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# Multi-frequency Power Routing for Cascaded H-Bridge Inverters in Smart Transformer Application

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**Abstract**—The smart transformer is a solid state transformer with advanced control functionalities that can efficiently manage a low-voltage micro-grid by also supporting the medium-voltage grid. Cascaded H-bridge (CHB) converters proved to be a suitable option to realize the MV stage of the smart transformer due to their modularity and multi-level output. Normally the power is equally split among the CHB cells, however, in order to delay failures of the system, certain cells can be unloaded if premature deterioration is detected. In this work, multi-frequency power transfer is used to control the power processed by the dc/dc converters that supply the dc link of the CHB. The potential is analyzed analytically and validated experimentally.

**Index Terms**—Power Electronics, Reliability, Active Thermal Control, Power Routing, Smart Transformer

## I. INTRODUCTION

The electrical grid is progressing from few centralized generators, which were managing the grid some decades ago, to many distributed generators and new loads such as electrical vehicle charging stations [1]. For the grid management, this evolution presents challenges, such as balancing the active/reactive power and controlling the voltage while respecting the grid codes in all grid nodes. As a solution, several researchers have proposed smart-grid technologies, mostly adopting decentralized controls in order to enhance power quality and power distribution reliability [2], [3]. This solution, however, requires that every grid-connected system embeds a decentralized and cooperative control.

An alternative solution is the replacement of the traditional distribution transformer, which is interconnecting the medium voltage grid with the low voltage grid, by a Smart transformer (ST) [4]. An ST is an evolution of the solid state transformer (SST), which originally only provided voltage conversion from ac to ac. Enabled by the development of the power semiconductor technology, it is even possible to design the SST with the capability of dc connectivity and the ability to provide services to the grids. This brings the SST control functionalities in the forefront, which makes the name smart transformer more suitable with respect to SST, where the focus is put on use of solid state technology, hence hardware aspects.

A possible candidate for the medium voltage (MV) converter side is the CHB, which offers multi-level output in a modular structure [5], [6]. A modular approach is usually pursued for three-stage solid state transformers, and DAB converters constitute a possible isolation stage [7], [8].

However, the long lifetime of the traditional transformer is hard to achieve with power semiconductor technology and in order to constitute a possible replacement for the low-frequency transformer, the ST needs to ensure competitive availability. As a solution to improve the availability of the ST, a repairable system is proposed, in which cells of the converters can be replaced. In order to prolong the operation of the smart transformer, it is of interest to unload the dc/dc converters that present premature deterioration.

Considering the advancement of condition monitoring techniques, it is possible to estimate the residual lifetime of power semiconductors [9], whereby a simpler approach only takes into account the time in operation of the cells. The information about the age or health status can be utilized by unloading the devices with higher deterioration for extending the overall time to failure. In order to maximize the capability for this algorithm, the multi-frequency power transfer is proposed. In contrast to the application in [10], [11], the algorithm is not balancing cells for battery storage integration, but it improves the unbalanced power control ability in comparison with the conventional methods.

In this work, the advanced power routing control for the CHB converter is proposed, which can regulate uneven power transfer between the converter in the isolation stage and the CHB to affect different stress among the cells of the modular structure. The concept of using multiple frequencies for power routing is introduced and analyzed. Experimental results are presented to demonstrate the claim to control the power in the different cells.

In section II, the development from SST to ST is described and power routing for ST applications is motivated in section III. Section IV explains the concept of power routing, while section V investigates the implementation of the unbalanced power routing and its potential impact on lifetime. An experimental validation is demonstrated in section VI before the

