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# Smart Transformer Reliability and Efficiency through Modularity

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**Abstract**—The application of the Smart Transformer (ST) in the electrical distribution system follows the trend to install more intelligent devices in the grid. In competition with the traditional transformer, the winning argument of the ST can be the grid services, while the system needs to be designed for the targets of high efficiency, high reliability and high availability. This work proposes a modular ST design, which uses power semiconductors rated for lower current and voltage for high efficiency, while the reliability and the availability are targeted by directly routing the power within the modular system. An overview is given on promising modular ST architectures and the concept of power routing for improved reliability is presented.

## I. INTRODUCTION

The increase of decentralized energy production challenges the actual distribution grid [1], [2]. In many countries the generation and the consumption are spatially separated and the energy needs to be transferred over a long distance [3]. This calls for concepts to transfer the power to the loads without overloading grid feeders and connecting new intelligent loads and storage at the same time without big centralized power plants [4]. In the current configuration, the transformers are passive devices, which do not enable active grid management. To react on the current and the future system level challenges, there is a trend to install more intelligent devices in the grid, which enable autonomous grid management with new loads by also giving the opportunity to provide grid services [5].

A solution, which provides DC connectivity and possible control of the power flow is the smart transformer (ST), which is based on power electronic converters and a medium frequency transformer for galvanic isolation [6]. This ST has to compete with the traditional transformer not only in the field of functionality, but also in the field of efficiency and reliability. In the field of reliability, the traditional transformer is hard to outperform, because its lifetime is in the range of several decades with low maintenance effort, a target hardly achievable with today's power semiconductor technology.

The ST found a reception in traction applications and ships, because of the reduced space requirements and higher efficiency compared to the low frequency transformer [7]. However, to the current state, it has not achieved market breakthrough. Other projects target to replace the distribution transformer between the medium voltage and low voltage distribution grid with STs. The crucial point in this application

field are possible solutions for system level challenges in working conditions characterized by highly dynamical power profiles and frequent contingencies like faults. Major challenges for making this device competitive with the well established traditional transformer are improvements in terms of efficiency and reliability. The reliability of the ST is limited by the thermal stress for the power semiconductors caused by heating up and cooling down, which has been investigated for STs in the distribution system in [8]. A possible concept for the target of high efficiency is a modular design of the ST by using power semiconductors rated for lower voltage and current [9]. In partial load operation, the control can be used to optimize the conflicting goals between high efficiency and low thermal stress for the power semiconductors, realized by active thermal control [10]. In combination with condition monitoring, stress can be loaded on components with low wear out and faults can be delayed. After a significant wear out, maintenance can be made, which prevents failures and increases the availability of the system.

This work gives an overview on different ST designs and their advantages and disadvantages with respect to the number of stages and the degree of modularity. The influence of modularity on the efficiency and the reliability is demonstrated in an analytical case study for parallel converters in the low voltage side and series converters in the medium voltage side.

In section II, ST topologies are classified and section III introduces the concept of power routing for increasing the availability for the system. Section IV reviews possible modular ST architectures and compares them with special focus on the degree of modularity and power routing capability. In the fifth section, the influence of modularity on the efficiency of the ST is investigated, while section VI examines on the influence of modularity on the reliability. Finally, the results are concluded in section VII.

## II. ST TOPOLOGIES

In literature, several ST topologies have been introduced, which can be grouped in single, double and three-stage STs as shown in Fig. 1. The single-stage ST is a matrix converter, which offers limited grid services, while the biggest advantage is the low component count. The two-stage ST is based on an isolated AC/DC conversion either in the medium voltage side or in the low voltage side, feeding one DC link. This comes

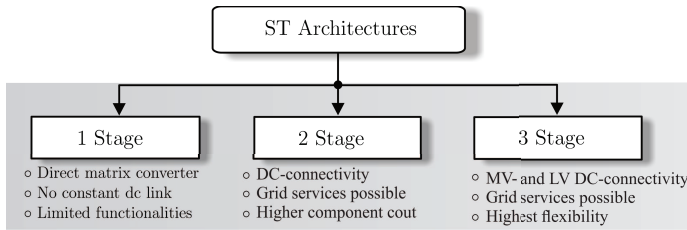


Fig. 1: Classification of architectures.

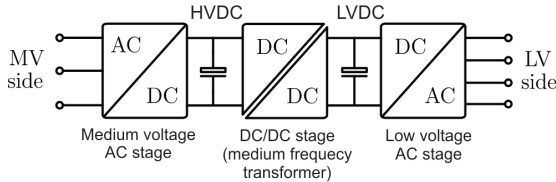


Fig. 2: Three stages of an ST in the distribution system.

at the expense of more components, which can fail. The two-stage ST can be realized either with a common DC-link or with separated DC-links fed by multi-winding transformers.

