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# Solid-State-Transformers: Key Components of Future Traction and Smart Grid Systems

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# Solid-State-Transformers: Key Components of Future Traction and Smart Grid Systems

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***Abstract*—The efficient supply of electric power relies strongly on the selection of suitable voltage levels for different sections of the energy distribution system. When higher levels of power are required, a medium-voltage level in the tens of kilovolts range is typically selected. In accordance to current trends in energy conversion, the supply of power must fulfil several functionality requirements among which high power-quality and access to a low-voltage DC interface can be highlighted. Moreover, low energy losses, high power-density, low failure rate and low total cost of ownership remain as major research challenges. Solid-state-transformers (SSTs) comply with these functionality requirements as well as with the demanded high performance levels while directly connecting to medium-voltage.**

**This paper reviews the implementation of SST technology for transportation and Smart-Grid applications. The envisioned architectures for locomotive systems, remotely-operated-vehicles and large scale ships, which benefit from the compactness and high performance of SST are shown. In addition, the possible arrangement of micro-grid systems comprising SST concepts for integration of renewable energy and implementation of DC-microgrids is detailed.**

**The different SST concepts proposed for these applications can be grouped into distinctive categories, leading to a comprehensive classification of, first, general isolated AC-AC conversion systems and later to a specific classification of SST concepts based on the different levels of modularity. Finally, a detailed review of the numerous previously reported and functional SST concepts is presented and a comparison to systems employing low-frequency transformers is given.**

***Keywords*—Converter Topology Classification, Multicell and Multilevel Converter Topologis, Medium-Frequency Isolation, Performance Evaluation.**

## I. Introduction

The existing electric power supply network is characterized by different voltage levels, e.g. a Medium-Voltage (MV) level, ranging from 7.2 kV up to 24 kV for larger distance power distribution while a Low-Voltage (LV) level, ranging from 127 V up to 690 V is selected for the final supply of the loads [1]. The adaptation and isolation between the different network sections is realized by passive transformers operated at line frequency (50 Hz/60 Hz), whereby in case of high-power applications, these transformers are conveniently placed in close vicinity to the load in order to minimize the losses in the energy transmission.

On the other hand, current trends in electric energy supply, as shown in Fig. 1, demand concepts featuring high multi-objective performance levels. Among these performance indexes, low supply chain and mission energy losses, low floorspace requirement and low total cost of ownership constitute a critical triad given the trade-offs present in their selection [2]. Moreover, with the continuous integration of power electronic circuits performing critical energy conversion tasks, low failure rate, i.e. high reliability, is becoming a major concern, whereby the concept of fault-tolerant systems has gained increased attention [3, 4]. A final modern specification is the requirement of low manufacturing and recycling efforts of the energy supply system.

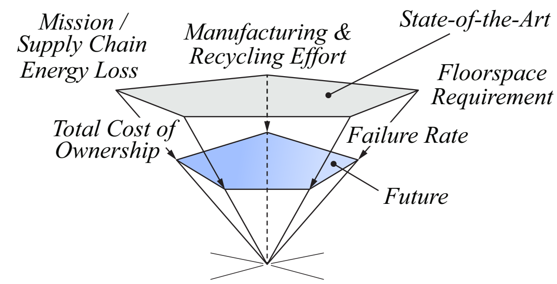


Figure 1: Performance trends in supply of electric energy.

In addition, these power electronic circuits should provide unprecedented functionality features such as:

- available LV DC-link
- power-factor correction
- VAr compensation
- active filtering
- disturbance isolation
- smart protection.

Among these new required features, the access to a LV DC-link, in order to e.g. ease the integration of renewable energy sources [1, 5], or other power-quality related features such as power-factor-correction, reactive-power compensation and active filtering are of primary concern [6, 7]. Other considered features in supply of energy are related to smart protection approaches able to effectively isolate load and grid side transients, including load short circuit conditions and unbalanced input voltages, among others, hence increasing the power quality of the system.

These newly demanded performance and functionality features are not fully covered by the standard electric power supply concept, which is based on passive Low Frequency Transformers (LFT).

The first step towards accomplishing these stringent performance requirements is the integration of power-electronic

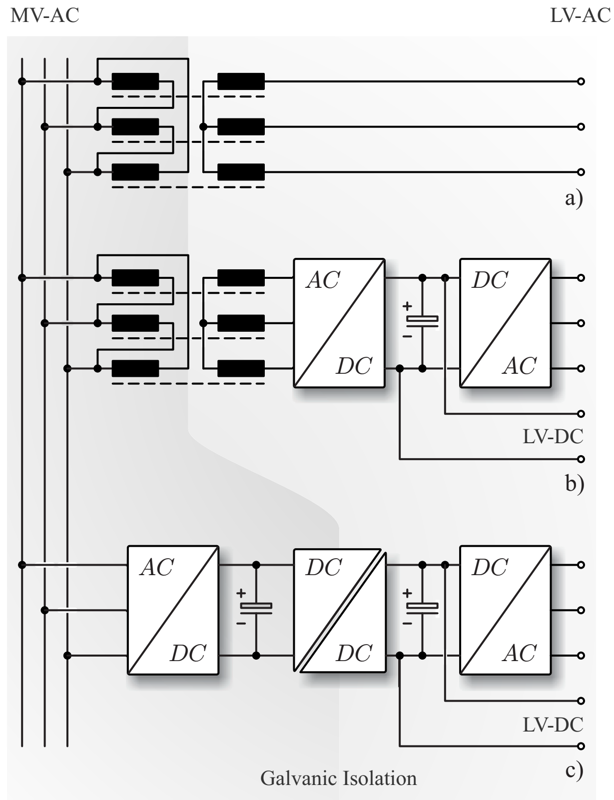


Figure 2: Conversion of electric energy from MV-AC to LV-AC through a) standard line frequency operated passive transformer; b) incorporation of a back-to-back rectifier/inverter stage and c) integration of a medium-frequency isolated DC-DC conversion stage, boosting performance indexes such as power-density and efficiency.

circuits in the supply chain in order provide active control of the power flow. A circuit structure fulfilling all previously mentioned functionality features is shown in Fig. 2-b), where a back-to-back rectifier-inverter stage with access to the LV DC-link is presented. In contrast to the standard solution shown in Fig. 2-a), this concept, when equipped with a proper rectifier topology, enables the active and continuous shaping of the input (MV-AC) current, thus fulfilling the requirements of power-factor correction, reactive power compensation, active filtering and disturbance isolation. On the load (LV-AC) side, a regulated output voltage is supplied, whose frequency is independent from the MV-side's frequency. Moreover, given the controlled nature of power electronic switching devices, a smart protection concept can be elaborated.

Most importantly, with the availability of a LV-DC port, numerous features can be added to this supply chain, including connection to an energy storage system, thus enabling operation as a Uninterrupted-Power-Supply (UPS), direct connection of Photo-Voltaic (PV) arrays [8] or implementation of future local DC-grids [5], among others [1].

Nevertheless, the structure shown in Fig. 2-b) suffers from low flexibility in the optimization of performance indexes such as efficiency (mission energy loss) and power density (floorspace requirements), which do not fulfil the needs of e.g. space-limited and/or high-efficiency applications. In these cases, an advanced concept as shown in Fig. 2-c) is required. This concept enables equal functionality features as the arrangement in Fig. 2-b), while incorporating a DC-DC conversion stage responsible for the galvanic isolation and voltage adaptation. This DC-DC converter stage is operated in the Medium-Frequency (MF) range, thus achieving a considerable reduction in the size of reactive components [9, 10], namely the now MF-operated transformer. Furthermore, the operation at MF facilitates the optimization of the system for a set of specific performance indexes [2, 11], making it suitable for applications with high performance requirements. Given the inclusion of a high number of semiconductor devices, this new advanced concept is often referred to as Solid-State-Transformer (SST).

This paper presents an overview of SST technology with special focus on applications in transportation and the Smart-Grid. First, in Section II the envisioned architectures including the SST concept in traction and Smart-Grid technologies will be reviewed. In **Section III** an overview of previously reported SST concepts and their respective classification concerning different modularization criteria is described. In **Section IV** a summary of functional research and industrial prototypes reported in literature is presented. Finally, an outlook and future research questions related to the SST concept will be outlined in **Section V**.

## II. Solid-State-Transformer Concept

As mentioned earlier, the SST concept offers important benefits when applied to traction and Smart-Grid applications due to the high levels of available functionality and the potential to improve efficiency and power density when compared to standard MV-AC to LV-DC conversion architectures. For these reasons, the specific arrangement of power electronic conversion stages within these applications will be reviewed in the next sections.

### *A. SSTs in Traction Applications*

Traction and subsea systems are clear examples of space-critical applications, where a low volume and weight of the systems directly boosts its performance. Traction converter manufacturers are incorporating this technology into their product lines [12–18], whereby the main considered architecture is shown in Fig. 3-a). The arrangement consists on an input rectifier connected directly to the MV catenary line whose voltage resides between 15 and 25 kV [19]. The rectified voltage supplies a high-power DC-DC converter stage which is now responsible for the voltage adaptation and the isolation of the primary to secondary side. This DC-DC converter provides a low voltage DC-link supplying the 3-phase inverters driving the locomotive's traction motors as well as supplying all relevant auxiliary loads. With the inclusion of a MF transformer within the DC-DC converter, the size/weight of the traction solution can be greatly reduced while increasing the system's efficiency [20].