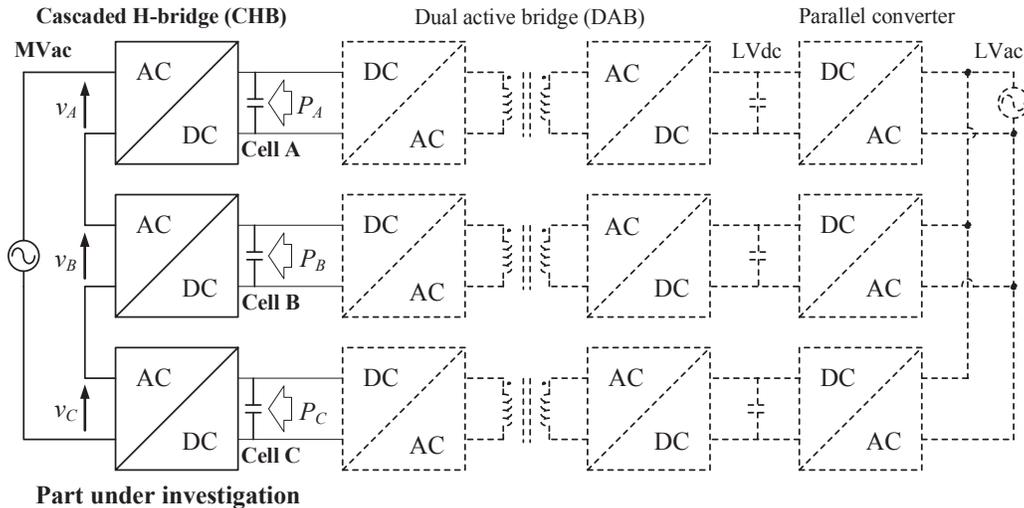


Fig. 1: Single phase version of a three stage ST architecture consists of CHB, DAB, and full bridge converters.

work is concluded in section VI.

## II. FROM SST TO ST

The concept of an SST was first introduced in 1968 by McMurray, who proposed a device based on solid-state switches with high-frequency isolation, which behaved like a traditional transformer. Since then, the SST concept has been refined by new opportunities, offered by new technologies and application requirements. Considering different possible application fields, the SST has high potential to be used in electric distribution grid, as the enabling technology for smart grid functionality. In this application field, the SST is supposed to replace the standard low frequency transformer, connecting the medium-voltage (MV) grid to the low-voltage (LV) grid, enabling dc connectivity and offering services to both LV and MV grids. The services requirement, together with the need for control and communication functions make this device a smart SST, leading to a new concept: the Smart Transformer (ST). Mainly due to the power electronics and semiconductors technology evolution, new ST implementation possibilities have been proposed and classified in literature.

As an example, Fig. 1 presents a possible architecture, where the three-stage configuration enables low voltage side dc-link (LVdc) connectivity and also guarantees input/output decoupling of voltages and currents, which provides more degrees of freedom to the system control. Hence, it is the preferred candidate for an ST [4].

The next choice in terms of architecture is the degree of modularity. Modular architectures consist of several cells rated for low voltage or low current, which are used as building blocks for the entire system. In contrast to this, a non-modular system is based on a single power converter, usually taking advantage of high-voltage wide-bandgap semiconductors [12]. To handle the MV level involved in the power converter, special devices with high voltage capability, such as 15 kV SiC Mosfet [12], need to be employed. Since these devices are still not available on the market (only for the research

purpose), there is no available product using this technology. The non-modular architectures have the advantage of using a small number of semiconductors, drivers, and sensors, as well as a single transformer, leading to a lower number of possibly faulty components. On the other hand, modular architectures bring several advantages to power and voltage scalability, maintenance and the implementation of fault-tolerance strategies [13]. In comparison to the non-modular architecture, the modular one has reduced EMI emission (due to the low  $dv/dt$  and  $di/dt$ ) and the possibility to use standard low voltage rating devices, which present good performance, leading to a highly efficient system [13].

## III. POWER ROUTING IN ST APPLICATIONS

Even if the application of the ST in the distribution grid is motivated by services for the grid and dc connectivity, it still needs to compete with the traditional transformer in the fields of reliability, efficiency and costs. Efficiency can be optimized in the design process and costs might be compensated with the services. Reliability instead, is getting even more relevant, if the lifetime of 50 years for a transformer is taken into account. This calls for concepts to maximize the reliability during the lifetime of the ST.

