Approaching Repetitive Short Circuit Tests on MW-Scale Power Modules by means of an Automatic Testing Setup

Reigosa, Paula Diaz; Wang, Huai; Iannuzzo, Francesco; Blaabjerg, Frede

Published in:
Proceedings of 8th IEEE Energy Conversion Congress and Exposition (ECCE), 2016

DOI (link to publication from Publisher):
10.1109/ECCE.2016.7854884

Publication date:
2016

Document Version
Accepted author manuscript, peer reviewed version

Approaching repetitive short circuit tests on MW-scale power modules by means of an automatic testing setup

Díaz Reigosa, Paula; Wang, Huai; Iannuzzo, Francesco; Blaabjerg, Frede

Published in:
IEEE Energy Conversion Congress and Exposition (ECCE),

DOI (link to publication from Publisher):
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7854884&isnumber=7854636

Publication date:
Sept. 2016

Approaching Repetitive Short Circuit Tests on MW-Scale Power Modules by means of an Automatic Testing Setup

Paula Diaz Reigosa, Huai Wang, Francesco Iannuzzo, Frede Blaabjerg
Centre of Reliable Power Electronics (CORPE)
Department of Energy Technology Aalborg University
Pontoppidanstraede 101, Aalborg East DK-9220, Denmark
pdr@et.aau.dk, hwa@et.aau.dk, fia@et.aau.dk, fbl@et.aau.dk

***Abstract*— An automatic testing system to perform repetitive short-circuit tests on megawatt-scale IGBT power modules is presented and described in this paper, pointing out the advantages and features of such testing approach. The developed system is based on a non-destructive short-circuit tester, which has been integrated with an advanced software tool and a semiconductor device analyzer to perform stress monitoring on the considered device under test (DUT). A case-study is included in the paper concerning a 1.7 kV/ 1 kA IGBT module, which has been tested safely up to 30,000 repetitions with no significant damage. The developed system has been demonstrated to be very helpful in performing a large number of repetition tests as required by modern testing protocols for robustness and reliability assessment. The software algorithm and a demonstration video are available for download.**

I. INTRODUCTION

Power semiconductor devices (e.g. IGBTs - Insulated Gate Bipolar Transistor, and power MOSFETS - Metal-Oxide Semiconductor Field-Effect Transistor) are considered as one of the most reliability-critical components in power electronic systems [1]. The failure of IGBTs and MOSFETs in a power converter may lead to malfunction of the entire system, which may be caused by component wear-out or abnormal events [2]. The most severe case of abnormal operation is the short circuit as discussed in [3]. Reliability becomes an increasingly important performance factor in applications such as onshore and offshore wind turbines, medium-voltage drives, and tractions, where medium-to-high power modules are adopted [4]–[6]. Therefore, the short-circuit capability, behaviour and its impact on the degradation of these power modules are important aspects to be investigated.

Many efforts have been devoted to the short-circuit testing of power semiconductor devices. The minimum dissipated energy that leads to failure of the specific device after a single short-circuit is referred to the critical energy E_C [7]. If the dissipated energy is less than E_C, the device is able to survive after Repetitive Short-Circuit (RSC) testing. The aim of RSC testing is to study how safe short-circuit operation will affect the electro-thermal parameters and the degradation of power semiconductors, or to benchmark the short-circuit robustness of different devices. Various research activities on RSC testing of Si IGBTs and MOSFETs, and SiC MOSFETs have been presented in [7]–[15]. In [8], the RSC testing of a 600 V customized IGBT module is performed, with a measured saturation current of around 50-60 A. The power module failed after 10,000 times of short-circuit operation. The on-state voltage of the IGBT module is found to be increasing and its short circuit saturation current is reducing along with the testing times. The results in [9] from 600 V single-chip discrete IGBTs reveal negligible change of the above two electrical parameters. In contrasts, the study on a 600 V/ 20 A Si MOSFET shows that the device short-circuit current is significantly decreased and on-state resistance is increased after 17,000 times of short-circuit testing under 84% of its E_C. In [12], the tested Si MOSFET is observed with no evolution of the above two parameters after 35,000 times of testing, with a relatively lower dissipated energy. In [7], [10], [11], the testing focuses on the discrete 1.2 kV SiC MOSFETs, with the current rating in the range of 20 A to 50 A. In [13], [14], RSC testing is performed for discrete 1.2 kV single-chip normally-on SiC JFET. It can be noted that the existing RSC testing falls in the following limitations:

1) The DUTs are mainly low power modules or discrete devices, suitable for low-to-medium power applications. A testing setup that has the capability of RSC testing for medium-to-high power Si and SiC modules is highly demanded.
2) The results of the RSCs discussed above are not in well consistency between MOSFETs, between IGBTs and MOSFETs, or between power modules and discrete devices. The discrepancies could be due to the testing protocols, the materials, the chip technologies, and also the packaging technologies. It is still an open question to be investigated, especially for medium-to-high power modules.
3) The Devices Under Test (DUTs) are limited to brand-new devices before the RSC testing. Power semiconductors in field service experience both normal operation and abnormal operation. The degradation due to normal operation may affect the short circuit capability (e.g.,

reduce the critical energy E_C), and vice versa. Extensive research have been done in power cycling testing of IGBT modules to emulate the normal operation at an accelerated level [16]–[19]. The combination of power cycling testing and RSC testing will enable a more realistic testing close to real field operation.

