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Applicability of Solid-State Transformers in Today's and Future Distribution Grids

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Applicability of Solid-State Transformers in Today's and Future Distribution Grids

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***Abstract*—Solid-state transformers (SSTs) are power electronic converters that provide isolation between a medium-voltage and a low-voltage (LV) system using medium-frequency transformers. The power electronic stages enable full-range control of the terminal voltages and currents and hence of the active and reactive power flows. Thus, SSTs are envisioned as key components of a smart grid. Various SST concepts have been proposed and analyzed in literature concerning technical aspects. However, several issues could potentially limit the applicability of SSTs in distribution grids. Therefore, this paper discusses four essential challenges in detail. It is found that SSTs are less efficient than low-frequency transformers (LFTs), yet their prospective prices are significantly higher. Furthermore, SSTs are not compatible with the protection schemes employed in today's LV grids, i. e., they are not drop-in replacements for LFTs. The limited voltage control range typically required in distribution grids can be provided by competing solutions, which do not involve power electronics (e. g., LFTs with tap changers), or by hybrid transformers, where the comparably inefficient power electronic stage processes only a fraction of the total power. Finally, potential application scenarios of SSTs (AC-DC, DC-DC, weight/space limited applications) are discussed. All considerations are distilled into an applicability flowchart for SST technology.**

***Index Terms*—Solid-state transformers, hybrid transformers, distribution grid, smart grid**

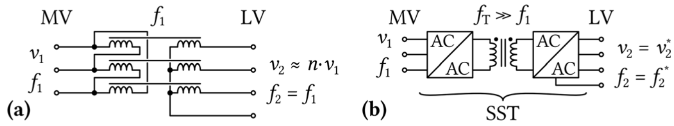

Fig. 1. Overview schematics (a) of a typical delta-wye-connected low-frequency distribution transformer (LFT), and (b) of a solid-state transformer (SST).

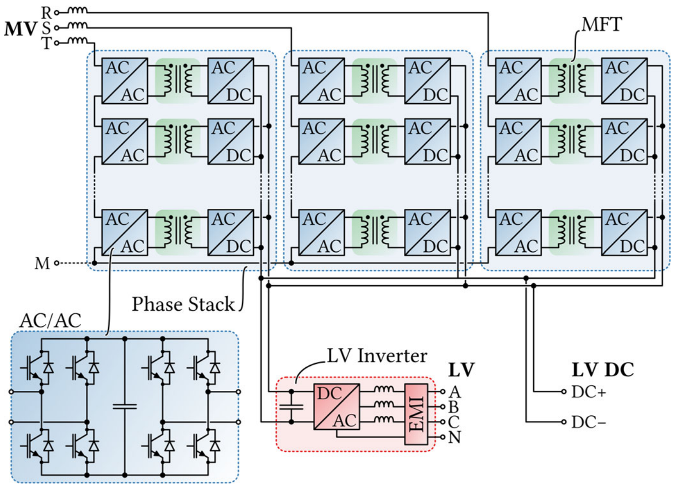

Fig. 2. Typical topology of an MV/LV SST emplyoing a cascaded converter structure on the MV side in order to handle the high voltage levels. Note that the AC-AC stages at the cascaded cells' MV sides can feature a local DC link (AC-DC-AC-structure as shown in the figure) or be of a matrix-type (direct AC-AC conversion).

I. Introduction

A solid-state transformer (SST)—also known as Electronic Transformer, Power Electronic Transformer, Smart Transformer, Energy Router, etc.—is a power electronic interface between a medium-voltage (MV) system and a low-voltage (LV) system, which provides galvanic isolation by means of medium-frequency (MF) transformers (MFTs) [1]. In contrast to a conventional low-frequency (LF) transformer (LFT), the power electronic converter stages of the SST enable full-range control of the terminal voltages and currents and hence of the active and reactive power flows. Fig. 1 illustrates this schematically.

