Test setup for accelerated test of High Power IGBT modules with online monitoring of V_{ce} and V_f voltage during converter operation

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***Abstract*— Several accelerated test methods exist in order to study the failures mechanisms of the high power IGBT modules like temperature cycling test or power cycles based on DC current pulses. The main drawback is that the test conditions do not represent the real performance and stress conditions of the device in real application. The hypothesis is that ageing of power modules closer to real environment including cooling system, full dc-link voltage and continuous PWM operation could lead to more accurate study of failure mechanism. A new type of test setup is proposed, which can create different real load conditions like in the field. Furthermore, collector-emitter voltage (V_{ce}) has been used as indicator of the wear-out of the high power IGBT module. The innovative monitoring system implemented in the test setup is capable of measure the V_{ce} and forward voltage of the antiparallel diode (V_f) during converter operation, which is also demonstrated.**

Keywords*— *accelerated test setupt, high power IGBT module , online Vce monitoring , wear out .

I. INTRODUCTION

One of the major factors of failures in wind turbines are related to power converters, which represents approximately 15% of all failures [1]. Within the power converters, high power IGBT modules are the weakest part because of continuous exposition of temperature cycles caused by conduction and switching power losses in the chip [2]. In order to reduce the incidents caused by high power IGBT modules in the power converters, it is necessary to study the failure mechanisms.

This paper presents an improvement and enhancement of a previous test setup [3]-[4], where it is possible to test IGBT power modules in different field application. One example of different field application can be seen in [5], where the test setup has been used as an experimental validation of the efficiency using adaptive control for grid converter (50 Hz). However, in this paper the rotor side of the Doubly Fed Induction Generator has been selected as wind turbine application. A DFIG system is selected as it is the most common used of this generator in the wind turbine industry. Moreover, the rotor side operating point of converter is within few Hz. This fact causes high stress on the IGBT modules due to the high temperature produced by low frequency operation, and thereby, heavy thermal cycling which stress the different layers of IGBT modules, as they typically have different coefficients of expansion (CTE), and thus, the cycling will cause failure of IGBT module.

In order to study the failure mechanisms a real and continuous PWM power cycle is used in the proposed test setup. Normally, accelerated temperature cycle test or DC current pulses test have been used as a source for wearing out the IGBT devices [6]-[7]. Besides these power cycling methods, a periodic PWM load is shown in [8]-[9], in which PWM is stopped when chip reaches the desired increment of ΔT. This method allows more realistic electrical stress than the other methods.

In addition to the realistic stresses, the proposed method in this paper is directly implementable for continuous sinusoidal applications. Therefore, the test setup uses as ageing component a continuous sinusoidal current which emulates the same working points as the rotor side of DFIG. The advantages of wearing out the IGBT modules applying real working points will give a more accurate study of the failure mechanism in the power modules. However, the test system is not only used for wearing out the IGBT modules, but it is used as a platform to develop and test new devices that may be applied in the field. For example, V_{ce} parameter is well known as indicator of internal failure and it is one of the main methods to evaluate the junction temperature because of V_{ce} is Temperature Sensitive Electrical Parameter (TSEP) [10]. Therefore, an online V_{ce} monitoring system has been developed and implemented in the test setup.

This paper will describe the test system for IGBT power modules including the cooling system. Next the V_{ce} online measurement system will be described and finally some laboratory results of the test setup will be shown.

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II. TEST SETUP CONVERTER

In order to realize the accelerated ageing process of high power IGBT modules a test setup has been built which is formed by different parts, such as, the module under test (DUT), the control power modules , protection system, cooling system, and also the online V_{ce} monitoring system.

A. Device Under Test

The high power IGBT modules used in the accelerated test setup are a half bridge 1000A and 1700V. However, it is possible to test any other IGBT module with different current and voltage ratings due to an easy adaptation of the controlled parameters, which allows a great flexibility when testing different IGBT modules and operating points.

