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# Reliability Enhancement of Modular Smart Transformers by Uneven Loading of Cells

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## Abstract

A Smart Transformer (ST) is a power electronics based transformer developed for the electrical distribution grid, where it can provide many advanced grid services. The advanced functionality comes with the concern of lower reliability affected by the complexity and the higher number of components. To overcome the reliability concerns, this work proposes to utilize a modular architecture for routing the power in the cells such that cells with shorter remaining lifetimes are less stressed and the time to the next failure in the system is delayed.

## 1. Introduction

The proliferation of renewable energy resources, increasing Electric Vehicles (EV) charging stations have altered the operation of conventional distribution grids and opened up many technical and operational challenges [1]. Power electronics play a significant role in this scenario, since most of the sources or loads are connected to the electrical distribution grid through power converters. Currently, the transformer, an integral part of electric grid, is a passive device which has no dc connectivity or provide any ancillary grid services. One among the different solutions to the challenges posed by the altered grid system is the Smart Transformer (ST). ST is a solid-state transformer (SST) with dc-link connectivity and capable of providing grid services through its ac and dc connection points facilitated by advanced control and identification techniques. ST acts as an intelligent voltage node providing services to both MV/LV grids while retaining compatibility with the existing equipment in the actual grid.

Compared to its counterpart, the main challenges for a ST are the efficiency and the reliability, since

the conventional low frequency passive transformers offers very high efficiency and lifetime. In literature, reliability and efficiency of the modular power converters has been widely investigated [2, 3], and supports the claim that the modular architectures offers an increase of the efficiency. With respect to reliability, studies show that the power modules and the capacitors contribute to the major share of failures in wind and photovoltaic systems [4]. This paper focuses only on the failures caused by the power semiconductors. Failure mechanisms of different components in a converter system are different and some of them depend on the processed power [5]. Since the modular system is comprised of many single cells, it is reasonable that when one cell fails, it is sent to maintenance and replaced, irrespective of the failed component. The Fig. 1 shows the replacement cycle of faulty cells in a modular system. The repaired cell becomes available again as a replacement unit for STs. Consequently, a modular ST system is comprised of cells with different ageing [6].

This paper describes the concept of power routing in modular STs to increase the reliability of the system through unevenly loading the cells of the modular system. Through unequal distribution of power, the goal is to delay or eliminate processed power dependent failures, by shifting the major share of load from aged cells to the less stressed ones. The paper is organized as follows: Section II describes the ST architecture and services. The reliability of ST and the power routing concept are explained in section III. Section IV illustrates the results and the conclusion is drawn in section V.