Fig. 2 shows a typical example (cf., e. g., [2], [3], [4], etc.) of a three-phase SST, where the MVAC-LVDC conversion stage is realized as an input-series output-parallel (ISOP) configuration of converter cells, which comprise the MF isolation transformers. Since the blocking voltage of readily available silicon power semiconductors is limited to 6.5 kV and silicon carbide (SiC) devices with higher blocking voltages are still only in a prototype state, such an ISOP configuration is required in order to employ LV power semiconductors for interfacing the MV system. Furthermore, series-interleaved operation of the cascaded converter cell's input stages allows to generate a multilevel AC voltage on the SST's MV side, which reduces the required filtering effort to maintain limits on total harmonic distortion (THD) of the grid currents, etc. A detailed analysis of such cascaded cells converter systems is given in [2], where realizations based on power semiconductors with blocking voltages of 1200 V or 1700 V have been identified to yield optimum results in terms of efficiency and power density.

Even though an "electronic transformer" had first been proposed already in the early 1970s [5], the concept was seriously considered for traction applications only starting around the turn of the millennium [7]–[10]. Since the allowable weight and volume of a traction transformer is limited, traction LFTs tend to be quite inefficient (typically around 90 %) as a result of the high current densities required to realize high power densities. This creates a motivation for the application of SSTs, where the operating frequency of the transformer offers another degree of freedom to reduce volume and weight. Thereby, and despite introducing power electronic converter stages, a significant increase of the overall efficiency can

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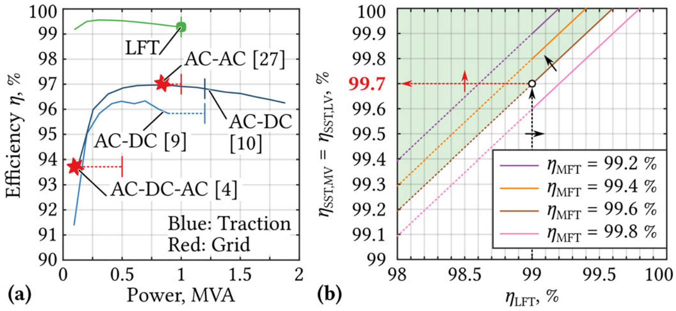

Fig. 3. (a) Efficiency curve of a 1000 kVA LFT and available efficiency data of four industrial SST prototypes (the vertical bars indicate the rated power; the published efficiency measurements are not always for rated power); (b) conversion efficiency challenge for AC-AC SSTs: the power electronic stages require extreme efficiencies in order to realize an SST with an overall efficiency comparable to an LFT's. The shading highlights that the lines are lower bounds of the required efficiencies.

be realized, as has recently been demonstrated by industrial hardware demonstrators, one of them even mounted on an actual locomotive [9].

With the first consideration on a future "smart grid" around the year 2000 [11], SSTs were also considered for applications in the distribution grid because of their high degree of controllability (voltages, currents, power flows, etc.) [11]–[15]. Up to know, several research projects have been or are dedicated to SSTs for grid applications [16]–[23], i. e., the *technical* feasibility has been demonstrated multiple times. Whereas [24] provides a review of envisioned SST applications in the distribution grid, a first direct comparison of a 1000 kVA SST against an LFT in terms of volume, weight, costs, and losses [3] revealed significantly higher losses and material costs of the AC-AC SST, as well as only a minor reduction of volume and weight. Considering also potential future MVAC-LVDC applications, these concerns were less pronounced. However, a full assessment of the applicability of SSTs in the distribution grid is largely missing.

The aim of this paper is thus to discuss four fundamental challenges that may hinder the successful application of SSTs in the distribution grid for the foreseeable future, especially as direct replacements for conventional LFTs: the conversion efficiency challenge (Section II), the cost challenge (Section III), the compatibility challenge (Section IV), and the competing approaches challenge (Section V). Nevertheless, potential application scenarios exist, which are discussed in Section VI. In order to support a decision process, finally an applicability flowchart for SSTs based on the considerations made throughout the paper is proposed.

