.2%. The double pulse switch test conducted after repetitive switching test shows no change in IGBT performance. When the double

pulse switch test is repeated after the power cycling test, the dynamic characteristics of survived IGBT shows no degradation even the accidental high temperature broke one of the IGBT modules and melted the package plastic. Therefore, the IXYS^{TM} has a much great long-term stability. The Tyco^{TM} IGBT module should have a better long-term stability than the IXYS^{TM} IGBT because of the better package structure which can effectively conduct the produced energy to heatsink. By repeating the same experiment on different modules, the accuracy and credibility of used methodology were confirmed.

As the testing has shown that the IGBT module can survive at extremely high temperature for a limited time period, measuring the IGBT dynamic characteristics at 180 ^{o}C is possible and necessary. The power cycling test employed in this project was much less stressful than the standard testing method. Further tests should follow the mounting tips or use better thermal grease to ensure good contact with the heatsink, and then run it under the standard conditions [61].

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Appendix

As there is too much data to cover all of them at here, just parts of the results and pictures will present at here. For the full double pulse switch testing results of IXYS NO.1 can refer to "Original Data for IXYS", and all of the data has recorded with Excel File. The data of power cycling test and repetitive switching test also recorded in Excel Files. All of the data can get by send e-mail to dix@stud.ntnu.no. The IGBT datasheets download from IXYS^{TM} and Tyco^{TM} official documents. The gate driver and the inverter circuit abstract form SINTEF Memo.
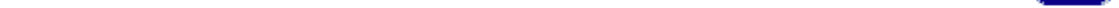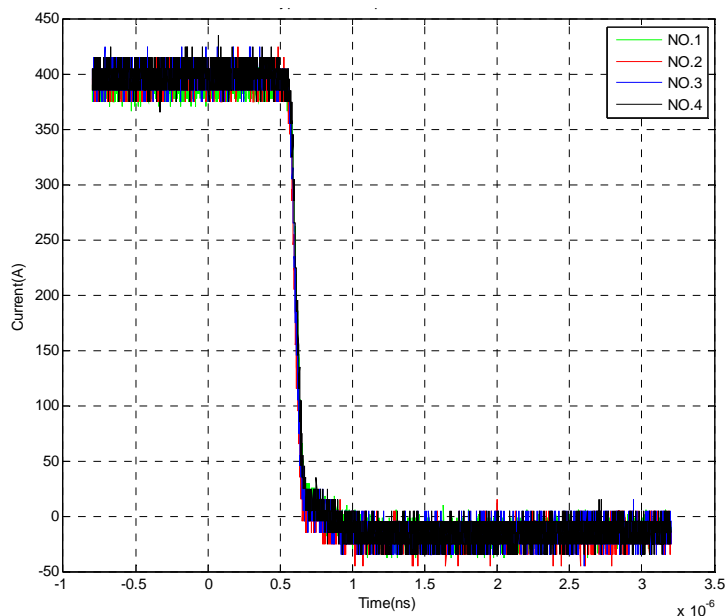
Fig A1. Four IXYS IGBT module turn off at same conditions

Table A. Switching time and energy losses at different current and temperature levels