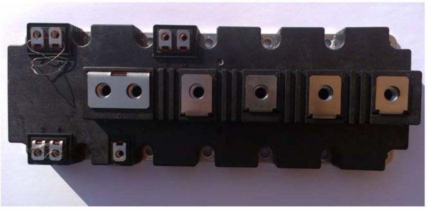

Fig. 1. Type of High Power IGBT module used in the test

The only limitation is the package of the IGBT module that can be tested, which must be PrimePack (see Fig. 1). This constrain is due to the liquid cooling interface which is design for these type of modules.

B. Converter

A H-bridge converter is the proposed topology for the converter, which is formed by DC-link, one leg which is Device Under Test (DUT), two parallel legs which are the control side, one main inductor (L_1), and two sharing inductors (L_2 and L_3) as shown in Fig 2.

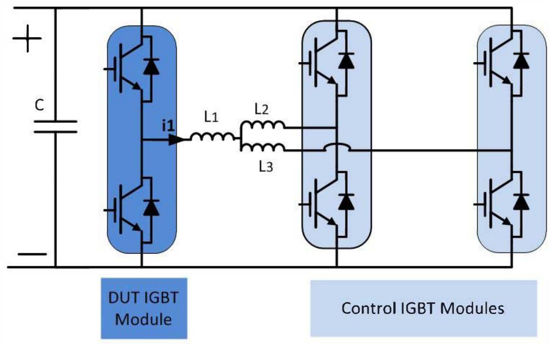

Fig. 2. High power test setup for IGBT modules.

Previous test bench showed in [3], [4], used only one leg in the control side, which has as a consequence that the ageing processes were started simultaneously at both DUT and control IGBT modules. Since the aim is to wear out only the DUT IGBT module and not the control IGBT module, an additional leg and two sharing inductors have been added into the topology, which reduces the total load of the control modules to half of the current. Therefore, the ageing process of the control modules becomes slower in comparison to the DUT ones.

C. Converter mounted on WT power stack

Besides the additional components, the converter was mounted on a power stack which is used in real wind turbines, see Fig 3. This fact provides a realistic test setup and further it offers more safety and reliable test setup than the previous test setup.

Finally, the test setup is designed to make nonstop accelerated test until the desired end point. This means that the system may be running 24/7. Therefore, the test setup must be reliable and safe. Different parameters are under continuous supervision in order to protect the setup such as overcurrent, shoot through, pump-stop, over temperature or even fire. In case that one or more malfunctions could take place the protection system will shut down the power, turns off the PWM and an email will be sent in order to notify a malfunction in the setup.

Fig. 3. A power stack module where the IGBT modules are mounted.

III. COOLING SYSTEM

The cooling system is of paramount importance for the test system as continuous high power is involved in the system. There is a total power loss of 7 kW in nominal operation which must be dissipated from the system.

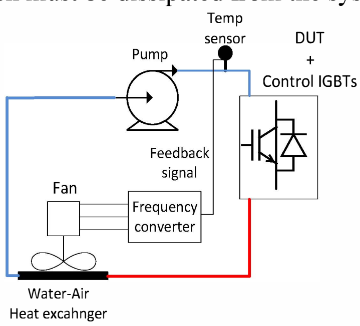

Fig. 4. Cooling system.

The dissipation of this power is done by means of a liquid cooling system as illustrated in Fig4. This is formed by one pump, one expansion vessel, one temperature sensor, one heat exchanger, one fan and one frequency converter which controls the fan speed using a built in PI controller.

The liquid used in the cooling system is a mixture of water and ethylene glycol. This mixture of water-ethylene glycol has the drawback such as reduction thermal conductivity and density increment in comparison to pure water [11]. Nevertheless, the purpose of the test setup is to be as close as possible to real field application where the cooling systems use this mixture (water-glycol) in order to decrease the liquid freezing point. The advantage for the test setup is a slight increment of the boiling point.

Additionally, the power stack interfaces the liquid cooling system with the baseplate of the IGBT modules by means of Shower Power ™ technology which offers lower gradients temperature on the baseplate in comparison to other technologies [12]-[13]. The test system is located in a room where the temperature is controlled and kept constant to 20±2ºC. The stability that provides the controlled temperature allows a better control and more stable measurement of the V_{ce}, which initially will cause an easier calibration and estimation of the junction temperature. Calibrations and estimation of the online junction temperature are shown and explained in [14]-[15].