The reliability analysis for an ST needs to use a physics of failure approach [14]. Based on this approach, every failure of a component needs to be traced back to its physical mechanisms. In power converters, it has been found, that power semiconductors and capacitors are among the components, which fail most frequently [15] and most of their failure mechanisms are dependent on the mission profile, consequently the power. The mechanism for the power semiconductor is related to thermal cycling, which is the heating up and cooling down of the power semiconductors. This is referred to as thermal cycling and causes failures like bond wire lift-off, baseplate solder fatigue and others [16]. As a result, the number of cycles to failure of the power semiconductors  $N_f$  can be expressed in dependence of the thermal swing of the power semiconductor

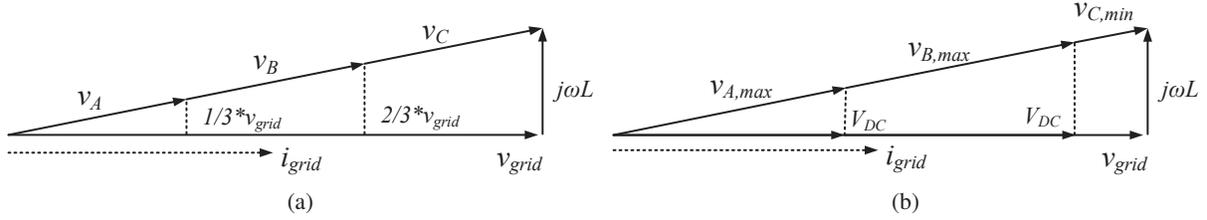


Fig. 2: Power imbalance by only using the fundamental voltage. (a) Balanced and (b) maximum unbalanced condition.

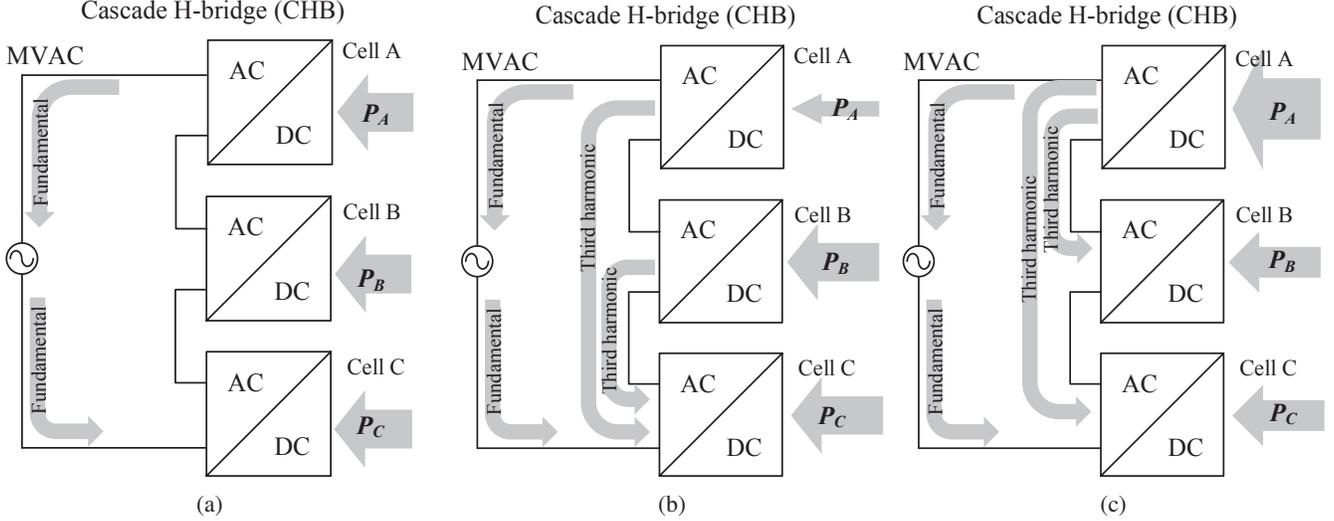


Fig. 3: Power flow between CHB cells by multi-frequency method in case of (a) balanced loading C, (b) unloading cell A, and (c) overloading cell A.