4) Detailed discussion on the implementation of the RSCs in [7]–[15] are not given, especially the testing procedures, automation of the testing, and safety issues, which need to be considered [20].

In this paper, a new RSC testing setup for Si and SiC power modules is proposed. The developed setup is based on a Non-Destructive Testing (NDT) method described in [21] for high power modules. It has the following features:

1) Capable of RSC testing of power Si and SiC modules up to 6 kA short-circuit saturation current with different testing fixtures to adapt various packages.
2) Capable of heating plate temperature control from -40°C to 250°C, where the testing devices are mounted on.
3) Highly automated testing and electro-thermal parameter characterizations, and safety protection with remote control.

The purpose of this paper is to present the automatic hardware and software description of the RSC testing setup. It provides the basis for the future research activities on the systematic RSC testing of Si and SiC modules and the integrated testing with power cycling and RSC. It will be organized as follows: Section II reveals the developed approach for repetitive short circuit testing. Section III gives the details of the hardware and software implementations. Section IV presents a case study on RSC testing of a 1.7 kV/ 1 kA Si IGBT module to demonstrate the testing setup capability, followed by the conclusions.

II. Proposed Approach for Repetitive Short Circuit Test

The proposed automatic RSC testing approach is shown in Fig.1. It includes three major steps. A Graphic User Interface (GUI) is developed for setting up the experiment parameters and the operating limits for approaching the repetitive experiment in an automatic way. A NDT is applied to perform safe short circuit tests. The device characterization is performed thanks to a semiconductor device analyzer, Keysight B1506A, which can automatically create the power device datasheet for a wide operation range. The detailed description is provided in the following together with the hardware and the software implementations. discussed in the next section.

III. Hadrware and Software Implementations

A. Handware implementation

The Non-Destructive Tester (NDT) has been presented previously in [22] whose main features are summarized in the following paragraph. Referring to Fig. 2, the tester structure includes the following parts: a high-voltage power supply V_{DC} which charges up a capacitor bank C_{DC}, whose energy is

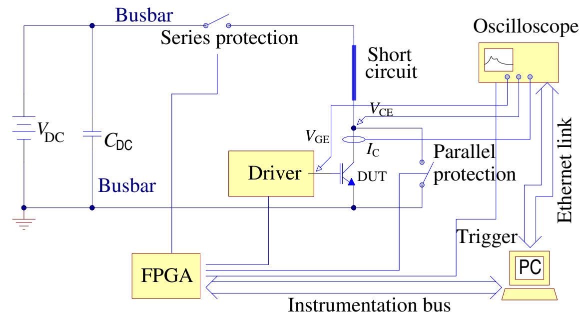

Fig. 2. Principle schematic of the non-destructive tester adopted for the measurements.

TABLE I
Non-Destructive Tester Components' Ratings.

Characteristics	Value
C_{DC} capacitors	5 × EPCOS B25620B1118K103 1.1 kV, 1100 μF film capacitors
Series protection	2 × Dynex DIM1500ESM33-TS000 3 kA/3.3 kV
Parallel protection	2 × Mitsubishi CM1200HC-66H 2.4 kA/ 3.3 kV
DUT gate driver	Concept 2SP0320x2Ax-FF1000R17IE4
Measured busbar inductance	37 nH

used to perform the tests; a series protection switches off, breaking the circuit right after the tests in order to prevent explosions of the DUT in the case of failure and thus allowing post-failure analysis; a computer-designed busbar minimizing the overall circuit inductance; a parallel protection turning on at the same time the series protection turns off in order to prevent dangerous voltage overshoots on the DUT, which typically occurs during fast turnoffs at extreme conditions; a 100 MHz Field-Programmable Gate Array (FPGA) providing the driving signals for the DUT and the protection switches, together with the trigger used for measurements. The repetitive operations and relative data acquisition are achieved by a Personal Computer (PC) running MATLAB® [23], which supervises operations, connected to a LeCroy HDO6104-MS oscilloscope via an Ethernet link and to the FPGA board through an instrumentation bus. A commercial IGBT driver is used for the DUT, whose desaturation protection has been inhibited in order to perform short-circuit tests. During tests, the collector current, collector voltage and gate voltage waveforms are acquired. Fig. 3 shows the details of the experimental setup, where the DUT is placed in the test position. The operation sequence adopted for the tests is shown in Fig. 4, where the signals sent from by the FPGA to the DUT are reported. Every time interval defined in Fig. 4 can be set by the MATLAB® software running on the PC. The main components' specifications of the NDT setup have been summarized in Table I.