The third opportunity is the three-stage ST with AC/DC conversion in the medium voltage side and the low voltage side, while the LV-DC link and the MV-DC link are interfaced with a medium frequency DC/DC converter as shown in Fig 2. Depending on the topology, the MV-DC link is not always available, but in general the three stage ST offers the highest degree of freedom for providing additional services to the grid. The voltage level and the power rating have significant influence on the choice of the modularity of the ST. Depending on the country, the medium voltage level is in the range between  $2.3kV$  and  $35kV$ . For a realization of a  $2.3kV$  prototype, there are even Silicon components available, which can be used, while higher voltages require wide-bandgap devices or the series connection of multiple devices, if 2-level converters should be used. However, even Silicon Carbide devices cannot be used for a grid voltage of  $35kV$  in a single stage. High voltage normally requires multilevel converters, which can be realized in a modular architecture. In Fig. 3 the architectures are grouped in dependence of the degree of modularity: not modular, semi-modular and modular with additional distinction for capacitors. None of the categories outperform the others and advantages depend on the

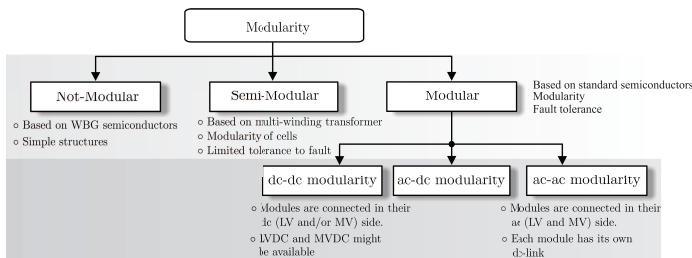


Fig. 3: Possible realization of modularity in an ST.

desired grid services, grid voltages, the criteria for efficiency, reliability and others.

### III. POWER ROUTING

Modularity has been widely adopted in power electronics to share power between multiple cells. However, in most applications the modules process the same amount of power, and closed loop control is employed to this aim. As an alternative, an operation method based on processing different power by the individual module gives more degree of freedom for the system operation, that can be used to optimize some parameters, such as efficiency and lifetime.

#### A. Concept

Fig. 4 shows a modular system based on three modules, where  $p_1$ ,  $p_2$  and  $p_3$  are the power processed by the modules 1, 2 and 3 respectively, and the total power is given by  $p_T = p_1 + p_2 + p_3$ . In a standard operation scheme, the modules process the same amount of power and therefore  $p_1 = p_2 = p_3$ . An operation method based on the activation and deactivation of modules in order to improve the efficiency in light load was proposed in [11]. Currently, this concept is known as phase-shedding technique and it is commonly used in multiphase systems. In this work, the concept of processing a different amount of power is extended to modular systems (not only multiphase systems) and takes the name of power routing. This is done because the condition that optimize the efficiency and the reliability may not be the one where each module processes an equal share of the power, i.e.  $p_1 \neq p_2 \neq p_3$ .

#### B. Classification

The power routing can be classified according to the control possibilities and also according to the control scheme. Fig. 5 shows a flowchart with the classification of the power routing method for modular systems. Regarding the power flow control technique, there are two main possibilities in the power routing concept: on/off control and direct power control. In the on/off control, the modules can be only activated or deactivated, as a

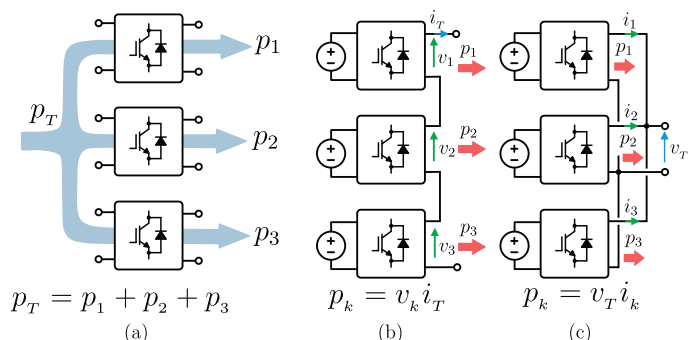


Fig. 4: Power routing concept and possibilities to implement a modular system: (a) power routing concept in a modular system. (b) Series connection of modules, where the module voltage is used to control the power and (c) parallel connection of the modules, where the current is used to control the power.

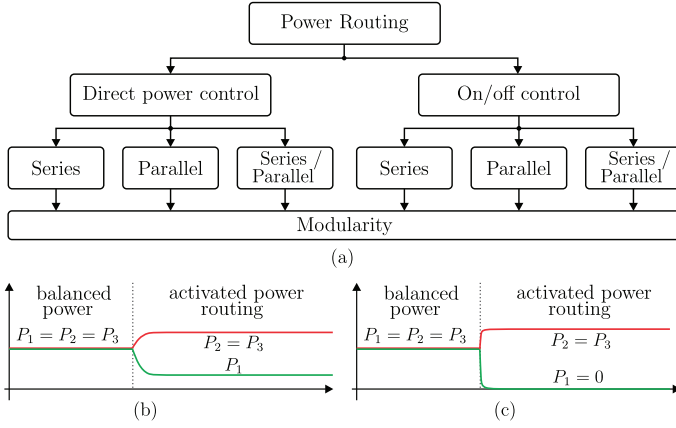


Fig. 5: (a) Classification of the power routing concept according to the power control technique and structure implementation, (b) power behavior on the modules of the system, when direct power control is used, (c) power behavior on the modules of the system, when on/off control is used.

binary logic. Therefore, when one module is deactivated, the remaining ones have to share the total power of the system. As an example, all the three modules of the Fig. 4 (a) process the same amount of power  $p_1 = p_2 = p_3 = p_T/3$  in balanced condition. If the module 1 is deactivated  $p_1 = 0$ , the remaining ones process the whole power  $p_2 = p_3 = p_T/2$ . For this example, the power processed by each module is illustrated in the graphic shown in Fig. 5 (c).

