

© 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Print ISBN: 978-3-8007-4424-4

PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management; Proceedings of; May 2017

**Mission Profile Based Reliability Evaluation of Building Blocks for Modular Power Converters**

Frederik Hahn  
Markus Andresen  
Giampaolo Buticchi  
Marco Liserre

**Suggested Citation**

F. Hahn, M. Andresen, G. Buticchi and M. Liserre, "Mission Profile Based Reliability Evaluation of Building Blocks for Modular Power Converters," PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management; Proceedings of, Nuremberg, Germany, 2017, pp. 1-7.

# Mission Profile Based Reliability Evaluation of Building Blocks for Modular Power Converters

Frederik Hahn, Markus Andresen, Giampaolo Buticchi, Marco Liserre  
Chair of Power Electronics, University of Kiel, Kaiserstrasse 2, 24143 Kiel, Germany  
frha@tf.uni-kiel.de, ma@tf.uni-kiel.de, gibu@tf.uni-kiel.de, ml@tf.uni-kiel.de

## Abstract

The major challenge of the power electronics design is to be cost effective while fulfilling the reliability requirements. Since the thermal cycling is one of the most severe causes of failure in power electronics, this paper presents a test bench for the thermal testing of power converters. This is particularly important for modular power converters consisting of several building blocks, which cannot be tested easily. For thermal design evaluation it is proposed to test the building blocks under real mission profiles. As a study case, the thermal behavior of an Modular Multilevel Converter (MMC) is given to demonstrate the approach.

## 1. Introduction

The development of power electronics in the recent years has shown that the optimal thermal design of power converters is of paramount importance. Its diffusion, at first limited to particular equipment, has nowadays spread even to the strategical sectors of transportation [1], power generation and distribution. However, despite the great number of advantages, one concern of more systems based on power electronics is a possible overall reduced reliability. Appropriate methods for the analysis and estimation of the lifetime require to apply a physics of failure based approach including mission profile testing.

During operation, the power modules, the basic brick of a power electronics converter, undergo power cycles and ambient temperature changes, which create junction temperature fluctuations in the module. These temperature fluctuations cause mechanical stress and they are the main reason for aging, failures and consequent lifetime reduction. Every converter needs to be designed for its mis-

sion profile, because not only the operation conditions are different, but also the lifetime requirement is dependent on the application. Thereby the stress depends on the maximum temperature, the average temperature and the magnitude of the thermal cycles. To ensure a reasonable module lifetime, the temperature has to be limited and thermal cycles have to be either reduced in magnitude or in the total number of cycles. Due to the price of the power semiconductors, their current rating and their thermal behavior needs to be optimized, while they still need to withstand the stress in all possible operating conditions and fulfill the reliability target [2].

Modular power converters, which have become popular in high power applications, offer several advantages like lower switching frequency, the use of lower rated components with lower losses, lower EMI and others [3, 4, 5]. These converters consist of many building blocks in each phase, whose components need to be designed in an appropriate way. Beside simulation based tests in the design process, practical tests of the converter are required. As an example the Modular Multilevel Converter (MMC) [6] in High Voltage Direct Current (HVDC) applications could consist of several hundreds of building blocks, leading to high implementation effort, but also high potential savings if all components are sized optimally [7]. This prevents over-rating of the components, resulting in savings for the component costs.

This work proposes a mission profile based test of modular power converters for optimizing the electrical and thermal design of the power semiconductors in the system. As a study case, the thermal behavior of an MMC is given to demonstrate the capability of the proposed set-up.

## 2. Experimental Bench

Modular building blocks as half-bridges or full-bridges are the core of each modular power converter. Since the systems of modular power converters can be huge and expensive, the building of the full converter is not always practical and economic. However, the single building blocks of the converters can be tested under realistic conditions to evaluate the thermal stress and the reliability. For this purpose, a universal experimental bench has been developed, as shown in Fig. 1, to test building blocks of modular power converters under its real mission profiles. With the help of the setup, both the electrical and thermal behavior of the building block and of each semiconductor can be investigated by experiments, also taking into account special operation conditions as fault operation conditions and active thermal control [8]. The most important system data of the experimental bench are summarized in Table 1. Half-bridge cells has been selected as building blocks based on an open 1200 V IGBT module from Danfoss. The applied DC voltage has to be limited for protection since the absence of the filling gel makes high-voltage operation riskier.