The waveforms of a typical short-circuit test can be observed in Fig. 5, where the collector voltage, collector current and gate voltage are shown. The collector voltage exhibits

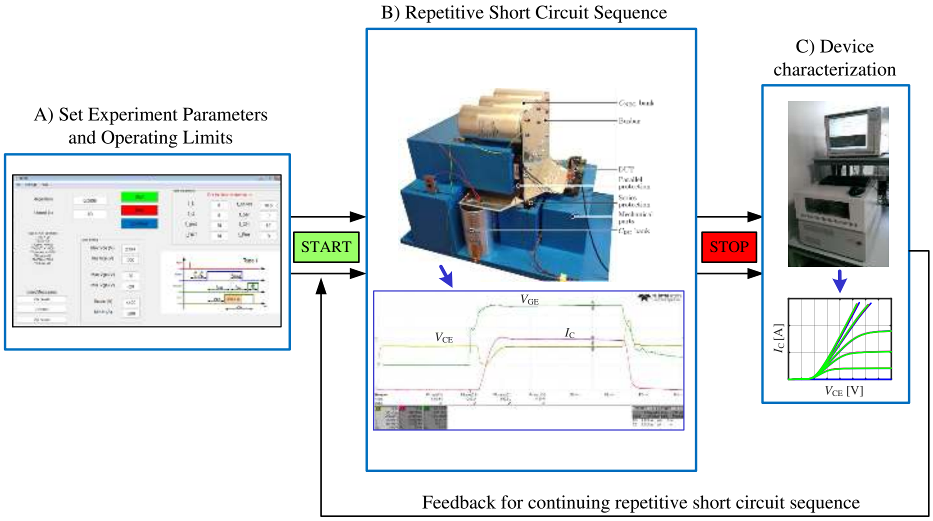

Fig. 1. The proposed approach for repetitive short circuit test on the 1.7 kV/ 1 kA IGBT power module.

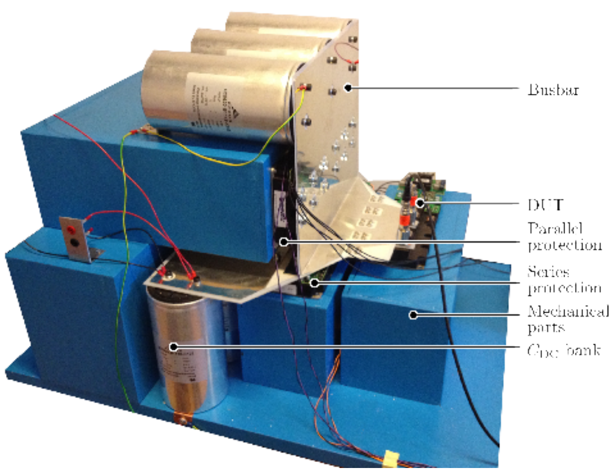

Fig. 3. Picture of the Non-Destructive Tester (NDT) used in the experiments including device under test.

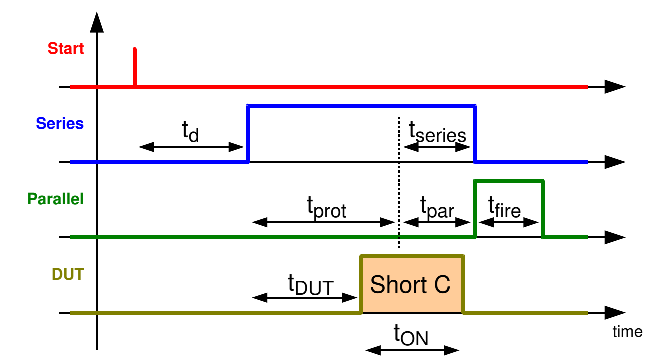

Fig. 4. Typical time sequence used for the short circuit tests including the time settings: t_d = delay time locked by the user, t_{series} = series protection time, t_{DUT} = t_{prot} time delay between the series protection and DUT and t_{on} = short circuit time.

negative and positive peaks related to the current variation through the circuit stray inductance. The collector current peak is 4 kA and then decreases according to the junction temperature increase, which is a well-known phenomenon related to the positive thermal coefficient of IGBTs. Finally, it is worth to note that the gate voltage waveform does not exhibit any Miller plateau as, contrarily to normal-conditions turn-on, no significant voltage fall occurs in the short-circuit tests.