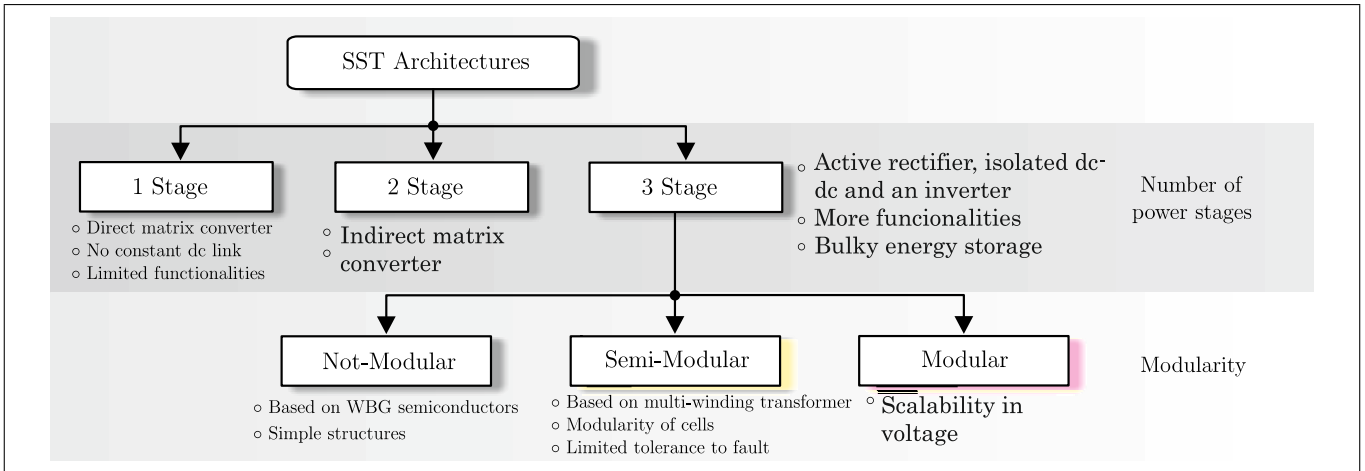


Fig. 2: Classification of SST architectures [6].

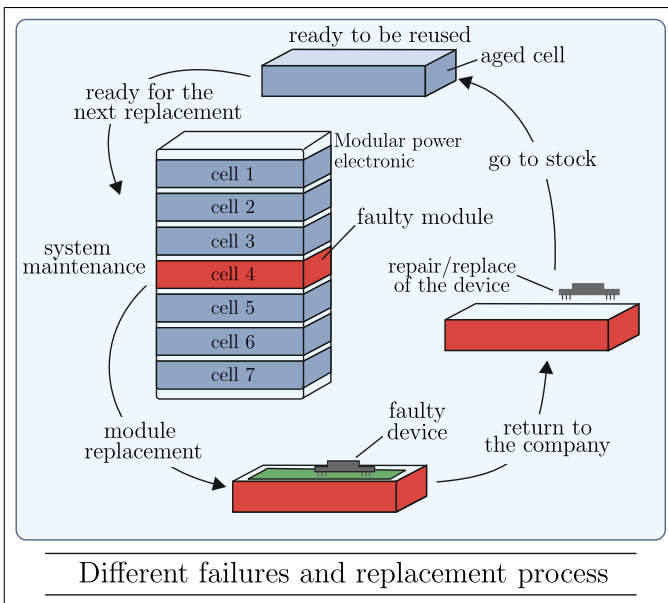


Fig. 1: Replacement cycle in a repairable modular converter system [6].

## 2. ST Architecture and Services

Due to the advancement in power electronics and semiconductors technologies, new SST topologies have been proposed and classified in the literature and they are summarized in Fig. 2. Among these topologies, the three-stage configuration enables dc-link connectivity and also guarantees input-output decoupling of voltages and currents, providing the system control more degrees of freedom and making it the preferred candidate for an ST [7].

ST with modular architecture is composed of several cells with lower voltage or current rating. On

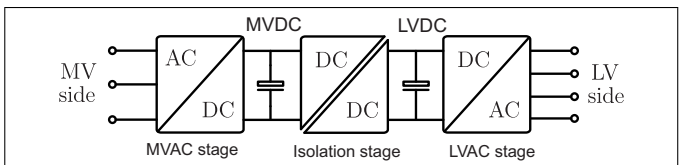


Fig. 3: Schematic architecture of the three-stage ST

the other hand, a non-modular system is based on a single power converter and usually takes advantage of high-voltage, wide-band-gap semiconductors. Since non-modular architectures use a small number of semiconductors, drivers, transformers and sensors, the number of potentially faulty components is lower. However, modular architectures facilitates power and voltage scalability, easier maintenance, and the implementation of fault-tolerance strategies. Considering grid services for the distribution grid, a three-stage ST architecture in Fig.3 is the preferred configuration [9], and is the selected topology for the paper. The three stages serve different control functionality: the low voltage (LV) converter implements a voltage control so as to ensure optimal grid waveforms with low Total Harmonic Distortion (THD). The dc/dc converter stage controls the LV dc-link voltage, ensuring a stable supply for the LV converter. The dc/dc converter also performs the voltage balancing of the medium voltage (MV) cells. Finally, the MV converter controls the ac line current, input power factor and regulates the total MV dc-link voltage.