II. Conversion Efficiency Challenge

The main task of LFTs in distribution grids is to provide galvanic separation and voltage scaling, ideally with very low losses. Thus, the efficiencies of typical oil-filled 1000 kVA LFTs are well above 99 % for most of the load range (cf. Fig. 3a) according to [25]; considering other manufacturers yields similar results.

In contrast to an LFT, an AC-AC SST contains—in addition to the actual MF transformer—two AC-AC converter stages, i. e., an LF to MF AC-AC converter and an MF to LF AC-AC converter stage: one on the MV and one on the LV side (cf. Fig. 1). Considering given efficiencies of the LFT and MFT and assuming equal efficiencies of the two AC-AC converter stages (i. e., $\eta_{\mathrm{SST,MV}} = \eta_{\mathrm{SST,LV}}$, and $\eta_{\mathrm{SST}} = \eta_{\mathrm{SST,MV}} \cdot \eta_{\mathrm{MFT}} \cdot \eta_{\mathrm{SST,LV}}$),

$$\eta_{\mathrm{SST,MV}} = \eta_{\mathrm{SST,LV}} = \sqrt{\frac{\eta_{\mathrm{LFT}}}{\eta_{\mathrm{MFT}}}} \quad (1)$$

describes the required efficiencies of the AC-AC stages in order to achieve an overall efficiency of the SST that is equal to that of an LFT, η_{LFT}, i. e., $\eta_{\mathrm{SST}} = \eta_{\mathrm{LFT}}$. Fig. 3b shows this relation considering different efficiencies of the MFT. This efficiency depends on the selection of an optimum switching frequency [26], and also on the utilization of the active materials, i. e., its size. It should be noted that possibly a lower utilization and hence a higher efficiency could be permissible for MFTs than for LFTs, because the absolute material usage and hence costs are lower. Nevertheless, Fig. 3b clearly illustrates the conversion efficiency challenge: even with a highly efficient MFT with $\eta_{\mathrm{MFT}} = 99.6\,\%$, achieving an overall MV to LV efficiency of 99 % requires the efficiency of each of the two AC-AC conversion stages to be *at least* 99.7 %. This is an extremely high value and clearly out of reach for today's high-power converters and likely also not achievable in the foreseeable future.

To illustrate this, the available efficiency data of four industrial SST prototype systems is shown in Fig. 3a in comparison to the already mentioned efficiency curve of a 1000 kVA LFT. The two blue curves are for traction SSTs rated at 1.2 MVA, i. e., for AC-DC conversion only (!), and achieve peak efficiencies of about 96 % [9] and 97 % [10], respectively. The light load efficiency is lower due to load-independent loss contributions such as semiconductor switching losses or core losses of the magnetic components. Regarding grid applications, a 500 kVA AC-DC-AC SST with a structure similar to that shown in Fig. 2 achieves a measured efficiency of about 93.6 % (not at rated power) [4]. Furthermore, a 1 MVA matrix-type direct AC-AC SST using latest 15 kV SiC technology achieves a peak efficiency of around 97 % [27]. Even though these differences of the efficiencies of SSTs and LFTs may seem minor: in terms of losses, the best industrial SST systems realized so far are generating about 3. . . 6 times higher losses than a comparable LFT. To narrow this gap is an extremely challenging undertaking, especially considering the related higher realization effort and therefore costs.

III. Cost Challenge

LFTs are off-the-shelve products, whose specific (selling) price is in the range of $c_{\mathrm{LFT}} = 10\,\$/\mathrm{kVA} \ldots 25\,\$/\mathrm{kVA}$ for 1000 kVA units according to [28] and pricing information obtained from a major European transformer manufacturer. Of course, prices may vary depending on the optimization target, e. g., low losses or low cost, etc.

Currently, so far there are no SST products that would allow a direct comparison of prices. Therefore, [3] estimates material costs of a 1000 kVA SST, which are found to be at least 5 times higher than those of an equally rated LFT. The price of a product, however, is not necessarily closely related to material costs, since other contributions such as compensation of development costs, labor costs of manufacturing, shares of infrastructure costs, and profits, etc. may be significant. Thus, here the price of an SST is best estimated based on prices of readily available high power converter systems.