600V	23°C switching time (ns) and energy (mJ)				80°C switching time (ns) and energy (mJ)				125°C switching time (ns) and energy (mJ)			
	t_{on}	t_{off}	E_{on}	E_{off}	t_{on}	t_{off}	E_{on}	E_{off}	t_{on}	t_{off}	E_{on}	E_{off}
400A	184.4	594.2	49.3	31.9	200	630.8	51.5	40.2	232.8	663.8	61.8	44.5
300A	160	600	27.9	27.7	173.2	636	30.6	31.3	211.4	683.2	40.0	34.3
200A	136	612.5	13.5	15.2	149.6	645.8	16.8	16.1	188	768.8	22.3	20.4
100A	111.2	624	9.1	12.2	116.2	774.8	9.8	12.5	161.6	845.2	12.4	13.7
50A	76.6	753.2	5.2	4.8	97.2	784	5.8	5.6	134.8	898.8	8.1	8.2
25A	73.6	594.2	3.1	N/A	85.6	630.8	3.8	4.0	127.2	663.8	5.2	4.8
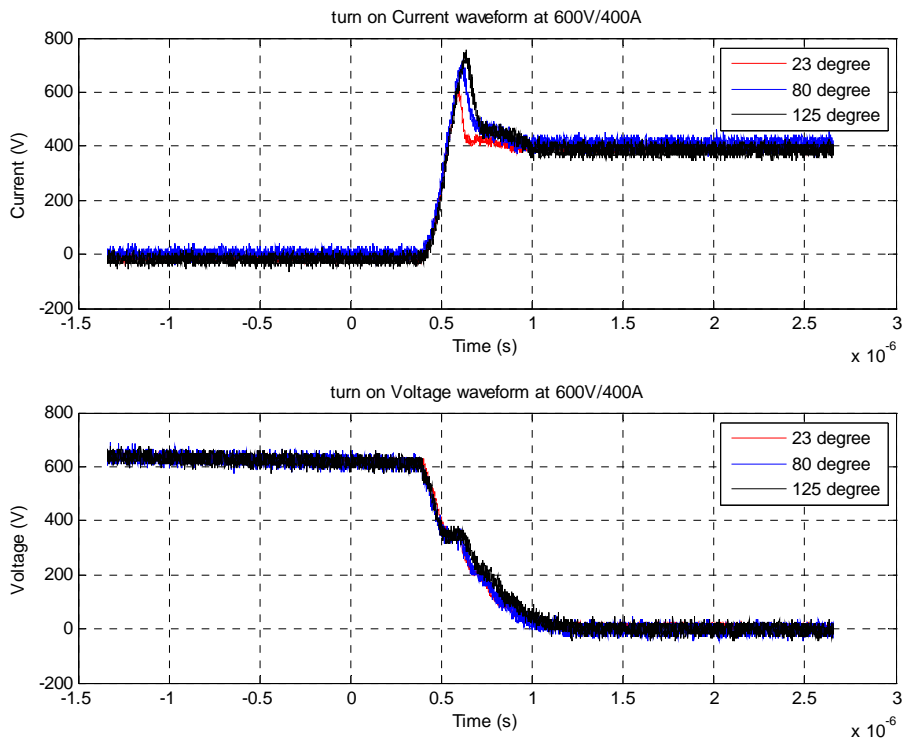
Fig A2. Turn on time comparison at different temperatures
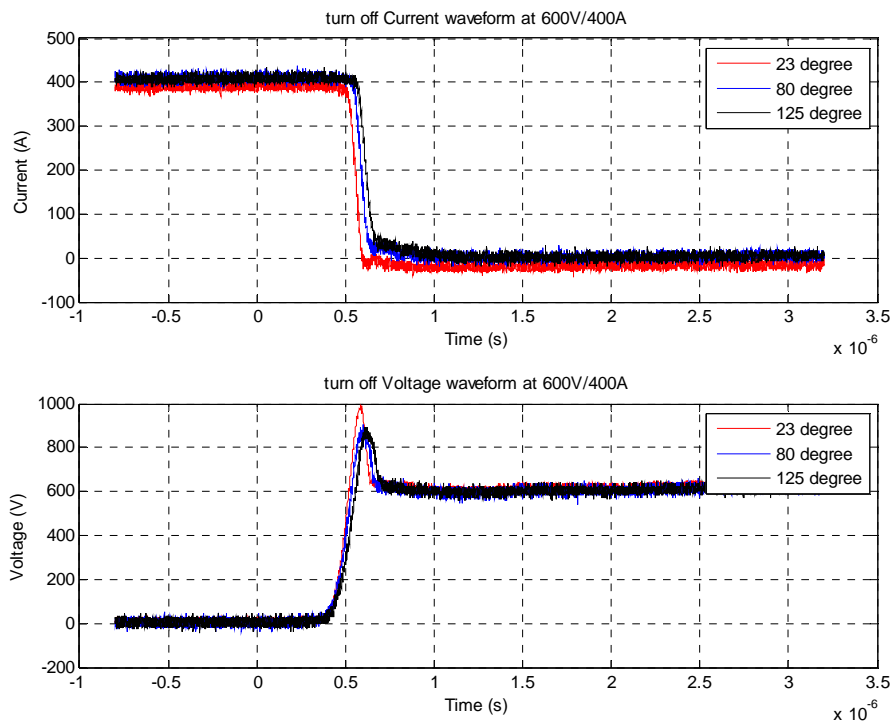
Fig A3. Turn off current waveform at different temperatures
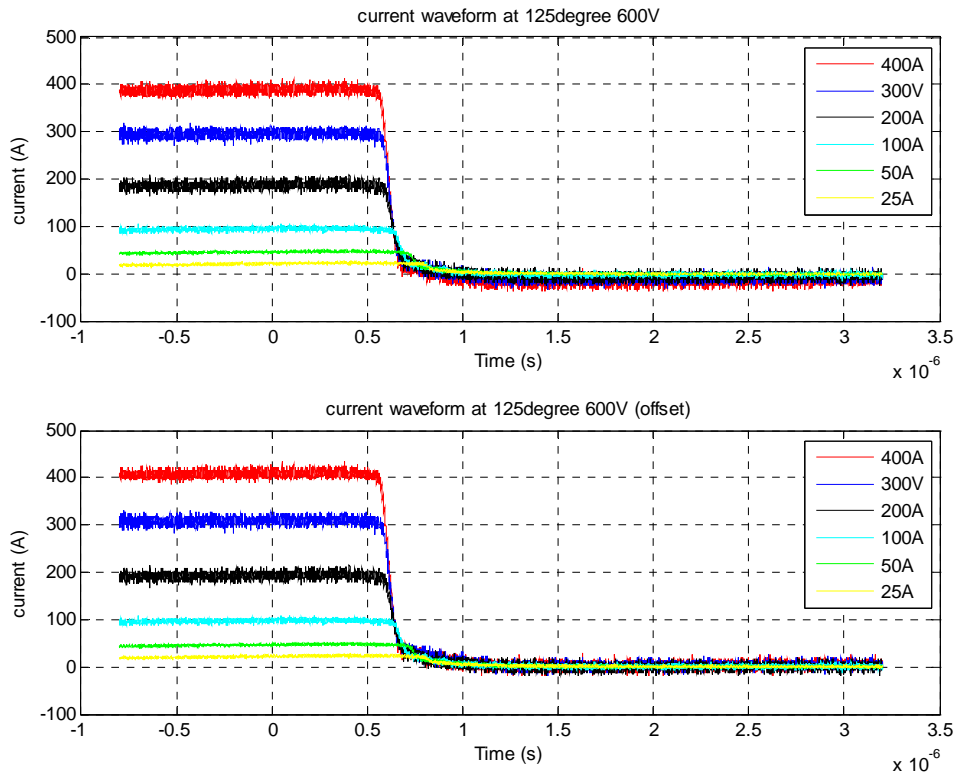
Fig A4. Current waveform before and after offset
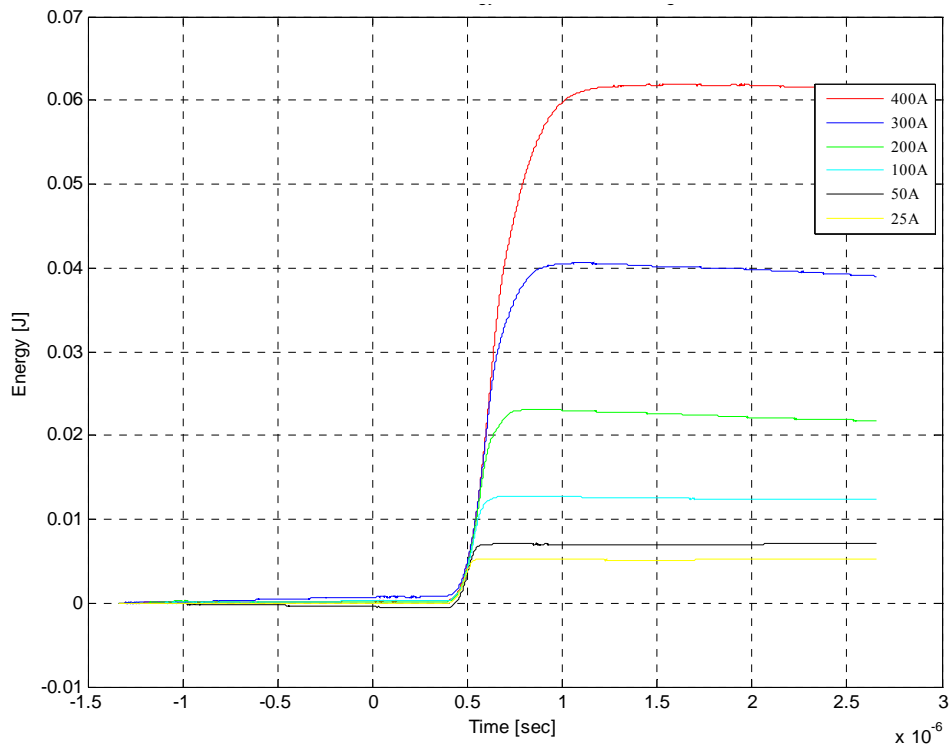
Fig A5. Turn-on Energy loss at different current levels
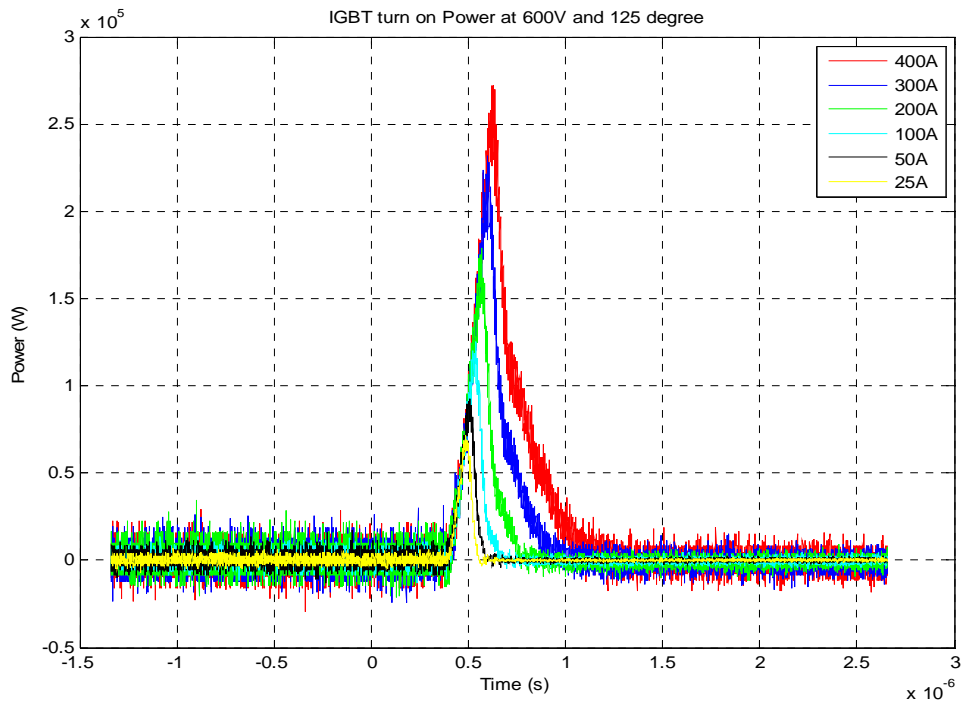
Fig A6. turn-on power loss at different current
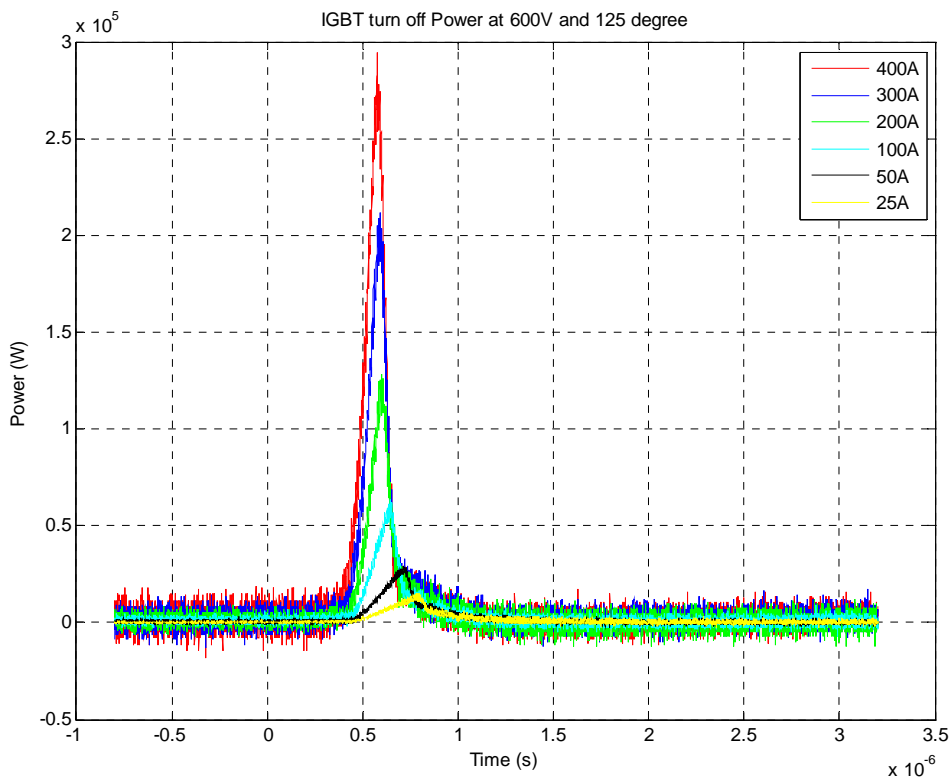
Fig A7.   turn-on power loss at different current
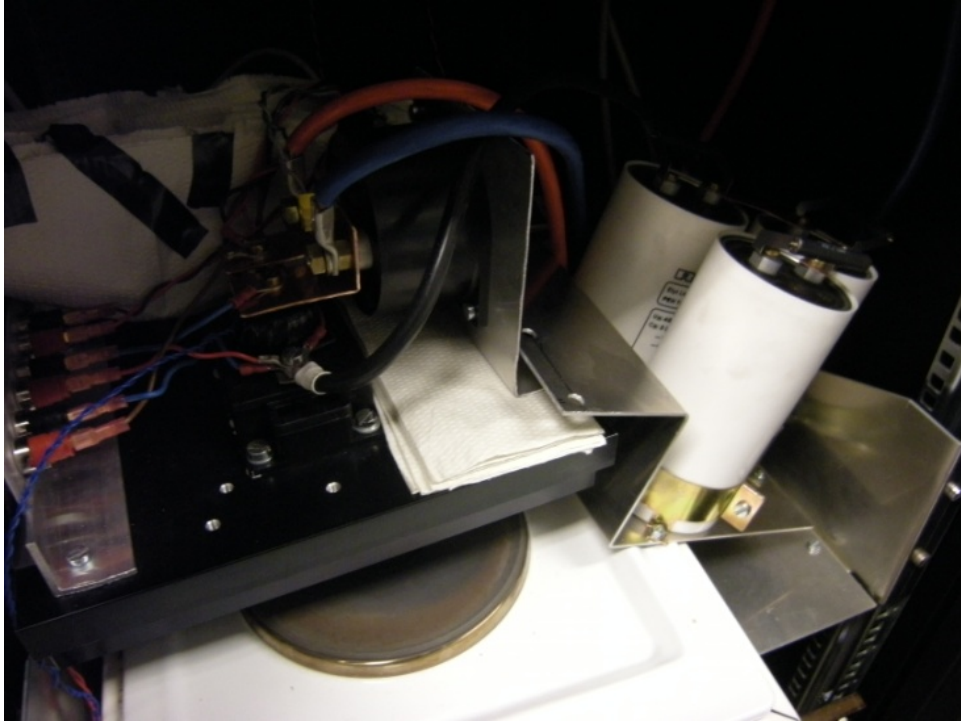
Fig A8. Capacitor location whiter (first time) and black (Later) to reduce the stray inductance

IXYS IGBT module NO.2 at 23 $^\circ$C

200V 50A 23 $^\circ$C
Turn on
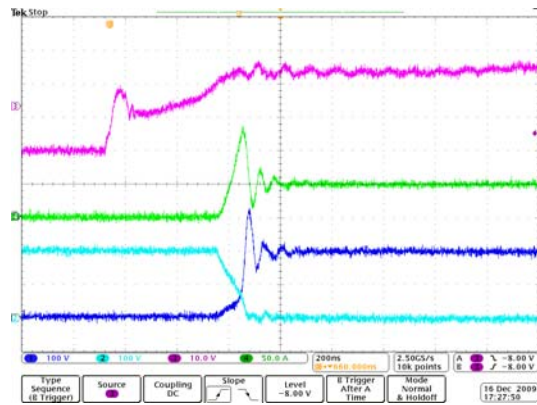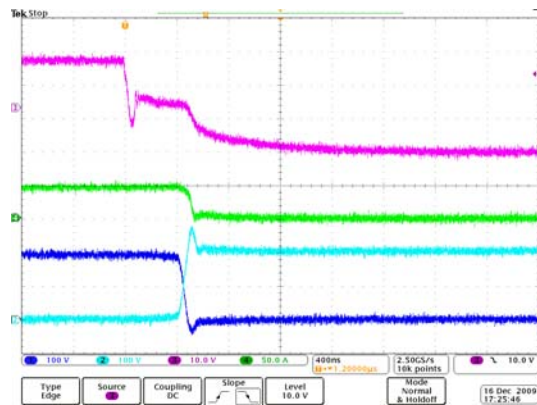
Turn off