Another space-limited application which benefits from SST technology are Remotely-Operated-Vehicles (ROVs) [21]. Typically the supply of these vehicles is through a long AC cable powered from the topside ship's electric system. Given

[1] The structure in Fig. 2-b) can be modified in order to partially fulfil the mentioned functionalities, which result in simplified structures. Some of these will be discussed in a later section.

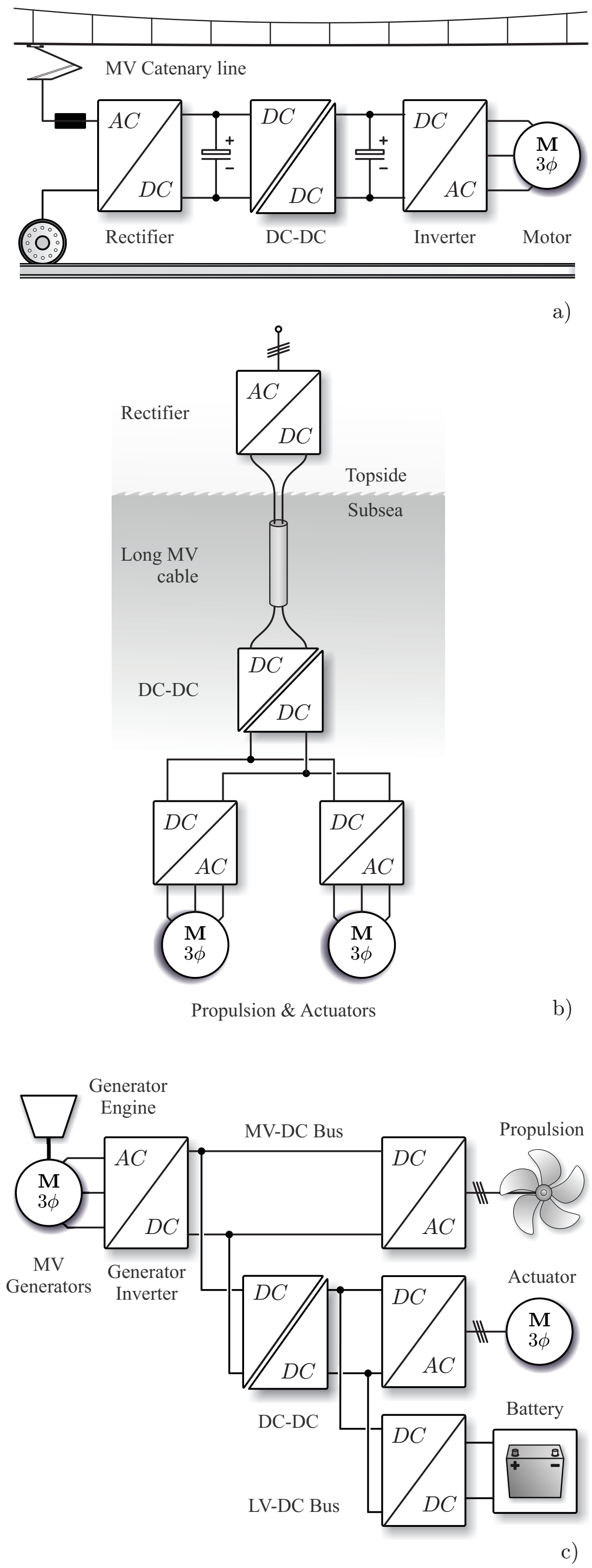


Figure 3: SST technology in space-limited applications: a) Traction locomotive with direct 1-phase MV AC connection; b) Remotely-Operated-Vehicle supplied through long MV-DC cable; c) DC-powered ship architecture.

its highly capacitive behavior, however, this results in high amounts of reactive power supplied to the cable, and thus in considerable conduction losses. In order to avoid this problem, a topside rectifier supplies a DC-DC converter, installed within the ROV, through a long MV-DC cable as shown in Fig. 3-b). This DC-DC converter down-steps the voltage in order to be utilized by the on-board propulsion and actuator systems. Here, the transmission through a long MV-DC cable increases the overall system's efficiency.

A further application where SST technology could provide significant benefits is in large ships, whereby the utilization of MV-DC networks is gaining considerable attention [22–24]. The proposed architecture is shown in Fig. 3-c). Here, a power-electronic rectifier, placed in close vicinity to the generator engine, supplies a MV-DC bus. A large portion of the power is fed directly from this MV-DC bus to the inverter driving the propulsion motors. A DC-DC converter is responsible for providing a LV-DC bus utilized for all other electrical loads. In addition, an energy storage system may be linked to this LV-DC bus in order to provide electrical energy in case of a generator failure.

### B. *SSTs in Smart-Grid Applications*

SSTs are considered to be one of the key enabling technologies for the implementation of the future electric power system architecture: the Smart-Grid [1, 25, 26]. This concept consists on an efficient distribution of electric energy which is based on flexible routing mechanisms and comprehensive information about the end-user's energy consumption, which ultimately facilitates the coordination and integration of renewable energy sources and energy storage systems into the current electrification network.

A possible implementation of this concept is clearly visualized in local microgrids [5], battery charging facilities, and data centers [27], where possible implementations utilizing standard and SST technologies are presented in Figs. 4-a) and b) respectively. In both cases, a set of different (AC and DC) loads, battery stacks and renewable energy sources are interconnected within the local grid. With this arrangement, a flexible flow of electric power is achieved, effectively integrating renewable energy sources and powering loads of DC and AC nature.

With the conventional arrangement shown in Fig. 4-a) however, all aforementioned power quality issues, such as reactive power compensation, active filtering and grid-side/load-side protections are not easily achievable since these tasks would be distributed among several power electronic converter systems, which require to be precisely coordinated. Therefore, the solution presented in Fig. 4-b), which incorporates a central rectification stage and a DC-DC converter, represents an attractive solution. Here, the distribution of electrical energy is no longer done in LV-AC, but in the shape of LV-DC. With respect to the standard solution, the final conversion supplying the loads is now realized from LV-DC into AC or other lower voltage DC values. Moreover by utilizing a MF-operated DC-DC converter, the efficiency and power density of the solution can be increased [11].

So far, only the general configuration of the converters shown in Figs. 3 and 4-b) has been presented. In order to

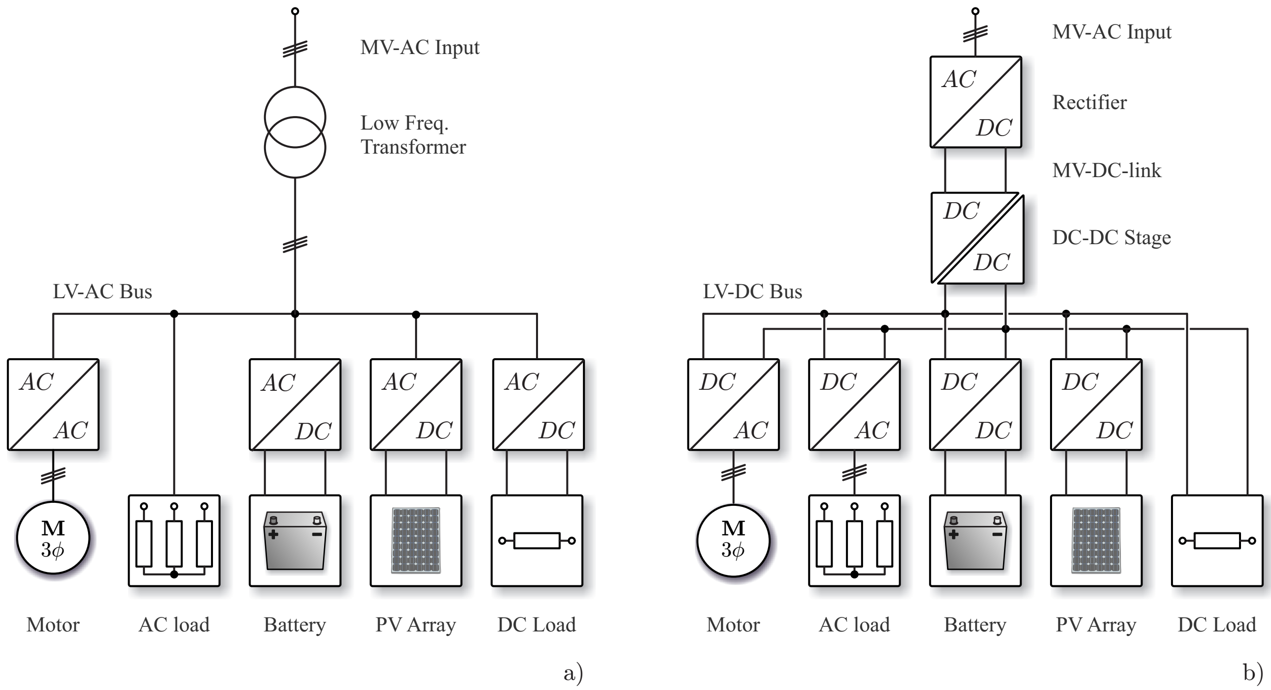


Figure 4: Microgrid structures integrating AC and DC loads as well as energy storage systems linked to renewable energy sources. In a) an implementation based on standard low-frequency technology is presented, whereas b) displays the SST-based solution.

discuss the possible architectures of the SST, a classification concerning the different potential features of general 3-phase AC-AC conversion systems will be extensively covered in the next section, which should ultimately aid in the selection of the most suitable topology for a specific application.