The three-stage architecture facilitates ST to provide ancillary services to the grid. On the MV side, the current is drawn from the MV grid to satisfy the

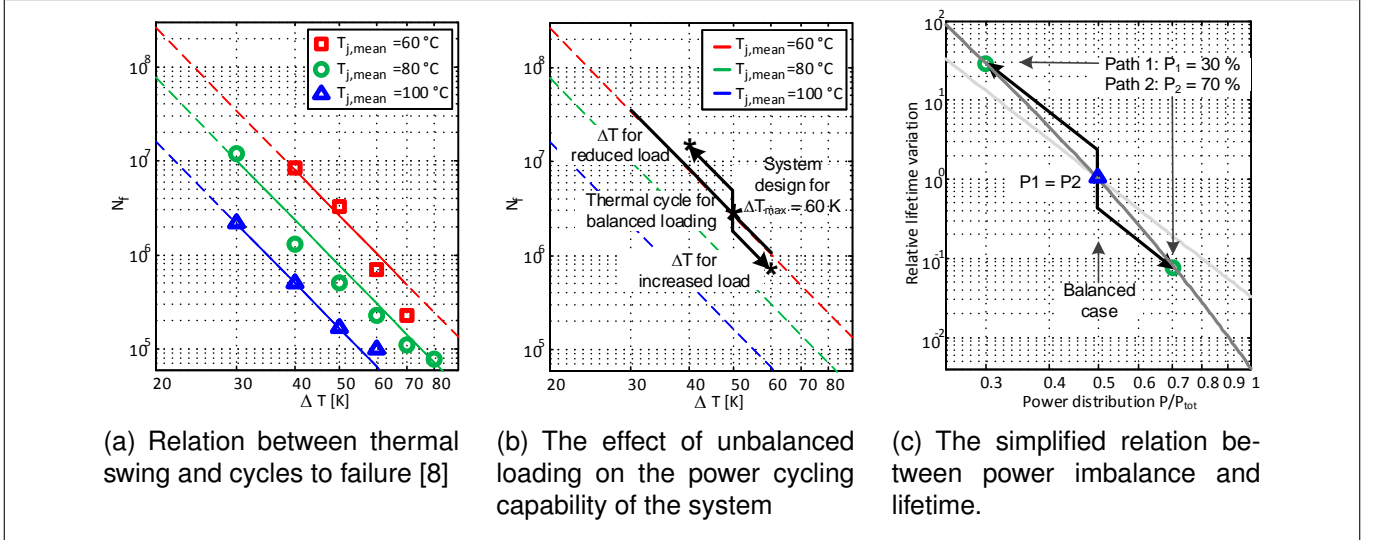


Fig. 4: Effect of loading of cells on thermal cycling and lifetime [6].

active power request from the loads on the LV side. The ST can control the reactive power separately on the MV grid from phase to phase [10] and moreover, because of the dc-links, it is decoupled from the LV reactive power request. Therefore, the ST has inherent capability to work with unity power factor and provide grid services like harmonic compensation and voltage support on the MV side. Since many electronic loads in distribution grid contribute to high harmonic content, the ST can be deployed as an active filter to improve the power quality of the grid and to reduce the stress on the HV/MV transformer.

In a LV grid with many distributed generations (DG), the power can flow from LV to MV side when the generation exceeds the power consumed by the loads, leading to a voltage increase in the MV grid. This reverse power flow condition can be alleviated by the ST through interaction with the local generators, increasing the grid frequency [11] to decrease the power injection of the DGs.

### 3. Reliability and Power Routing

The first part of the section discusses about the reliability in a modular system and the effect of cell loading on the reliability. The concept of power routing and its impact of the lifetime of the ST is described in the following part.