B. Software Implementation

In order to perform repetitive short circuit tests on the analyzed device, an original automated tool having a user-friendly Graphical User Interface (GUI) has been developed and implemented in MATLAB® (see Fig. 6). Such an interface provides the possibility to perform repetitive tests with a set of parameters defined by the user, i.e. the time parameters described in Fig. 4, as well as the total number of tests to be performed and the time interval among them. Last but not least, the developed GUI provides a list of limits (pass conditions) to be verified to proceed automatically for the next test. After setting up the test parameters, the user sets the high voltage power supply to the operating voltage and starts the repetitive test sequence (START button in Fig. 6). Tests are performed completely equal to each other, according with the time sequence set by the user. The GUI communicates to the FPGA the exact time sequence at the beginning of every test through the instrumentation bus. A data check protocol has been implemented in order to avoid communication errors that would eventually lead to a fatal test. To make the user aware of the last parameters sent to the FPGA, a local echo is included on the left-hand side of the GUI. At the end of every test, the waveforms sampled by the oscilloscope are acquired through Active-X functions, in order to fully exploit the instrument capabilities. The acquired waveforms are stored

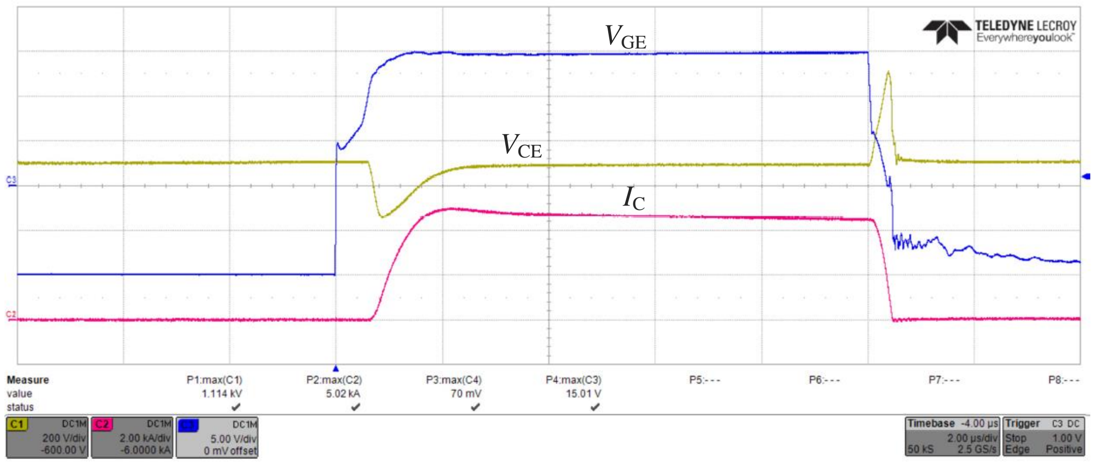

Fig. 5. Typical short circuit waveforms for an IGBT module rated at 1.7 kV/ 1 kA. Test conditions: DC-link voltage V_{DC} = 700 V; gate voltages: $V_{GE,OFF}$ = -10 V and $V_{GE,ON}$ = +15 V; temperature T = 25 °C. Collector voltage resolution: 200 V/div; collector current resolution: 1 kA/div; gate voltage resolution: 5 V/div.

Fig. 6. Graphical User Interface (GUI) developed in MATLAB® to perform repetitive short-circuit tests. A sample violation condition has been evidenced in the picture.

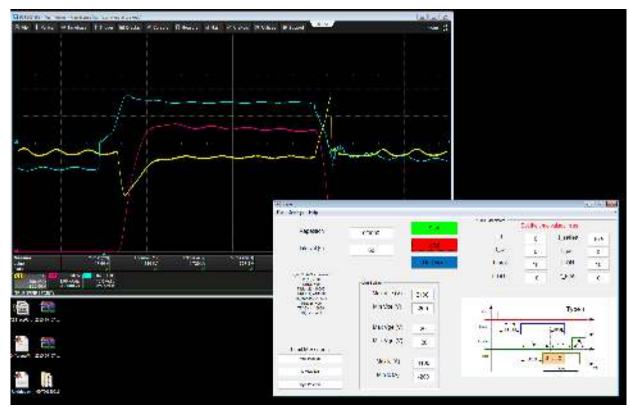

Fig. 7. Snapshot of the user screen during tests. Background: oscilloscope remote control screen where the acquired waveforms are displayed. Foreground: GUI for Repetitive Short Circuit (RSC).

including test index and time-stamp. Fig. 7 shows a typical user screen during the tests.

It is worth to note that the type of experiment necessarily requires a pass/fail evaluation after each test. To do that, the experimental waveforms acquired by means of the oscilloscope are stored and analyzed at the end of every test; then the pass/fail condition is evaluated basing on predefined limits set by the user at the beginning of the experiment. The violation of the limits results in an immediate stop of the experiment. An email is sent for reporting the issue with the type of violation occurred. The limits are specified in terms of V_{CE}, I_C and V_{GE}. For these three quantities, a lower and an upper limit can be specified by the user, as can be seen in Fig. 6. The complete flow chart of the experiment is depicted in Fig. 8.