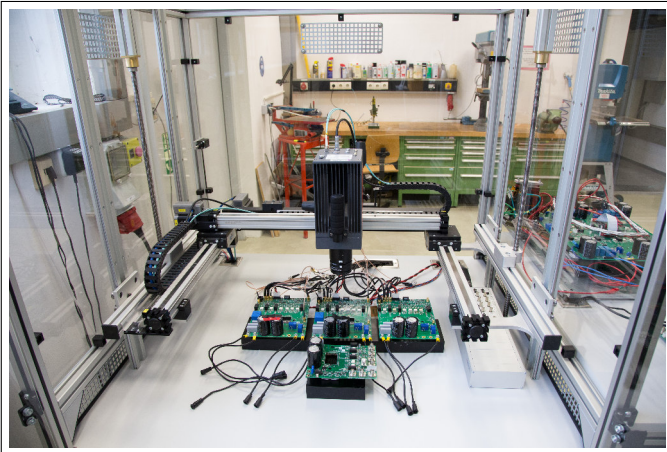


Fig. 1: Laboratory setup of the experimental bench.

The basic concept of the experimental bench is summarized in Fig. 2. The mission profile is obtained by theoretical analysis and has to be applied to the selected building block by a proper control. Beside the control of the electrical parameters like voltages and currents, the thermal behavior needs to be measured and recorded, which is done by optic sensors and an infrared (IR) camera. The obtained thermal characterization can be exploited for

Tab. 1: System data of the experimental bench.

Building block:	Half-bridge cells
IGBT module:	<i>DP25F1200T101666</i>
Breakthrough voltage:	1200 V
DC-link voltage:	max. 600 V
Nominal current (DC):	max. 75 A
Switching frequency:	max. 20 kHz
IR camera:	InfraTec Image IR
Optic sensors:	OPsSens PSR-100

an accurate thermal modeling and for lifetime predictions. Based on the results the converter and cooling design can be adapted for both a reliable and cost-efficient system. Selected test procedures are summarized and motivated in Table 2 to assist for an optimized converter design.

## 3. Emulation of Building Blocks for the MMC

One important modular power converter topology is the MMC, depicted in Fig. 3 [6]. The MMC has become a very popular topology in hybrid networks, however the number of cells can be huge, particularly in HVDC applications. The building of such big and expensive systems would be not practical only for testing. On the other hand, simulation models are always based on certain simplifications and have to be verified by experimental results. For this purpose, it is useful to put the focus on the MMC cells, the core of the converter. The emulation of one cell by the introduced experimental bench is exemplary done in this section. The emulation of each cell can figure out the behavior of the full MMC system. Fig. 4 shows the switching states and the possible current paths of one half-bridge cell during normal operation [9].

In Fig. 5 the electrical behavior of a simulated high-voltage MMC with 150 half-bridge cells per arm is depicted whereby the applied system parameters and control can be found in [10]. The converter voltages  $v_{conv}$  are generated by a nearest level modulation [11] controlling the grid current  $i_{ac}$  for a power injection of 300 MVA into the high-voltage grid  $v_{grid}$  (power factor: 0.95). The emulation of one cell's