## III. Solid-State-Transformer: State-of-the-Art

The first form of AC-AC power electronic circuit with galvanic isolation and power flow control, presented in Fig. 5, was proposed in the early seventies by W. McMurray [28] and it may be considered as the first conceived SST. This circuit consists of two four-quadrant switches on the primary side connected to a 1-phase grid while feeding the primary center-tapped higher-frequency transformer winding. On the secondary side, a similar structure comprising the required inductor and output capacitor is included. The switches $S_{11}$ and $S_{12}$ operate in complementary mode with $50\%$ duty-cycle, same as with the secondary switches $S_{21}$ and $S_{22}$. By adjusting the phase-shift between these two pairs of switches, the output voltage can be regulated while achieving sinusoidal input current [28]. It should be noted that the operation of this converter resembles in great manner that of the modern Dual-Active-Bridge DC-DC converter, reported originally in the nineties [29].

Numerous isolated 3-phase AC-AC converter systems have emerged since the conception of the first SST concept, including low-frequency front-end isolated and high-frequency isolation concepts. A comprehensive classification of these converter systems is presented in Fig. 6.

In order to select the most suitable solution for a specific application, the options for the construction of the isolated 3-phase AC-AC conversion systems are detailed and a comprehensive classification of these options is given. The first conceptual differentiation is made when selecting the operating frequency of the transformer, where the front-end low-frequency and high-frequency isolation are found. On the low frequency isolation side, a division between systems with and without capability of secondary side frequency adjustment is found. The first of these type of converters is the AC chopper, which is able to regulate output voltage without independent selection of frequency [30–32]. The electronic tap changer, as the name points out, is based on a tapped transformer where the switching between different taps is done with electronic circuitry [33]. With this concept, the output voltage can be actively regulated therefore compensating for disturbances from the primary side. The last concept in this category is the series voltage compensator [33, 34]. This circuit is able to control the output voltage within a certain range depending on the amount of power the respective converter system is designed for. Other concepts which are able to control the output frequency while implementing a front-end low-frequency transformer can be categorized in matrix type and DC-link based converters.

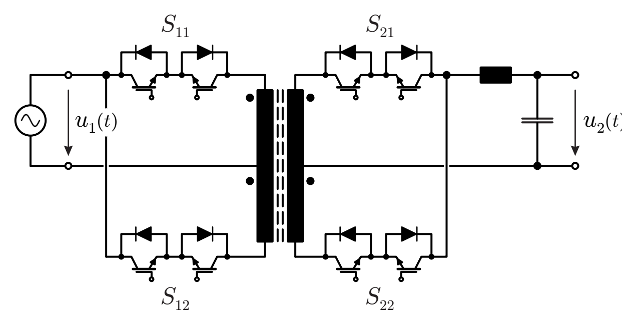


Figure 5: First reported SST concept [28] based on four quadrant switches able to control output voltage and/or input current amplitude while providing galvanic isolation.

Advanced concepts for isolated 3-phase AC-AC converter

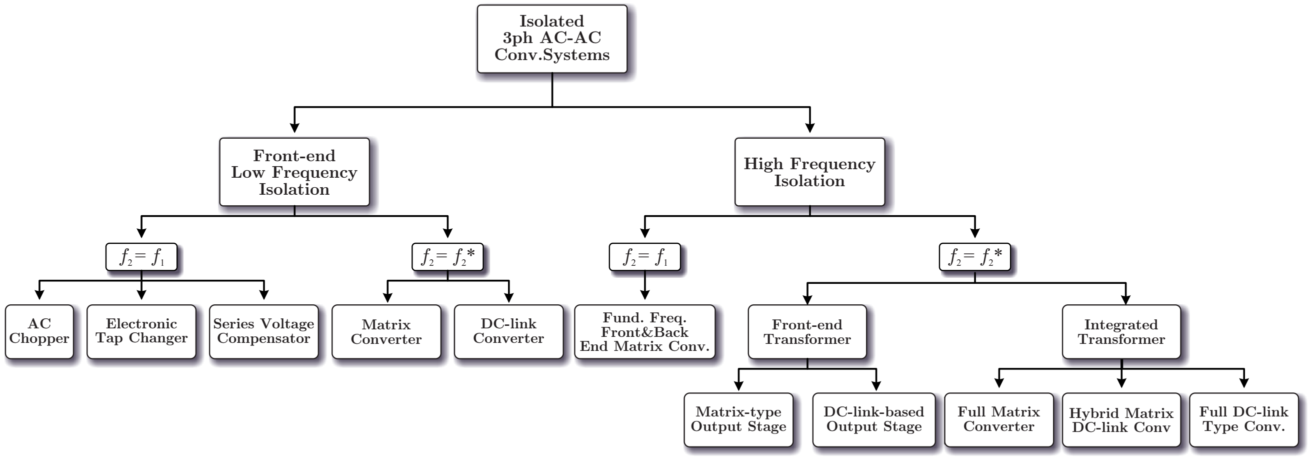


Figure 6: Classification of 3-phase AC-AC conversion system ($f_2^*$ denotes an output frequency, which can be selected independent of the input frequency $f_1$).

systems comprising high-frequency isolation principle, i.e. SSTs concepts, can be also subdivided into output frequency-controllable and non-controllable concepts. Systems unable to control the output frequency can be found in the shape of fundamental frequency front and back end matrix-based converters. Within the output frequency-controllable concepts, the transformer can also be placed at the front end while still being operated at higher frequencies, as is the case in [35, 36], which incorporates a matrix-type output stage.

Alternatively, the transformer can be integrated in the energy supply chain, leading to the last category of isolated AC-AC 3-phase conversion systems. Here, the main categorization consist of the modularity level in the direction of the power flow. The non-modular structure consists of a single-stage concept, where the voltage from the 3-phase grid is directly transformed into high-frequency by a direct matrix-type structure on both sides of the medium frequency transformer. Several realizations based on this concept can be found in literature [37–40]. Other concepts are comprising matrix-type structures on one side of the medium-frequency transformer while utilizing a DC-link based arrangement on the LV-side, leading to hybrid structures [41]. The full-modular arrangement concerning the direction of the power is represented by the MV- and LV-side DC-link-based structures, where the power flow is processed in three stages: AC-DC rectification, DC-DC conversion and finally DC-AC inversion [25, 42]

This last group, denominated as integrated transformer type, has gained intense attention due to its potential benefits in efficiency and power density, as described earlier, leading to a vast number of proposed converter units. In order to classify these proposed systems, an identification of the level of modularity is required in three different axes: 1) in the power flow direction; 2) concerning the connection to the 3-phase systems and 3) concerning the connection to the MV level, which is also beneficial for characterizing the complexity of the converter system. This classification regarding modularity level is described in the following.

*1) Modularization in Power Flow Direction:* All different options for modularization in the power direction are presented in Fig. 7 and they comprise all combinations starting from direct 3-phase matrix conversion, indirect matrix conversion and DC-link-based converters. These type of conversion systems can be either on the LV- or on the MV-side of the SST, completing a total of nine options.

The circuit diagrams of four of these concepts are presented in Fig. 8. In Fig. 8-a), the schematic representation of a single-stage direct-matrix type converter is shown. This concept utilizes six four-quadrant switches on the MV- and the LV-side. Since each of these switches comprises two IGBTs, a total of 24 devices is necessary in order to build this single-stage approach, which has been proposed in literature [37–40].

The first step in modularization is represented by the exchange of the direct matrix converter for an indirect type, as shown in Fig. 8-b). Here, similar functionality as with the direct matrix type structure can be achieved while utilizing two semiconductor devices less. Additionally, the two-level 3-phase inverter is operated as a synchronous rectifier, thus generating virtually no switching losses.

Adding a DC-link on one of the converter's sides represents the next step in modularization in the direction of the power flow. The version with MV-side direct matrix-type converter and LV DC-link based arrangement is shown in Fig. 8-c). This structure requires the same amount of semiconductor devices as the indirect matrix-type structure, with the addition of a DC-link capacitor on the LV-side. This capacitor effectively achieves a decoupling of the low-frequency AC side from the high-frequency AC side, which is beneficial for the design and optimization of the complete converter system.

The final step in modularization of the SST in the power flow direction is a fully modular 3-stage approach, where independent rectification, DC-DC conversion and inversion stages are utilized as shown in Fig. 8-d). This solution utilizes a total of 20 semiconductor devices, four less than the single-stage direct matrix-type system. Additionally, this approach allows the optimization of each converter stage in an individual manner, thus ensuring that an optimized/application-specific design is achieved. Moreover, the major challenge in the construction of this type of converter structure is now limited to the DC-DC conversion stage, where the operation at higher-frequencies combined with the medium-voltage level represents a major research challenge.