IV. ONLINE V_{CE} MONITORING SYSTEM

A new online V_{ce} monitoring system has been developed [16] and implemented in the present test setup.

Offline V_{ce} monitoring system used in [4] and the new online V_{ce} monitoring could measure either V_{ce} or V_f of the IGBT module. However, the mentioned offline V_{ce} monitoring system is reed relay based as shown in Fig. 5. Using these types of mechanical switches causes a slow operation due to its intrinsic mechanical contraction, which features a minimum switching time of 3 ms. As the minimum pulse of PWM is 100 µs applying test conditions shown in Table I, this V_{ce} monitoring system could only operate during offline operation. Measurement during offline can only offer the wear out status of the IGBT module, but the mayor drawback is that this V_{ce} monitoring system cannot be implemented in the field.

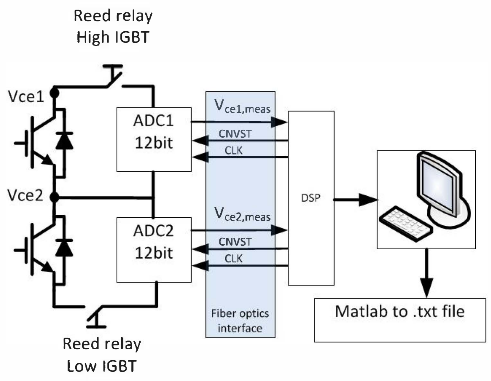

Fig. 5. Offline V_{ce} monitoring principle.

By contrast, the new online V_{ce} monitoring system is not implemented with reed relays, but it is double diode based as shown in Fig. 6. The principle of the proposed monitoring circuit is based on V_{ce} desaturation measurement which some gate drivers use as protection against short circuits [16]-[17].

The challenge to achieve the online measurement lies in blocking the high voltage when the non-conducting state of the IGBT module in order to protect the ADC circuitry, and being enough accurate in order to measure the V_{ce} and V_f voltage within interval of millivolts when the IGBT module is conducting [18]. The proposed V_{ce} monitoring system is implemented with an ADC of 14 bits which gives a resolution of 0.61mV:

$$V_{ADC\_res} = \frac{V_{ref}}{2^{bits}} \tag{1}$$

In addition, the V_{ce} monitoring system has been mounted on the top of the IGBT gate driver in order to reduce parasitic components and electromagnetic interferences (EMIs) which may cause inaccuracies during the measurements. Finally, D_1 and D_2 diodes must be identical and must be thermally coupled in order to achieve the adequate measurement.

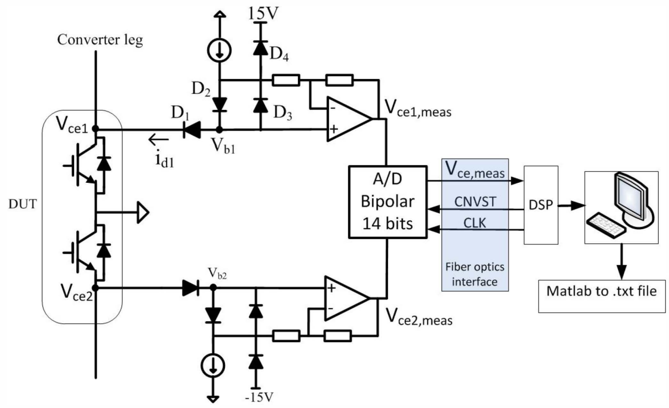

Fig. 6. Online V_{ce} monitoring principle.

V. MEASURING ROUTINE FOR WEAR OUT TEST OF IGBT MODULES

A. Selected Online and Offline measuring routines

A measurement routine is proposed to use both online and offline operation. Every 5 minutes, the system enters on offline measurement routine. The online measurement routine takes also place every 5 minutes but it is shifted 2.5 minutes in respect to the offline measurement routine, as shown in Fig 7.

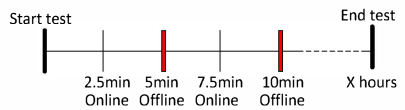

Fig. 7. Measuring routine used in the test setup.