#### 3.1. Reliability and Cell Loading

Conclusive analysis of reliability in power electronics requires more than pure statistical approach. This motivated for a physics of failure approach which traces back the failures to their physical root cause [12]. The major share of failures occur in capacitors and the power semiconductors as reported in the literature [13, 14]. This paper focuses on the semiconductors' lifetime and not considering the capacitors' one. The physics of failure concept used for the reliability analysis can be utilized for a lifetime prediction. The reliability analysis of power semiconductors are based on the lifetime models. The number of thermal cycles to failure  $N_f$ , is expressed in (1),

$$N_f = a_1 \cdot (\Delta T)^{a_2} \cdot e^{\frac{a_3}{T_{j,av} + 273^\circ\text{C}}} \quad (1)$$

where  $\Delta T$  is the magnitude of the thermal swing, whereas  $T_{j,av}$  is the average junction temperature during this swing and  $a_1$ ,  $a_2$  and  $a_3$  are fitting parameters. The thermal cycles lead to fatigue and leads to bond-wire liftoff. For fatigue analysis, Miner's rule can be applied to calculate the accumulated damage using [15]

$$D_{acc} = \sum \frac{N_i}{N_{fi}} \quad (2)$$

where  $D_{acc}$  is the accumulated damage,  $N_i$  the number of cycles and  $N_{fi}$  the durability of the  $i$ -th stress range. When the accumulated damage becomes

1, the device fails. It is assumed that the damage accumulates linearly.

In principle, it is possible to analyze the effect of a thermal design on the lifetime of the system using this knowledge. It is evident that the design of semiconductor modules for a high-maximum junction temperature limits lifetime whereas a design for a very low-junction temperature might change the dominant failure mechanism. As an example, relationship between thermal cycles and number of cycles to failure (1) is shown in Fig. 4 (a). Fig. 4 (b) depicts a system design for a maximum junction temperature  $\Delta T = 60 K$  with a maximum junction temperature of  $T_{j,max} = 90 ^\circ C$  for an ambient temperature of  $T_a = 30 ^\circ C$ . As expected, the design for a lower junction temperature decreases the maximum thermal swing and the average junction temperature during this swing, but increases the total system cost with bulky and expensive cooling requirement.

Since the impact of unequal loading on a modular system needs to be analyzed, the study is extended to a modular system of two parallel converters with similar design parameters. This effect is illustrated in Fig. 4(c). First, the converters are equally loaded and both undergo the same thermal swing as it was shown in Fig. 4(b) and result in similar lifetime consumption. As a consequence of the reduction of the power in the cell, lower thermal cycles are observed and thus the detected thermal cycles shift to lower stress region. On the other hand, an increase in the loaded power shifts the thermal cycles to higher stress regions. To quantify the impact of unequal loading on the lifetime, a case with an unbalanced loading with 30% : 70% is analyzed. Fig. 4(c) indicates a significant increase of the lifetime of the lightly loaded cell and a decrease of the highly loaded one. In summary, it is concluded that a significant influence of the lifetime of the modular system is achieved by controlling the power processed by the individual cells.

### 3.2. Power Routing Concept

ST with modular architecture can be assumed to be composed of cells with different aging [6]. Moreover, from efficiency perspective, activation/ deactivation of one or more redundant converters is the

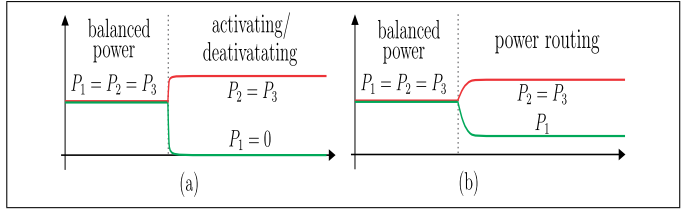


Fig. 5: Power routing concepts. (a) The activation/deactivation of cells (b) Cells with unbalanced power transfer [6].

state of the art to improve the efficiency during partial load operation [16]. One of the major disadvantages of activation or deactivation technique is the negative impact on the power quality in terms of current and voltage ripple. It is evident that the deactivation/ activation of a cell changes the thermal stress distribution in the system. Consequently, the active cells are loaded with more power leading to more severe thermal cycles. The deactivated cells are completely saved from the stress induced by the mission profile. Since thermal cycles are the main cause of aging in power electronic modules, activation/ deactivation results in unequal aging of the cells in modular system.