In the previous examples, the 3-phase grid is interfaced with a 3-phase integrated converter, either of matrix or of DC-

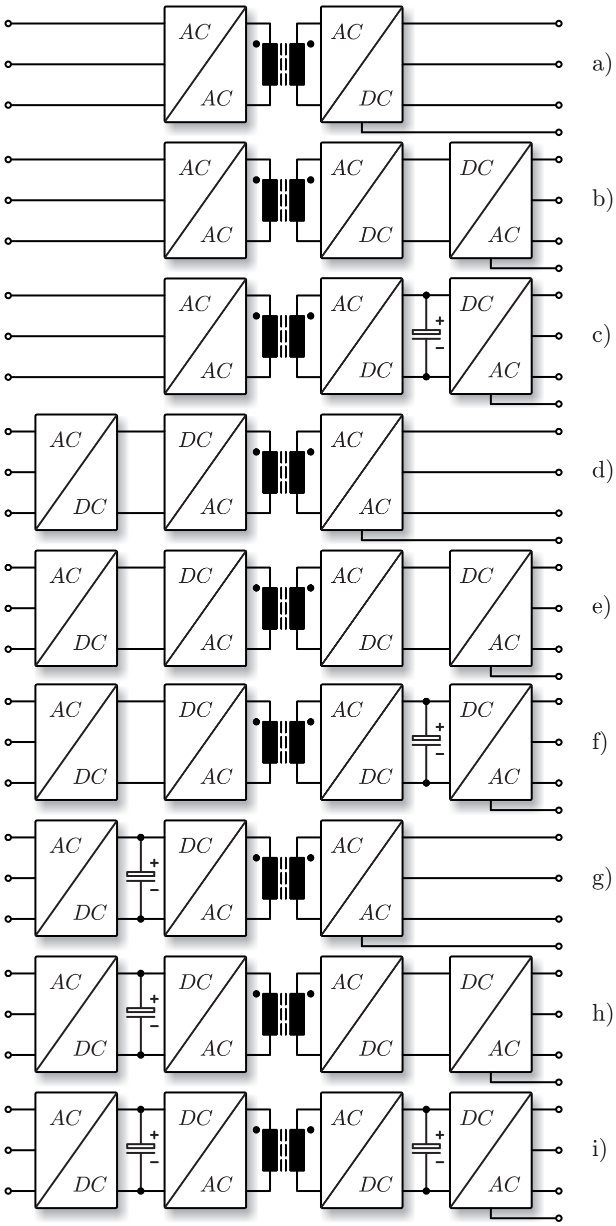


Figure 7: Possible full-scale 3-phase to 3-phase SST concepts: a) MV-side direct matrix converter / LV-side direct matrix converter; b) MV-side direct matrix converter / LV-side indirect matrix converter; c) MV-side direct matrix conv. / LV-side DC-link back-to-back conv.; d) MV-side indirect matrix converter / LV-side direct matrix converter; e) MV-side indirect matrix conv. / LV-side indirect matrix converter; f) MV-side indir. matrix conv. / LV-side DC-link back-to-back conv.; g) MV-side DC-link back-to-back conv. / LV-side direct matrix conv.; h) MV-side DC-link back-to-back conv. / LV-side indir. matrix conv.; i) MV-side DC-link back-to-back conv. / LV-side DC-link back-to-back converter.

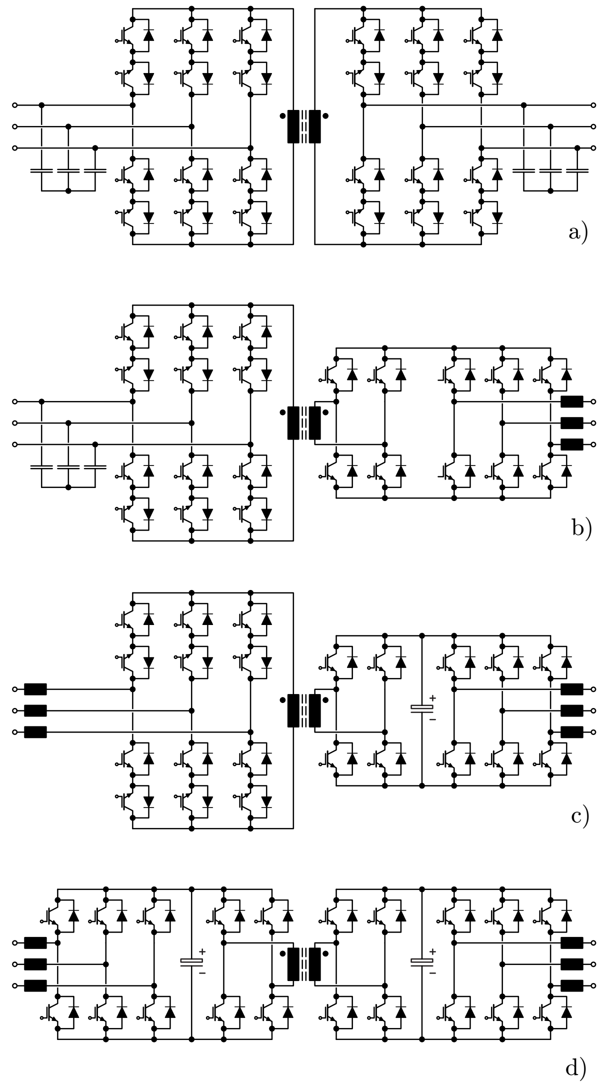


Figure 8: Possible full matrix-type SST concepts: a) MV-side direct matrix converter / LV-side direct matrix converter; b) MV-side direct matrix converter / LV-side indirect matrix converter; c) MV-side direct matrix converter / LV-side DC-link back-to-back conv.; d) MV-side DC-link back-to-back conv. / LV-side DC-link back-to-back converter.

link type. This solution, however, can be modified in order to, for example, utilize an independent converter for each of the phases, thus achieving a phase-modular structure in terms of the connection to the 3-phase grid, which is covered in the next section.

*2) Modularization of Connection to the 3-phase System:* Another axis of modularization potential is represented by the different strategies to connect to the 3-phase system, which could be either on the grid or on the transformer side. The different options for modularization in this axis are presented in Fig. 9 whereby, in order to simplify the classification, only direct matrix-converter systems are considered, i.e. no modularization in the power flow direction.

The lowest modularization level is represented by a solution which fully integrates the MV- and LV-side 3-phase system while the high-frequency link is done with a 1-phase transformer, as shown in Fig. 9-a). This isolation transformer can be also built as a 3-phase system, whereby the respective

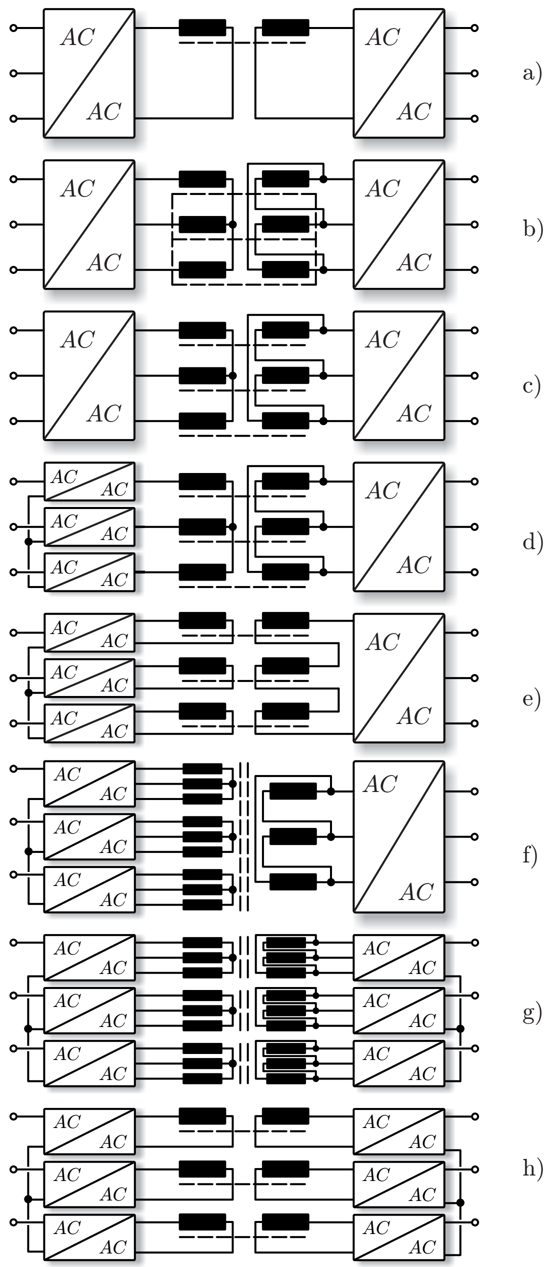


Figure 9: Direct matrix-type 3-phase SST topologies showing different degrees of phase-modularity; a) Three-phase integrated MV- and LV-side low-frequency interfaces and 1-phase MV- and LV-side high-frequency transformer; b) as a) but 3-phase magnetically integrated high-frequency transformer; c) as b) but independent magnetic circuits (cores) of the 3-phase transformer; d) as c) but phase-modular MV-side LF AC interface; e) as d) but individual 1-phase transformers connected to the MV-side phase modules and series connection of the transformer secondary windings forming a 1-phase output connected to a LV-side converter stage as shown for a); f) as e) but 3-phase output of the phase modules and magnetically fully integrated transformer arrangement with three-sets of 3-phase MV windings and a single 3-phase LV winding; g) Phase-modular MV- and LV-side converter interfaces with converter phase modules connected through individual 3-phase transformers; h) as g) but 1-phase instead of 3-phase transformers.

magnetic circuit can be either integrated, i.e. a single multi-limb magnetic core would be employed (cf. Fig. 9-b)) or it can comprise independent magnetic circuits as shown in Fig. 9-c).