Power routing can also be implemented to control the power processed by each cell. In that case, all the modules contribute to the power sharing, even if the power processed by them individually is different. As an example, the power processed by the module 1 illustrated in Fig. 4 (a) can be reduced to  $p_1 = 0.2p_T$  and then the remaining modules have to process the remaining power, in that case  $p_2 = p_3 = 0.4p_T$ . For this example, the power processed by each module is illustrated in Fig. 5 (b).

Besides the power control schemes, the structure of the modular system is also important for the power routing concept and a classification according to the modules connections is also presented in Fig. 5 (a). The modules can be connected in series, parallel or even a mixture of both. In the series connection, the modules share the same current  $i_T$ , as illustrated in Fig. 4 (b), but each module has the degree of freedom to control its output voltage, defined by  $v_1$ ,  $v_2$  and  $v_3$  for the modules 1, 2 and 3, respectively. Since the power of a generic module  $k$  is given by  $p_k = v_k i_T$  (where  $k = \{1, 2, 3\}$ ), the power of the individual module can be controlled by changing the output voltage of the module.

Likewise, in the parallel configuration, the modules share the same voltage  $v_T$ , as illustrated in Fig. 4 (c), but each module has the degree of freedom to control its output current, defined by  $i_1$ ,  $i_2$  and  $i_3$  for the modules 1, 2 and 3, respectively. In that case, the parameter used to control the power of the modules is the current instead of the voltage.

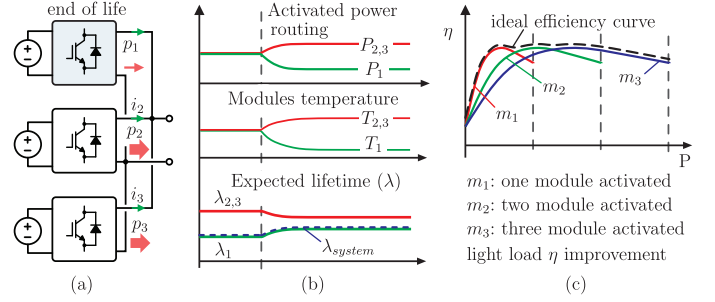


Fig. 6: Example of the power routing impact on the lifetime and efficiency of a modular system: (a) block diagram of an example system highlighting that one module is close to the end of life, (b) expected lifetime graphic showing the impact of the power routing on the system's lifetime, (c) efficiency improvement in light load, when power routing is used.

Finally, both previously described connections can be combined in a series/parallel configuration, where the modules share neither the same current nor the same voltage. In that configuration, they have the complete degree of freedom to control the power through the current or the voltage control.

### C. Benefits

As aforementioned, the power routing concept can bring benefits for the system, by the means of efficiency and lifetime improvement. The efficiency improvement through the phase-shedding concept has already been demonstrated in literature in [11] - [13]. This concept is illustrated in Fig. 6 (c), where the efficiency curves are shown for the following cases: a single activated module ( $m_1$ ), two activated modules and all three activated modules. As it can be observed in this figure, the efficiency can be improved in light load operation when some modules are deactivated.

Besides the efficiency, the power routing can increase the lifetime of the system. As an example, a system based on three modules connected in parallel is shown in Fig 6 (a). In that system, each module has an expected remaining lifetime defined by  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  for the modules 1, 2 and 3, respectively. In the example shown in Fig. 6 (a), the remaining lifetime for the module 1 is lower than the other modules. This means that the module 1 is closer to its end of life than the other modules. Once it is reached, the entire system will fail. Therefore, to extend the expected lifetime of the entire system, it is necessary to increase the lifetime of module 1. One strategy to increase the lifetime of the power modules is to reduce the operation temperature of the modules, since the temperature and lifetime are directly related [14]. This example is illustrated in Fig. 6 (b), where in the first moment all modules process the same amount of power, resulting in similar operation temperature, but the module 1 has a reduced lifetime. By the means of the power routing concept, the power processed by the module 1 ( $p_1$ ) can be reduced in order to reduce its temperature, as shown in Fig. 6 (b). As a result, the expected lifetime of the module 1 and, consequently, the