The concept of power routing in modular system offers the flexibility of operating the power converters under unequal loading conditions for the maximization of the time to the next maintenance. The Figure 5 illustrates the difference between the power routing concept and activation/ deactivation technique. To delineate the benefits of power routing, a modular system based on three cells is shown in Fig. 6 is considered. Here, the power processed by the cells 1, 2 and 3 are given by  $p_1$ ,  $p_2$  and  $p_3$  respectively. The total power is given by  $p_T = p_1 + p_2 + p_3$ . In a conventional system, each converter processes the same power and therefore  $p_1 = p_2 = p_3$ . In a modular system, an optimized strategy where each cell processes a specified amount of power in accordance with their remaining useful lifetime is termed as power routing. The aim of the optimization technique is to improve the system's reliability with minimal impact on the total system efficiency [17]. This is expressed as  $p_1 \neq p_2 \neq p_3$ .

To study the impact of power routing on reliability, an example with a system based on three cells connected in parallel as shown in Fig 6 (a) is considered. Each cell of this system, cells 1, 2 and 3,

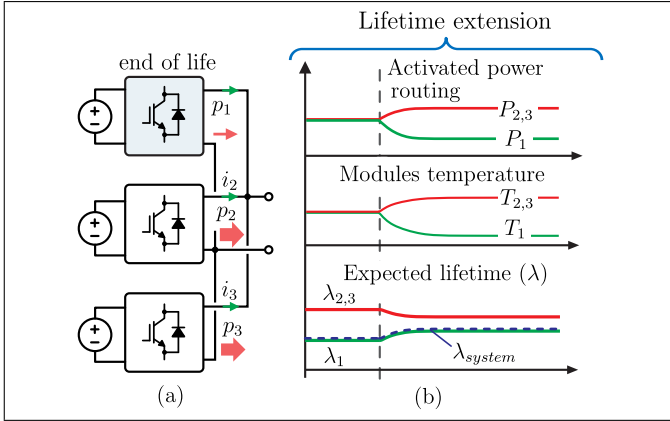


Fig. 6: Example for the impact of power routing on the lifetime of a modular system: (a) block diagram of a example system highlighting that one cell is close to the end of life, (b) expected lifetime graphic showing the impact of the power routing on the system's lifetime [6].

has an expected remaining lifetime defined by  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  respectively. The cell 1 has a lower lifetime than the other cells and the total system will fail once cell 1 reaches its end of life. In order to extend the expected lifetime of the entire system, the lifetime of cell 1 should be increased. Since the lifetime of the power cells is dependent on the operating temperature (1), one solution is to reduce the operating temperature of the cells [18]. The Fig. 6 (b) shows the operation of three cells with equal power distribution and with power routing. When all cells process the same amount of power, it results in similar operating temperature. However, the cell 1 has a reduced lifetime than others. With the power routing, cell 1 processes less power ( $p_1$ ) and thereby reducing its operating temperature, as shown in Fig. 6 (b). Consequently, the expected lifetime of the cell 1 and thus the lifetime of the entire system is increased. Since the total system power remains constant, the power processed by the cells 2 and 3 will increase and hence their operating temperatures. As a result, the expected lifetime of the cell 2 and 3 are slightly reduced. In nutshell, this study shows that the power-dependent failures can be delayed and an increased availability of the system is ensured through power routing.