The first step of the modularization on the low-frequency sides (input and output side) is shown in Fig. 9-d), whereby the MV-side converter has been split into three independent 1-phase converters each of them connected to one of the phases of the 3-phase network. Each of these converters feeds a winding of a magnetically independent 3-phase transformer. A special case is found when the LV-side windings of the transformer in Fig. 9-d) are connected in series, leading to a 1-phase transformer seen from the LV-side as shown in Fig. 9-e).

The solutions presented so far utilize a single 3-phase transformer arrangement, where the magnetic circuits are either integrated or independent. The next step is to construct independent transformers fed by independent converter modules. The solution in Fig. 9-e) can be extended with independent 3-phase windings on the MV-side magnetically coupled to a single 3-phase winding on the LV-side, as shown in Fig. 9-f). The fully modular structures, i.e. low-frequency MV and LV phase-modular and independent transformers, are shown in Figs. 9-g) and h) for the 3-phase and 1-phase transformer solutions respectively. These last levels of high modularity result beneficial in high power solutions, as each component can be independently designed to meet specific requirements.

Two examples of the aforementioned phase-modular solutions are presented in Figs. 10-a) and b), for the fully 3-phase integrated converter solution from Fig. 9-c) and the MV-side modular 3-phase magnetically integrated solution from Fig. 9-f). The fully integrated solution comprises bidirectional switches which connect directly the MV and LV low-frequency sides to the high-frequency transformer, realizing the conversion of energy in a single stage. This solution however, requires the implementation of four-quadrant switches, thus requiring a high number of semiconductor devices. The solution in Fig. 10-b) incorporates a MV-side modular magnetically integrated 3-phase transformer, whereby the LV-side converter comprises two-level 3-phase integrated bridges on both high and low-frequency sides.

The means to split the converter into phase power conversion stages and the different concepts utilized to connect to 3-phase systems on the high and low frequency sides have been clarified. It is now necessary to study the possibilities available to deal with the medium-voltage level. The desire to operate at higher frequencies while still reaching high efficiency values presents a key challenge within the realization of SSTs. The different options available to deal with this MV level will be covered in the next section as a final axis of the different modularization directions.

*3) Modularization in the Connection to the MV Level:* The last step in modularization of the SST is required in order to deal with the voltage levels encountered in this applications, which typically reach up to the tens of kilovolts. The current semiconductor technology does not provide single devices designed for these voltage levels. For this reason, advanced converter structures able to block these high voltages while operating at higher frequencies and reaching high efficiency levels become mandatory.

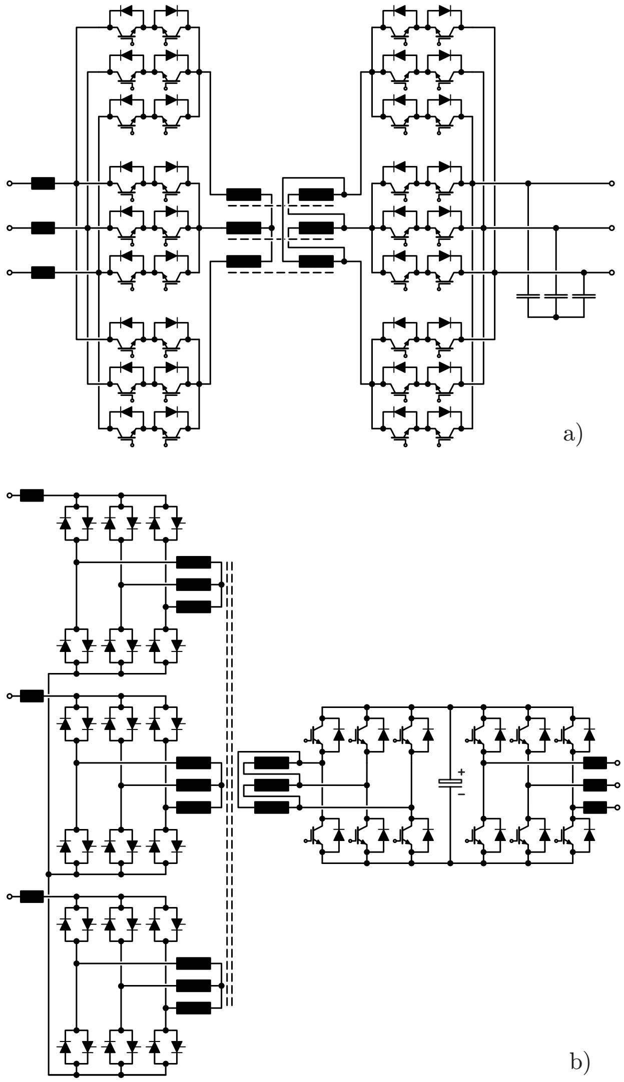


Figure 10: a) Direct matrix-type, 3-phase integrated MV- and LV-side LF interfaces and 3-phase high-frequency transformer with individual magnetic cores of the phases (cf. Fig. 9-c); b) Phase-modular MV-side and 3-phase integrated LV-side low-frequency interface and MV-side phase-modular 3-phase magnetically integrated high-frequency transformer (cf. Fig. 9-f).

Fig. 11 present the main options for modularization in the voltage direction. It should be noted that this modularization can be performed either on the DC or AC side of the converter in case a multi-stage solution is implemented. The first option, in Fig. 11-a) is a fully integrated solution, which comprises power semiconductor bridge legs of the type shown in Fig. 12-a). The MV-side voltage can be subdivided into lower voltage DC-links whereby the respective semiconductor devices are of the low-voltage class. The first of these options is shown in Fig. 11-b). This solution would result from an implementation of a bridge leg as shown in Fig. 12-b) on the MV AC side, whereby the independent stages of the DC-link voltage are available. In case the MV-side converter is built with a cascaded concept, as the bridge shown in Fig. 12-c), the structure shown in Fig. 11-c) is suitable. Here, the MV-side converter relies on a series connection in order to deal with the voltage level, while the LV-side is still constructed with a single bridge.

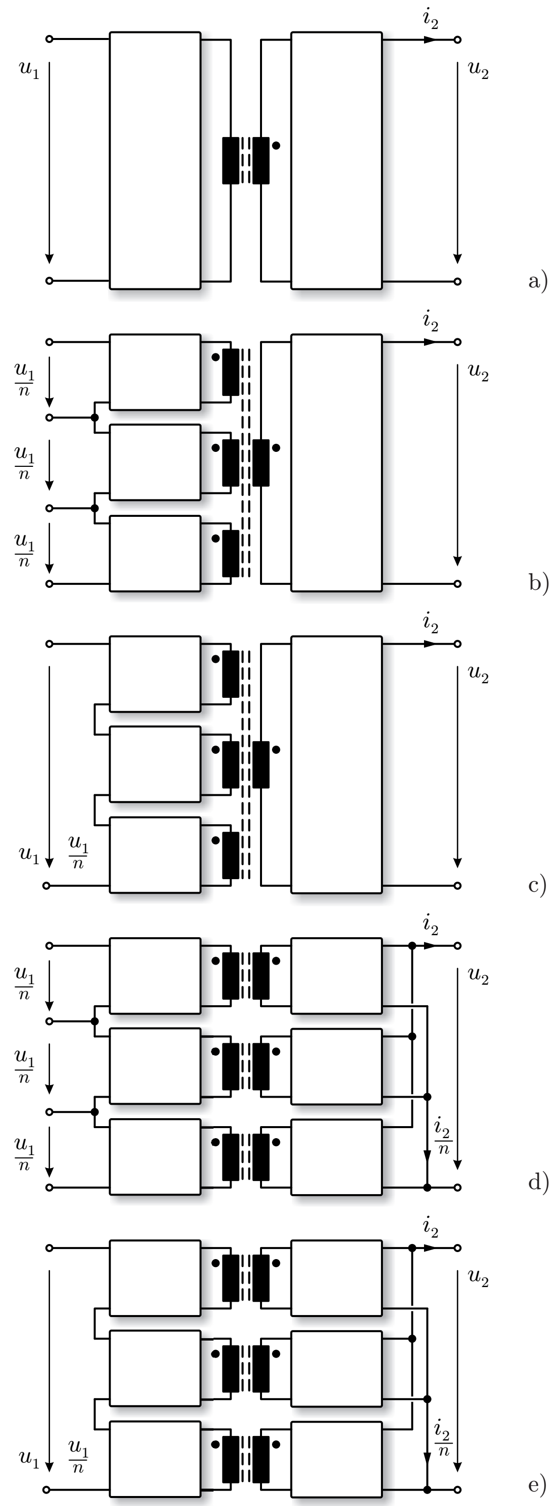


Figure 11: Modularization in voltage direction: a) Non-modular MV- and LV-sides; b) Modular series connected MV-side with access to intermediate levels and non-modular LV-side; c) Modular series connected MV-side with internal intermediate levels and non-modular LV-side; d) Modular series connected MV-side with access to intermediate levels and modular parallel connected LV-side; e) Modular series connected MV-side with independent intermediate levels and modular parallel connected LV-side.