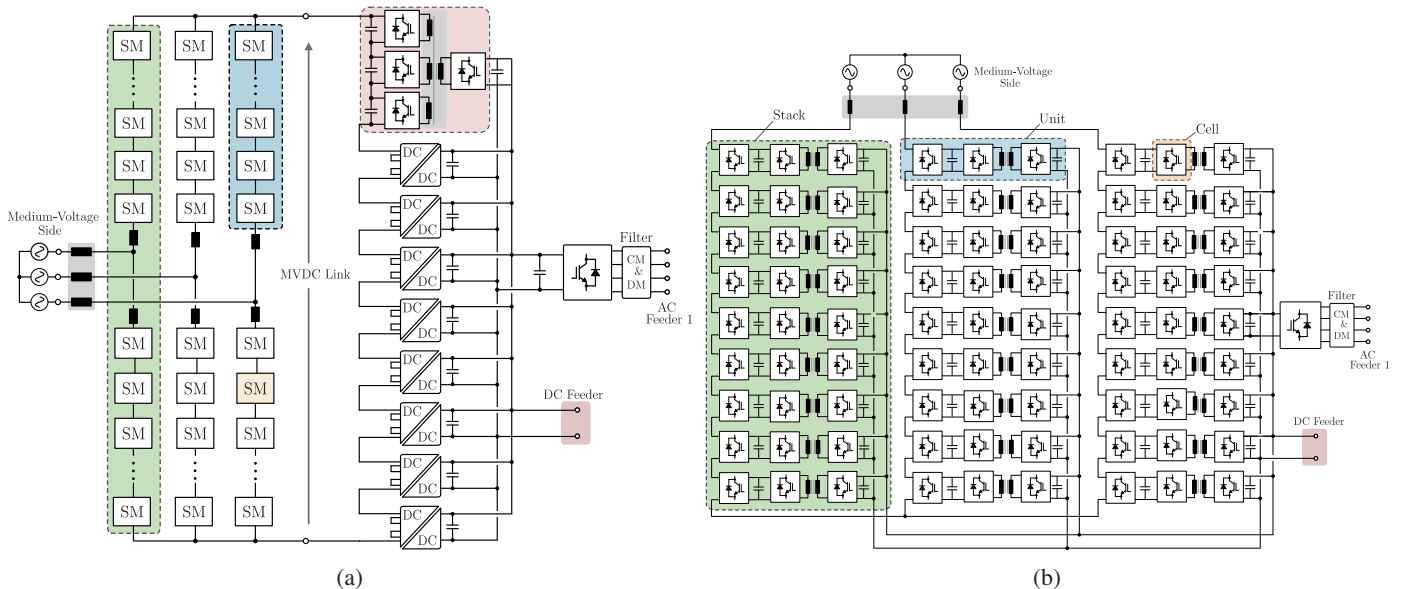


Fig. 7: Full ST architectures: (a) Modular multilevel converter (MMC), quadruple active bridge (QAB) and 2-level voltage source converter (VSC)/ Full bridges (FB), (b) Cascaded H-bridges (CHB), dual active bridges (DAB) and 2-level voltage source converter (VSC)/ Full bridges (FB).

lifetime of the entire system is increased. Of course, the power processed by the modules 2 and 3 will increase, as well as the temperature of these modules is increased. Although the expected lifetime of the modules 2 and 3 are slightly reduced, the system lifetime is increased. Thus, this example has shown that it is possible to delay the time to the next failure and therefore improve the availability of the system by the means of the power routing.

#### IV. POWER ROUTING CAPABILITY OF THREE STAGE ST TOPOLOGIES

Two Examples for promising modular three stage ST topologies are presented in Fig. 7. Both topologies utilize the modularity in the medium voltage side and the isolation stage with series connected power converters and in the low voltage side with parallel connected power converters. The advantages and disadvantages of the topologies are reviewed in Tab. II.

In addition to possible system level advantages, such as DC-link access, special attention is given to the proposed concept of power routing in the system. In the medium voltage side, the two possible converter topologies considered are the MMC and the CHB. From the system level perspective, the MMC is the better solution, because of the availability of the MV-DC link, which can be used for the connection of transmission lines or large PV/wind power plants. The power routing capability of the MMC is limited to a controlled imbalance of the voltage in the cells, which has limited influence due to the very low switching frequency while the conduction losses remain constant. In comparison to the MMC, the CHB enables redundant power flow paths, which can be controlled by the modulation of the converter. Here, each CHB-cell requires the connection of one DC/DC converter, which leads to the

disadvantage of more of DC/DC converters with respect to the MMC converter. Also a  $2^{nd}$  harmonic oscillation will affect the CHB-cells, stressing the capacitors and influence the soft switching capability of the converter in the isolation stage. Another disadvantage of the CHB is the interdependence between the CHB cell and the cell in the isolation stage. A failure in one of the parts will interrupt the operation in the corresponding other cell, too.

In the isolation stage, the Series Resonant Converter (SRC), the DAB and the QAB are considered as possible solutions. The SRC is the simplest solution, which has been applied in the SST prototype and does not require closed loop control. It is also expected to be the most robust solution with the lowest number of required sensors. The DAB instead enables closed loop control and more sensors are needed in the case of bidirectional power flow. In terms of power routing capability, the DAB is limited to voltage sharing as well and requires many cells. The QAB is the most complex solution, which is least investigated in literature, but provides multiple possible power flow paths [15]. It requires fewer magnetic cores in comparison to the DAB, whereby the core design is more difficult to optimize. If the multiple windings on the medium voltage side of the QAB are connected to CHB-cells, high power routing capability is achieved and multiple paths can be directly loaded and unloaded. The QAB in combination with the MMC requires the medium voltage side cells to be directly connected as shown in Fig. 7 (a), which limits the power routing capability. However, it is also possible to design the isolation stage with several lower rated converters in parallel, which enables further routing capabilities.