Specifically, the LV inverter of an SST as shown in Fig. 2 is essentially the equivalent of an active front end (AFE) converter of a high-power drive, e. g. from Schneider Electric's Altivar 61 series [29]. Pricing information for these converters is available [30] and indicates specific list prices of about $c_{\mathrm{SST,LV}} = 125\,\$/\mathrm{kVA}$ for a 1000 kVA unit. Furthermore, [31] gives a range of 100 €/kVA…120 €/kVA (114 \$/kVA…137 \$/kVA) for prices of utility-scale (500 kVA) PV inverters.

Considering the comparably higher complexity of the MV side converter part (cf. Fig. 2), which not only needs to interface to MV but contains also the MF isolation stage, it is conservative to assume that the specific price of the MV side converter is at least as high as that of the LV side converter, i. e., $c_{\mathrm{SST,MV}} \geq c_{\mathrm{SST,LV}}$. Then, as is shown in Fig. 4a, the prospective *price* of an AC-AC SST is *at least* 10 to 25 times higher than that of an equally rated LFT. Even if a significant discount on the list prices of, e. g., 50 %, would be possible, the price of an AC-AC SST would still be at least 5 times higher than that of an LFT. It should be noted that these figures are not even considering possibly high initial development costs of SSTs, because such AFE converters are standard products today.

Analyzing the price structure in more detail, it turns out that the estimated material *costs* from [3] for such an AFE converter account for only a comparably small fraction of the price, as is illustrated in Fig. 4b. Thus, the influence of possible future reductions of commodity prices, e. g., for power semiconductors or inductive components, may not have a significant impact on the prices of high-power converters.

As discussed in the previous section, the efficiency of an AC-AC SST is lower than that of an LFT, which corresponds to higher losses and hence higher operating costs. This and the significantly higher procurement price cause a total cost of ownership (TCO) consideration to clearly favor an LFT over an SST. This is especially true considering that the typical lifetime of an LFT is around 30 years, whereas typical lifetimes of power electronic converters are in the range of 10 years only.

On the other hand, SSTs provide much higher functionality than an LFT, such as reactive power compensation etc. Whereas there are many publications mentioning positive system-level impacts of such added functionality, only very few studies provide a corresponding quantitative analysis. The authors of [22] carried out load flow simulations using a validated model of a suburban LV grid in Switzerland to analyze potential benefits of replacing LFTs with SSTs. Whereas they confirm that SSTs can stabilize voltage levels, etc., they conclude that SST technology cannot compete with LFT technology based on these advantages alone. In [23], an SST model for load flow studies is introduced and several case studies are presented, where LFTs are replaced with

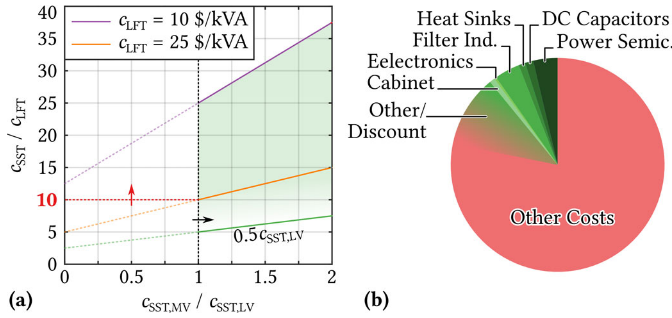

Fig. 4. (a) Cost challenge for AC-AC SSTs: the price of a 1000 kVA AC-AC SST is at least 5 to 10 times higher than that of an equally rated LFT; (b) comparison of estimated material costs (main components) of a 500 kVA LV inverter [3] with list price information from [30].

SSTs. The authors identify the comparably low efficiency of SSTs as a major limitation, and they conclude that total energy losses over time, i. e., losses in the LFTs and/or SSTs plus losses in the MV and LV grids, can typically not be improved by replacing LFTs with SSTs. Since these two studies have been published only recently, it seems that the need for quantification of the system-level impact of SSTs has finally triggered corresponding research endeavours.