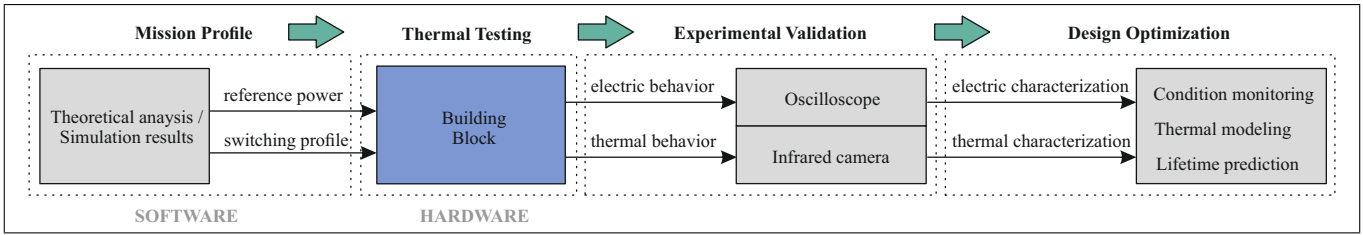


Fig. 2: Block scheme of the experimental bench to emulate building blocks of modular power converters.

Tab. 2: Test procedures contributing for an optimized converter and cooling design.

Test procedure	Motivation
<ul style="list-style-type: none"> <li>Mission profile recording with high precision instrumentation (oscilloscope).</li> </ul>	Actual power devices allows for very fast switching to happen, in order to correctly map the mission profile, a very high bandwidth and high accuracy measure instrument is needed. In this way, even high frequency behavior of the devices can be recorded and used for reliability data.
<ul style="list-style-type: none"> <li>Verification of thermal models, measure of the thermal impedance.</li> </ul>	For design purposes it is of paramount importance to have accurate way of prediction the temperature of the devices or the cooling system. The test bench will allow to tune the thermal models or the Finite Element Analysis results.
<ul style="list-style-type: none"> <li>Development of diagnostic/prognostic procedures.</li> </ul>	The measure of the electrical and thermal parameters, in relation to the mission profile, allows individuating the values that shows strongest dependence on the aging/deterioration. Then, rules can be extrapolated from experimental data to realize prognostic procedure that estimates the residual lifetime of the component, or diagnostic ones, where the damage is detected before it can become harmful for the equipment.

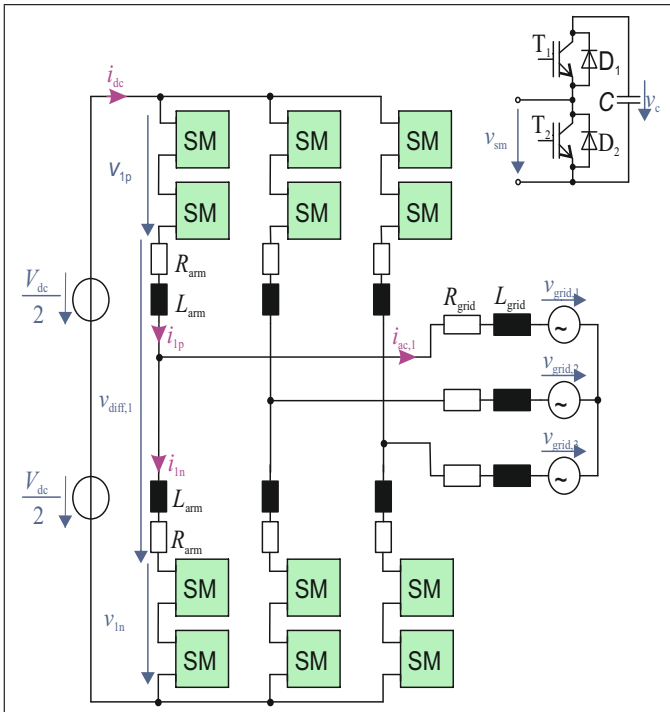


Fig. 3: Three-phase circuit of an MMC.