The low voltage stage of the ST faces the challenge of a high current rating. Possible power converter topologies for

	Advantages	Disadvantages
Medium voltage side:		
MMC	<ul style="list-style-type: none"> <li>• MV-DC-link access</li> <li>• Commercially available</li> <li>• Reduced number of DC/DC converters needed</li> </ul>	<ul style="list-style-type: none"> <li>• No direct connection to the individual DC/DC stage</li> <li>• High control complexity</li> </ul>
CHB	<ul style="list-style-type: none"> <li>• Redundant power paths</li> <li>• Higher expected efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• No MV-DC link access</li> <li>• <math>2^n d</math> harmonic oscillation on the DC-link cell voltages</li> <li>• failure in one cell affects the correspondent DC/DC cell</li> </ul>
Isolation stage:		
Series resonant converter	<ul style="list-style-type: none"> <li>• Simplicity</li> <li>• Already adopted in ST prototype for traction system</li> <li>• No closed loop control mandatory</li> <li>• Low number of sensors required</li> </ul>	<ul style="list-style-type: none"> <li>• Minimum flexibility</li> <li>• High number of cells required</li> </ul>
DAB	<ul style="list-style-type: none"> <li>• Simplicity</li> <li>• Mature technology, already adopted</li> </ul>	<ul style="list-style-type: none"> <li>• High number of cells required</li> <li>• Low flexibility</li> </ul>
QAB	<ul style="list-style-type: none"> <li>• Redundant power path</li> <li>• Lower number of high-frequency transformers</li> <li>• Fault tolerance</li> </ul>	<ul style="list-style-type: none"> <li>• High complexity</li> <li>• Medium frequency transformer optimization difficult</li> <li>• LV side full bridge with higher current rating</li> <li>• High control complexity</li> </ul>
Low voltage side:		
2-level VSI	<ul style="list-style-type: none"> <li>• Widespread adoption in industry</li> <li>• Low component number</li> </ul>	<ul style="list-style-type: none"> <li>• Access of the neutral point only possible with additional components</li> <li>• High losses</li> </ul>
H-bridges	<ul style="list-style-type: none"> <li>• Lower rated power semiconductors</li> <li>• Independent phase control</li> </ul>	<ul style="list-style-type: none"> <li>• Higher number of power semiconductors and filters</li> </ul>
3-level NPC 1 or NPC 2	<ul style="list-style-type: none"> <li>• Direct neutral line access</li> <li>• High efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• Higher number of components</li> <li>• uneven thermal stress</li> </ul>

TABLE I: Comparison of modular power converter topologies for ST application.

this stage are the standard 2-level converter, single phase H-bridges or 3-level converters, such as the NPC 1 or the NPC 2. A requirement given by the LV side grid is the fourth wire of the converter, which is especially easy to access in the 3-level converters. Also the efficiency of the three level converters is expected to be higher than the other alternatives. However, the main drawback of the converter topology is the uneven thermal stress distribution between the power semiconductors. In terms of power routing, the high current rating calls for parallel connected converters, which automatically enable power routing by means of current sharing.

## V. INFLUENCE OF MODULARITY ON THE EFFICIENCY OF THE ST

### A. Efficiency curves of power converters

The losses of the power converter can be divided into switching losses, conduction losses, output filter losses and additional constant (e.g. driving) losses. The impact of the different losses on the efficiency characteristics is examined in the following. Particularly, the dependence of the load current and the dc link voltage on the efficiency curves is of interest

to investigate the influence of the modularity in the power converters. For simplicity, the influence of the gate voltage is not considered. The switching losses of IGBTs are commonly derived from the load current  $I$  and the dc link voltage  $U_{dc}$  as shown in (1), where, the device dependent parameters are pooled up in the parameter  $a_{T,sw}$  and the junction temperature dependence is neglected.

$$P_{T,SW} = a_{T,sw} \cdot f_{SW} \cdot I \cdot U_{dc}^{1.3} \quad (1)$$

The switching losses are modeled with a constant voltage drop  $v_{ce,0}$  and the resistor  $r_{ce}$  as shown in (2).

$$P_{T,Cond} = u_{ce,0} \cdot I + r_{ce} \cdot I^2 \quad (2)$$

Similar to the IGBT, the losses of the diodes can be modeled as shown in (3) and (4) with the device dependent corresponding parameters  $a_{rr}$ ,  $u_{f,0}$  and  $r_f$ .

$$P_{D,rr} = f_{SW} \cdot a_{rr} \cdot I^{0.6} \cdot U_{dc}^{0.6} \quad (3)$$

$$P_{D,Cond} = u_{f,0} \cdot I + r_f \cdot I^2 \quad (4)$$

Beside these power semiconductor losses, there are driving losses for all power supplies and measurement circuits (5). These losses are not dependent on the output power, but influence the efficiency in low load operation.

$$P_{driving} = a_{const} \quad (5)$$

Furthermore, the windings of the converter's output filter affect losses. Here, only the winding losses are modeled with (6).

$$P_{filter} = I^2 \quad (6)$$

Other possible filter losses are magnetization losses of the inductor cores, which can be relevant in case of high switching frequencies. For higher order filters, like the LCL filters, equivalent series resistance losses might also be of interest. However, the losses, which are relevant for the system need to be identified by the system designer and can be taken into account for the proposed efficiency curve.