Note further that even though an SST provides much higher functionality, this may not be required in all aspects or there might be competing approaches that can achieve similar performance with higher efficiency and/or less realization effort (cf. Section V). Furthermore, an AC-AC SST is not directly compatible with the existing LV grid infrastructure, especially regarding the installed protection concepts, as will be described in the next section.

IV. Compatibility Challenge

Typically, the protection of LV grids against short circuits is based on fuses and/or circuit breakers, which have a configurable triggering characteristic. Selectivity is an important aspect of this protection scheme: when a fault occurs, only the closest upstream protection device should trigger in order to contain the effects of a fault in a as small section of the grid as possible. Fig. 5a shows a (simplified) example of a hierarchically organized LV grid with its protection devices. In order to realize selectivity, the rated currents of the fuses is low close to end customers and higher closer to the feeding transformer. Fig. 5b shows melting time vs. current characteristics of typical LV fuses [32], which illustrates that for a given short circuit current, a fuse with a lower rated current trips before a fuse with a higher current rating.

Fig. 5b indicates also the rated current $I_{\mathrm{N}} = 1440\,\mathrm{A}$ of a 1000 kVA transformer: even to trigger a comparably small 250 A fuse, which may protect a cable or a load on a lower hierarchical level of the LV grid (i. e., further away from the feeding transformer), within a reasonable time (i. e., less than one second), a current of about $1.5 I_{\mathrm{N}}$ is required. For fuses with higher rated current, i. e., on a higher hierarchical level of the LV grid and hence typically closer to the feeding transformer, the required short circuit current quickly reaches multiples of the rated current. This is especially also the

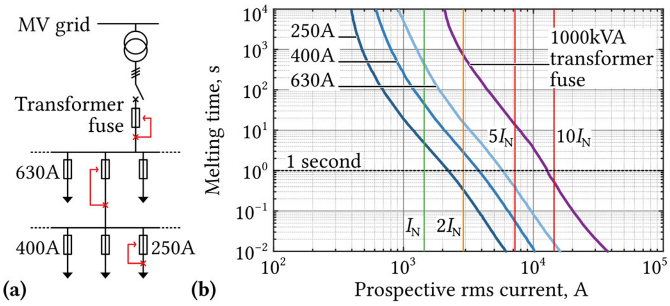

Fig. 5. (a) Exemplary LV grid structure with fuses at different branching levels and indicated selectivity; (b) melting time vs. current characteristics of LV fuses with different rated currents and a fuse for a 1000 kVA transformer in comparison to the nominal current and its multiples of a 1000 kVA SST or LFT—even breaking a comparably “small” 250 A fuse within 1 s requires about 50 % overcurrent from the SST.

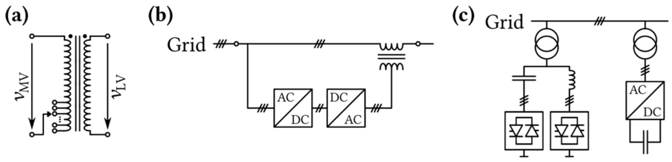

Fig. 6. Example of competing approaches to realize the required controllability in the distribution grid: (a) voltage regulation distribution transformer (VRDT), (b) active series voltage regulator, and (c) static VAr compensators (STATCOM).

case for the transformer protection fuses, which are located closest to the transformers. This short circuit current has to be supplied by the transformers at the interface to the MV grid. LFTs are supposed to deliver up to 25 times their rated current for at least two seconds [33]. In contrast, this is obviously not possible for a power electronic system without a significant overrating of the power devices, because the thermal time constants of the power semiconductor chips are in the order of 10. . . 50 milliseconds only; furthermore, a correspondingly high saturation limit of the filter inductors would be required [34].

On the other hand, an SST could limit short circuit currents. In order to utilize this interesting feature, however, advanced protection concepts would be required. Such advanced protection concepts typically involve communication between the SST and breakers and/or other switching devices in the grid [19], [35], [36].