200 V 400 A 23 $^\circ$C
Turn on
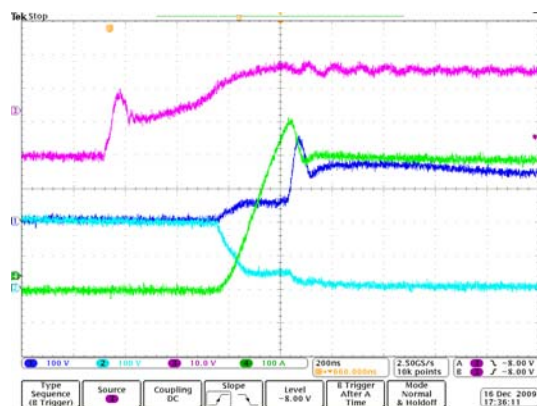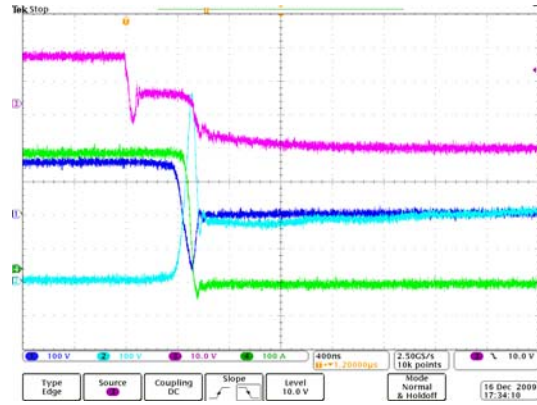
Turn off

400 V 400 A 23 $^\circ$C
Turn on
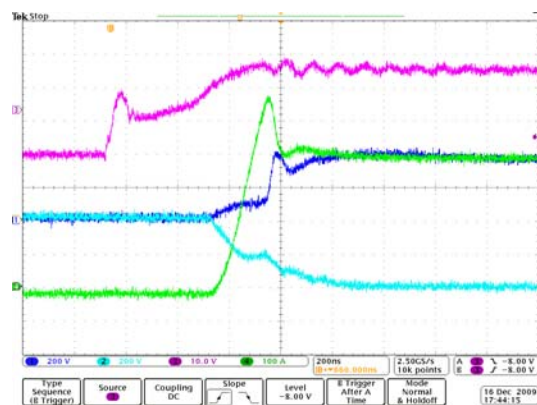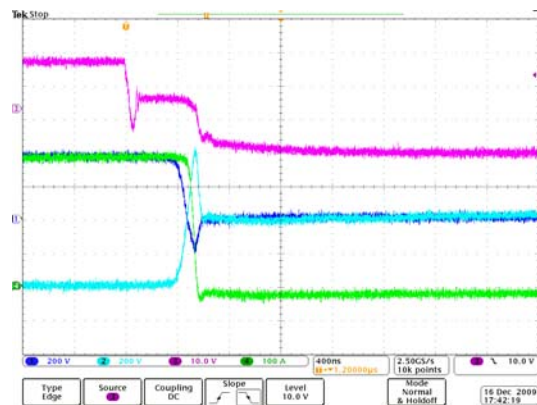
Turn off

600 V 400 A 23 °C
Turn on
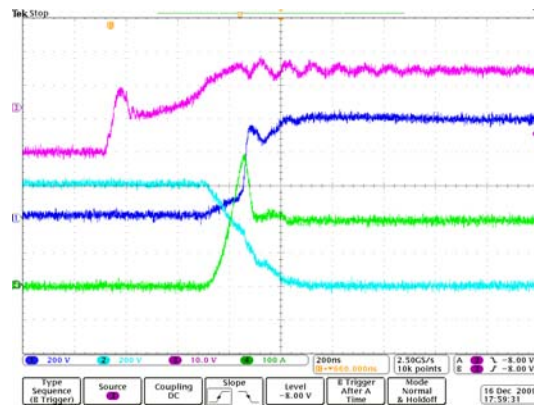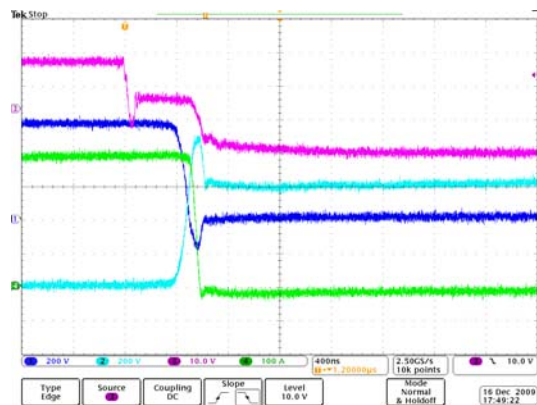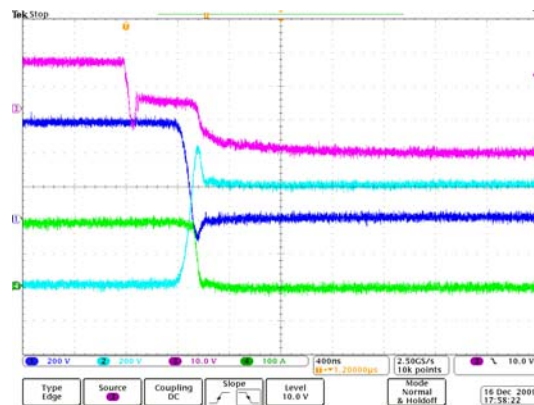
Turn off

600V 300A 23 °C
Turn on

Turn off

600 V 200 A 23 °C
Turn on
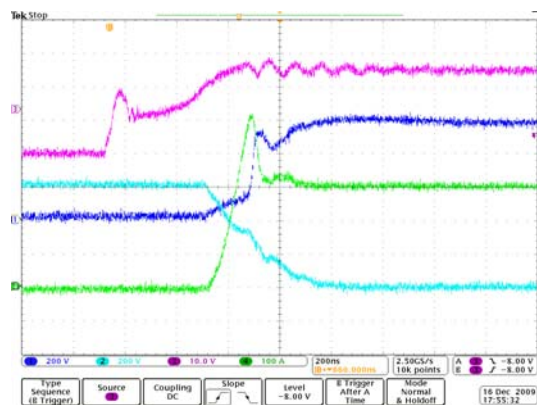
Turn off

600V 100A 23 °C
Turn on
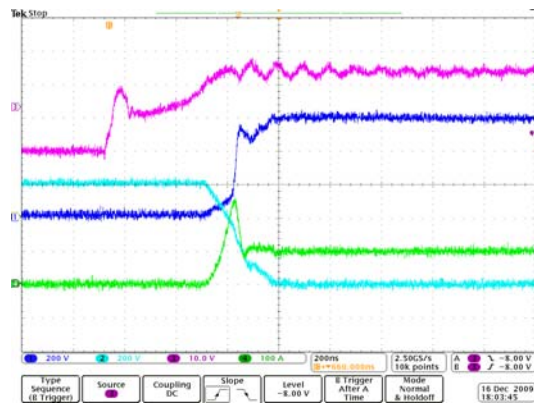
Turn off
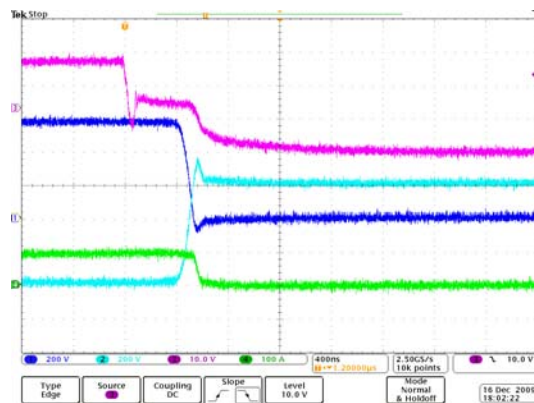
600V 50A 23 °C
Turn on
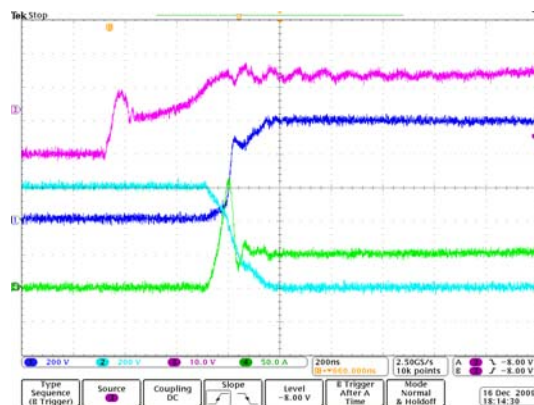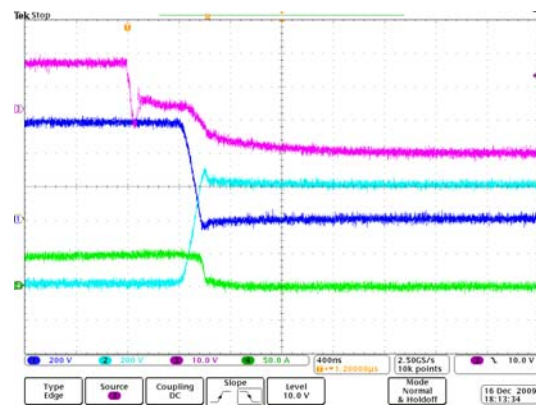
Turn off