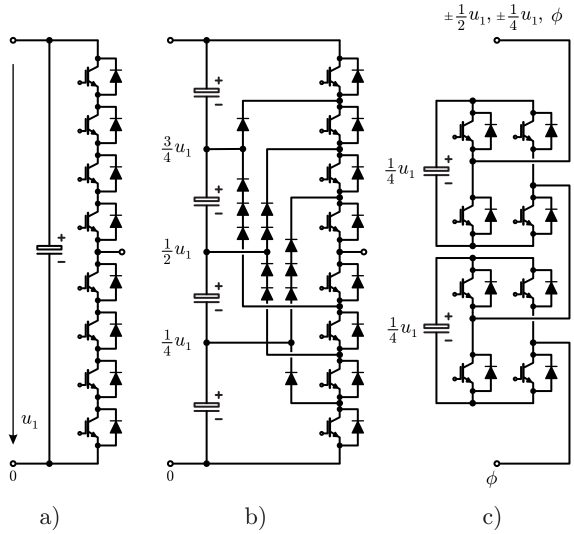


Figure 12: Bridge leg arrangements utilized to deal with the MV level: a) Series connection of devices; b) Series connection in multilevel (NPC) arrangement; c) Multicell arrangement.

The two fully-modular approaches, comprising series connection on the MV-side and parallel connection on the LV-side are presented in Fig. 11-d). Depending on the type of bridge leg arrangement utilized on the MV-side, the intermediate DC-link levels will be available, (cf. Fig. 11-d)) or unavailable (cf. Fig. 11-e)).

It is important to remark that the construction of the SST utilizing one of the aforementioned strategies is mandatory in order to deal with the MV level while reaching the high efficiency goals. This increased complexity brings new challenges in the construction of SSTs such as optimum number of series connected converter modules [43], common-mode currents, and mixed MV-DC and MF-AC electric field excitation of insulation materials [44]. This last topic is one of the keys for the successful deployment of SST technologies in the aforementioned application fields.

The numerous degrees of freedom for modularization available in the SST lead to a vast amount of possible arrangements depending on the different levels of modularization in the three discussed modularization axes: Degree of power conversion partitioning; Degree of phase modularity and number of levels or series connected cells. Since the level of modularity in each of these different directions is independent from each other, these three axes can be considered to be orthogonal to each other, enabling a representation as shown in Fig. 13. Here, each element represents a specific design with a certain degree of modularization in each of the axes.

For example, an element close to the origin would represent a low level of modularity in all axes, i.e. a direct matrix-type structure on the MV- and LV-sides without series connection in the MV-side and fully integrated 3-phase LF interfaces. On the other hand, an element distant from the origin would represent a highly modular structure, i.e. a multi-stage power conversion system with series connection of converter cells on the MV-side, parallel connection on the LV-side and independent modules interfacing to each of the three phases on both MV- and LV-side. In similar way, other concepts can be conceived,

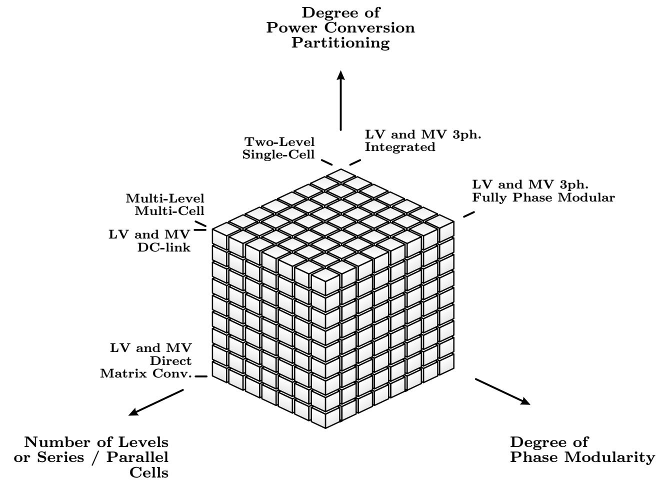


Figure 13: Graphical representation of the three main degrees of modularity of SST topologies: Degree of power conversion partitioning; Degree of Phase Modularity and Number of Levels or Series Connected Cells. Together these three modularity axes conform a fine mesh of options from which the SST can be constructed.

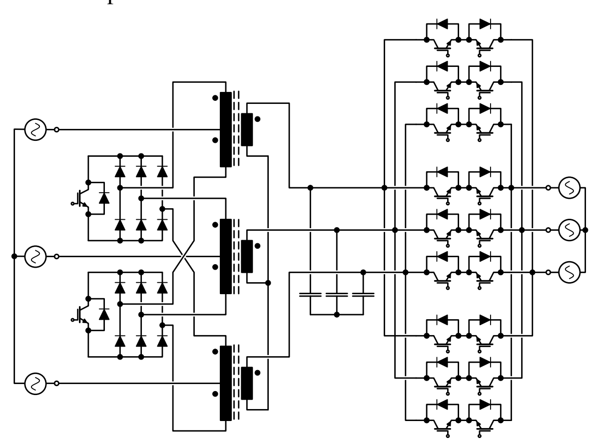

Figure 14: Front-end transformer high-frequency link concept with output matrix-type converter presented in [35].

with different levels of modularization in each of the different axes.

Fig. 13 qualitatively shows the vast amount of options available for the construction of SST for Smart-Grid applications. This classification based on level of modularity will be now utilized to describe the previously reported solutions for 3-phase AC-AC interfaces, most of which are also applicable in 1-phase systems, e.g. in traction solutions.

## IV. Previously Reported SST Structures

A number of concepts with various levels of modularity in the different aforementioned directions have been studied in previous research projects. In the following, a selection of these concepts which have been recently proposed will be briefly discussed together with their respective schematic representations.

Belonging to the front-end/matrix-type output stage category, the converter shown in Fig. 14 and discussed in detail in [35] achieves the high-frequency operation of the transformer by connection of a full-wave diode-rectifier to three independent center-taped transformers. An IGBT switch realizes the

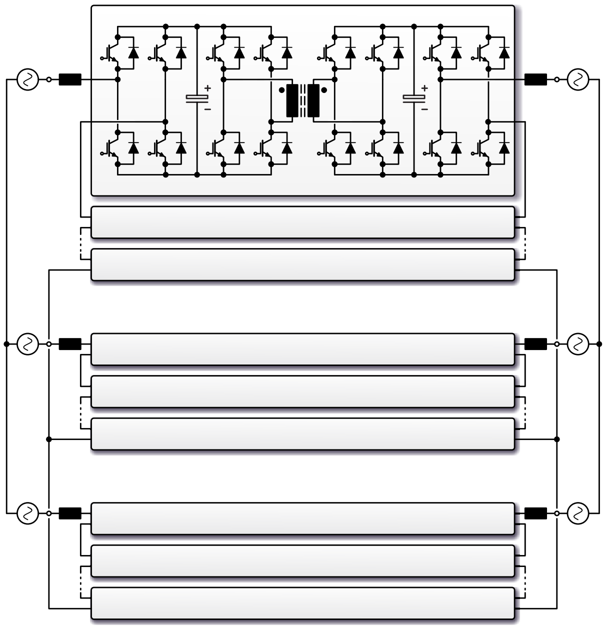

Figure 15: Fully-modular multicell structure as presented in [42].

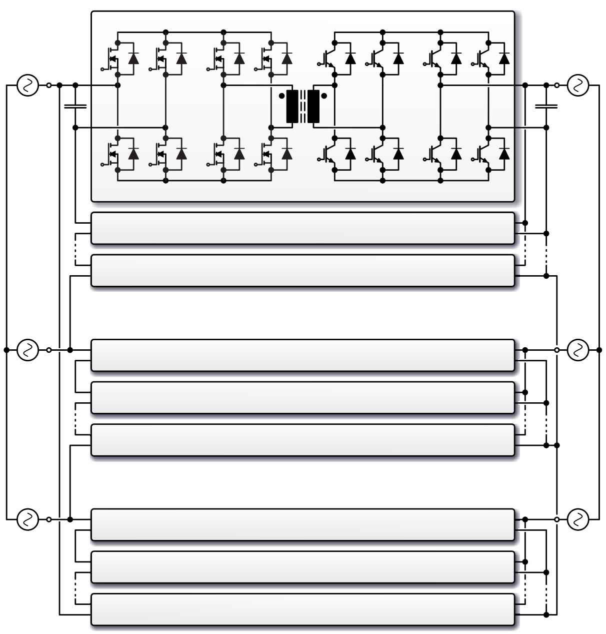

Figure 16: Indirect matrix-type, phase-modular multicell structure mentioned in [45].

connection of the star-point of these transformers at higher frequencies, thus selecting the polarity of the voltage applied to the secondary of the transformer by turning the upper or lower IGBT on. On the secondary side, a direct matrix type converter links the converter to the LV-side low-frequency grid.