In the following, the losses for an PWM converter are considered. This means the modulation index  $m$  and the phase displacement  $\cos(\varphi)$  are influencing the losses of the converter by defining the loading of the IGBT and the diode. Under the assumption  $u_{ce,0} = u_f$  and  $r_{ce} = r_f$ , these two parameters can be assumed to be constant, which leads to the dependency of the losses on the current as shown in (7).

$$P_{loss,parallel} = f(I, I^{0.6}, I^2, U_{dc}, U_{dc}^{0.6}, U_{dc}^{1.3}) \quad (7)$$

The influence of these non-linearities on the efficiency curve can be derived by assuming an output power, which is depending on the current, the voltage and the modulation index. This can be simplified and leads to the efficiency in dependence of the load current (8) and the efficiency in dependence of the voltage (9).

$$\eta(I) = 1 - a_{i0} - a_{i1} \cdot I - a_{i2} \cdot I^{-0.4} \quad (8)$$

$$\eta(U_{dc}) = 1 - \frac{a_{u0}}{U_{dc}} - a_{u1} \cdot U_{dc}^{0.3} - a_{u2} \cdot U_{dc}^{-0.4} \quad (9)$$

In Fig. 8 the different influencing factors of the losses on the efficiency curve are presented for a grid connected 2-level converter in dependence of the output power. Also the influence of different power semiconductor technologies can be analyzed: E.g. MOSFETS do not affect a voltage drop during the conduction losses, leading to an overall improvement in the efficiency curve or SiC power semiconductors without reverse recovery losses improve the efficiency in the whole operation area with high impact during low load operation.

### B. Influence of modularity on the efficiency

Modularity in power converters is applied in series and parallel connections. A mix of both is also possible, but in this case the parts can be divided into basic parallel and series connections. Depending on the degree of desired modularity,

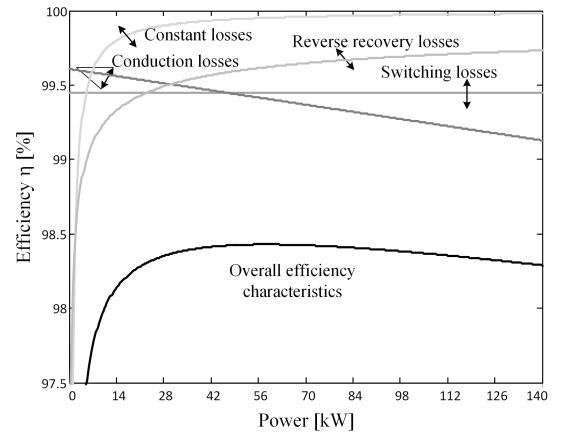


Fig. 8: Influence of losses on the efficiency of the converter.

$U_{dc}[V]$	700
$I_{max}[A]$	200
$f_{sw}[kHz]$	4
$U_{ll}[V]$	400
$\cos(\varphi)$	1
$m$	1
$U_{ce,max}[V]$	1200

TABLE II: Parameters of the studied modular parallel connected system.

components with different voltage and current rating can be used for the design, whereby lower rated power semiconductors usually perform better than higher rated ones. Furthermore, parallel converters enable interleaved operation, leading either to a reduction of the total harmonic distortion (THD) of the currents with the similar switching frequency or for a lower switching frequency and consequently lower losses with a constant THD. In Fig. 9 the effect of parallel power converters on the efficiency is shown for the case of a 2-level voltage source converter on the low voltage side of the ST with a blocking voltage of 1200 V and DC-link voltage of  $U_{dc} = 700V$  with either one, two or four parallel power modules (Infineon *fs50r12kt4\_b11*, *fs100r12kt4\_b11*, *fs200r12kt4\_b11*). The parameters of the study are displayed in Tab. I. In Fig. 9 (a) the case is shown for equal switching frequencies, while Fig. 9 (b) demonstrates the case for interleaved operation with similar THD of the currents. It can be seen that for an equal switching frequency, two modules achieve higher efficiency than one or four modules, but in case of the utilization of the redundancy, the higher number of parallel modules achieves higher efficiency than the other cases.

Similar to the case of parallel power converters, the effect of series connections on the efficiency is demonstrated in Fig. 10 with the parameters of Tab. III) for a DC-link voltage of  $U_{dc} = 2kV$ , which is realized either with two IGBT modules with a blocking voltage of  $U_{ce,max} = 1.7kV$ , three modules with  $U_{ce,max} = 1.2kV$  or five modules with  $U_{ce,max} = 650V$  (Infineon *ff200r17ke4*, *ff200r12ke4* and *fs200r07pe4*). For the comparison a constant modulation index and a constant