$\Delta T$  and the average junction temperature  $T_{j,mean}$  in the form of (1).

$$N_f = a_1 \cdot (\Delta T_j)^{-a_2} \cdot e^{-a_3 T_{j,mean}} \quad (1)$$

In this equation,  $a_2 \approx 5$ , which is defining it to be of major influence for the lifetime [17], while  $a_1$  is the linear influence of the power cycling capability and  $a_3$  the influence of the Arrhenius equation. An approach to utilize the model for an increase of the lifetime by either reducing the thermal cycles in magnitude or in their number of occurrences by means of software is active thermal control [18].

Power Routing is a particular active thermal control approach, which aims at controlling the loading of different power paths in the system for increasing the overall reliability [19]. In the presented ST architecture of Fig. 1, the loading of the three power path  $P_A$ ,  $P_B$  and  $P_C$  can be controlled. As a consequence of controlling the power in one path, e.g.  $P_A$ , the remaining paths  $P_B$  and  $P_C$  need to transfer the rest of the overall power.

To the current state, several techniques have been proposed for balancing the power in the cells of modular power converters in order to share the stress identically [20]. These algorithms rely on the sharing of the fundamental voltage among multiple CHB cells or employ advanced balancing schemes embedded in the modulator without an external

control loop [21]. In the similar way to the power balancing method, the fundamental voltage among multiple CHB cells can achieve the designated imbalance power routing, but offers a limited capability, which is heavily dependent on the ratio between dc link voltage and converter output voltage as shown in Fig. 2 (a) and (b). In addition, due to efficiency reasons, the dc-link voltage margins should be designed as low as possible. Therefore, in order to overcome the limitation of the conventional fundamental voltage method, the multi-frequency method, using the third-harmonic voltage, is proposed.

#### IV. CONCEPT OF THE MULTI-FREQUENCY POWER ROUTING

The algorithm is exploiting the third harmonic in order to improve the dc-link voltage utilization in a similar fashion to the third harmonic injected SPWM (TH-SPWM) [22]. As an advantage of the third harmonic, the stress for the DABs in the isolation stage is not coupled to the power flow of the fundamental and can thus operate independently. If premature deteriorated for a cell in the isolation stage is detected, it is unloaded to reduce its stress.

Active thermal control by means of power routing can be applied to increase the reliability and redundant power paths of modular converters offer a promising application for this purpose. This brings the potential to increase the reliability for the cost of higher stress for other power paths, if the power is controlled with a suitable algorithm. The application