IV. Case study: 1.7 kV/ 1 kA IGBT power module

A commercial 1.7 kV/ 1 kA IGBT power module is discussed in this section to demonstrate the proposed repetitive short circuit capability. The main applications of this IGBT module are typically wind turbine systems, trains, motor drives and other high power converters. The main specifications based on the datasheet information are summarized in Table II.

TABLE II
Main Specifications of the IGBT Device Under Test.

Parameter	Description	Value
V_{CES}	Collector-emitter nominal voltage	1.7 kV
$I_{C,nom}$	Continuous DC current	1 kA
$T_{vj,op}$	Maximum operation temperature	150$°C$
I_{sc}	Rated short circuit current	4 kA
t_{sc}	Maximum short circuit time	$\leq$ 10 μs
V_{GES}	Gate-emitter peak voltage	$\pm$ 20 V

The outline picture of the IGBT power module is shown in Fig. 9a. There are two power terminals for the DC positive connections (upper IGBT collectors), two power terminals for the DC negative connections (lower IGBT emitters) and one terminal with two screw connections for the output phase. There are two IGBT gate connection terminals for

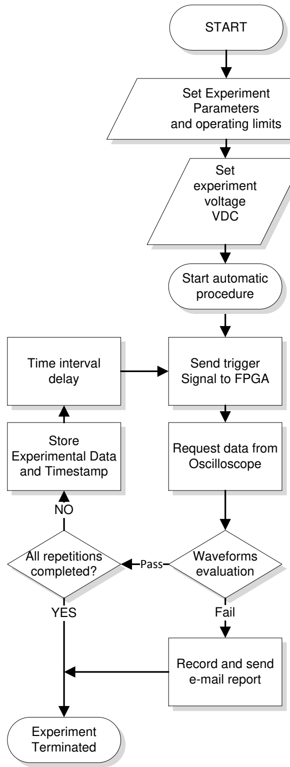

Fig. 8. Flowchart of the proposed measurement sequence.

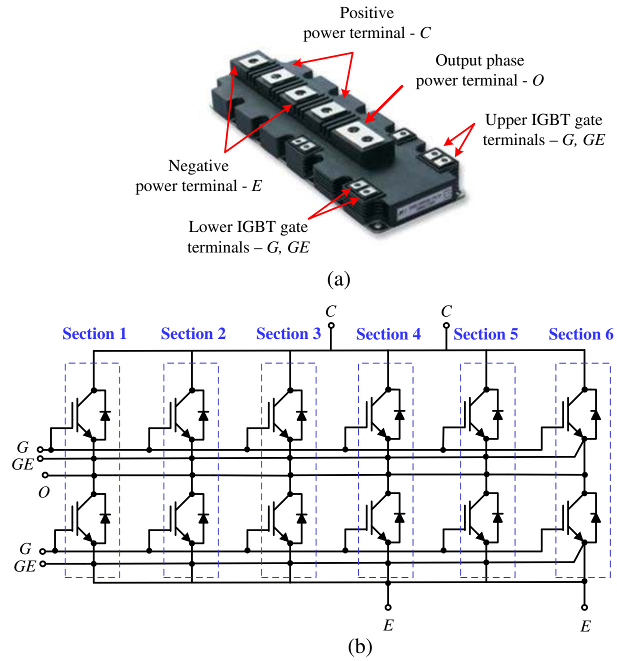

Fig. 9. The 1.7 kV/ 1 kA IGBT module including its terminals: (a) a picture of the package, and (b) the half-bridge structure.

the paralleled upper IGBTs and lower IGBTs. Six sections are connected in parallel to reach the rated 1 kA current capability, which has been pointed out in Fig. 9 (b). Each section contains two IGBTs and two free-wheeling diodes, which are configured as a half-bridge.

A. Set Experiment Parameters and Operating Limits

The functionality of the repetitive short circuit algorithm can easily be tested by means of the GUI where the set of parameters are defined by the user. The parameter settings related with the repetitive pattern, such as the total number of tests to be performed and the time interval among them, have been selected as 30,000 repetitions and with 30 seconds interval time. The parameters related with the FPGA supervising unit have been chosen with reference to the type of short circuit test, that is, a 10 μs short circuit type 1 [24]. Therefore, referring to Fig. 4, t_{prot}= 10 μs, t_{DUT} = 10 μs, t_{series}= 10.5 μs, t_{par}=0, t_{ON}= 10 μs and t_{fire}=0, as shown in Fig. 6. There are two more parameters in this GUI, i.e., t_L and t_Q, which they are set to 0 because they are only used when performing double pulse tests with a different circuit configuration. Moreover, the list of operating limits (pass conditions) are defined with reference to the short circuit waveform of the device, as shown in Fig. 5. The lower and upper collector current limits have been set to -100 A and 4.1 kA, the lower and upper collector-emitter voltage limits are -100 V and 1.4 kV and the lower and upper gate-emitter voltage limits are -20 V and +20 V. The violation of the mentioned limits results in an alarm e-mail message and an immediate stop of the test.