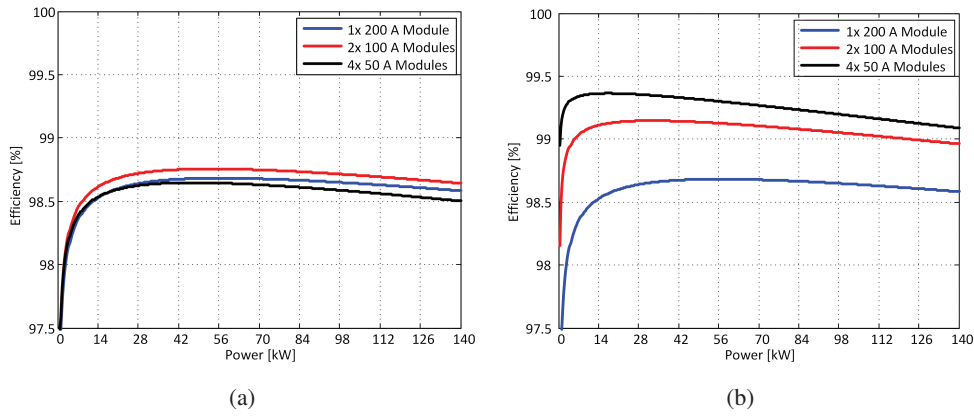


Fig. 9: Efficiency curve for converters with similar power realized with different components: (a) not interleaved (for constant switching frequency), (b) interleaved (for constant current ripple by reduction of switching frequency).

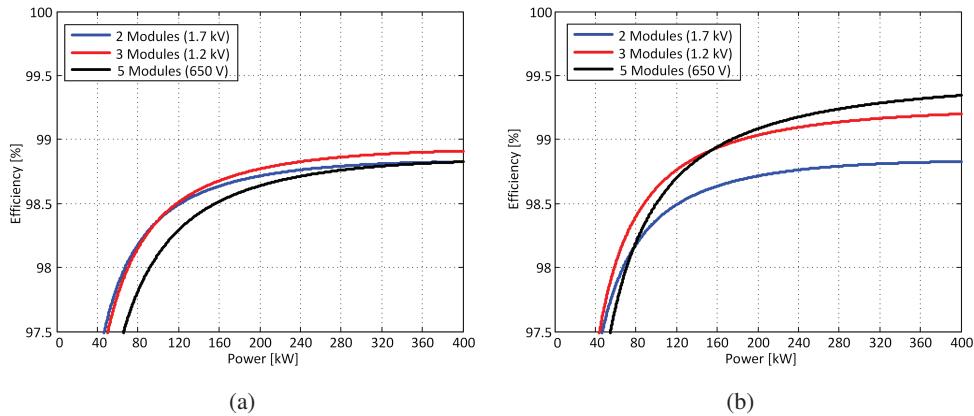


Fig. 10: Efficiency curve for converters with similar power realized with different components and constant current and modulation index: (a) for constant switching frequency, (b) for constant output current ripple.

output current are assumed. Fig. 10 (s) demonstrates the case for a constant switching frequency, whereby 10b utilizes the reduced  $du/dt$  for the series converters, which enables a reduction in the switching frequency for a constant THD of the currents by reducing the losses. In case of a constant switching frequency, the highest efficiency is achieved for the 1200V modules, while in case of 10 (b) the modularity outperforms the other modules with a higher efficiency.

## VI. INFLUENCE OF MODULARITY ON THE RELIABILITY OF THE ST

The effect of modularity on the reliability of the ST is hard to quantify with respect to the number of components because more components do not necessarily cause lower reliability and vice versa. For this reason, the reliability is investigated in terms of thermal stress on the components for different load variations. It is assumed that all systems are designed for an ambient temperature of  $T_a = 30^\circ C$  and for a maximum junction temperature  $T_{j,max} = 80^\circ C$  under full load and the losses of the single 200 A module. In Fig. 11 this is demonstrated for parallel power converters with the efficiency curves of Fig. 9 (b), where  $\Delta T$  is the increase of

the junction temperature compared to the ambient temperature. This is plotted in dependence from the load current for the three different cases under utilization of the modularity. From this figure, the effect of a variation in the load can be translated into thermal cycles for the power semiconductors. Due to the higher efficiency, the higher module number causes lower thermal cycles, leading to lower thermal stress. This can either be used for an increase in the lifetime or for a de-rating of the cooling system with the similar lifetime. The thermal swing can be translated with (10) into the damage of the power electronic module, which is applied for the lifetime estimation. This is applied in Fig. 11 (b), where the damage is considered independently from the power rating and is normed on one full power cycle for the system (0A to 200A) applied to the single module as in Fig. 11 (a). The damage is minimized for the modular power converters, because of the lower thermal cycles.

$$N_f = 4.48 \cdot 10^{14} \cdot (\Delta T_j)^{-5.024} \cdot e^{0.0555 \cdot (-T_{j,mean} + 77.5K)} \quad (10)$$



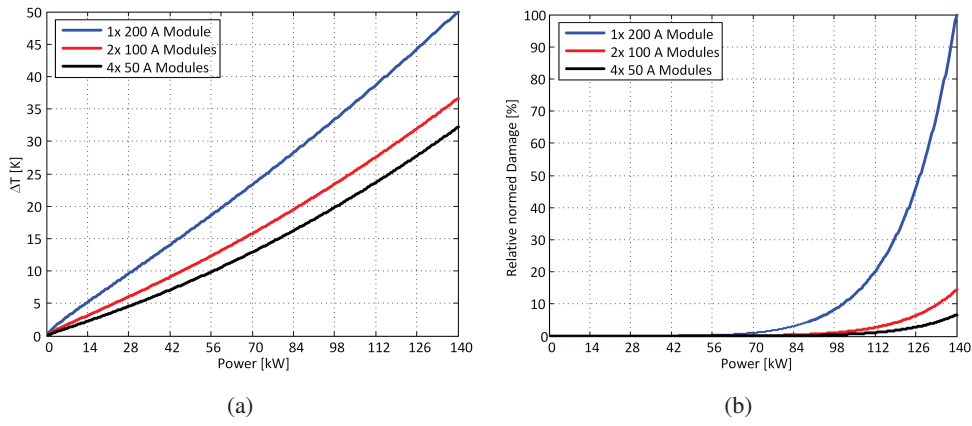


Fig. 11: (a) Thermal swing in dependence of the load, (b) accumulated damage for the case in (a).

