Intelligent DC- and AC Power-Cycling Platform for Power Electronic Components

Zhang, Kaichen; Fogsgaard, Martin Bendix; Iannuzzo, Francesco

Published in:
2022 IEEE Applied Power Electronics Conference and Exposition (APEC)

DOI (link to publication from Publisher):
10.1109/APEC43599.2022.9773518

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Intelligent DC- and AC Power-Cycling Platform for Power Electronic Components

Kaichen Zhang, Martin Bendix Fogsgaard, and Francesco Iannuzzo
Center of Reliable Power Electronics (CORPE)
Department of Energy, Aalborg University
Aalborg 9220, Denmark
kzh@energy.aau.dk, mbf@energy.aau.dk, fia@energy.aau.dk

Abstract—In this paper, a state-of-the-art, intelligent power cycling platform is introduced in detail. The test platform allows to perform both DC- and AC- power-cycling tests on power electronic discrete components as well as modules up to 70 ARMS / 700 VDC. Vital parameters of the device under test (DUT) as junction temperature and on-state voltage are measured during the test. A 19”-standard industrial rack is used, which enables a flexible and compact test platform design. Test results for power cycling are presented for validation purposes.

Index Terms—accelerated power cycling test, reliability, lifetime estimation, on-line monitoring, wear-out, test apparatus

I. INTRODUCTION

Working out the expected life of power components has become an essential part of the design process, which is generally achieved by extensive accelerated power-cycling tests [1].

Up to now, many different power-cycling test methods have been proposed and studied [2] - [4]. On the one hand, DC power cycling is proposed in many reliability standards [5] - [7]. On the other hand, AC power cycling has become very popular in recent years because of its more similar operating conditions to real operations [4]. However, AC power-cycling is challenging as the wear process depends on a lot more parameters compared to DC power-cycling, which makes AC testing platforms in general very complicated. Moreover, there is a significant lack of standards regarding AC power-cycling, which does not help designers to identify the best implementation.

With the ambition of stimulating discussions about the importance and the feasibility of AC power-cycling tests, this paper presents for the first time a complete design of a test platform for both DC- and AC power-cycling, with particular emphasis on the AC operation. All the parameters and the testing strategy can be fully customized via a National Instruments CompactRIO with LabVIEW program, which is also in charge of data logging and real-time communication with the user.

This paper is organized as follows. In Section II, details of the test platform design have been given in aspects from the hardware configuration to the software implementation. Section III shows several experimental results to validate the functions of the proposed platform. Section IV concludes this paper with a summary and outlook to the future work.

II. TEST PLATFORM DESIGN

A. Operation principle

Fig.2 shows a principle schematic of the proposed setup. In the main circuit, a device-under-test (DUT) converter and a load converter share the same DC-link and are back-to-back connected through a 0.42 mH inductive load in such a way to circulate the power. An Itech IT6018C-1500-40 DC power supply is connected to the DC-link to provide the power loss. Nominal 70 ARMS / 700 VDC are achieved using a SEMIKRON SKM100GB12T4 IGBT module for the load converter. To ensure a regulated case temperature on the DUT, two separate cooling plates with different cooling systems are adopted. More in detail, a Julabo Presto A40 chiller with glycol is used for the DUT, whereas a cooling system from the building with water at about 15 °C is used for the load converter without regulation. A fiber-optic system (“signal conditioner”) by opSens is used for junction temperature monitoring. An uninterruptible power supply (UPS) ensures...
that the control unit still operates during possible blackouts and has time enough to save the data in the pipeline and to put the system in a safe mode, including closing a solenoid valve on the cooling system to prevent dangerous condensation on the PCBs in absence of power.

The control system comprises a host PC running NI LabVIEW and a NI CompactRIO hardware. The host PC is equipped with a user graphical interface controlling the NI CompactRIO and other instruments. Several digital NI 9401 modules of the NI CompactRIO module are used both to provide the PWM signals and communicate with a set of analog-to-digital converters (ADC) used for $V_{ce(on)}$ logging. Furthermore, an NI 9202 and an NI 9210 module are used to log junction (fiber-optic) temperature and the case temperatures via thermocouples. Worth mentioning, all the communications among different instruments go through a multi-channel Ethernet switch.

B. 19” Rack configuration

Based on the schematic shown in Fig.2, a standard 19” industrial rack is chosen as demonstrated in Fig.1 (left). An array of six twin units has been built, which can be run independently. This gives a great benefit in terms of time-saving, as power-cycling is typically conducted on many samples for the sake of good statistics. In the same figure, the detailed configuration of one rack is shown (right). By using the standard-sized rack, the whole test setup can be benefited when the airflow management, cable management, and capacity planning are put into consideration. The placement of the several instruments is optimized to allow the best possible access to the DUT, which is put on a retractable drawer along with the load converter. Directly on top of it, a foldable monitor-and-keyboard set used in case of local access to the PC is placed. On the next level, an auxiliary power supply for gate drivers, $V_{ce(on)}$ monitoring circuits, and general services, is placed together with the host PC.