B. Repetitive Short Circuit Sequence

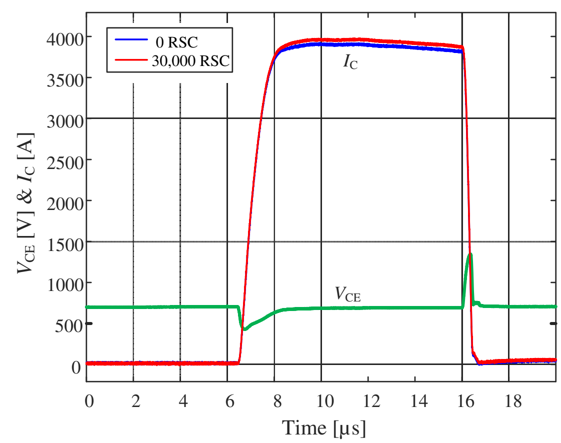

Fig. 10. Short circuit waveform of the brand new device and after 30,000 short circuit repetitions (T_{case} = 25°C and V_{CE} = 700 V).

After setting up the experiment parameters and operating limits, the repetitive short circuit sequence is ready to be started. The 1.7 kV/ 1 kA IGBT power module was tested during 30,000 equal repetitions and 10 μs short circuit time. During the test, the DC-link voltage, V_{DC}, was kept at 700 V while the case temperature was at room temperature -