Within time interval of 5 minutes, the IGBT modules experience a total of 1.8 kcycles according to the nominal test parameters. The selection of 5 minutes intervals between each measurement has been found optimal. Longer time between measurements would lead to an imprecise accuracy because of the lack of on state voltages variations. Latter fact becomes more critical when the IGBT module is close to the end of its lifetime, where fast and discrete variations of on state voltages take place as shown in Fig. 13. By contrast, shorter time would lead to a massive amount of data which is not necessary to process.

Furthermore, both measurement routines measure the V_{ce}, the V_f and the current through the converter. When the increment of V_{ce} or V_f reaches some predefined limits or wearing out level, the system is stopped and the IGBT module is considered for further study of internal failures.

B. Comparison between old offline routine and new offline routine

The new offline routine is formed by some subroutines where one V_{ce} and one V_f are measured sequentially. The first subroutine is explained in forthcoming paragraphs.

Initially, the control high IGBTs (CTL_{h1} and CTL_{h2}) and DUT low IGBT (DUT_l) are turned on until the current will rise up to 920A as depicted in next figure.

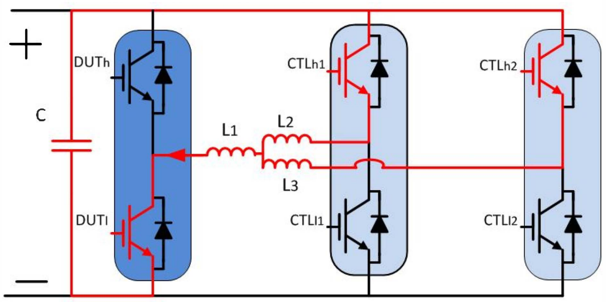

Fig. 8. Initial sequence in first offline subroutine

Afterwards, the IGBTs are turned off and the stored energy in the inductor flows through DUT_h Diode and CTL_{l1} - CTL_{l2} Diodes as shown in next figure.

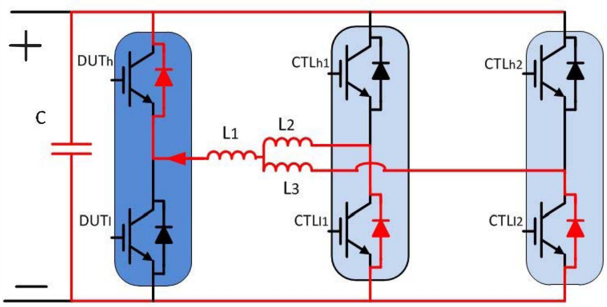

Fig. 9. Final sequence in offline subroutine

In Fig. 10 is illustrated the current through L_1 the explained subroutine. It should be noticed that the currents illustrated in the Fig 10. and Fig 11. present a scaling factor of 5000 with respect to the converter current as it was obtained by a hall current sensor.

The segment named D corresponds with the offline subroutine sequence shown in Fig 8. and the segment named E corresponds with offline subroutine sequence shown in Fig 9. During this subroutine DUT_l IGBT and DUT_h Diode components are measured. To complete the offline routine similar subroutines are used in order to obtain all the values of V_{ce} and V_f from the DUT module.

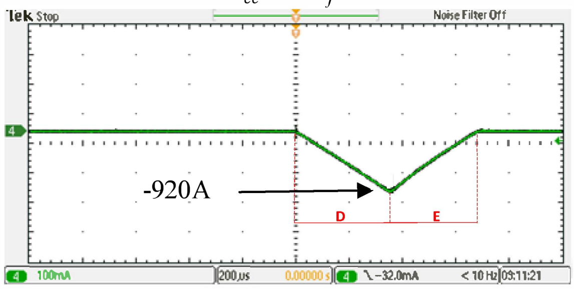

Fig. 10. New offline measuring pulse implemented for the new V_{ce} online monitoring system (double diode)

The offline routine used in [4] had an extra sequence due to the presence of the reed relays as shown in segment B in Fig 11.

The component to be measure (IGBT or diode) must be on state before the reed relay closes and connects the ADC circuitry to measure V_f. If not, the ADC would be connected to the high voltage and the consequence is the destruction of monitoring circuit and module.