In summary, the existing protection infrastructure could not be utilized anymore, which contributes to the notion that an SST cannot be seen as a direct replacement for an LFT in the distribution grid. In contrast, an SST essentially requires a grid environment that is adapted to the specific characteristics of an SST, e. g., by providing communication among protection relays. Such adaptions are not easy to implement in existing distribution grids, though, and would be associated with significant costs.

Furthermore, as is comprehensively discussed in [34], the protection of an SST in an existing grid environment, e. g., against overvoltages on the MV AC side caused by lightning strikes or switching actions, but also against short circuits in the MV or LV grid, is in general highly challenging, and might impose significant constraints on the design of an SST, e. g., by requiring minimum values for filter inductances or DC link capacitors. This, in turn, limits the possibilities of reducing raw material usage by means of employing more advanced power semiconductors that allow for higher switching frequencies.

V. Competing Approaches Challenge

As discussed in the previous sections, an SST is not well suited to directly replace an LFT. However, an SST can provide more functionality in addition to isolation and voltage scaling, e. g., reactive power compensation, active filtering, etc., because of its ability to *fully* control its terminal voltages and currents.

There clearly is a need for controllability in the distribution grid, e. g., to cope with changed voltage profiles along feeders as a consequence of power flow reversals caused by renewable energy sources connected to the LV grid [37]. However, a variety of approaches to provide the *required* amount of controllability already exists. In contrast to an SST, these solutions do not require that the entire power flow is processed by a conversion stage with a comparably low efficiency. A few of these approaches are briefly discussed in the following to give an impression of the competition the SST concept faces also with respect to its major selling point, i. e., its full-range controllability.

A. *Examples of Competing Technologies*

The voltage in the MV and LV distribution grids must be within a tolerance band of $\pm 10\,\%$ around the nominal value [38]. Since most power systems are traditionally designed for a power flow from sources on higher voltage levels to loads on lower voltages levels, the injection of significant power by renewable energy sources in the LV grid may increase the voltage levels at the end of a feeder above the upper tolerance band limit. An SST, of course, could dynamically adapt the MV-LV transformer's terminal voltage such that the voltage stays within the tolerance band. However, the same can be achieved by extending an LFT with automatic on-load tap changers. Such an arrangement is known as a voltage regulation distribution transformer (VRDT) [37], and conceptually shown in Fig. 6a. VRDTs are readily available industrial products, cf. e. g., [39], which can adjust the LFT's turns ratio in 10. . . 20 steps by means of the tap changers—however, without compromising the robustness nor the high efficiency of the LFT. Since the cost of such mechanical on-load tap-changers can be considerable (up to 40 % of the LFT's price according to information from industry), also electronic tap-changers are being considered, where the taps are contacted by means of thyristors instead of mechanical switches [40]. This results in lower procurement costs, however, in higher losses.

Similarly, distribution voltage regulators (e. g., [41]) can be deployed along a feeder, e. g., close to a large renewable power source, where they can inject a compensating series voltage by means of an auto-transformer and a mechanical tap-changing system. In case a more dynamic controllability is required, e. g., to protect sensitive loads from grid disturbances, active series voltage regulators (e. g., [42]) are available as industrial products. These are power electronic converters that can inject a series voltage with high dynamics into the power line by means of an injection transformer (cf. Fig. 6b), achieving high efficiencies above 99 % [42]. Active series voltage regulators can provide, e. g., fast correction of voltage sags, active filtering of harmonics or reactive power compensation.

Reactive power compensation can be provided by static VAr compensation systems, which are essentially shunt inductor or capacitor banks that can be switched by mechanical or thyristor switches, or in order to achieve a more granular control of the reactive current, the thyristors can be operated using firing delay-angle control [43]. Alternatively, three-phase AC-DC converters without a DC-side energy supply (which is not required since reactive power compensation is essentially moving instantaneous power between the phases [44]) can be employed [45]. These so-called STATCOMs feature much faster dynamics compared to the static VAr compensation systems mentioned above [43], i. e., a higher degree of controllability, which allows to compensate also, e. g., voltage harmonics, flicker, etc.