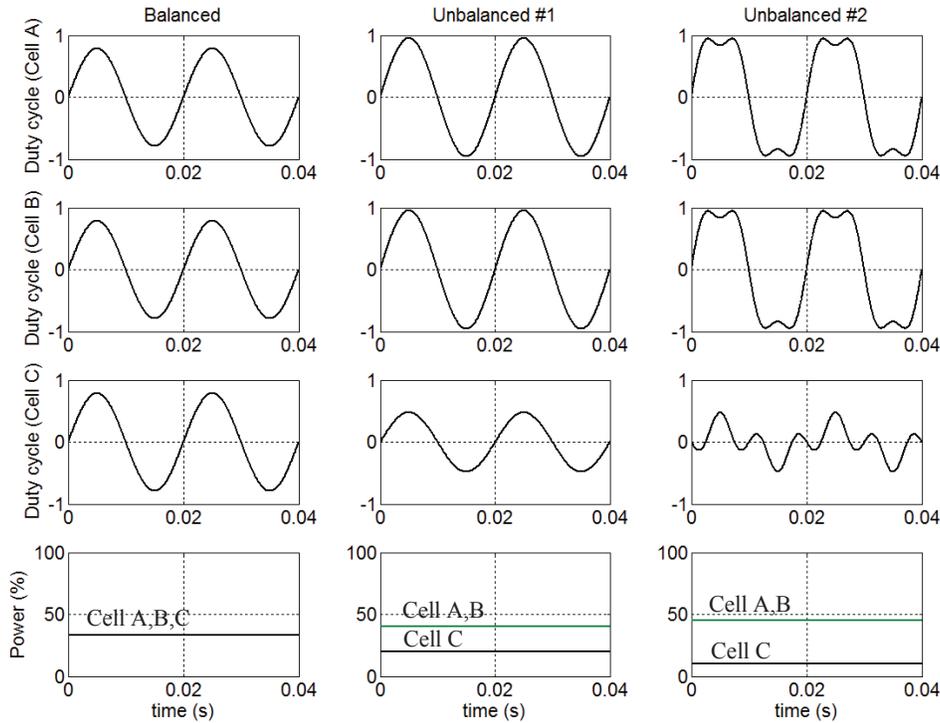


Fig. 4: Principle of imbalance power routing by multi-frequency method: Balanced is equal loading of all devcies, Unbalanced #1 is unloading cell C with the fundamental frequency and Unbalanced #2 is unloading cell C with multi-frequency power transfer.

of active thermal control brings advantages to the system, if the remaining lifetime among the components is different. Unequal lifetime of the cells can be caused by parameter variations in the manufacturing process or events during operation conditions, which cause damage only to some parts, while others are unaffected. In order to obtain the information about the remaining lifetime for the cells of the ST, condition monitoring is a possible solution. Measuring parameters like the collector emitter voltage of IGBTs or the on state resistance of MOSFETs enables to identify the wear out of the system [9]. However, for effectively applying active thermal control, the knowledge of the junction temperature is required and can be accessed by measurement, thermo sensitive electrical parameters, observers or estimators [23].

The concept of multi-frequency power routing can be applied to prevent or delay the failure of specific components. It holds the advantage not to influence the operation with the fundamental frequency, while the stress for the isolation stage is redistributed. As an example, the CHB converter in Fig. 1 has three cells with three power paths ( $P_A$ ,  $P_B$  and  $P_C$ ) and the components in one of them, e.g. in the DAB cells, show far higher degradation than the others. Since the converter is dependent on the operation of all cells, a failure of the one cells or power paths is the end of life. Instead of loading the cells equally (as shown in Fig. 3 (a)), unloading the power path with the highest degradation postpones the time to the failure, which is demonstrated in Fig. 3 (b) for unloading of

path A. As the opposite concept, it is possible to load one path higher and to bring it close to its wear out. This might be a solution, if the next maintenance is scheduled and the cell is planned to be replaced, while the remaining ones will not be replaced. This case is visualized in Fig. 3 (c).

In contrast to bypassing the cell, which is commonly done in modular converters, it holds two major advantages: First, with multi-frequency power transfer less cells are required to be keep the system operational after failures and second, the full reserve of the output voltage is preserved, enabling to continue operation.

In order to maximize the dc-link voltage utilization, the optimal magnitude of the third harmonic can be derived similar to the mathematical derivation in [22] made for the third harmonic injection in PWM converters. Therefore, the optimum magnitude of the third harmonic is found as  $k = -1/6$ . It enables to utilize the linear range of the converter cells up to the inverse of  $m_{max}$ , leading to  $M = 1.155$ . Of course, the power transferred with the third harmonic to one cell, needs to be provided by the remaining cells, which requires them to add the inverse harmonic sequence to their modulation function.

Fig. 4 shows the basic concept of the unbalanced power routing among three cells by means of the multi-frequency method, where from the first to the third row are the duty cycle of three cells, A, B, and C, respectively. The last row shows the output power with respect to each cell. Since the duty cycle is typically normalized to the dc-link voltage, it is used instead

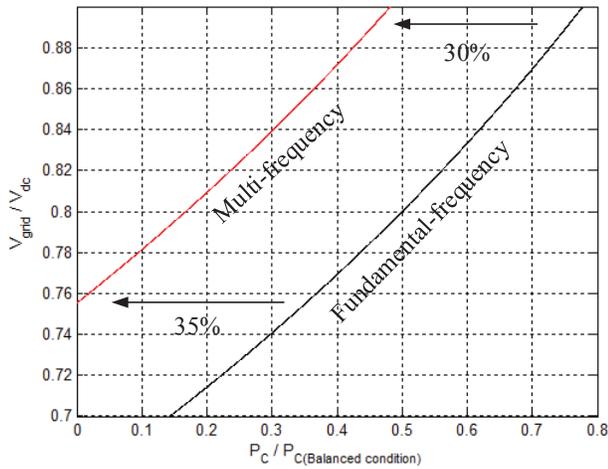


Fig. 5: Capability of unloading power depending on the ratio between output voltage  $v_{grid}$  and dc-link voltage  $v_{dc}$ .