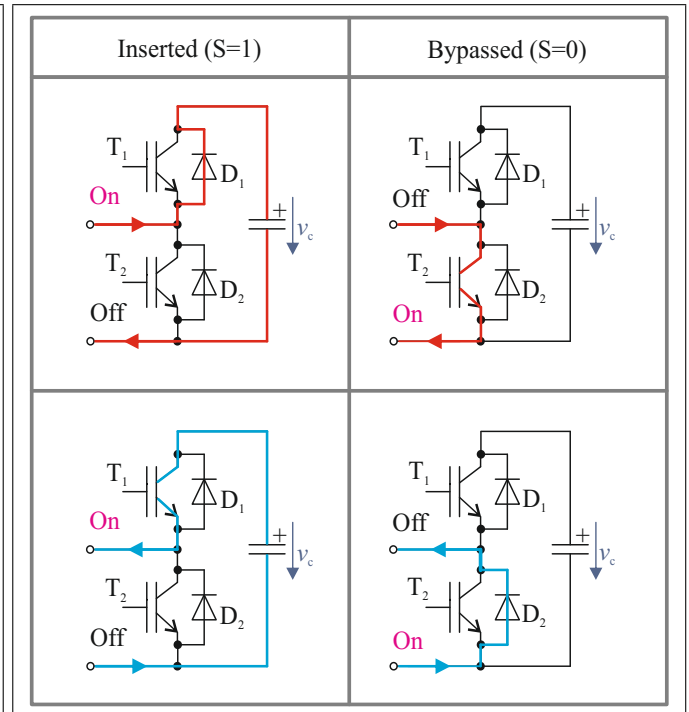


Fig. 4: Current paths in one MMC half-bridge cell.

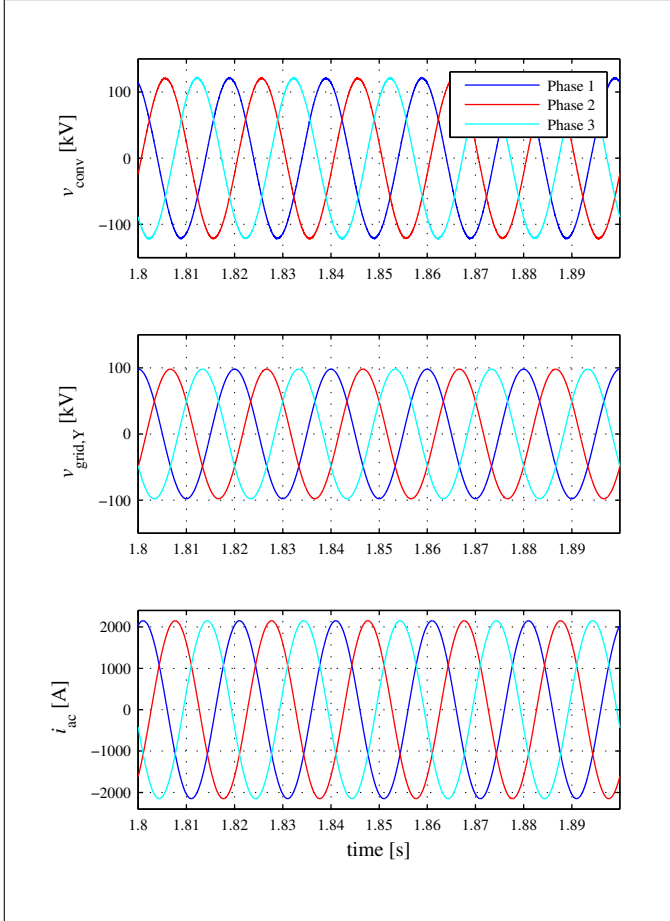


Fig. 5: Simulation results: Three-phase converter voltages, grid voltages and phase currents (steady state:  $P_{\text{grid}} = 300 \text{ MW}$ ,  $\cos \varphi = 0.95$ ).

voltage and the corresponding arm current at the downscaled prototype is exemplarily shown for cell no. 61 in Fig. 6. The power transfer from DC to AC side is illustrated by the DC part in the controlled arm current. The cell's switching profile is predefined by the simulated nearest level modulation. Both, the arm current and the switching profile are fully adjustable in the experimental setup according to the considered operation point and the selected modulation method.