To achieve flexibility, a test bench with four PCBs has been arranged in the way shown in Fig.3. Two twin main PCBs are used for the load converter and DUT converter, respectively, which both comprise DC-link capacitors and gate driver circuits, as well as on-state voltage-monitoring circuits. Two more small PCBs (“adapters”) host the power modules alone for the DUT converter and the load converter, respectively, allowing great ease of replacement when many units have to be tested. Moreover, only the adapter PCBs must be re-designed when another part number has to be tested, yielding a great saving of time and money. The DUT converter heat sink is mounted with height-adjustable standoffs to meet the different DUT height requirements. Measuring points have been reserved for temperature monitoring of both load and DUT converter heat sink. The feedback of the temperature close to the DUT converter heat sink will help to assure accurate temperature control using the chiller. Large space around the DUT adapter is saved for optical fiber holder placement. Besides, a sealed condensation-collection tray with a drainage pipe is included for operations below room temperature.

C. PCB design

The PCB boards implement the main test platform circuit in Fig.2, general description of the PCB boards and details of the design considerations are as follows.

The two main PCB DC-links are connected through a dual-row DIN 41612 flat connector configured as a busbar-like connection. The load and DUT adapters are connected through SAMTEC POWERSTRIP™ mixed signal-power connectors [11] which bring both DC power and gate signals, as well as Kelvin connections for the $V_{ce(on)}$ measurements. The main PCBs are connected to the NI CompactRIO via four DB-25 connectors for digital communication.

Referring to Fig.4(a), the $V_{ce(on)}$ measurement unit and the gate unit are both hosted on the main PCBs. The $V_{ce(on)}$ is measured over the DC and Kelvin terminals of the IGBT.
module, for both the DUT converter and the load converter. This enables not only the online monitoring of the DUT’s state of wear but also the on-time replacement of the load converter IGBT module, so that the test platform’s functionality can be ensured.

To meet the potential requirement of the DUT (either Si IGBTs or SiC MOSFETs), especially in the aspect of the gate drive current capability, the gate driver board has been designed in plug-and-play mode, which can be redesigned and changed correspondingly. The plug-and-play design also makes the maintenance easier when a failure-induced replacement of the gate driver is needed. Furthermore, an adjustable-voltage gate driver circuit allows testing DUTs which may require different on-voltages and/or off-voltages.

To be able to conduct the failure analysis and investigate the failure root causes of the failed device, it is essential to assure that the further damage is within a certain limit when the catastrophic failure happened under the long-lifetime test [8]. In case of a short circuit, the two converters should be able to be disconnected from the DC capacitor banks right away, preserving from further destruction, and the remaining current will be circulating between the two converters until it is fully damped. This feature is realized using a current sensing resistor and an analog compactor, by how a fast response time is guaranteed. Based on experience, the response time can be within hundreds of nano-seconds time scale, details can be found in [9]. In a longer time scale of millisecond time scale, the DC power supply will be shut down as the input DC voltage is also monitored and controlled, which will be further mentioned in the software part. Some other vital parameters like the circulating DC-link current $I_{DC}$ is measured via shunt resistors on one of the main PCBs. The three-phase load currents $I_L$ are measured using LEM current transducers located on the load adaptor PCB.

The DUT adapter PCB is designed to monitor as many parameters as possible of the DUT when the power cycling test is conducted. Normally, the lifetime of the multi-chip power module is dependent on the chip (or phase leg) which reaches up the earliest failure. To investigate the lifetime of every single chip inside the power module under test, a backup DUT concept has been proposed in the DUT adapter design. As shown in Fig.3, two of the same DUT will be put in parallel, sharing the same DC power and gate signals connection, by using the solder jumper to determine which phase leg from which DUT will come to play. Once one out of the six legs of the first DUT has been cycled to failure, the backup leg from the second DUT can be replaced conveniently. A detailed picture of the DUT adapter is shown in Fig.4(b).

The junction temperature $T_J$ of the DUT is measured using optical fibers. To have direct access to the chip top side, it is necessary to provide a cutout on the DUT adapter corresponding to the active area of the power module, in such a way the optical fiber can be run through the dielectric gel. Of course, the power module under test must be of a type with a removable lid. The maximum sampling rate of the fiber optic conditioner is 1 kHz [10]. If a higher sampling frequency is needed, or the DUT’s package limits the use of the optical fibers, thermosensitive electrical parameters (TSEPs) can always be used after preventive calibration of the on-state voltage [11]. Thermocouple are used in either case for the other temperatures, i.e., the case temperature, room temperature, as well as the main PCB temperature, which is also continuously monitored for safety reasons.