IXYS IGBT NO.2 at 80 °C

200 V 50 A 80 °C
Turn on
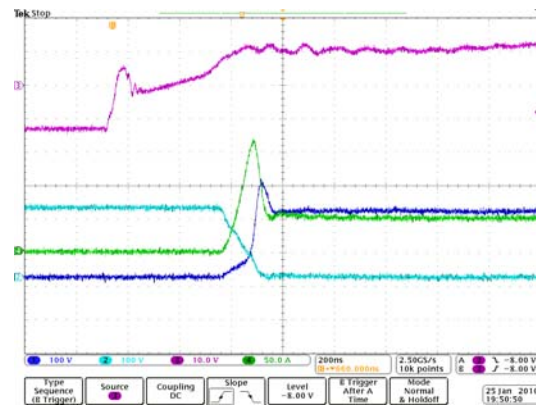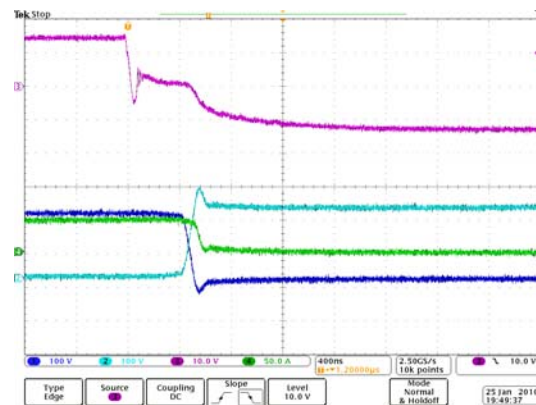
Turn off

200 V 400 A   80 °C
Turn on

Turn off
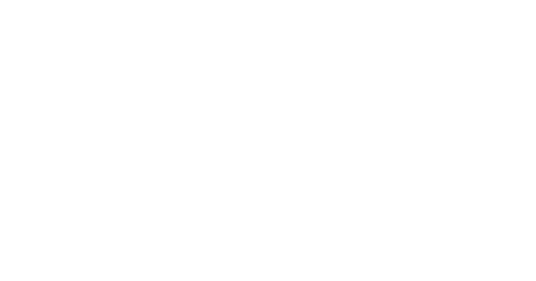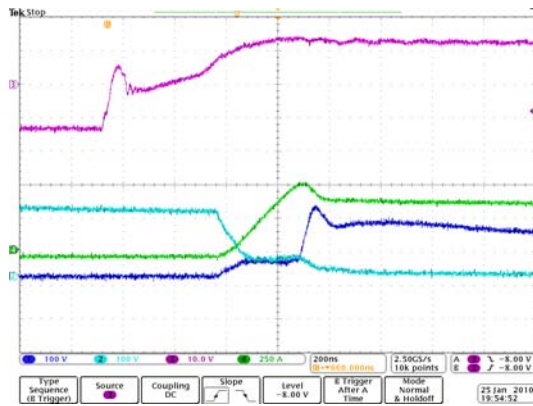
600V 400A 80 °C
Turn on

400V 400A 80 °C
Turn on
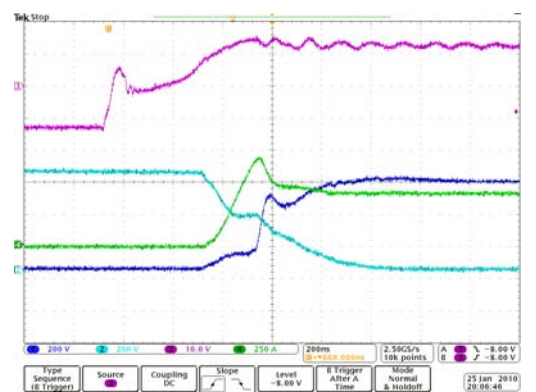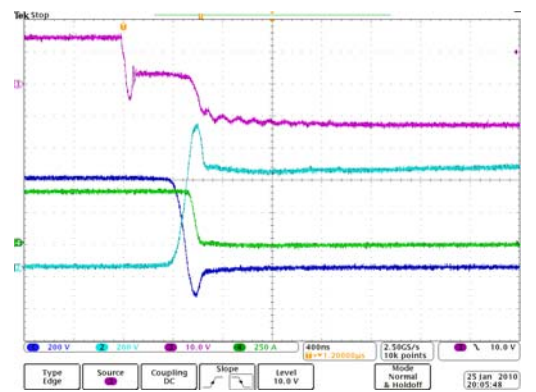
Turn off

Turn off

600V 300A 80 °C
Turn on
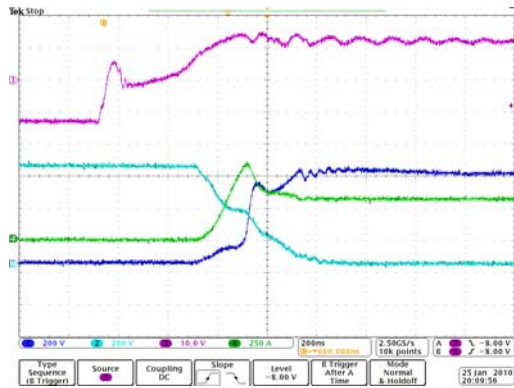
Turn off
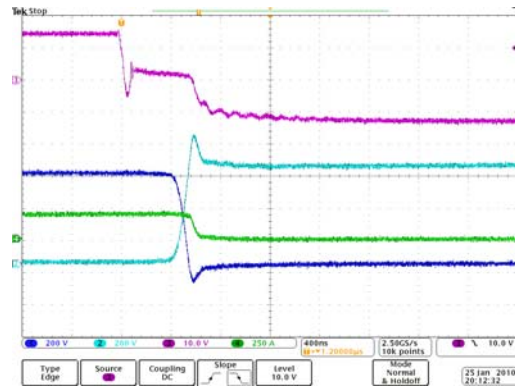
600 V 100 A 80 °C
Turn on
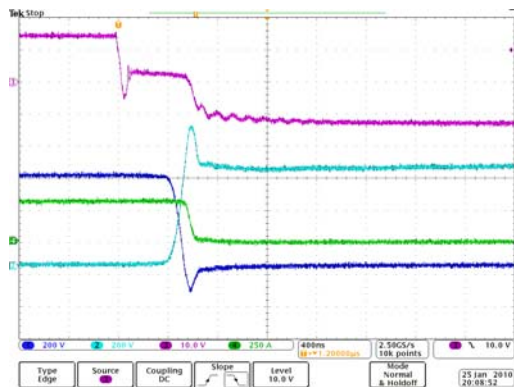
600V 200A 80 °C
Turn on
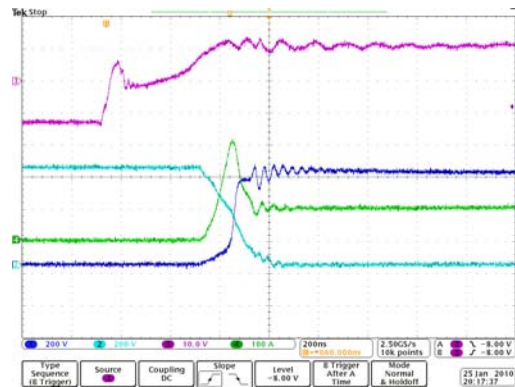
Turn off
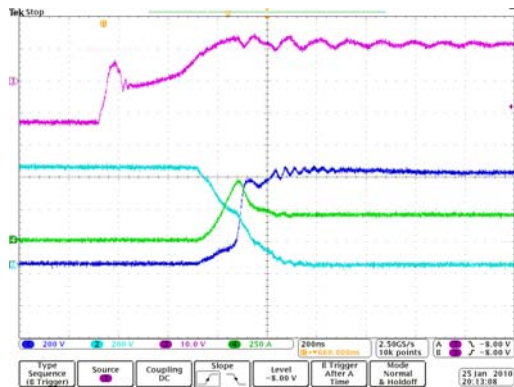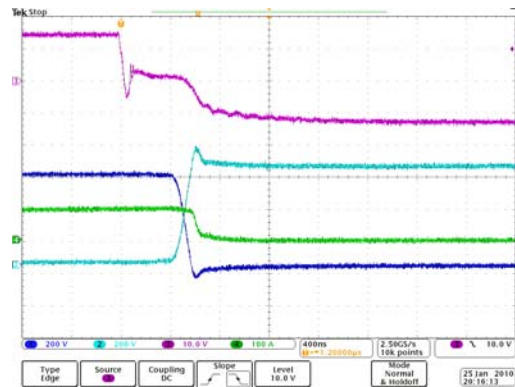
Turn off