## 4. Results

The Fig. 7 shows the experimental setup to demonstrate the concept of power routing. A high speed

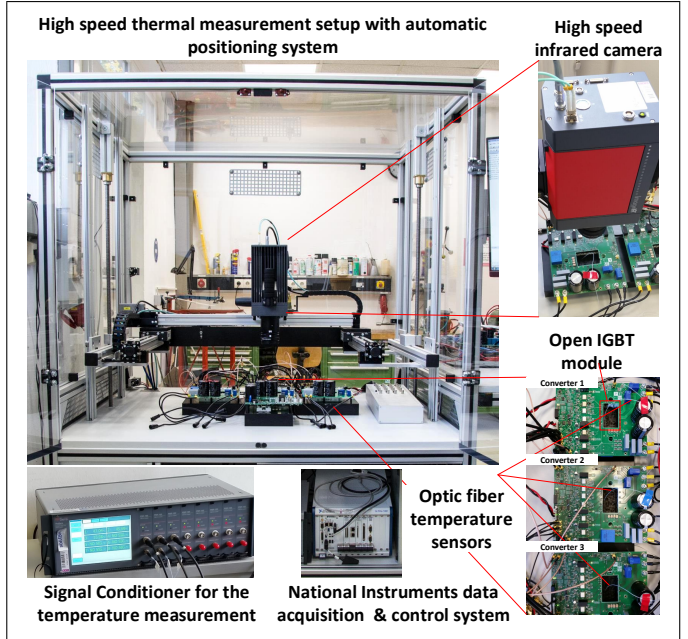


Fig. 7: Picture of the high speed thermal measurement setup with automatic camera positioning system, a signal conditioner for the fiber optic temperature sensors, *National Instruments* data acquisition and control system, the three parallel converters assembled on one heat sink and high speed infrared camera for junction temperature measurement.

thermal measurement setup with automatic camera positioning system is used for conducting the experiment. The availability of *LabVIEW* and *dSPACE SCALEXIO* systems facilitate rapid prototyping of advanced control algorithms. In order to verify the implementation of power routing concept, a system of three parallel converters with open IGBT modules, having a common dc-link, with single phase output inductors is considered. In order to facilitate the direct measurement of junction temperature, the IGBT modules are not filled with gel. As a consequence, the voltage blocking capability of the power module is decreased. The load used for the experiment is a three phase resistive load. The parameters of the setup are shown in Table 1.

Since the junction temperature is directly measured, the effect of unequal power sharing can be investigated conveniently. Special optical fiber instrument is used for the direct junction temperature measurement of the open modules shown in the setup. *ProSense OpSens PSR-100* signal conditioning unit is used for the conversion of special optical fiber measurement signals to electrical signals.

Tab. 1: Parameters of the laboratory setup.

Current rating	25 A
dc-link voltage	200 V
Filter size	1.8 mH
Load R	3.5 Ω
Fundamental frequency	50 Hz
Switching frequency	20 kHz
Semiconductor module	DP25H1200T101667

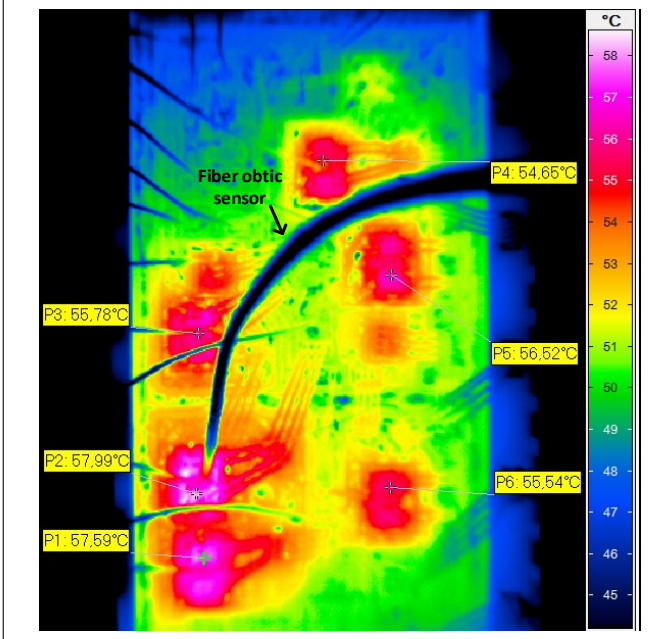


Fig. 8: Infrared camera picture of the power electronic module showing the thermal distribution of a full power electronic module highlighting the temperature on the IGBTs.