of actual voltage value in the figure. In the first column, the three cells share equal power, i.e. balanced power routing, with the same duty cycles. For the unbalanced power routing, the duty cycle of the overloaded cells increases while that of the unloaded cell decreases. As depicted in the second column, the unbalanced power routing by the fundamental component is restricted when two of the three duty cycles reach the maximum duty cycle. Finally, in order to achieve the further power imbalance, an appropriate third harmonic component is utilized, which is in phase with the fundamental component as shown in the third column. For the overloaded cells, the third harmonic component is added to the fundamental component so that the fundamental component increase over the maximum duty cycle. On the contrary, the fundamental component of the unloaded cell is reduced, absorbing the produced third harmonic component from the overloaded cells.

## V. IMPLEMENTATION AND IMPACT OF THE ALGORITHM

In the following section, the potential of the power routing capability is benchmarked in terms of potential power imbalance and the implementation in the controller is described. Furthermore, the influence of power routing on the wear out is shown.

### A. Imbalance potential and controller implementation

To demonstrate the energy routing potential, Fig. 5 shows the maximum ability of unloading a cell in dependence of the ratio between dc-link voltage and output voltage. As pointed out before, this ratio is commonly minimized in the converter design in order to achieve the required voltage reserve, but to optimize losses at the same time. However, it is shown, that by means of the multi-frequency method, the power imbalance can be increased by minimum 30 % and up to 35%.

For an utilization of the power routing, the implementation is done in an additional open control loop control nested in the standard current controller. This is indicated with "Power Routing" in Fig. 6 for a grid connected CHB converter. There

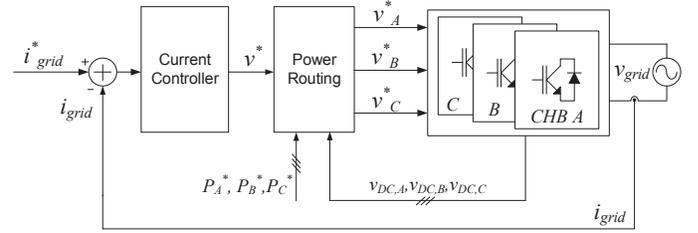


Fig. 6: Current control scheme of a grid connected seven level CHB applying multi-frequency power routing.

are no limitations in the bandwidth of this additional control loop, since it is operating in open loop. Also there is no affect on the output voltage or current, because the third harmonic component is canceling out itself within the CHB converter cells. Consequently, there is no influence on the grid, which is caused by the multi-frequency power routing.

### B. Power routing for wear-out control

Based on the system in Fig. 1, the CHB cells exchange power with the DAB in the isolation stage. On the LV side, the DABs are connected to converters, whose outputs are connected in parallel. Consequently, the CHB cells can control the power flowing the DAB and the parallel converters by transferring similar overall power to the LV side. As pointed out before, this can be utilized in order to unload the power paths with higher degradation for preserving its current health status and to stress the components as low as possible. Here, the power cycling, is assumed to be the main failure mechanism, which leads to the requirement to prevent power variations for unloading the components. It is important to point out, that this failure mechanism is less influenced by the constant power operation.

In Fig. 7, the application of the algorithm is presented in a case study under consideration of the power routing limitations of the CHB converter. A mission profile with fluctuating power is presented and the multi frequency power routing is applied to control the loading, particularly preventing power fluctuations in path one. The converter cells are designed for an ambient temperature  $T_a = 40^\circ\text{C}$  and the maximum junction temperature  $T_{j,max} = 90^\circ\text{C}$  under full load. The power fluctuations result in reduced thermal fluctuation on the power semiconductors, which usually would be shared equally by the cells. Since the path with the power  $P_A$  should be unloaded, it is operating with the constant mean power whenever it is possible. As a consequence, the fluctuations in the other paths are increased. Consequently, the damage caused by the thermal cycling is reduced to  $1/5^{\text{th}}$  for the unloaded path, while the higher loaded paths increase to approximately 3 times more damage.