600 V 50 A 80 °C
Turn on
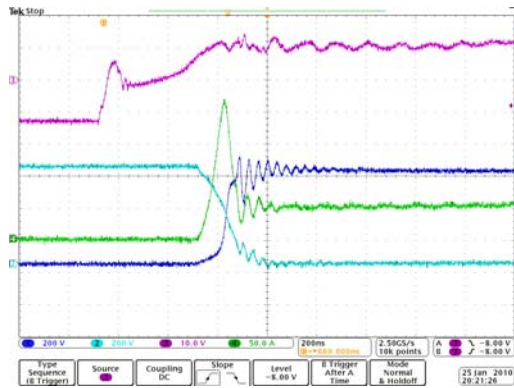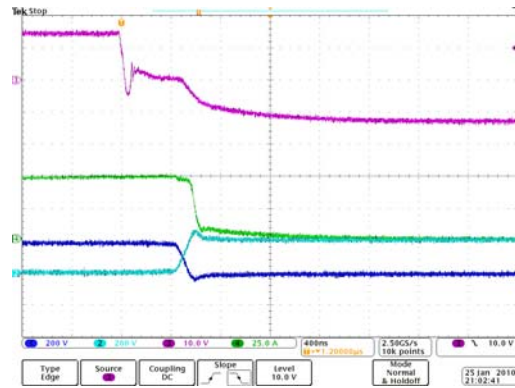
Turn off

200 V 400 A 125 °C
Turn on
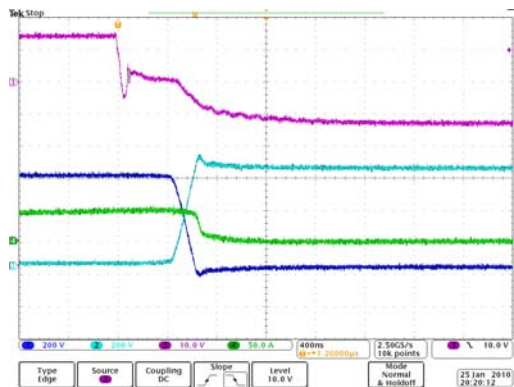
IXYS IGBT NO.2 at 125 °C

Turn off

200 V 50 A 125 °C
Turn on
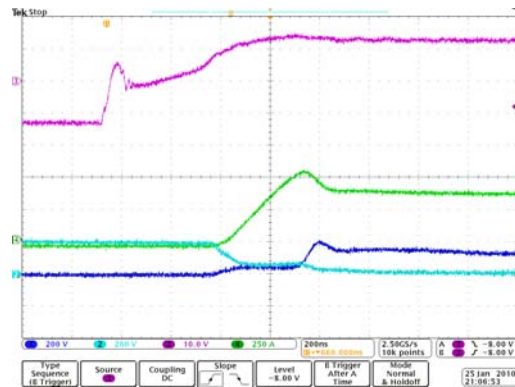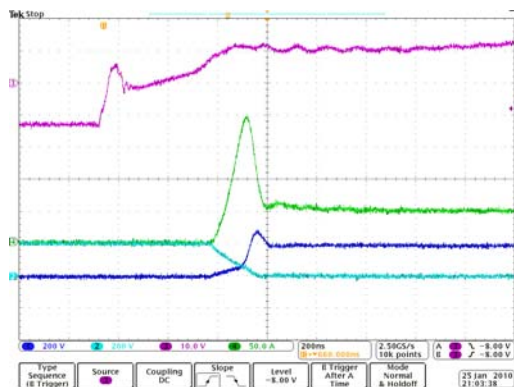
Turn off
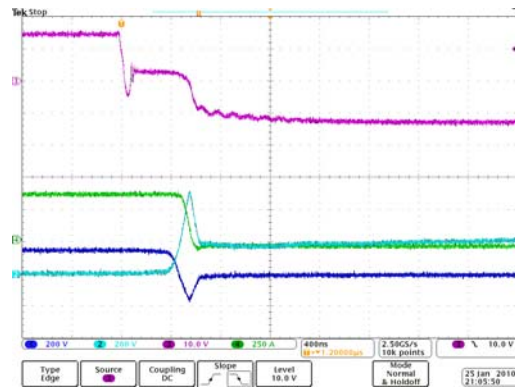
400 V 400 A 125 °C
Turn on
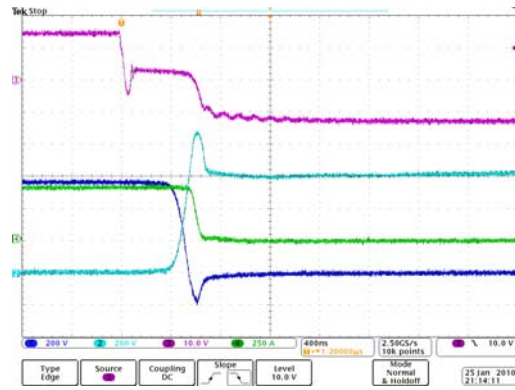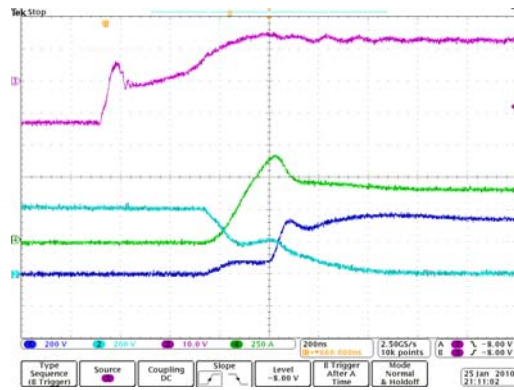
Turn off

600 V 400 A 125 °C
Turn on

Turn off

600 V 300 A 125 °C
Turn on
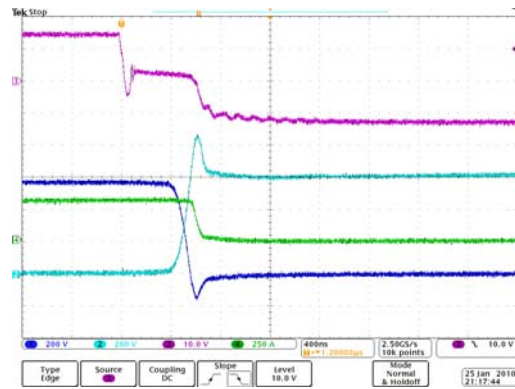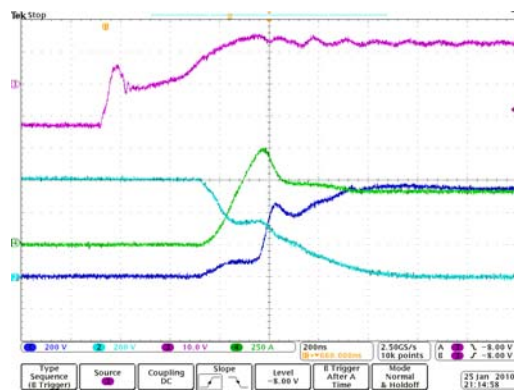
Turn off

600V 200A 125 °C
Turn on
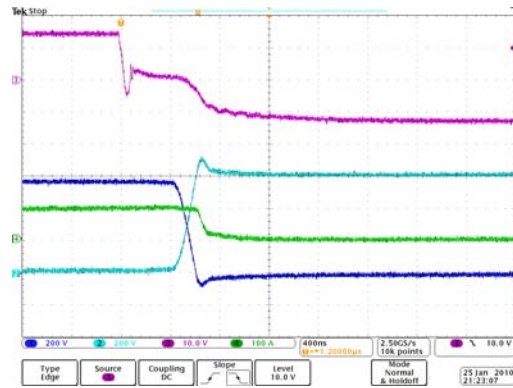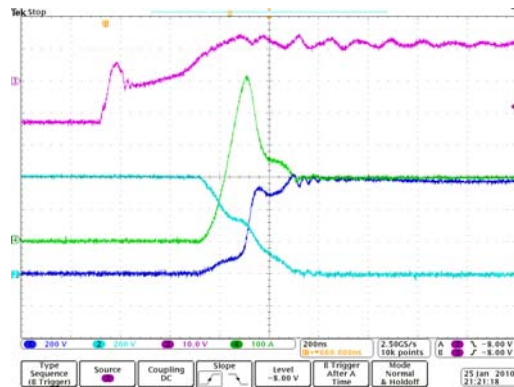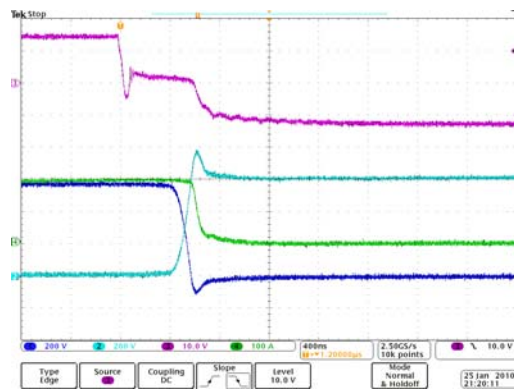
Turn off

600V 200A 125 °C
Turn on
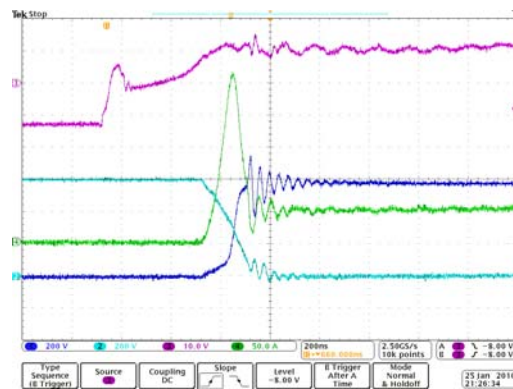
Turn off

600 V 100 A 125 °C
Turn on
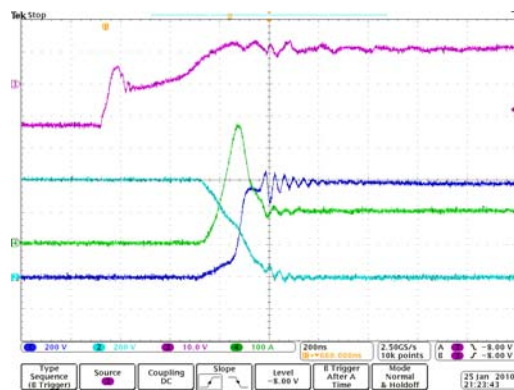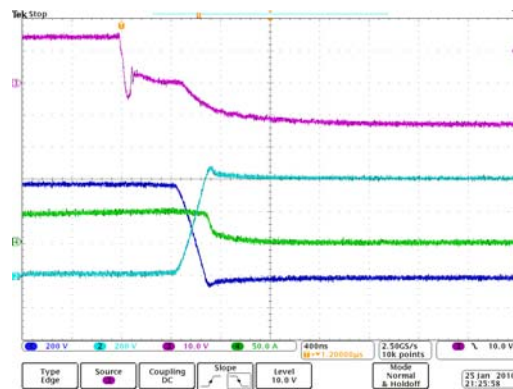
Turn off

Some Useful MATLAB Command

Info_loading = xlsread ('filename', 1) ;   %loading excel file sheet 1.

Time=Info_loading (2:end, 1);   %Time is the matrix of column 1 in sheet 1.

CH1=Info_loading(2:end,2);   %CH1 is the matrix of column 2 in sheet 1.

CH2=Info_loading(2:end, 3);

CH3=Info_loading(2:end, 4);

CH4=Info_loading(2:end, 5);

plot(Time, CH1,'k');   % plot the figure of Time-CH1, and curve is black.