### D. Safety precautions

Three operation statuses are possible: “run”, “halt”, and “emergency”. Interlock switches are placed on the rack doors which trigger a halt status. For each rack, a smoke detector placed close to the DUT- and the load converter and a webcam with motion detection are used to monitor the system 24/7 and
to trigger the emergency status along with other anomalies, such as over-current on the DC-link or zero output current, which happens in the case of fail-to-open conditions. The operation status is constantly shown by beacon lights placed on top of each rack (see Fig.1 left).

In case of failure or a control-system crash due e.g., to electro-magnetic interference (EMI) happening during the experiment, a fast electronic fuse is implemented, which comprises a group of parallel-connected IGBTs connected between the DC-link capacitors and the DUT converter.

As is mentioned above, a sealed tray has been embedded in the drawer holding both the DUT- and load converter (see Fig.3) to collect the condensation water that inevitably comes from the heatsinks when operated below room temperature. A drainage pipe (not shown) is used to get rid of the collected water.

Vital instruments such as auxiliary lab power supply, host PC, foldable monitor, NI CompactRIO, and fiber optic signal conditioner are all powered by the UPS, which assures no experimental data loss when a power outage happened. Other important instruments such as DC power supply, UPS, and chiller are all in communication with NI CompactRIO, the test will be automatically stopped by the LabVIEW control system when the communication is lost.

E. LabVIEW Program

The National Instruments CompactRIO and the implemented LabVIEW program are the core control part of the whole test setup. In order to control the instruments, perform tests under close-to-realistic operating conditions, and visualize the operation status of the platform, a LabVIEW graphical user interface (GUI) program was developed (shown in Fig.5). The designed LabVIEW GUI program mainly includes the following parts: 1) communication among multiple instruments; 2) indication of the test platform status; 3) circuit operation condition: input voltage, reference frequency, switching frequency, modulation index, the phase shift between two converters; 4) visualization of the key measurement results: junction temperature of the power module under test, the ambient temperature inside the cabinet, heatsink temperature, \( V_{on} \), DC-link current and load current; 5) data logging into the cloud storage; 6) generating the pulse width modulation (PWM) signal; 7) implement closed-loop control by sensing the load current and send to an FPGA-based proportional-integral (PI) or proportional-resonant (PR) controller, which enables an accurate control of the current amplitude, frequency, total harmonic distortion (THD), etc. [13] - [15]; 8) test status notification sent to the laboratory personnel via E-mail or SMS (short message service).

The design of such a LabVIEW GUI program has the following advantages: 1) safe running can be assured by implementing multiple safety precautions in the program; 2) key values and parameters are listed and summarized, which is convenient for users; 3) high accuracy and reliable performance makes it ideal for long-time aging tests; 4) As the entire set-up is controlled through one user interface, algorithms can be set up to automate the initiation of power cycling at pre-set work-points.

III. RESULTS AND DISCUSSION

In this Section, power-cycling tests for both DC- and AC-have been carried out to validate the effectiveness and accuracy of the platform design.

A. DC Power-Cycling Test

The DC power-cycling test is carried out with the configuration of 2s on-time/2s off-time under 20A injection current. The driving signal is implemented with 10ms overlapped time to eliminate the overshoot voltage during current commutation. The on-state voltage of the low side of phase A and the gate voltage of phase legs are shown in Fig.6, where a clear sign of on-state voltage increase can be notified.

B. AC Power-Cycling Test

The AC power-cycling test is tested under an open-loop configuration, carried out under 400 \( V_{DC} \). The sinusoidal pulse width modulation (SPWM) technique is used at the fundamental frequency of 50Hz and switching frequency of 10kHz. The ac output current waveform is shown in Fig.7.

IV. CONCLUSIONS AND FUTURE WORK

A smart and user-friendly power cycling test platform with modular architecture has been introduced. The presented test platform is capable of conducting both DC- and AC-automated power-cycling test and is suitable for power IGBTs and MOSFETs up to 700 \( V_{DC} \), 70 \( A_{RMS} \). Vital parameters of DUT and test platform health status are monitored and saved during the running experiments. Various safety precautions have been implemented to assure a safe and stable operation. One user-friendly LabVIEW GUI has been designed to meet multiple functionality requirements. Different experimental results were shown to prove the effectiveness and accuracy of the platform design.

Further development will be focusing on conducting both the DC- and AC power-cycling tests with under various load conditions, which will generate a huge amount of data that can be used for lifetime prediction under different operating conditions, and failure mode investigation.

![Fig. 5. LabVIEW GUI program.](image)
ACKNOWLEDGMENT

This work is funded by the X-POWER project from Danish Agency for Science and Higher Education. The authors would like to thank J. Christiansen, M. Lund, B. B. Jensen for their support in the setup implementation.

REFERENCES