It needs to be pointed out, that the capability of controlling the stress depends highly on the system design and the mission profile. With only small variations in the power, the thermal fluctuations can be completely eliminated from cells, while high fluctuations, as in the presented case study affect all cells.

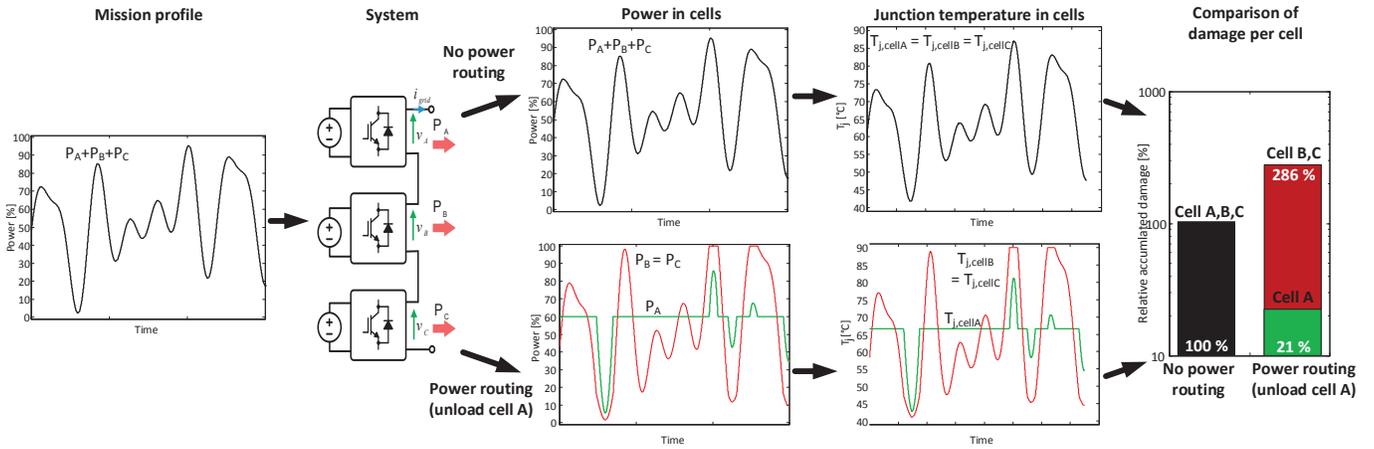


Fig. 7: Effect of power routing in the CHB on the thermal loading and the normed damage caused in the power semiconductors in the DAB with  $v_{grid}/v_{dc} = 0.8$ .

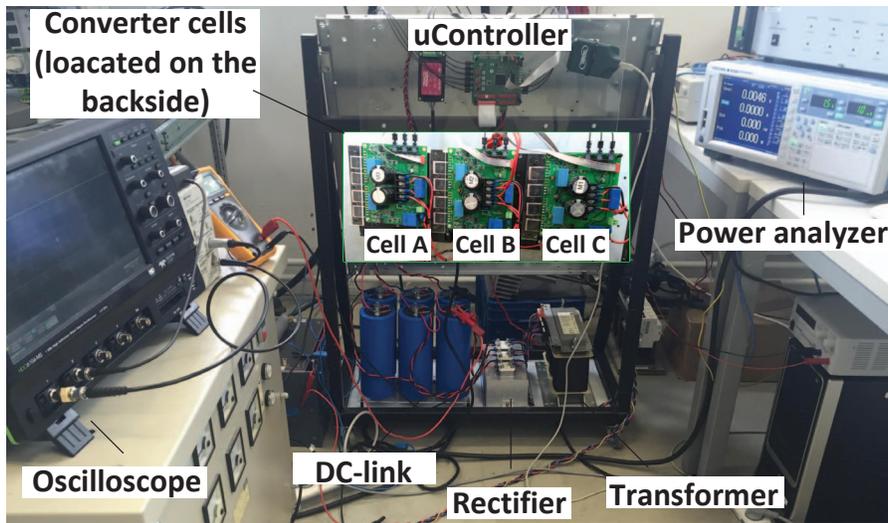


Fig. 8: Picture of the laboratory setup showing the 7 level CHB converter.