Energy loss calculator:

clear P98

RCH298=CH298;   %IGBT Voltage, Off set voltage

RCH498=CH498+15;   %IGBT   Current, Off set current

P98=RCH298.*RCH498;   % Power Calculator

clear E

detaT= Time98(6)-Time98(5)

E(1)=P98(1)*detaT

  for i=2:10000;   %Energy loss calculator

      E(i)=E(i-1)+P98(i)*detaT;

end

plot(Time98,E)

grid on

hold off

IXYS

IGBT Module
phaseleg and chopper topolgies

MII 400-12E4
MID 400-12E4
MDI 400-12E4

I_{C25} = 420 A
V_{CES} = 1200 V
$V_{CE(sat)\ typ.}$ = 2.2 V

Preliminary

MII **MID** **MDI**
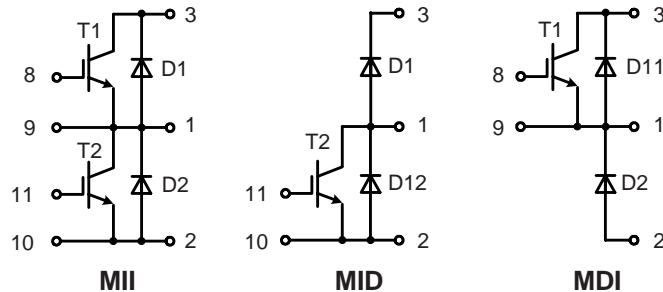
IGBTs T1-T2		

Symbol	Conditions	Maximum Ratings	
V_{CES}	T_{VJ} = 25°C to 150°C	1200	V
V_{GES}		± 20	V
I_{C25}	T_C = 25°C	420	A
I_{C80}	T_C = 80°C	300	A
I_{CM}	V_{GE} = ±15 V; R_G = 4.7 Ω; T_{VJ} = 125°C	450	A
V_{CEK}	**RBSOA**, Clamped inductive load; L = 100 µH	V_{CES}	
t_{SC} (SCSOA)	V_{CE} = 900 V; V_{GE} = ±15 V; R_G = 4.7 Ω; T_{VJ} = 125°C non repetitive	10	µs
P_{tot}	T_C = 25°C	1700	W

Symbol	Conditions	Characteristic Values $(T_{VJ}$ = 25°C, unless otherwise specified)			
		min.	typ.	max.	
$V_{CE(sat)}$	I_C = 300 A; V_{GE} = 15 V; T_{VJ} = 25°C		2.2	2.8	V
	T_{VJ} = 125°C		2.6		V
$V_{GE(th)}$	I_C = 10 mA; V_{GE} = V_{CE}	4.5		6.5	V
I_{CES}	V_{CE} = V_{CES}; V_{GE} = 0 V; T_{VJ} = 25°C		0.8	3.3	mA
	T_{VJ} = 125°C		3.5		mA
I_{GES}	V_{CE} = 0 V; V_{GE} = ± 20 V			600	nA
$t_{d(on)}$			150		ns
t_r	Inductive load, T_{VJ} = 125°C		60		ns
$t_{d(off)}$	V_{CE} = 600 V; I_C = 300 A		680		ns
t_f	V_{GE} = ±15 V; R_G = 4.7 Ω		50		ns
E_{on}			36		mJ
E_{off}			30		mJ
C_{ies}	V_{CE} = 25 V; V_{GE} = 0 V; f = 1 MHz		17		nF
Q_{Gon}	V_{CE} = 600 V; V_{GE} = 15 V; I_C = 300 A		2.25		µC
R_{thJC}	(per IGBT)			0.08	K/W
R_{thJH}	with heatsink compound		0.15		K/W

Features

- IGBT
  - low saturation voltage
  - positive temperature coefficient
  - fast switching
  - short tail current for optimized performance in resonant circuits
- HiPerFRED™ diodes
  - fast and soft reverse recovery
  - low operating forward voltage
  - low leakage current
- Package
  - low inductive current path
  - screw connection to high current main terminals
  - use of non interchangeable connectors for auxiliary terminals possible
  - kelvin emitter terminal for easy drive
  - isolated ceramic base plate

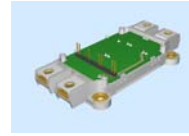**Applications**

- drives
  - AC
  - DC
- power supplies
  - rectifiers with power factor correction and recuperation capability
  - UPS

225

1 - 2

**Dimensions in mm (1 mm = 0.0394")**

Free wheeling diodes D1-D2

Symbol	Conditions	Maximum Ratings	
I_{F25}	$T_C = 25°C$	450	A
I_{F80}	$T_C = 80°C$	290	A

Symbol	Conditions	Characteristic Values			
		min.	typ.	max.	
V_F	$I_F = 300$ A; $V_{GE} = 0$ V; $T_{VJ} = 25°C$		2.3	2.7	V
	$T_{VJ} = 125°C$		1.7		V
I_{RM}	$I_F = 225$ A; $di_F/dt = -2000$ A/µs; $T_{VJ} = 125°C$		240		A
t_{rr}	$V_R = 600$ V; $V_{GE} = 0$ V		220		ns
R_{thJC}	(per diode)			0.15	K/W
R_{thJH}	with heatsink compound		0.3		K/W

Chopper anti parallel diodes D11-D12

Symbol	Conditions	Maximum Ratings	
I_{F25}	$T_C = 25°C$	150	A
I_{F80}	$T_C = 80°C$	95	A

Symbol	Conditions	Characteristic Values			
		min.	typ.	max.	
V_F	$I_F = 100$ A; $V_{GE} = 0$ V; $T_{VJ} = 25°C$		2.3	2.7	V
	$T_{VJ} = 125°C$		1.7		V
I_{RM}	$I_F = 75$ A; $di_F/dt = -750$ A/µs; $T_{VJ} = 125°C$		80		A
t_{rr}	$V_R = 600$ V; $V_{GE} = 0$ V		220		ns
R_{thJC}	(per diode)			0.45	K/W
R_{thJH}	with heatsink compound		0.9		K/W

Module

Symbol	Conditions	Maximum Ratings	
T_{VJ}		-40...+150	°C
T_{stg}		-40...+125	°C
V_{ISOL}	$I_{ISOL} \leq 1$ mA; 50/60 Hz	4000	V~
M_d	Mounting torque (module, M6)	2.25 - 2.75	Nm
	(terminals, M6)	4.5 - 5.5	Nm

Symbol	Conditions	Characteristic Values			
		min.	typ.	max.	
d_S	Creepage distance on surface	2			mm
d_A	Strike distance in air	2			mm
Weight			250		g

Optional accessories for modules

keyed twin plugs
(UL758, style 1385, CSA class 5851, guide 460-1-1)

- Type ZY180L with wire length 350mm
  – for pins 4 (yellow wire) and 5 (red wire)
  – for pins 11 (yellow wire) and 10 (red wire)

- Type ZY180R with wire length 350mm
  – for pins 7 (yellow wire) and 6 (red wire)
  – for pins 8 (yellow wire) and 9 (red wire)

*flow*PHASE 2	1200V / 300A

Features
● Reliable solder and screw contacts ● Compact and low inductive design

*flow*SCREW 2 housing

Target Applications
● Motor Drive ● Uninteruptable Power Supply (UPS) ● Welding

Schematics
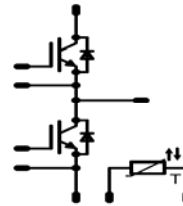
Types
● V23990-P610-F02-PM with connector PCB

Maximum Ratings

Parameter	Symbol	Condition		Value	Unit
Transistor Inverter					
Collector-emitter break down voltage	V_{CE}			1200	V
DC collector current	I_C	$T_j=T_j$max	$T_h=80°C$	278	A
			$T_c=80°C$	tbd	
Repetitive peak collector current	I_{cpuls}	tp limited by $T_j$max		900	A
Power dissipation per IGBT	P_{tot}	$T_j=T_j$max	$T_h=80°C$	560	W
			$T_c=80°C$	tbd	
Gate-emitter peak voltage	V_{GE}			±20	V
SC withstand time*	t_{SC}	$T_j≤125°C$ $V_{GE}=15V$ $V_{CC}=900V$		10	µs
Maximum junction temperature	Tjmax			150°C	°C

* It is recommended to not exceed 1000 short circuit situations in the lifetime of the module and to allow at least 1s between short circuits

Parameter	Symbol	Condition		Value	Unit
Diode Inverter					
DC forward current	I_F	$T_j=T_j$max	$T_h=80°C$	130	A
Repetitive peak forward current	I_{FRM}	tp limited by $T_j$max		2000	A
Power dissipation per Diode	P_{tot}	$T_j=T_j$max	$T_h=80°C$	280	W
			$T_c=80°C$	tbd	
Maximum junction temperature	Tjmax			150°C	°C

Revision: 1

Maximum Ratings

Parameter	Symbol	Condition	Value	Unit
Thermal properties				
Storage temperature	T_{stg}		-40…+125	°C
Operation temperature	T_{op}		-40…+125	°C
Insulation properties				
Insulation voltage	V_{is}	t=1min	4000	Vdc
Creepage distance			min 12,7	mm
Clearance			min 12,7	mm

Characteristic Values

Parameter	Symbol	Conditions				Value			Unit
		$V_{GE}(V)$ or $V_{GS}(V)$	$V_r(V)$ or $V_{CE}(V)$ or $V_{DS}(V)$	$I_C(A)$ or $I_F(A)$ or $I_D(A)$	T(C°)	Min	Typ	Max	
Transistor Inverter									
Gate emitter threshold voltage	$V_{GE(th)}$	VCE=VGE		0,012	Tj=25°C	5	5,8	6,5	V
					Tj=125°C				
Collector-emitter saturation voltage	$V_{CE(sat)}$	15		300	Tj=25°C	1,3	1,8	2,2	V
					Tj=125°C		2		
Collector-emitter cut-off	I_{CES}	0	1200		Tj=25°C			2	mA
					Tj=125°C				
Gate-emitter leakage current	I_{GES}	30	0		Tj=25°C			1400	nA
					Tj=125°C				
Integrated Gate resistor	R_{gint}						2,5		Ohm
Turn-on delay time	$t_{d(on)}$				Tj=25°C				ns
					Tj=125°C		310		
Rise time	t_r				Tj=25°C				ns
					Tj=125°C		40		
Turn-off delay time	$t_{d(off)}$	Rgoff=2Ω Rgon=2Ω	±15	600	300	Tj=25°C			ns
					Tj=125°C		540		
Fall time	t_f				Tj=25°C				ns
					Tj=125°C		170		
Turn-on energy loss per pulse	E_{on}				Tj=25°C				mWs
					Tj=125°C		52		
Turn-off energy loss per pulse	E_{off}				Tj=25°C				mWs
					Tj=125°C		32		
SC withstand time	t_{SC}								µs
Input capacitance	C_{ies}	0	25		Tj=25°C		22		nF
					Tj=125°C				
Output capacitance	C_{oss}	f=1MHz 0	25		Tj=25°C		4,2		nF
					Tj=125°C				
Reverse transfer capacitance	C_{rss}	0	25		Tj=25°C		3,6		nF
					Tj=125°C				
Gate charge	Q_{Gate}	±15			Tj=25°C		2800		nC
					Tj=125°C				
Thermal resistance chip to heatsink per chip	R_{thJH}	Thermal grease thickness ≤ 50 um λ = 0,61 W/mK					0,125		K/W
Coupled thermal resistance diode-transistor	R_{thJH}						tbd		K/W
Coupled thermal resistance transistor-transistor	R_{thJH}						tbd		K/W
Diode Inverter									
Diode forward voltage	V_F			300	Tj=25°C	1	1,85	2,4	V
Peak reverse recovery current	I_{RM}	Rgon=2Ω diF/dt=6000 A/us	0	600	300	Tj=25°C			A
						Tj=125°C	300		
Reverse recovery time	t_{rr}	Rgon=2Ω diF/dt=6000 A/us	0	600	300	Tj=25°C			ns
						Tj=125°C	800		
Reverse recovery charge	Q_{rr}	Rgon=2Ω diF/dt=6000 A/us	0	600	300	Tj=125°C		77		µC
Reverse recovery energy	Erec	Rgon=2Ω diF/dt=6000 A/us	0	600	300	Tj=25°C			mWs
						Tj=125°C	30		
Thermal resistance chip to heatsink per chip	R_{thJH}						0,25		K/W
Thermal resistance chip to case per chip	R_{thJC}	Thermal grease thickness ≤ 50 um λ = 0,61 W/mK					tbd		K/W
Coupled thermal resistance transistor-diode	R_{thJH}						tbd		K/W
Coupled thermal resistance diode-diode	R_{thJH}						tbd		K/W
NTC Thermistor									
Rated resistance	R_{25}				Tj=25°C	4,46	4,7	4,94	kOhm
Deviation of R100	$D_{R/R}$	R100=226Ω			Tc=100°C		3		%/K
Power dissipation given Epcos-Type	P				Tj=25°C		210		mW
B-value	$B_{(25/100)}$	Tol. ±3%			Tj=25°C		4500		K