Based on loss analysis [12] and the thermal model in Fig. 7, the junction temperatures of each semiconductor are simulated, whereby a 3.3 kV IGBT module CM1200HC-90R from Mitsubishi is considered. The obtained junction temperatures  $T_j$  for the first 21 MMC cells are depicted in Fig. 8, whereas  $T_2$  and  $D_1$  are the most stressed semiconductors at the selected operation point. By means of the experimental bench, the thermal behavior of cell

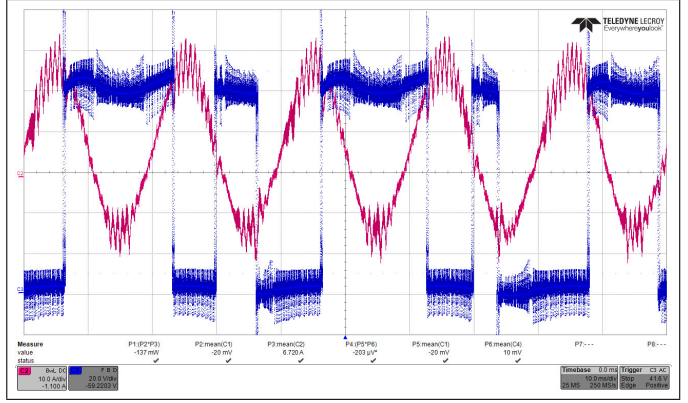


Fig. 6: Experimental results: Arm current (red) and voltage at one MMC half-bridge cell.

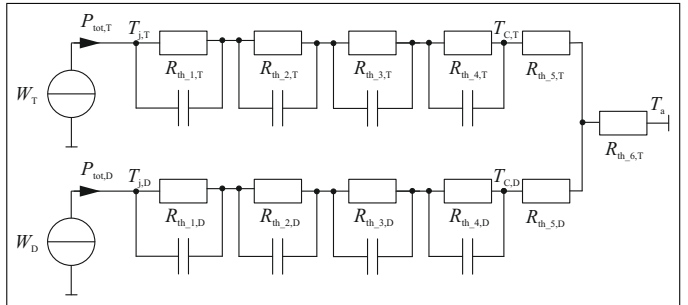


Fig. 7: Foster model for IGBT module and cooling system.

no. 61 has been emulated as well. The real temperature distribution is recorded by IR camera for each semiconductor in Fig. 9 whereby the hottest temperatures in the open Danfoss module occur at the bond wires and at the chip  $T_2$ . The temperature profile is recorded by IR camera as well. Fig. 10 shows thermal cycles up to 5K. In Fig. 11 the results from the thermal model for the Mitsubishi module and the IR measurements for the Danfoss module are compared. The matching of the thermal profiles is excellent, the differences in the absolute temperatures are caused by the downscaling of the prototype. An optimized calibration of the thermal model can be achieved by adapting the model to the real behavior measured by IR camera as it has been done in [13].

Based on an appropriate thermal model the lifetime of the semiconductors of each cell can be estimated by (1) where the number of power cycles to failure  $N_f$  are approximated [14].