Therefore two delays were present previously. The first one is related to the waiting time until the component is fully conducting, and thus, the reed relay can be safely switch on, and the second one is related to minimum switching time of the relay, 3 ms.

The result is lower available current in order to measure V_f at high current level. The additional segment B shows the current flowing through converter and was not used for measurement purposes. The consequence is that the available current was up to 600A and in the new offline routine is up to 920A.

The increment in the current available during measurement is of paramount importance in order to obtain better resolution during calibration process at high current level.

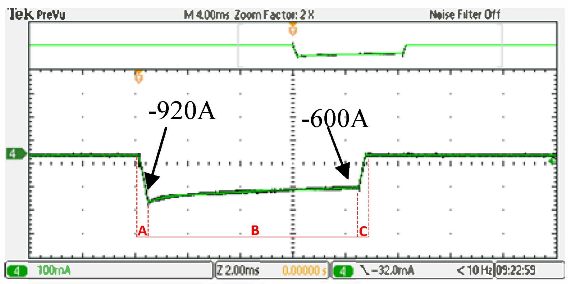

Fig. 11. Old offline measuring pulse implemented in the new V_{ce} online monitoring system.

C. Online measurement routine

As mentioned before, an online measurement of the on state voltage not only offers the status of the power module at any time, but it allows in combination with current measurement and baseplate temperature the possibility of acquire the estimation of the junction temperature at any time during converter operation.

The measuring routine consists of 4 measurements in total which are the on state voltages (V_{ce} and V_f), the current through converter and liquid temperature of the cooling system. The data is sampled in the middle of PWM when there is no effect of the switching transients of the IGBT module, which is 10 µs for the applied conditions. Moreover, the whole data is obtained for 3 cycles of the current.

In Fig. 12 (upper graph) presents the online measurement of the voltages (V_{ce} and V_f) at high and low side of the IGBT module. Fig. 12 (lower graph) presents the current through the converter.

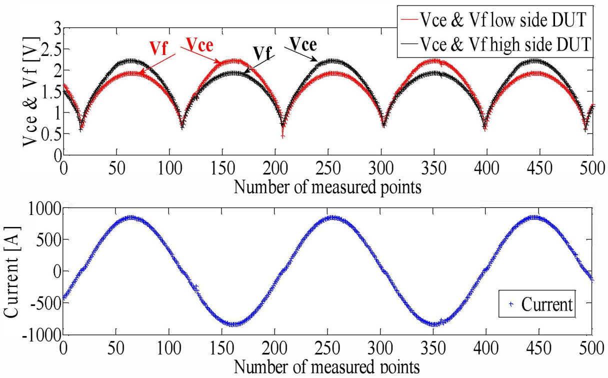

Fig. 12. Online measurement result at one measurement routine

D. *Offline vs online measurement results*

Offline and online measurement results can show the status of the IGBT modules. However, the results cannot be strictly compared because of the intrinsic measurement principle. During offline measurement the converter and the fun of the cooling system are stopped.

Moreover, the offline routine is run one minute after the stopping of converter. These facts allow more homogenous temperatures along the IGBT module.

However, during offline routine the switching effect can be neglected and only the current flowing through the component causes power dissipation inside the power device. By contrast, during online measurement the power dissipation is affected by converter operation.

Therefore, the thermal behavior will not be the same, and thus, the on state voltages values will differ between offline and online measurements for the same current level.

VI. ACCELARATED TESTS

A. *Selected test conditions*

TABLE I
USED PARAMETERS FOR TESTING IGBT MODULE

Symbol	Meaning	Value
$V_{DC\text{-}LINK}$	Voltage at Dc-Link	1000V
V_{DUT}	Voltage at middle point	253V
I_l	Current through L_1	$890A_{peak}$
F_{OUT}	Fundamental current frequency	6Hz
F_{SW}	Switching frequency	2.5Khz
T_c	Coolant temperature	80±0.7ºC
T_{Lab}	Room temperature	20±2ºC

As cited previously, the test setup can be used for testing high power IGBT modules at different scenarios, where different voltages, current and frequency levels can be applied. However, the results presented in the forthcoming paragraphs have been achieved applying the parameters shown in previous table.