## VI. EXPERIMENTAL VALIDATION

The electric measures of the multi-frequency power routing are demonstrated and the capability of the power transfer is validated on a laboratory prototype shown in Fig 8. The dc-link voltage of the cells are adapted to generate an output voltage of 230V (rms) with the chosen ratio between dc link voltage and output voltage. The output is connected to a passive load. In the setup, IXBY82N120C3H1 IGBTs are used.

For the demonstration of the standard operation, Fig. 9 is presented. Similar to Fig. 4, it shows the duty cycles and the power distribution for three different cases. The first case, Fig. 9 (a) shows the similar loading of all devices, Fig. 9 (b) demonstrates the power routing with only the fundamental frequency and Fig. 9 (c) the power routing with multi frequency power transfer. For all three cases the output current is similar, while the duty cycles show good fit those in Fig.4. Particularly interesting is the modulation index of cell C in all three configurations. For the chosen ratio between

dc link voltage and output voltage, the capability to unload parts is already high, as in can be seen in case (b), where the modulation index of cell A and B is increased to its maximum, 1. The case in Fig. 9 (c) demonstrates the increase of the modulation index in cell A and B to 1.05, while they are also processing 0.1 in the third harmonic. Therefore, cell C is not processing power with the fundamental frequency, but transfers power with a modulation index of 0.2 in the third harmonic.

## VII. CONCLUSION

This work presented the advanced power routing method based on the multi-frequency power transfer theory to control the power sharing between the cells in a CHB converter for smart transformer applications. The power routing is applied to route the power in the converter in such a way, that the stress for the cells in the isolation stage is controlled. Thus possible failure mechanisms, which are dependent on the power transfer are delayed and the reliability is increased.

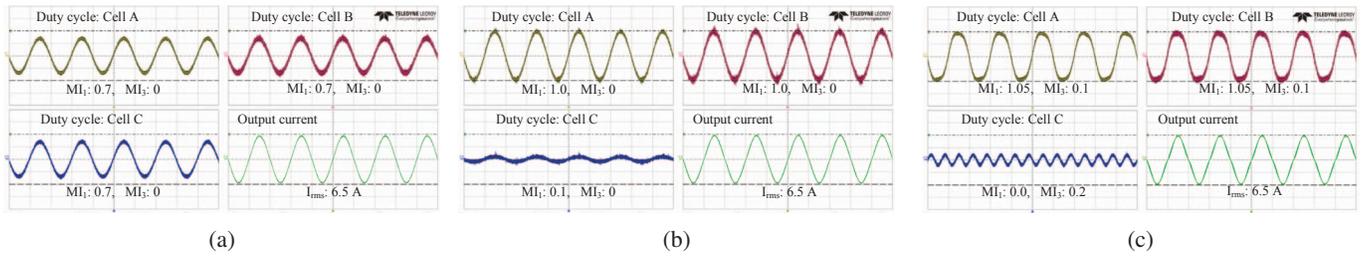


Fig. 9: Measurement of duty cycles of each cell and output current under  $v_{grid}/v_{dc} = 0.7$ ,  $V_{dc} = 155$  V,  $R = 35.4$   $\Omega$  and  $L = 1.3$  mH: (a) balanced, (b) unbalanced by fundamental component, (c) unbalanced by multi-frequency.

By employing the proposed method, the ability to route the power between the cells is improved by more than 30 % in comparison with the conventional method that use only the fundamental voltage. The capability of the algorithm to unload a power path is demonstrated for a highly fluctuating mission profile, which results in one fifth of the lifetime consumption for the cost of three times higher damage in the other cells. The power routing capability is validated with measurements on a single phase seven level CHB converter.

#### ACKNOWLEDGMENT

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