$$N_f = a_1 \cdot (\Delta T_j)^{-a_2} \cdot \exp^{\frac{a_3}{T_j}} \quad (1)$$



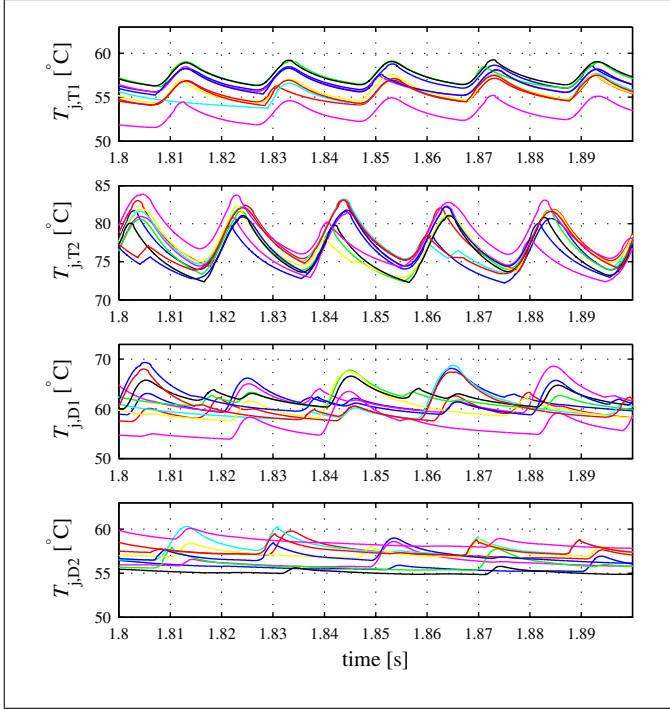


Fig. 8: Simulation results: Thermal behavior of the semiconductors in the first 21 MMC cells in the upper arm, phase 1 (steady state:  $P_{\text{grid}} = 300 \text{ MW}$ ,  $\cos \varphi = 0.95$ ).

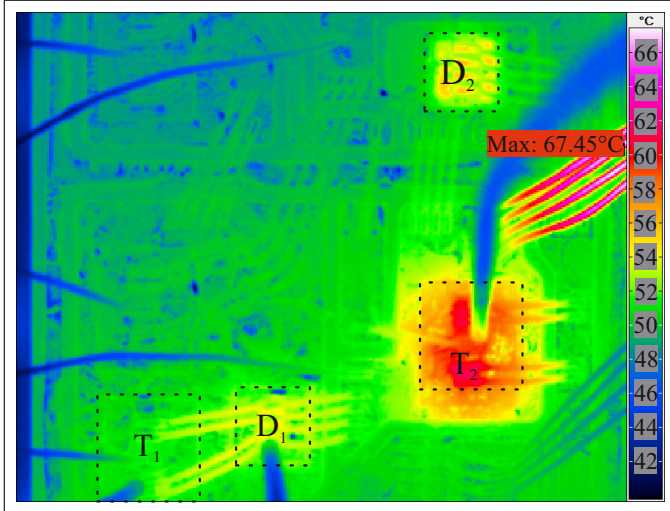


Fig. 9: Experimental results: Temperature distribution in the open IGBT module (recorded by IR camera).

The constants  $a_1$ ,  $a_2$  and  $a_3$  have to be fitted by cycling tests. Since this model only considers one magnitude of thermal cycles  $\Delta T_j$ , the Miner rule is commonly applied to apply linear damage accumulation as given in (2).

$$C_m = \sum_{i=0}^{\infty} \frac{n_i}{N_i} \leq 1 \quad (2)$$

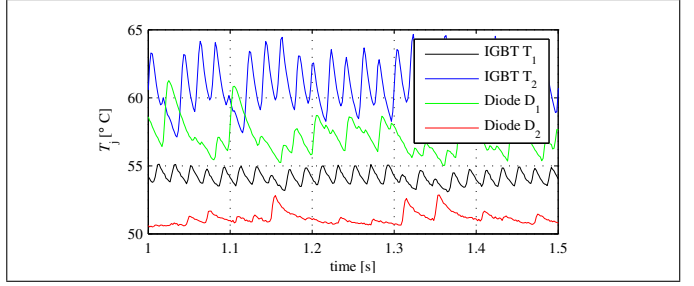


Fig. 10: Experimental results: Semiconductor's junction temperatures in one MMC cell (no. 61) recorded by IR camera.