All of these competing approaches either do not employ power electronics at all, or if they do, the power electronic stages are only processing a fraction of the total power—an approach that is sufficient to provide the *required* controllability, but does not suffer from the high losses or the extreme costs of an SST.

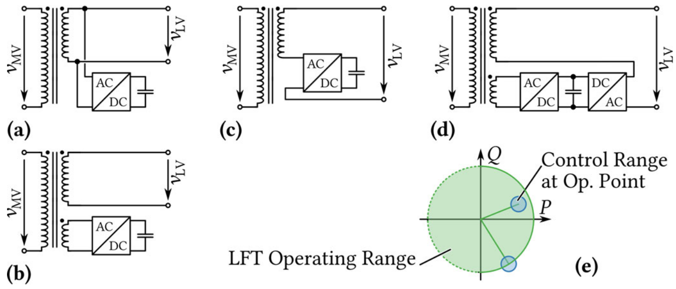

Fig. 7. (a)-(c) Different configurations of hybrid transformers [46]; (d) qualitative illustration of the limited control range around a given operating point (defined by the LV-side load) that can be provided by a hybrid transformer according to (c)—the other configurations can only operate in the Q-axis direction, i. e. they cannot process active power.

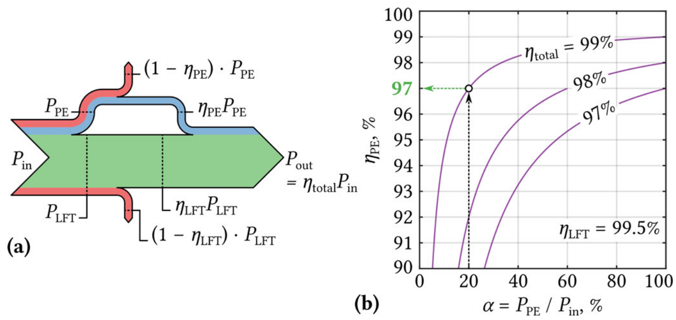

Fig. 8. (a) Qualitative Sankey diagramm illustrating the power flows in a hybrid transformer; (b) overall efficiency of a hybrid transformer in dependence of the power share processed by the power electronic stage and the efficiency of that stage for an assumed LFT efficiency of $\eta_{\mathrm{LFT}} = 99.5\,\%$.

B. Hybrid Transformers

As can be seen from the successful deployment of voltage regulation distribution transformers, etc., it is often sufficient to provide *some* controllability, not the *full* controllability of voltages and currents that could be achieved with an SST. Therefore, a combination of a highly-efficient and robust LFT with a power electronic converter that can provide the required amount of controllability, however, without processing the bulk power, could be an attractive solution: hybrid transformers [46], [47]. In a sense, hybrid transformers can be considered as LFTs with an integrated series voltage compensator and/or active filter. Fig. 7 shows the four main configurations of hybrid transformers, where basically a shunt connection (a) and (b) or a series connection (c) of the power electronics converter and the LFT's LV winding can be distinguished. Configuration (d) is a back-to-back connection of a shunt and a series converter, which allows for the highest flexibility, since the DC bus of the series stage can exchange active power with the grid by means of the shunt stage [47]. Therefore, arbitrary (within the converter ratings) voltages can be injected in series to the LFT's LV winding voltage in order to provide harmonic filtering, power factor correction, flicker control, etc. Fig. 7e illustrates the limited control range that can be provided by such a hybrid transformer.