A structure comprising full modularity in the power flow direction, phase modularity and series connection of cells is presented in Fig. 15. This fully-modular arrangement subdivides the complete complex converter structure into standardized units, which allows to independently design and optimize the different converter modules.

An advanced SST structure utilizing SiC devices on the MV-side was mentioned in [45] and is depicted in Fig. 16.

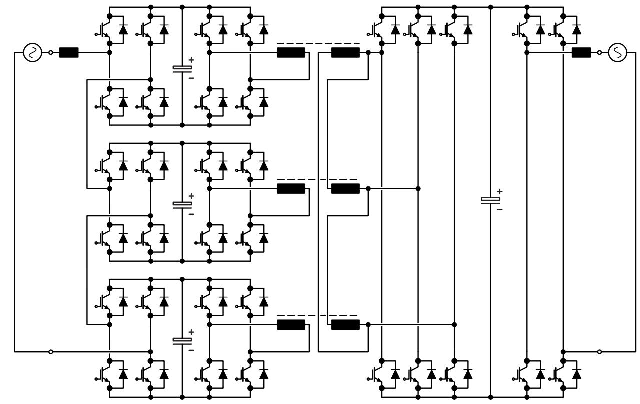

Figure 17: DC-link converter based SST, with MF side phase-modular, magnetically independent 3-phase transformer and 3-phase integrated (transformer and converter) LV-side, presented in [46].

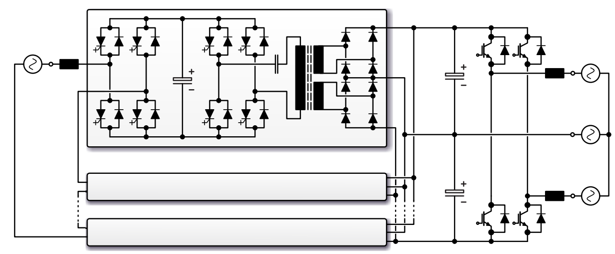

Figure 18: Unidirectional SST with DC-link-based cascaded and phase-modular MV-side and 3-phase integrated LV-side; independent 1-phase transformers of the individual cells with parallel connected secondary side rectifier stages [47]; representation of MV-side limited to one phase.

This converter implements an indirect matrix-type conversion in the MV- and LV-sides. Additionally, as can be seen, full modularity in the 3-phase connection and in the cascading of converter cells is performed in order to deal with the selected voltage levels.

Fig. 17 presents a phase-modular concept with MV-side cascaded cells and magnetically independent transformers with electrically integrated 3-phase LV-side high- and low-frequency AC connections. Given the lower voltage level on the LV-side, this structure relies on the availability of single power semiconductor devices in this voltage range, which simplifies the construction of the LV-side power electronic bridges.

In order to deal with higher voltages while keeping a low component count, the concept presented in Fig. 18 and proposed in [47] utilizes gate-turn-off devices on the MV-side. These semiconductor devices, however, are characterized by slow switching performance, which compromise the flexibility on the selection of the transformer's operating frequency. Additionally, this DC-link based structure is constructed with a series connection at the MV-side and a 3-phase integrated LV-side concept.

Structures with unidirectional power transfer capability have also been proposed, as is the case for the converter in Fig. 19 which was presented in [48]. This converter is characterized by a multicell boost-type input stage based on a full-wave diode rectifier. The boost converters are arranged into modules whereby their isolated DC sides are connected in parallel and feeding a 3-phase two-level inverter linked to the

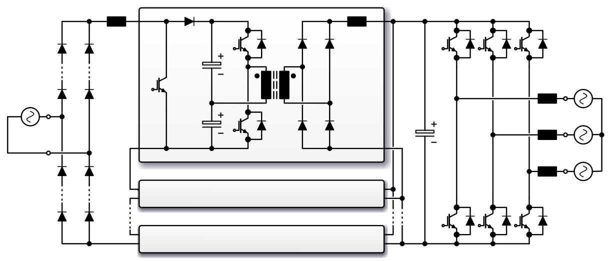

Figure 19: Unidirectional SST with single diode bridge rectifier input stage with series connected diodes and following multi-cell current shaping and isolation stage with parallel connected output rectifiers supplying the DC link of a 3-phase integrated LV-side mains interface, as presented in [48]; representation of MV-side limited to one phase.

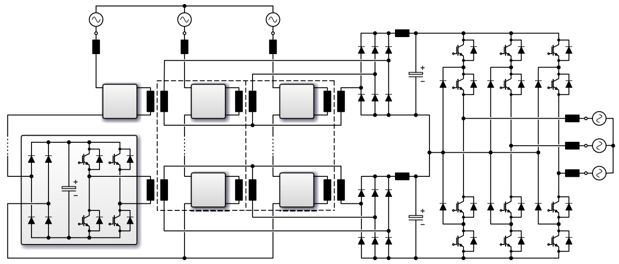

Figure 20: DC-link three-stage converter with cascaded MV-side arrangement and integrated 3-phase LV-side. The transformer consists on a 3-phase magnetically integrated construction, as presented in [49].

LV-side network. It should be noted that this unidirectional structure reduces considerably the complexity of the system when compared to the discussed fully bidirectional structures.

The magnetic integration of a 3-phase transformer results attractive due to the potential reduction of required magnetic core material. This is the case for the concept proposed in [49] and shown in Fig. 20. This modular arrangement connects to the MV-side through a series connection of modules, i.e. a multicell structure. Each of the MV-side modules feeds an individual winding of a 3-phase/magnetically-integrated transformer. On the LV-side, two full-wave diode bridges feed two series connected DC-links which form part of a multilevel NPC structure utilized to link to the LV grid with a 3-phase integrated bridge.

Similar to the previous concept, the MV-side modules can be replaced by matrix-type bridges in order to eliminate

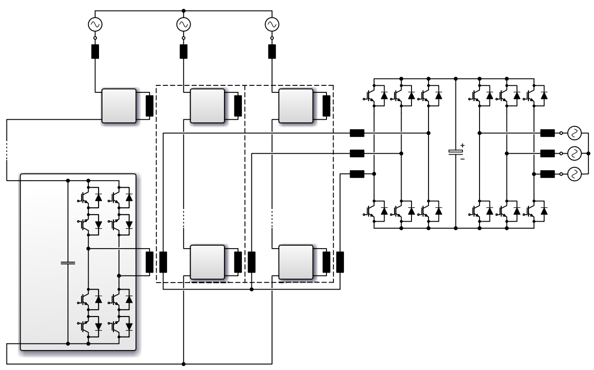

Figure 21: MV-side direct matrix-type converter with cascaded MV-side arrangement, integrated 3-phase LV-side and magnetically integrated 3-phase transformer [50].

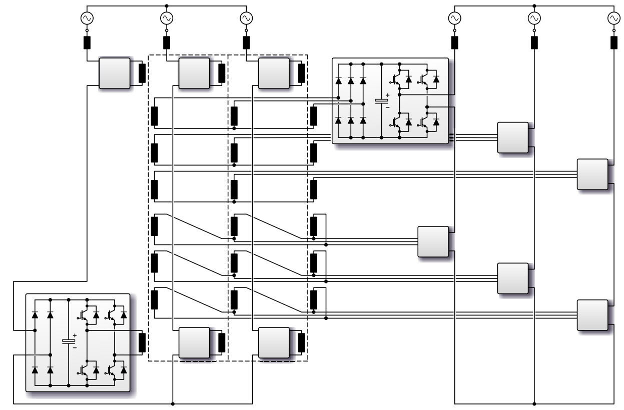

Figure 22: DC-link-based modular cascaded MV- and LV-side with 3-phase magnetically integrated 3-phase high-frequency link [51].

one conversion stage, as presented in Fig. 21 and studied in [50]. Here, at the input side, four-quadrant switches in H-bridge configuration are utilized to feed a 3-phase magnetically integrated transformer with high-frequency excitation. A single 3-phase secondary winding linked to a 3-phase integrated bridge which supplies a DC-link connected to a two level inverter linked to the LV-side grid.

Another type of three-stage, phase-modular and multicell arrangement with magnetically integrated 3-phase transformer is presented in Fig. 22. This structure, proposed in [51] utilizes a multiwinding transformer with combination of star and delta connections on the secondary sides. It should be noted however, that the magnetic integration of the 3-phase transformer results in a complex magnetic circuit, where the coupling between the different transformer windings must be carefully accounted for.

A highly modular structure able to interface three 3-phase grids is presented in Fig. 23. This structure was developed in a large scale European project [52] studying flexible AC conversion systems for future electric power distribution. The core component in this arrangement is a back-to-back full-bridge-based module which interfaces on the one side the LF grid and on the other side performs the high-frequency switching which feeds the isolation transformer. As can be seen, this converter structure is realized with full modularity in all aforementioned directions.