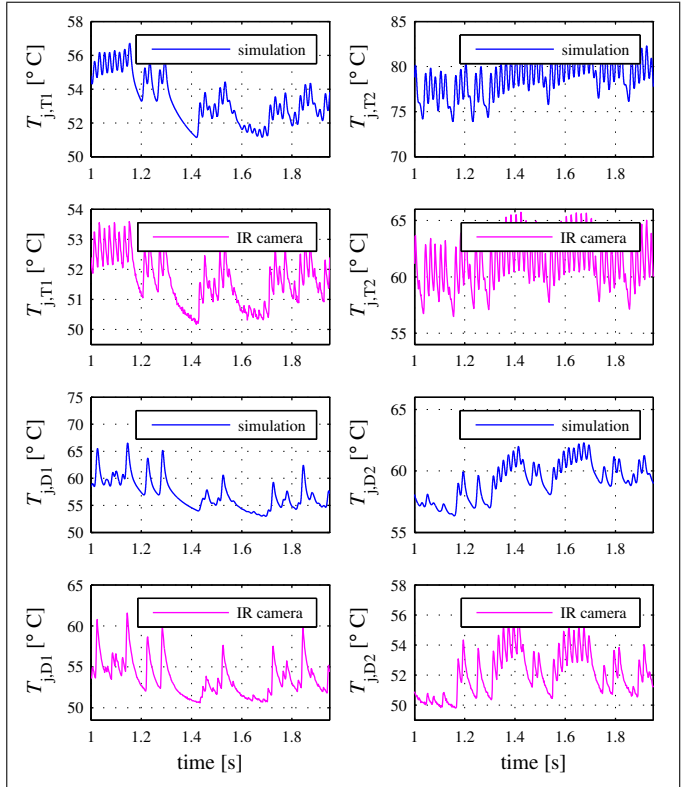


Fig. 11: Junction temperature profile for one MMC cell (no. 61) from simulation and from experimental bench (steady state:  $P_{\text{grid}} = 300 \text{ MW}$ ,  $\cos \varphi = 0.95$ ).

$N_i$  is the number of cycles to failure in the stress range  $i$  and  $n_i$  the number of detected cycles in the  $i^{\text{th}}$  stress range. The device is expected to fail, as soon as the accumulated damage is  $C_m = 1$ . The estimated lifetimes of the most stressed semiconductors  $T_2$  and  $D_1$  are depicted in Fig. 12 for all 150 MMC cells. By means of the analysis, the converter and thermal design can be tested and adjusted to achieve an optimal balance between system costs and expected lifetimes. The expected lifetimes are directly correlated to the maintenance intervals and costs.

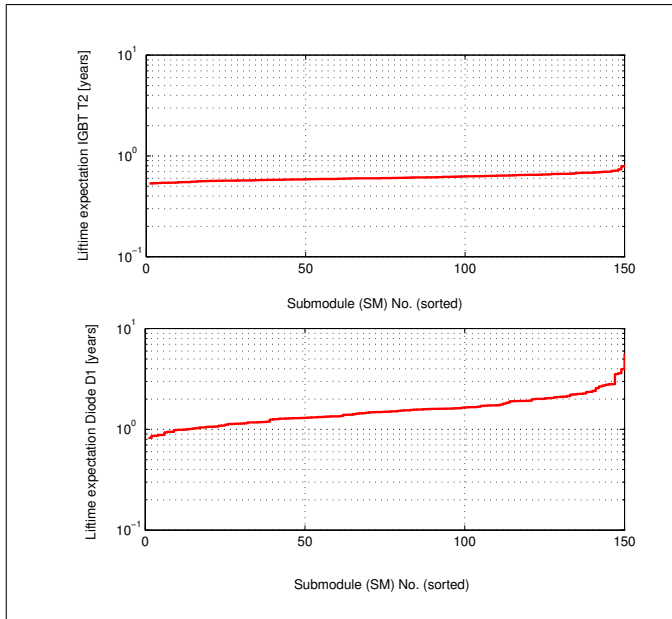


Fig. 12: Lifetime expectation for IGBTs  $T_2$  and diodes  $D_1$  of all submodules in the upper arm, phase 1 (steady state:  $P_{\text{grid}} = 300 \text{ MW}$ ,  $\cos \varphi = 0.95$ ).