$U_{dc}$ [kV]	2
$I$ [A]	200
$f_{sw}$ [kHz]	2
$U_{ll}$ [V]	variable
$\cos(\varphi)$	1
m	1

TABLE III: Parameters of the studied modular series connected system..

## VII. CONCLUSION

Smart Transformers are a solution for the interconnection of the medium and the low voltage distribution grids. Several design considerations of possible modular Smart Transformers architectures for the distribution grid have been given with attention to the number of stages and the influence of modularity. The concept of modularity has been proposed for designing highly efficient power converters with the capability to internally route the power in the system for improving the reliability of the system. The advantage of modular power converters with respect to efficiency enhancement and reliability by means of power routing within the system has been demonstrated for differently rated components.

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## REFERENCES

- [1] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid converters for photovoltaic and wind power systems*. John Wiley & Sons, 2011, vol. 29.
- [2] A. Ipakchi and F. Albuyeh, "Grid of the future," *Power and Energy Magazine, IEEE*, vol. 7, no. 2, pp. 52–62, 2009.
- [3] S. Yang, D. Gunasekaran, Y. Liu, U. Karki, and F. Z. Peng, "Application of transformer-less upfc for interconnecting synchronous ac grids," in *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*. IEEE, 2015, pp. 4993–4999.
- [4] L. Mackay, T. G. Hailu, G. C. Mouli, L. Ramirez-Elizondo, J. Ferreira, and P. Bauer, "From dc nano-and microgrids towards the universal dc distribution system—a plea to think further into the future," in *Power & Energy Society General Meeting, 2015 IEEE*. IEEE, 2015, pp. 1–5.
- [5] V. K. Sood, *HVDC and FACTS controllers: applications of static converters in power systems*. Springer Science & Business Media, 2006.
- [6] X. She, A. Q. Huang, and R. Burgos, "Review of solid-state transformer technologies and their application in power distribution systems," *Emerging and Selected Topics in Power Electronics, IEEE Journal of*, vol. 1, no. 3, pp. 186–198, 2013.
- [7] J. W. Kolar and G. Ortiz, "Solid-state-transformers: key components of future traction and smart grid systems," in *Proc. of the International Power Electronics Conference (IPEC), Hiroshima, Japan, 2014*.
- [8] M. Andresen, K. Ma, M. Liserre, and F. Blaabjerg, "Thermal stress comparison in modular power converter topologies for smart transformers in the electrical distribution system," in *Power Electronics and Applications (EPE'15 ECCE-Europe), 2015 17th European Conference on*. IEEE, 2015, pp. 1–10.
- [9] G. Quartarone, M. Liserre, F. Fuchs, N. Anglani, and G. Buticchi, "Impact of the modularity on the efficiency of smart transformer solutions," in *Industrial Electronics Society, IECON 2014-40th Annual Conference of the IEEE*. IEEE, 2014, pp. 1512–1518.
- [10] M. Andresen, G. Buticchi, and M. Liserre, "Study of reliability-efficiency tradeoff of active thermal control for power electronic systems," *Microelectronics Reliability*, 2015.
- [11] P. Zumel, C. Fernandez, A. de Castro, and O. Garcia, "Efficiency improvement in multiphase converter by changing dynamically the number of phases," in *Power Electronics Specialists Conference, 2006. PESC'06. 37th IEEE*. IEEE, 2006, pp. 1–6.
- [12] M. Pavlovsk, G. Guidi, and A. Kawamura, "Assessment of coupled and independent phase designs of interleaved multiphase buck/boost dc-dc converter for ev power train," *IEEE Transactions on Power Electronics*, vol. 29, no. 6, pp. 2693–2704, June 2014.
- [13] A. Costabeber, P. Mattavelli, and S. Saggini, "Digital time-optimal phase shedding in multiphase buck converters," *IEEE Transactions on Power Electronics*, vol. 25, no. 9, pp. 2242–2247, Sept 2010.
- [14] K. Ma, M. Liserre, F. Blaabjerg, and T. Kerekes, "Thermal loading and lifetime estimation for power device considering mission profiles in wind power converter," *Power Electronics, IEEE Transactions on*, vol. 30, no. 2, pp. 590–602, 2015.
- [15] G. Buticchi, M. Andresen, L. Costa, and M. Liserre, "Modular dc/dc converter structure with multiple power flow paths for smart transformer applications," in *Power Electronics and Applications (EPE'15 ECCE-Europe), 2015 17th European Conference on*, Sept 2015, pp. 1–9.