Package Outline and Pinout

Outline

117
91
17,75

DC- 3

OUT 1

64
38
22
43
50

DC+ 4

OUT 2

63,1
77 +0,3
104

Ex2	G2	Ex1	G1	Cx1	T2	T1
20,66	18,12	7,96	5,42	0	4,74	14,9	17,44

convex: min. −0,025mm
max. 0,025mm

Pinout

DC+

Cx1

G1
Ex1

OUT1/2

G2
Ex2

DC-   T1   T2   T

4

Revision: 1
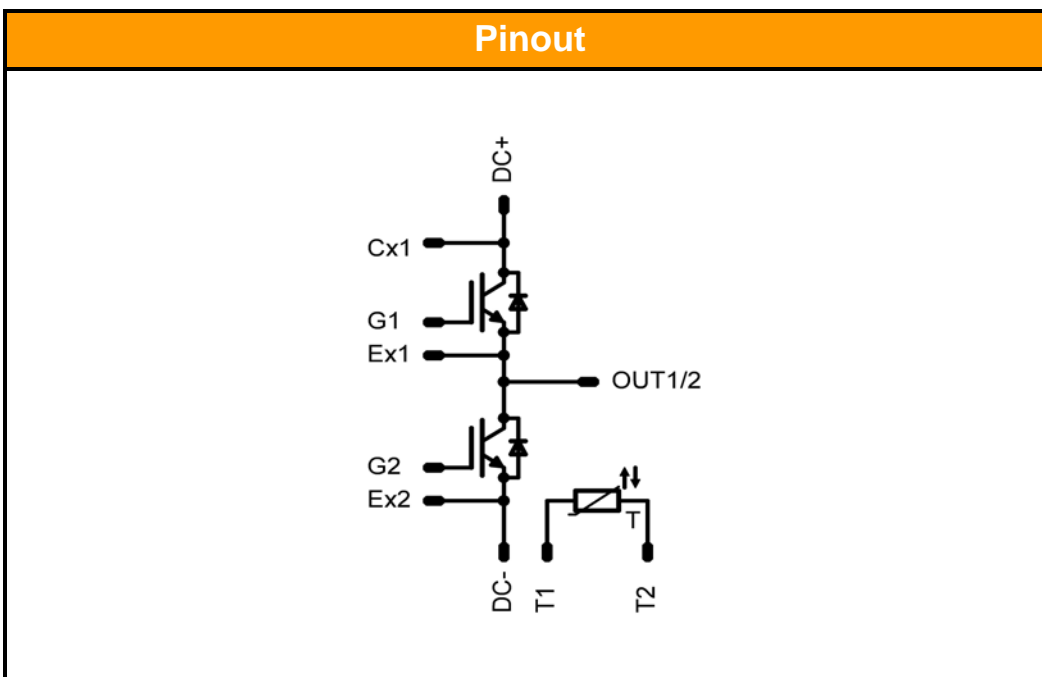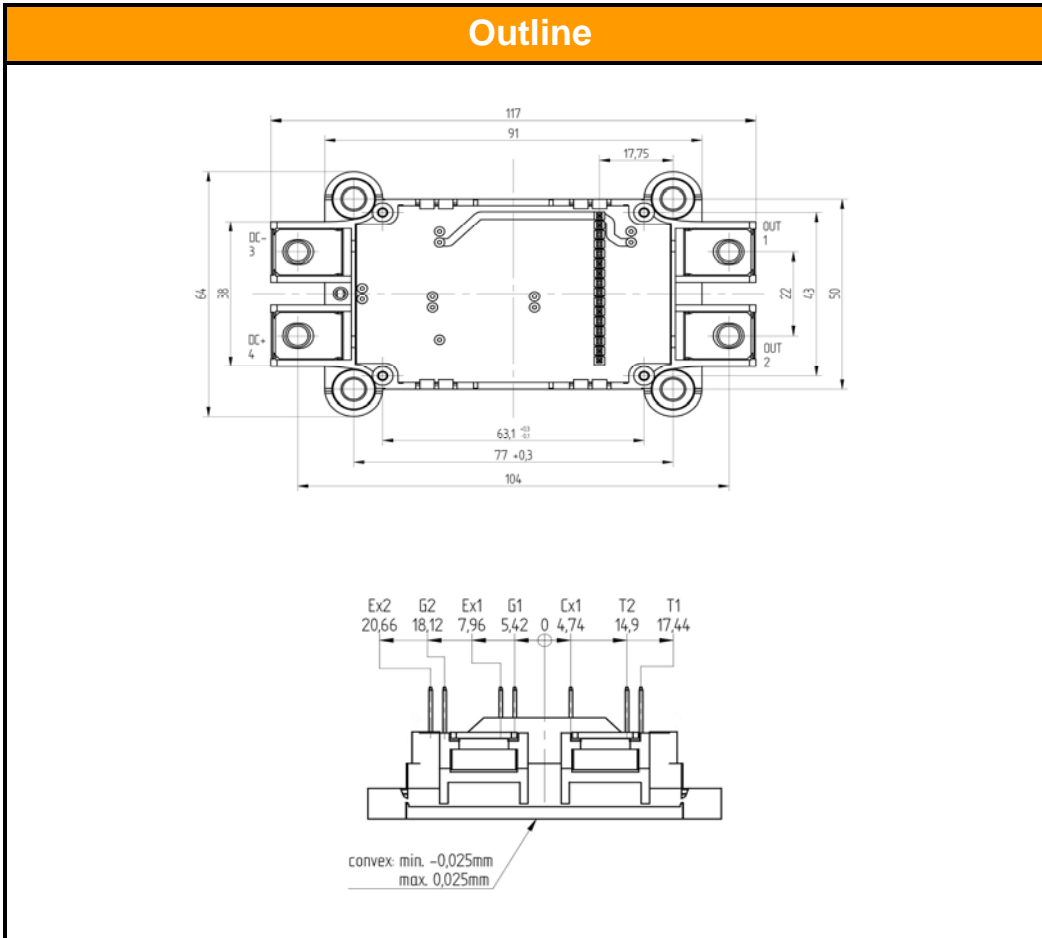
PRODUCT STATUS DEFINITIONS

Datasheet Status	Product Status	Definition
Target	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice. The data contained is exclusively intended for technically trained staff.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data may be published at a later date. Tyco Electronics reserves the right to make changes at any time without notice in order to improve design. The data contained is exclusively intended for technically trained staff.
Final	Full Production	This datasheet contains final specifications. Tyco Electronics reserves the right to make changes at any time without notice in order to improve design. The data contained is exclusively intended for technically trained staff.

APPENDIX C: 20kW Laboratory Inverter [3]