For the detection of hottest spots in the power semiconductor module, a high speed high resolution infrared camera, *InfraTec ImageIR*, is used. The thermal cross coupling of the power semiconductors also affects the temperature in the open module. An infrared image of the power electronic open module is shown in Fig. 8. It is observed that the chips are hotter than the bond wires. Moreover, the closely spaced power semiconductors have the hottest chip temperature. The measurement point 'P2' which measures the temperature IGBT 1 indicates the highest temperature. Therefore, the junction temperature of the IGBT 1 is measured in each converter.

To investigate the effect on power routing on thermal cycling, the reference current  $i_{ref}^*$  is varied to

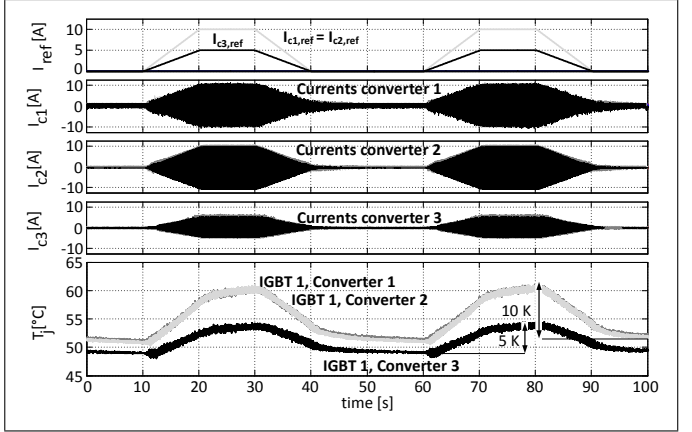


Fig. 9: Measurement: Power routing in three parallel converters for power cycle.

achieve unequal power distribution in the parallel converter setup. The power distribution for the experiment is given in (3).

$$\begin{bmatrix} P_{c1} \\ P_{c2} \\ P_{c3} \end{bmatrix} = \begin{bmatrix} 40 \% \\ 40 \% \\ 20 \% \end{bmatrix} \quad (3)$$

Here, the only varying parameter is the current and thereby the power. The Fig. 9 shows the current distribution among the converters which follows the reference current  $i_{ref}^*$ . This shows that the experimental setup is able to implement the power routing concept. The power cycling naturally affects the junction temperature cycling. Converter 1 and converter 2 undergoes a thermal cycling with  $\Delta T = 10 K$  while that of converter 3 is only  $\Delta T = 5 K$ . Moreover, the average junction temperature of the converter 3 is lower resulting in less processed power dependent failures.

The lifetime model expressed in (1) clearly shows that the thermal cycles,  $\Delta T$ , affects the lifetime consumption exponentially ( $a_2 \approx 5$ ). Thus the lifetime consumption of converter 1 and 2 is 32 times higher than that of converter 3 resulting in unequal lifetime consumption. Since the lifetime model is also influenced by the average junction temperature, the impact of lifetime consumption is further enhanced by a small change in power unbalance. Thus by actively controlling the power reference for each cell in a modular converter system, the lifetime consumption and consequently, the reliability, can be influenced.

## 5. Conclusion

For applications requiring very high reliability and availability of services, such as the ST serving in an electric grid, advanced control strategy for increased reliability is vital. This paper has proposed the concept of power routing through uneven loading of cells in a modular system for controlling the lifetime of converters. The power routing facilitates prognostic maintenance by actively shifting the failure of highly stressed cells. Thus the reliability of the total system is increased. The concept of power routing and its effect on the lifetime of the semiconductor modules have been analyzed and experimentally verified using special thermal measurement setup.

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