B. *Number of High Power IGBT modules tested*

A total of 4 High Power IGBT modules have been tested and presented in following paragraphs.

Initially, one IGBT module was tested until its destruction in order to know approximately its life duration applying the selected test conditions. The total number of cycles until its final destruction was 5100 kcycles.

The other 3 IGBT modules were tested before their destruction and at different wear out levels, such as 2500 kcycles, 3500 kcycles and 4500 kcycles.

When the modules are worn out until predefined level, they are considered for further study of internal degradation or failure. Although detailed results regarding internal degradation are out of the scope of this paper some images will be shown.

C. *Offline measurement result*

In Fig. 13 is depicted the offline measurements of Low DUT diode for the 4 tests. The results are shown for the same current level as explained in [3] which was 550A. The 5100 kcycles test led to final failure of the device and presented a total increment of 62 mV.

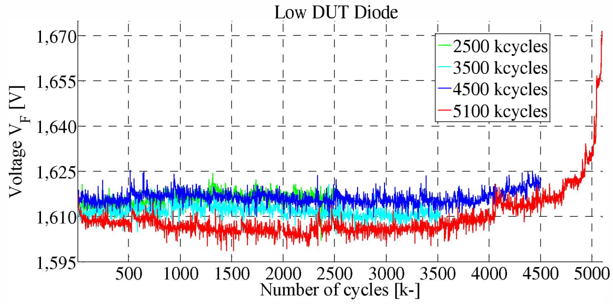

Fig. 13. Offline measurement result

The result for 2500 and 3500 kcycles tests did not show a significant on state voltage increment. The 4500 kcycles test presented a linear increment from 4000 kcycles which may be caused by reconstruction in the metallization surface. However, latter fact must be ratified by physical test of the modules.

Finally, in the case of 5100 kcycles test can be seen how fast and steep are the increments increment of V_f before the failure. These steep steps are caused by bond wire lift off as cited before in [3]-[7].

D. *Online measurement result for 5100 kcycles wear out level module*

The online results were achieved as describes in *online measurement routine* paragraph. Furthermore, the temperature in the baseplate is kept constant at 80±0.7ºC during the entire testing time.

However, the results depicted in forthcoming figures show the on state voltages at 900 A and -900A as depicted in Fig. 14.

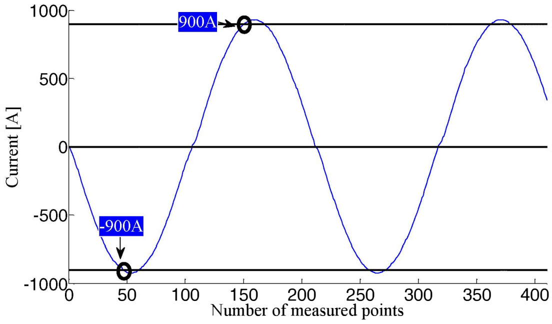

Fig. 14. Current during online measurement

In the next figure can be seen the initial on state voltages of Low side components of DUT module when starting the test and the final on state voltages when the test was stopped.

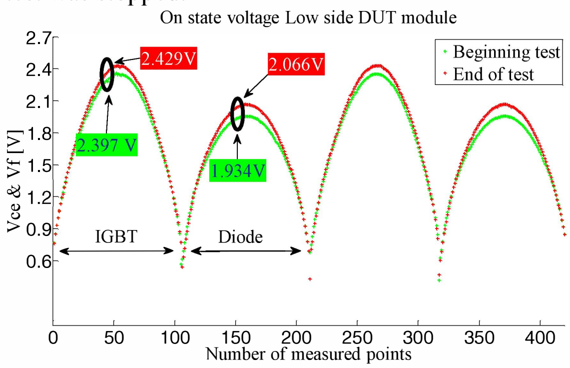

Fig. 15. On state voltage Low side DUT module for 5100 kcycles test. (Green: beginning test- Red: end of test)

The Low side IGBT component varied 32 mV; in turn the Low side Diode component underwent an increment of 132 mV.