6   KOBLINGSSKJEMA
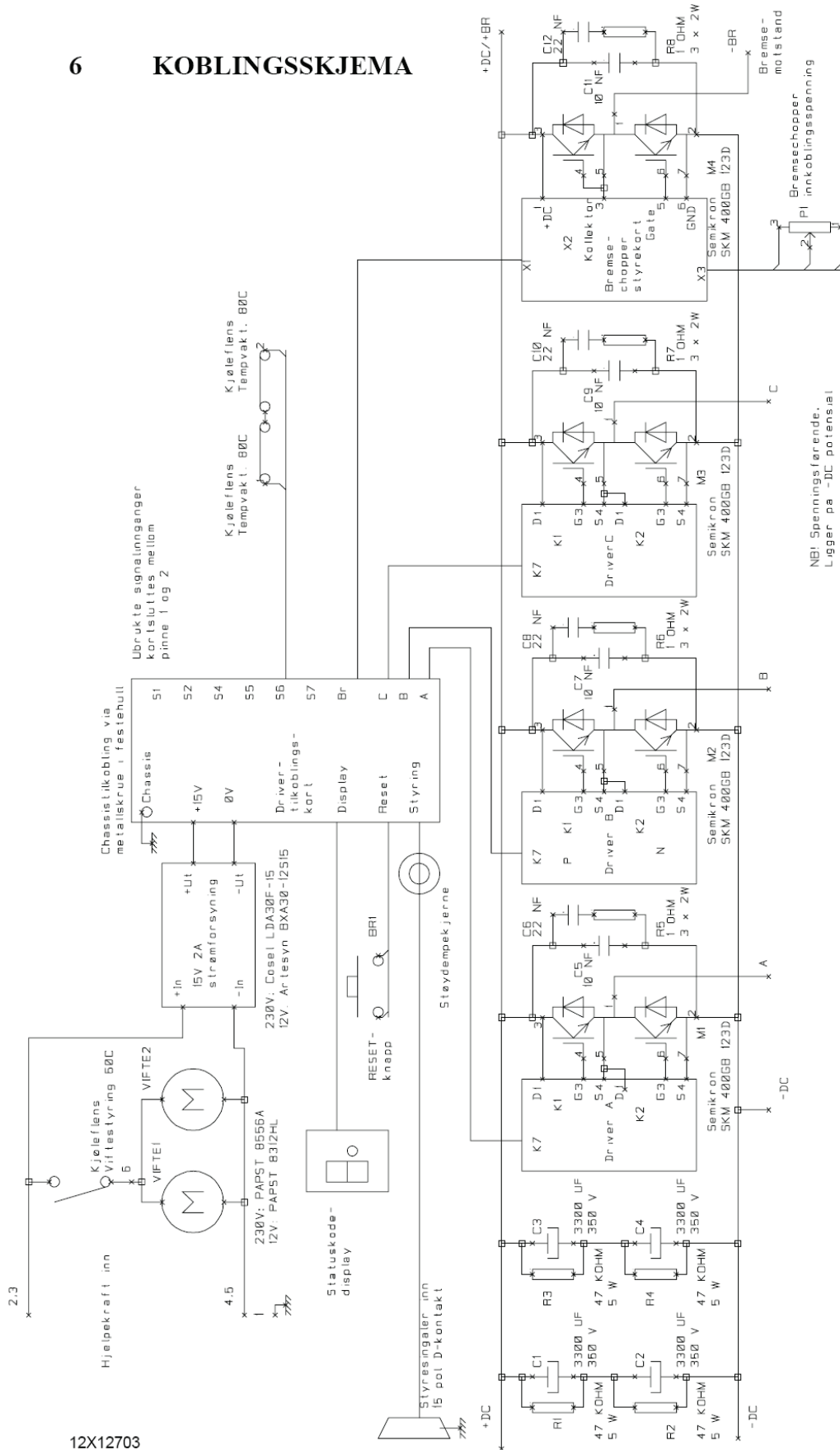
APPENDIX D: Analog Current Control Board [13]

![SINTEF Energiforskning logo]	ARBEIDSNOTAT	
SINTEF Energiforskning AS	**GJELDER** **Analog strømregulatorkort. v1.0**	
Postadresse: 7034 Trondheim Resepsjon: Sem Sælands vei 11 Telefon: 73 59 72 00 Telefaks: 73 59 72 50 http://www.energy.sintef.no F. nr.: NO 939 350 675	**GÅR TIL**	

AN NR.	GRADERING	GJENNOMGÅTT AV	
AN98.13.44	Åpen	Terje Rogne	
ELEKTRONISK ARKIVKODE		FORFATTER(E)	DATO
J:\DOK\13\klj\98004216.DOC		Kjell Ljøkelsøy	1998-11-17
PROSJEKTNR.			ANTALL SIDER
13X081.01		Kjell.Ljokelsoy@energy.sintef.no	14
AVDELING		BESØKSADRESSE	LOKAL TELEFAKS
Elektriske anlegg		Sem Sælandsvei 11	73 59 72 50

Dokumentet inneholder: Skjema, komponentplassering, deleliste, tilkoblingsliste, kommentarer.
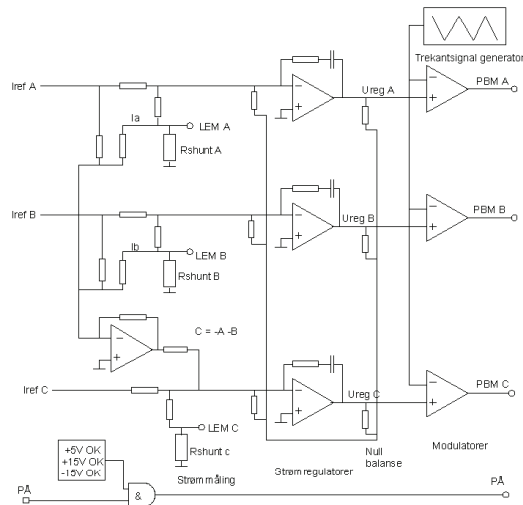
Kortet inneholder tre analoge strømregulatorer med tilhørende pulsbreddemodulatorer, samt shuntmotstander for strømmåling med LEM transfoshunter.
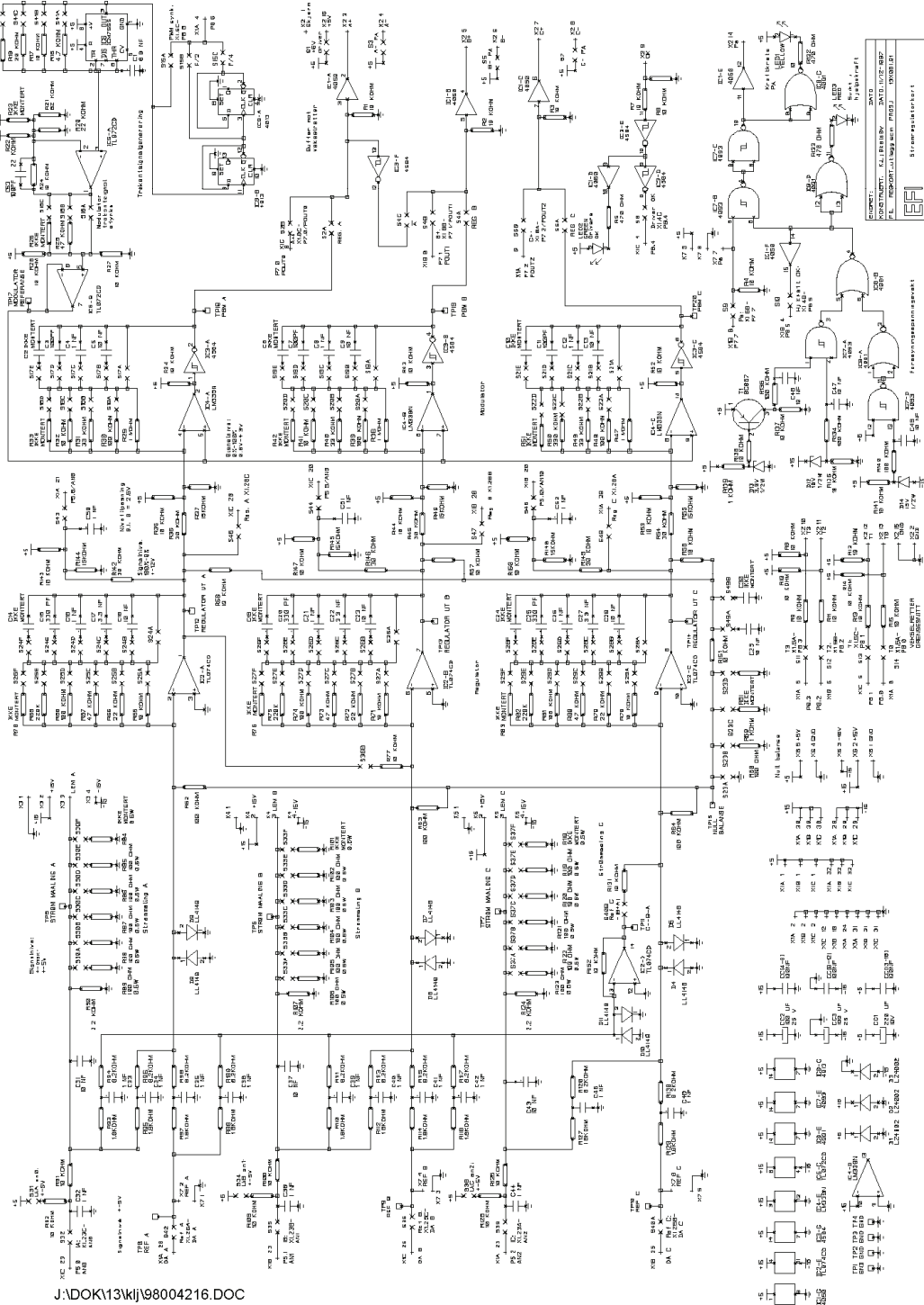
Regulatorinnstillinger og konfigurering bestemmes av et sett med strappinger.

Ved bruk i motorstyringer kan kortet konfigureres slik at kun to strømmålinger og referansesignaler benyttes. En nullpunktsbalanseringskrets sikrer da en midlere utstyring på 50%

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4

2   SKJEMA

J:\DOK\13\klj\98004216.DOC

	Name	Conditions	Standards
HTRB	Hot reverse test	MOS/IGBT: 1000h, T_{vjmax}, V_{CEmax} ($\leq$ 2.0 kV), $0.8 * V_{CEmax}$ (>2.0 kV) Conv.; 1000h, $T_j = 125°C$, $V_{RM} = 0.9 * V_{RRM}$, $V_{RM}/V_{DM} = 0.8 * V_{RRM}/V_{DRM}$ [a]	IEC 60747-2/6 Kap. V IEC 60747-9: 1998
HTGS	High temperature gate stress test	1000h, $\pm V_{GEmax}$, $T_j = 125°C$	IEC 60747-9: 1998
H3TRB	High humidity high temperature reverse bias test	1000h, 85°C, 85%RH, $V_{CE} = 0.8 * V_{CEmax}$, however max. 80 V, $V_{GE} = 0V$	IEC 60749: 1996
TST	Thermal shock[1]	T_{stgmin} - T_{stgmax}, typ. $-40°C$ to $+125°C$, but $\Delta T_{max} \leq 165K$, $t_{storage} \geq 1h$, $t_{change} \leq 30$ s High power, standard: 20 cycles High power, traction: 100 cycles Medium power: 50 cycles Conv.: 25 cycles [a]	IEC 60749: 1996
TC	Temperature cycling[1]	External heating and cooling 2 min. < $t_{cycl.}$ < 6 min; $\Delta T_C = 80K$, $T_{cmin} = 25°C$ High power, standard: 2 000 cycles Medium power: 5 000 cycles Conv.: 5000 cycles [a]	IEC 60747-2/6 Kap. IV IEC 60747-9: 1998
TC	Temperature cycling[2]	External heating and cooling T_{stgmin} - T_{stgmax} 100 cycles Conv. modules: 25 cycles [a]	IEC 60068-2-14 test Na
PC	Power cycling[1]	Internal heating and external cooling $0.5 < t_{cycl}$ < 10 sec; $\Delta T_j = 60K$, $T_{jmax} = 125°C$, 130 000 cycles	IEC 60747-9: 1998
PC	Power cycling[2]	Internal heating and external cooling $\Delta T_j = 100K$, 20 000 cycles Conv. modules: 10 000 cycles [a]	IEC 60747-9: 1998
V	Vibration	Sinusoidal sweep, 5g, 2 h per axis (x, y, z)	IEC 60068-2-6 Test Fc
MS	Mechanical shock	Half sine puls, 30g, 3 times each direction ($\pm$x, $\pm$y, $\pm$z)	IEC 60068-2-27 Test Ea
PC	Power cycling[1]	Internal heating and external cooling $0.5 < t_{cycl}$ < 10 sec; $\Delta T_j = 60K$, $T_{jmax} = 125°C$, 130 000 cycles	IEC 60747-9: 1998
PC	Power cycling[2]	Internal heating and external cooling $\Delta T_j = 100K$, 20 000 cycles Conv. modules: 10 000 cycles [a]	IEC 60747-9: 1998