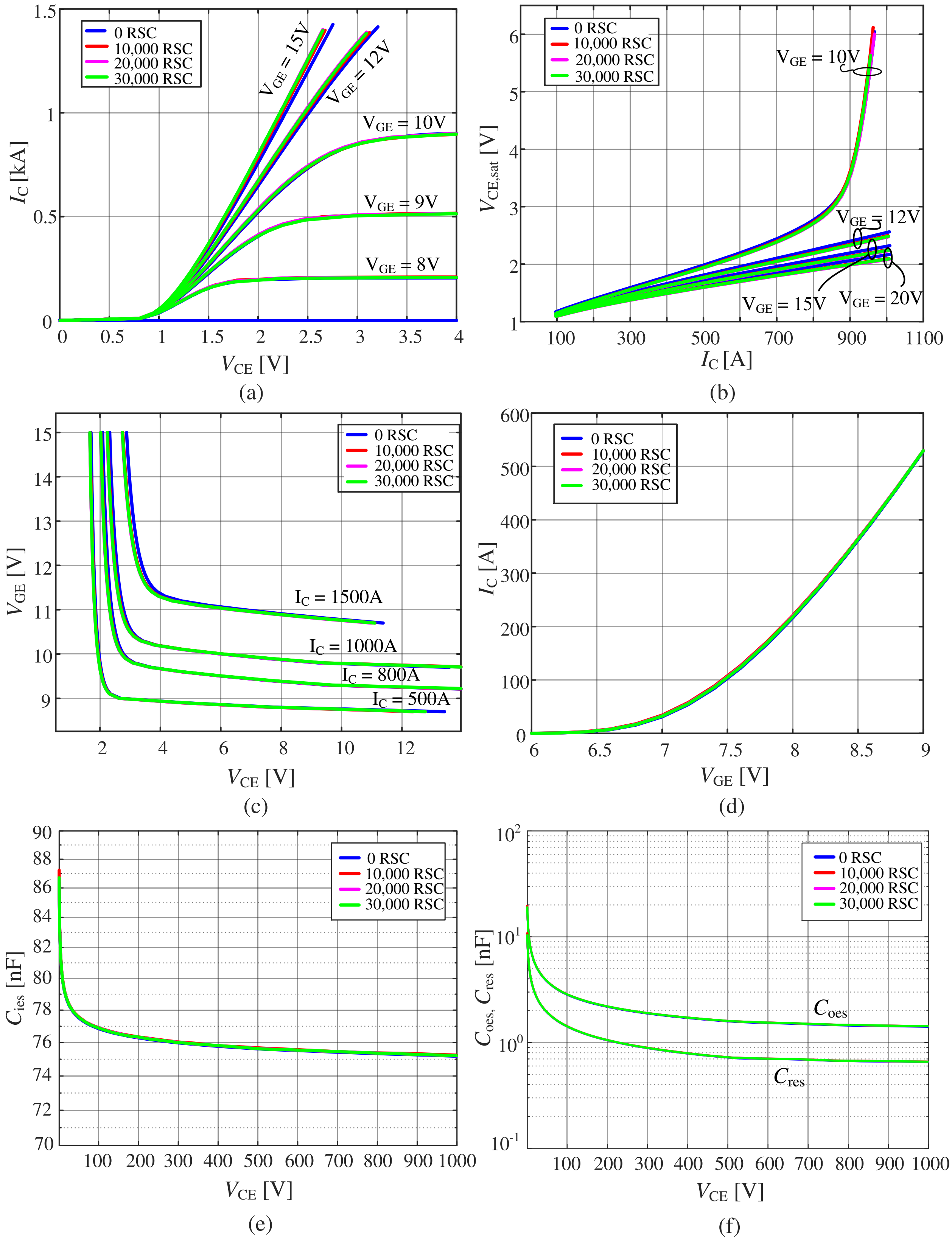

Fig. 11. Measured static characteristics of the 1.7 kV/ 1 kA IGBT power module during repetition of short circuit operations (T_{case} = 25°C): (a) $I_C - V_{CE}$ output characteristics, (b) collector-emitter saturation voltage characteristics, $V_{CE,sat}$, (c) $V_{CE} - V_{GE}$ output characteristics, (d) $I_C - V_{GE}$ output characteristics, (e) input capacitance, C_{ies}, and (d) output capacitance and reverse capacitance, C_{oes} and C_{res}, respectively. RSC: number of Repetitive Short Circuits

about 25°C. The waveforms sampled by the oscilloscope are acquired at the end of every test, that is, the collector-emitter voltage, V_{CE}, the collector current, I_C, and the gate-emitter voltage, V_{GE}. The acquired waveforms are stored including test index and time-stamp with the aim of monitoring the collector current tendency with the number of repetitions, as shown in Fig. 10.

C. Device Characterization

During the repetitive short circuit sequence, some electrical parameters may be shifted from their initial value due to the ageing of the device. These parameters are often named ageing indicators and used to predict the amount of the device degradation. Since the purpose of this work is to experimentally validate the versatility of the repetitive short circuit algorithm, the 1.7 kV/ 1 kA IGBT power module was regularly characterized (i.e., each 10,000 repetitions) by means of an Agilent B1506A power device analyzer [25]. The B1506A power device analyzer/curve tracer operates over a wide range up to 3 kV/ 1.5 kA, enabling the device characterization of medium-to-high power modules in an automated way. Fig. 11 reveals the trend of the static electrical characteristics, that is, the $I_C - V_{CE}$, the $V_{CE,sat}$ and the $V_{GE,th}$ curves during repetitive short circuit testing. Additionally, Fig 11 shows the trend of the dynamic electrical characteristics, that is, the C_{ies}, C_{oes} and C_{res} curves. The results evidence that the 1.7 kV/ 1 kA IGBT module is quite robust against repetitive short circuit testing with very little change on its electrical characteristics.

V. CONCLUSION

This paper describes the implementation of a medium-to-high power Repetitive Short Circuit (RSC) test setup. The automated testing procedures and safety protection with remote control are provided as a guideline for a more standardized future research activities. A study case on a 1.7 kV/ 1 kA IGBT power module has been presented to evaluate the capability of the RSC setup. The device has been tested with a short circuit dissipated energy less than E_C, in order to do RSC testing. No significant change has been observed in the electro-thermal parameters after 30,000 short circuits, evidencing a very high robustness against repetitive short circuit testing. Thanks to this automatic software, which consists of a GUI for setting up the design parameters, a non-destructive test setup and a device characterization instrument, the following future activities can be done: a) evaluate the degradation of Si and SiC power modules up to 6 kA to benchmark their short circuit robustness, b) integration of power cycling tests and repetitive short circuit tests for a more realistic testing closer to the field operation, and c) evaluate the degradation during short circuit for a wide range of temperatures (i.e., -40 to 250°C). The developed software algorithm and a demonstration video are available for download in the following link: http://www.corpe.et.aau.dk/research/ndt/rsc.

REFERENCES

[1] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1441–1451, May 2011.

[2] H. Wang, M. Liserre, F. Blaabjerg, P. de Place Rimmen, J. Jacobsen, T. Kvisgaard, and J. Landkildehus, "Transitioning to physics-of-failure as a reliability driver in power electronics," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 1, pp. 97–114, March 2014.

[3] F. Ianuuzzo, C. Abbate, and G. Busatto, "Instabilities in silicon power devices: A review of failure mechanisms in modern power devices," *IEEE Industrial Electronics Magazine*, vol. 8, no. 3, pp. 28–39, Sept 2014.

[4] F. Blaabjerg, Z. Chen, and S. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Transactions on Power Electronics*, vol. 19, no. 5, pp. 1184–1194, Sept 2004.

[5] C. Busca, R. Teodorescu, F. Blaabjerg, S. Munk-Nielsen, L. Helle, T. Abeyasekera, and P. Rodriguez, "An overview of the reliability prediction related aspects of high power IGBTs in wind power applications," *Journal of Microelectronics Reliability*, vol. 51, pp. 1903–1907, 2011.

[6] H. Wang, M. Liserre, and F. Blaabjerg, "Toward reliable power electronics: Challenges, design tools, and opportunities," *IEEE Industrial Electronics Magazine*, vol. 7, no. 2, pp. 17–26, June 2013.