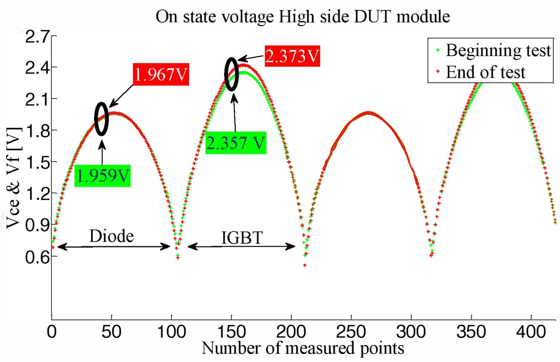

Fig. 16. On state voltage High side DUT module for 5100 kcycles test. (Green: beginning test- Red: end of test)

In the case of the High side components the IBGT increased only 8 mV and the diode varied 16 mV as shown in preceding figure.

From on state voltages results can be derived that the Low side of the IGBT module suffered. In case of Low side Diode the on state voltage presented the greatest increment in comparison to the rest of the components inside the module. In fact, the Low side Diode was the failed component. By contrast, the high side of the module did not show as great increment as low side, especially the High side IGBT which only presented an increment of 8 mV.

VII. BRIEF PHYSICAL ANALYSIS

To understand the variations in the electrical parameters a physical study after wearing out the High Power IGBT modules is of paramount importance. For example, a steep or discrete step in the on state voltage is related to bond wire lift off [7], nonetheless this is not the unique degradation phenomena and more degradation process may be involved as reconstruction of metallization surface, solder fatigue etc. Therefore, a complete and detailed exam must be done to understand the physics of failure mechanism. Although detailed exam of physical failure and analysis is out of the scope of this paper some images will be shown.

A. High Power IGBT module

The IGBT module used as DUT consists of 12 IGBT chips and 12 diode chips. Power terminals, IGBT and diode are interconnected with 10 aluminium bond wires.

Following figure shows an IGBT and a diode chips in one of the sections.

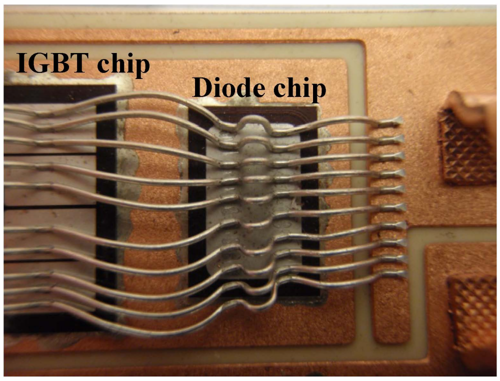

Fig. 17. Half section of High Power IGBT module used in the test setup

A. SEM images for 5100 kcycles test module

The exploded module could not be studied in detail because of the explosion when the device failed. The failure caused high internal destruction of the module as can be seen following image.

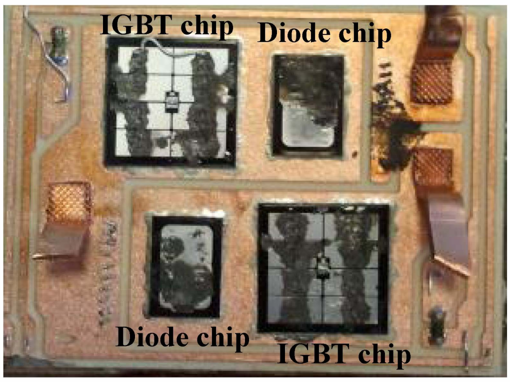

Fig. 18. One section of the exploded IGBT module

VIII. CONCLUSIONS

A new test setup is presented in this paper to accomplish an accelerated test for high power IGBT modules. The proposed test setup offers more robust, reliable and advanced wear out test system because of the converter structure, controlled room temperature and the online V_{ce} monitoring system. Furthermore, the test setup is flexible to set different loading parameters which are suitable for field applications.

Finally, proposed monitoring technique is a potential method for field application whereas the setup can be used to study the degradation mechanism of power modules in the laboratory realizing a field mission profile.

ACKNOWLEDGMENT

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