The converter presented in Fig. 24, denoted as MEGALink [53] is based on a series multicell connection at the MV-side and DC-link based power conversion chains on the MV- and LV-side. On the LV-side, two parallel 3-phase integrated two-level bridges are utilized in order to link to the 3-phase grid. The DC-DC stages consist of a series resonant structure and are parallel connected on the LV-side, where they are linked to the aforementioned two-level inverters.

The converter shown in Fig. 25 realizes the link to the MV-side grid with a multilevel NPC-based arrangement comprising SiC semiconductor devices [54, 55]. The high-frequency conversion is performed by a 3-phase magnetically integrated transformer with two secondary windings connected in star and delta respectively. Active rectifiers transform this high frequency waveforms from the transformer's secondary to a single LV DC-link feeding a two-level, 3-phase integrated bridge linked to the LV-side grid.

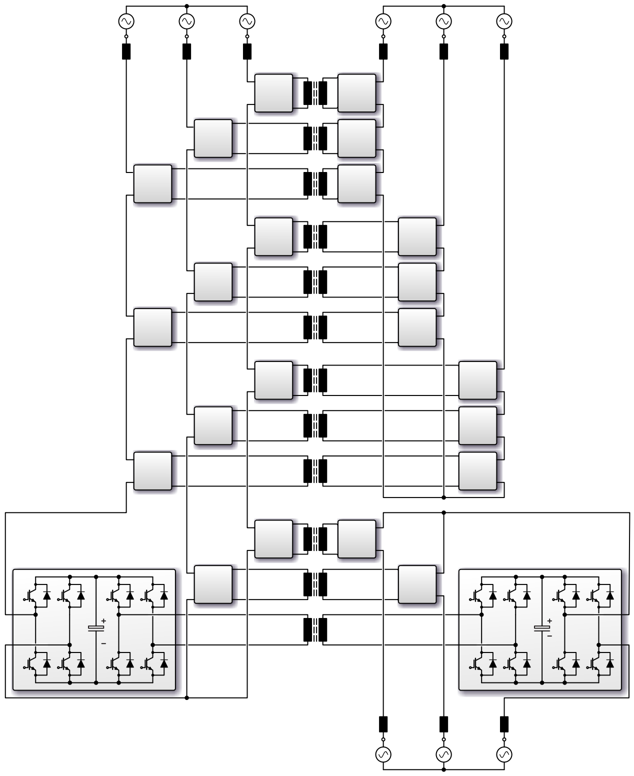

Figure 23: Fully phase-modular arrangement with cascaded input and output sides, independent 1-phase transformers and additional 3-phase output [52].

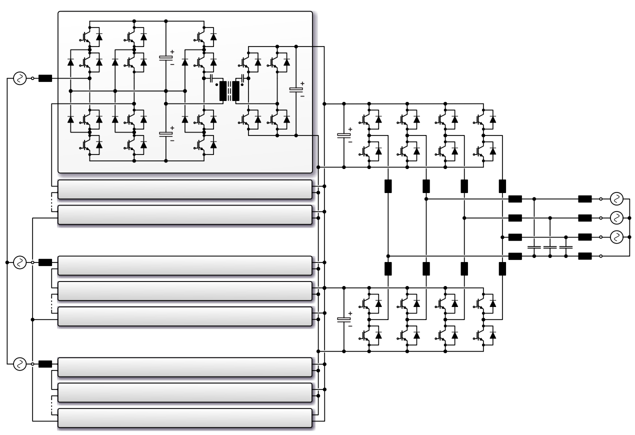

Figure 24: SST with DC-link-based cascaded and phase-modular MV-side where the converter cell DC links are connected to DC-DC converter stages comprising 1-phase transformers; the transformer secondary windings are connected via individual rectifier stages in parallel to the DC link of the LV 3-phase integrated inverter stage interfacing to the LF 3-phase grid [53].

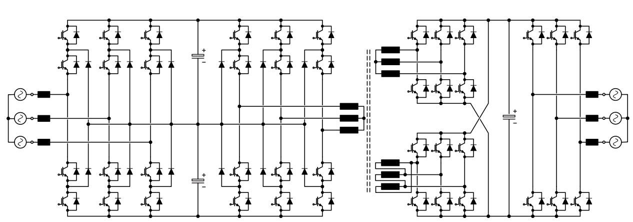

Figure 25: Three-stage DC-link based approach with integrated MV- and LV-side 3-phase arrangement and integrated 3-phase high-frequency AC link [54, 55].

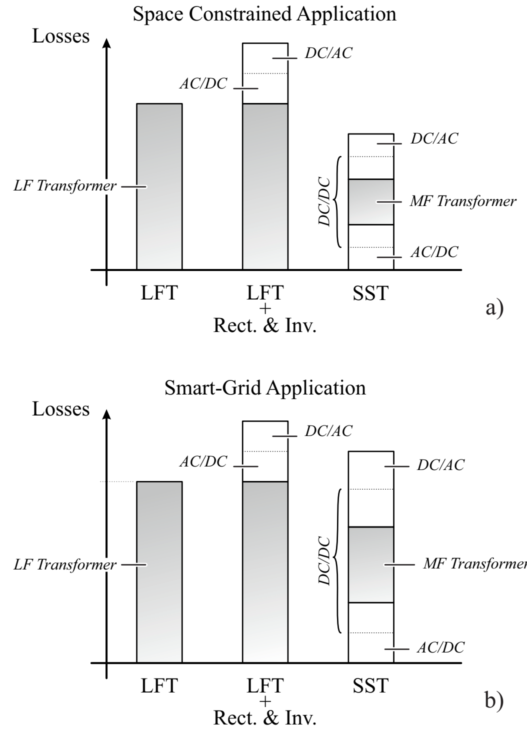


Figure 26: Schematic breakdown of losses for the standard LFT-based and the SST-based solution for a) traction and b) Smart-Grid application.

## V. Conclusions / Outlook

SST technology enables the direct connection of power electronic converters to MV networks while realizing the task of isolation and voltage adaptation, e.g. within an isolated DC-DC converter. The availability of power electronic circuits on the front and load end of the system allows a complete control of the power flow, enabling a transfer of energy with high power-quality level. Moreover, the availability of intermediate DC levels offers the possibility to connect DC loads/sources to the system, e.g. facilitating the integration of renewable sources.

This increase in functionality, however, must be weighted against the increased losses due to the introduction of new conversion stages into the supply chain. In case of space constrained applications, where a high power-density level is mandatory, the reduction in losses achieved by the operation of the transformer with MF results in an overall system loss reduction, as shown qualitatively in Fig. 26-a). In Smart-Grid applications, where the space limitation is not as critical as in e.g. traction applications, the introduction of additional conversion stages of the SST results in an increase in overall losses with respect to the state-of-the-art LFT transformer-based system, as presented in Fig. 26-b). In this context, modern semiconductor technologies such as silicon-carbide represents an attractive option, as it would enable a significant overall system loss reduction.

Nevertheless, as stated earlier, the increase in losses of Smart-Grid-oriented SSTs with respect to LFTs represents the price for the increased functionality in the system. Among these, the availability of a DC port has to be highlighted due to the continuous trend towards renewable energy integration and general implementation of DC-microgrids. In order to more

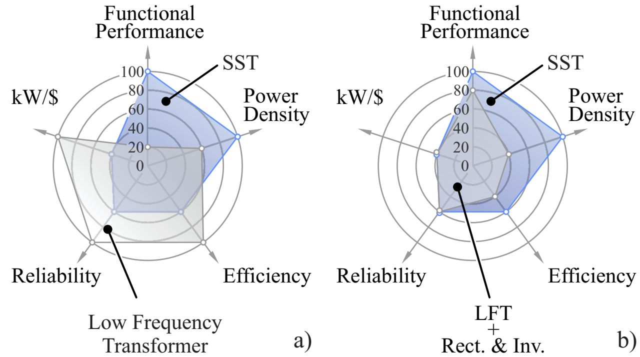


Figure 27: Challenges in SSTs for Smart-Grid applications. The higher reached functionality with respect to a LFT (cf. a)) has mainly the price of lower reliability, lower efficiency and higher costs. When compared to an equally functional system comprising a LFT and a back-to-back rectifier/inverter stage in b) the SST offers superior power density and efficiency performance.

clearly visualize the different performance improvements provided by SST technology in Smart-Grid applications, Figs. 27-a) and b) show the performance space of SSTs against LFT technology and LFT with series-connected rectifier-inverter stage, respectively. When compared to LFTs, SSTs offer a significant increase in functionality and power density. However, efficiency, reliability and costs will be impaired due to the large amount of switching devices required in the system. With respect to the straightforward solution represented by a LFT coupled to a rectifier-inverter stage, the SST offers a significant improvement in power density and efficiency with a comparable cost level, rendering this solution very attractive for Smart-Grid applications.

The shift of focus in modern energy supply solutions towards higher levels of functionality must be accompanied by strong efforts towards higher reliability, which should ideally be competitive with LFT transformer technology. Fulfilling this high reliability standard while reaching high efficiencies is critical for the successful deployment of SST technologies in traction and Smart-Grid applications.

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