[7] C. Chena, D. Labrousse, S. Lefebvre, C. Buttay, and H. Morel, "Study of short-circuit robustness of SiC MOSFETs, analysis of the failure modes and comparison with BJTs," *Journal of Microelectronics Reliability*, in press, DOI: 10.1016/j.microrel.2015.06.097.

[8] M. Arab, S. Lefebvre, Z. Khatir, and S. Bontemps, "Investigations on ageing of IGBTs under repetitive short-circuit operations," *Power Electronics Europe Magazine*, pp. 22–24, 2008.

[9] S. Lefebvre, Z. Khatir, and F. Saint-Eve, "Experimental behavior of single-chip IGBT and COOLMOS devices under repetitive short-circuit conditions," *IEEE Transactions on Electron Devices*, vol. 52, no. 2, pp. 276–283, Feb 2005.

[10] A. Castellazzi, A. Fayyaz, L. Yang, M. Riccio, and A. Irace, "Short-circuit robustness of SiC power MOSFETs: Experimental analysis," in *Proc. of IEEE 26th International Symposium on Power Semiconductor Devices IC's (ISPSD)*, June 2014, pp. 71–74.

[11] D. Othman, S. Lefebvre, M. Berkani, Z. Khatir, A. Ibrahim, and A. Bouzourene, "Investigation of 1.2 kV investigation of SiC MOSFETs for aeronautics applications," *Microelectronics Reliability*, vol. 53, pp. 1735–1738, Sept 2013.

[12] S. Pietranico, S. Pommier, S. Lefebvre, Z. Khatir, and E. Cadel, "Study of ageing of the metallization layer of power semiconductor devices," in *Proc. of Power Conversion and Intelligent Motion (PCIM)*, 2010.

[13] M. Bouarroudj-Berkani, D. Othman, S. Lefebvre, S. Moumen, Z. Khatir, and T. Ben Sallah, "Ageing of SiC JFET transistors under repetitive current limitation conditions," *Journal of Microelectronics Reliability*, vol. 50, pp. 1532 –1537, 2010.

[14] M. Berkani, S. Lefebvre, and Z. Khatir, "Saturation current and on-resistance correlation during during repetitive short-circuit conditions on SiC JFET transistors," *IEEE Transactions on Power Electronics,*, vol. 28, no. 2, pp. 621–624, Feb 2013.

[15] C. Abbate, G. Busatto, and F. Iannuzzo, "Operation of SiC normally-off JFET at the edges of its safe operating area," *Journal of Microelectronics Reliability*, vol. 50, pp. 1532 –1537, 2010.

[16] A. Hutzler, F. Zeyss, S. Vater, A. Tokarski, A. Schletz, and M. Marz, "Power cycling community 1995-2014 - an overview of test results over the last 20 years," *Bodos power systems,*, May 2014.

[17] A. de Vega, P. Ghimire, K. Pedersen, I. Trintis, S. Beczckowski, S. Munk-Nielsen, B. Rannestad, and P. Thogersen, "Test setup for accelerated test of high power IGBT modules with online monitoring of Vce and Vf voltage during converter operation," in *Proc. of 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE-ASIA)*, May 2014, pp. 2547–2553.

[18] V. Smet, "Aging and failure modes of IGBT power modules undergoing power cycling in high temperature environments," Ph.D. dissertation, Dept. IES (Southern Electr. Inst.), Montpellier 2 Univ., Montpellier, France, 2010.

[19] M. Held, P. Jacob, G. Nicoletti, P. Scacco, and M.-H. Poech, "Fast power cycling test of IGBT modules in traction application," in *Proc.*

of International Conference on Power Electronics and Drive Systems, vol. 1, May 1997, pp. 425–430.

[20] "IEC 61010-1 safety requirements for electrical equipment for measurement, control, and laboratory use - part 1: General requirements," 2010.

[21] R. Wu, P. Diaz Reigosa, F. Iannuzzo, L. Smirnova, H. Wang, and F. Blaabjerg, "Study on oscillations during short circuit of MW-scale IGBT power modules by means of a 6-kA/1.1-kV nondestructive testing system," *IEEE Journal of Emerging and Selected Topics in Power Electronics,*, vol. 3, no. 3, pp. 756–765, Sept 2015.

[22] R. Wu, L. Smirnova, F. Iannuzzo, H. Wang, and F. Blaabjerg, "Investigation on the short-circuit behavior of an aged IGBT module through a 6 kA/1.1 kV non-destructive testing equipment," in *Proc. of 40th Annual Conference of the IEEE Industrial Electronics Society, IECON 2014*, Oct 2014, pp. 3367–3373.

[23] MathWorks(R). [Online]. Available: http://www.mathworks.com/

[24] A. Sattar, *Insulated Gate Bipolar Transistor (IGBT) Basics*. IXYS Corporation, Appl. Note IXAN0063.

[25] Keysight Technologies. [Online]. Available: http://www.keysight.com/en/pd-2404038-pn-B1506A/