## 4. Conclusion

In this paper, a universal experimental bench has been introduced to investigate the thermal behavior of building blocks from modular power converters under real mission profiles. Both, ac and dc load currents are controlled so that even single MMC cells can be emulated under realistic conditions, whereas the applied switching pattern is provided by the selected modulation method. The knowledge of the real thermal behavior and lifetime estimations can be exploited for both, an efficient system design and for an adequate reliability. By means of the experimental bench, it becomes possible to emulate the electrical and thermal behavior of huge and complicated modular systems where an appropriate and cost efficient converter design is essential. Beside the MMC, also other modular power converters can be investigated.

## Acknowledgment

The research leading to these results has received funding from the European Research Council under the European Unions Seventh Framework Program (FP/2007-2013) / ERC Grant Agreement n. [616344] - Heart.

## 5. References

- [1] Mahera Musallam, Chunyan Yin, Christopher Bailey, and Mark Johnson. Mission profile-based reliability design and real-time life consumption estimation in power electronics. *IEEE Transactions on Power Electronics*, 30(5):2601–2613, 2015.
- [2] Huai Wang, Marco Liserre, Frede Blaabjerg, Peter de Place Rikken, John B Jacobsen, Thorkild Kvisgaard, and Jørn Landkildehus. Transitioning to physics-of-failure as a reliability driver in power electronics. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2(1):97–114, 2014.
- [3] Leopoldo G Franquelo, Jose Rodriguez, Jose I Leon, Samir Kouro, Ramon Portillo, and Maria AM Prats. The age of multilevel converters arrives. *IEEE industrial electronics magazine*, 2(2):28–39, 2008.
- [4] Martin Glinka and Rainer Marquardt. A new ac/ac multilevel converter family. *IEEE Transactions on Industrial Electronics*, 52(3):662–669, 2005.
- [5] G. Buticchi, M. Andresen, and M. Liserre. Lifetime based power routing of a quadruple active bridge dc/dc converter. *IEEE Transactions on Power Electronics*, 2017.
- [6] A. Lesnicar and R. Marquardt. An innovative modular multilevel converter topology suitable for a wide power range. In *Power Tech Conference Proceedings, 2003 IEEE Bologna*, volume 3, pages 6 pp. Vol.3–, June 2003.
- [7] Ionuț Vernica, Ke Ma, and Frede Blaabjerg. Advanced derating strategy for extended lifetime of power electronics in wind power applications. In *2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, pages 1–8. IEEE, 2016.
- [8] M. Andresen, K. Ma, G. Buticchi, J. Falck, F. Blaabjerg, and M. Liserre. Junction temperature control for more reliable power electronics. *IEEE Transactions on Power Electronics*, 2017.

- [9] M. Davies et al. HvdC plus - basics and principle of operation. Technical report, Siemens, August 2008.
- [10] F. Hahn, G. Buticchi, and M. Liserre. Active thermal balancing for modular multilevel converters in hvdc applications. In *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*, pages 1–10, Sept 2016.
- [11] G. Konstantinou, J. Pou, S. Ceballos, R. Darus, and V. G. Agelidis. Switching frequency analysis of staircase-modulated modular multilevel converters and equivalent pwm techniques. *IEEE Transactions on Power Delivery*, 31(1):28–36, Feb 2016.
- [12] M. H. Bierhoff and F. W. Fuchs. Semiconductor losses in voltage source and current source igbt converters based on analytical derivation. In *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551)*, volume 4, pages 2836–2842 Vol.4, 2004.
- [13] M. Andresen, M. Schloh, G. Buticchi, and M. Liserre. Computational light junction temperature estimator for active thermal control. In *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2016.
- [14] R. Bayerer, T. Herrmann, T. Licht, J. Lutz, and M. Feller. Model for power cycling lifetime of igbt modules - various factors influencing lifetime. In *Integrated Power Systems (CIPS), 2008 5th International Conference on*, pages 1–6, March 2008.