However, in contrast to an SST a hybrid transformer's power electronic stage processes only a small fraction of the overall power. Even if it's efficiency is comparably low, the impact on the overall losses, i. e., on the combined losses of the power electronic stage and the LFT, is only minor. This is illustrated qualitatively by a Sankey diagram in Fig. 8a. Let $\alpha = P_{\mathrm{PE}}/P_{\mathrm{in}}$, i. e., α denotes the share of the input power processed by the power electronic stage. Then, the overall efficiency is given by

$$\eta_{\mathrm{total}} = \alpha \cdot \eta_{\mathrm{PE}} + (1-\alpha)\cdot \eta_{\mathrm{LFT}}. \tag{2}$$

Solving this equation for η_{PE} allows to calculate the required efficiency of the power electronic stage as a function of the desired overall efficiency η_{total} and α, which is shown in Fig. 8b. For example, if $\eta_{\mathrm{LFT}} = 99.5\,\%$ and the power electronic stage processes 20 % of the power, in order to achieve an overall efficiency of $\eta_{\mathrm{total}} = 99\,\%$, the power electronic stage does only require an efficiency of 97 %. This is comparably easy to achieve with single-stage power electronic converters. Also, the compatibility with existing LV grid protection schemes can be maintained, e. g., by employing a bypass switch for the power electronic converter stage [48].

The advantages of the hybrid transformer concept have already triggered the development of corresponding products, such as a 50 kVA system from GRIDCO, which can provide a $\pm 10\,\%$ voltage control range and up to 10 % reactive power, while achieving a high efficiency above 99 % [49].

Another variant of hybridization is the direct parallel connection of an SST to an existing LFT [50] as shown in Fig. 9a: this adds controllability and also increases the power transfer capacity but without increasing the available short-circuit power (because of the SST's ability to limit its output current). Fig. 9b shows the dual concept that could be tought

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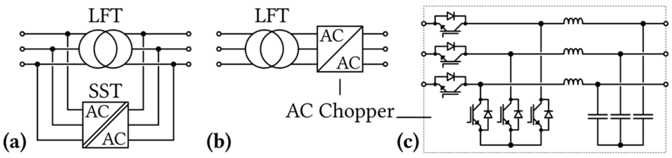

Fig. 9. (a) Parallel configuration of an LFT and an SST [50]; (b) series configuration of an LFT and an AC chopper and (c) realization option of an AC chopper [51].

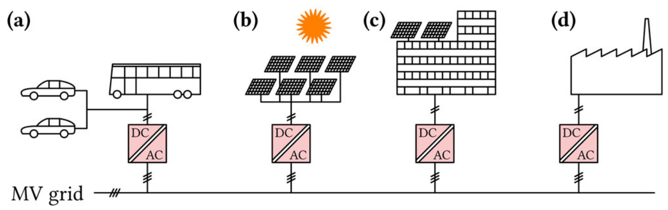

Fig. 10. Examples of DC microgrid applications: (a) EV charging, (b) large PV installations, (c) future residential/office buildings, and (d) future factories, datacenters, etc.

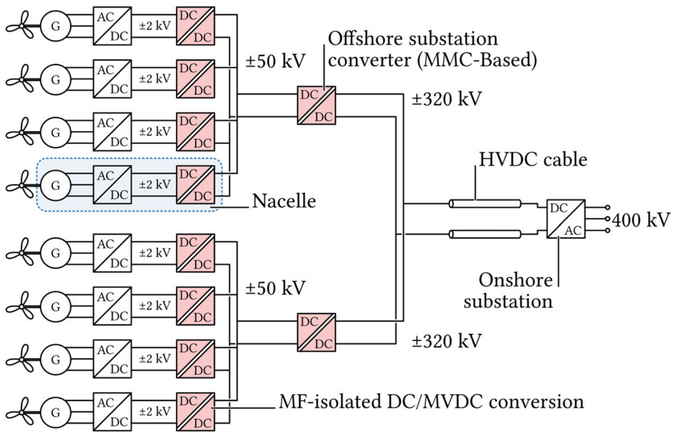

Fig. 11. DC collecting grid for offshore wind parks as proposed in [56].

of: a series configuration of an LFT and an AC chopper, which could provide voltage control and current limitation in cases where such functionality may be required.

VI. Potential Application Scenarios for SSTs

The conclusion from the previous sections is, in short, that an SST as a direct replacement of an LFT is not feasible from an economical point of view, in addition to concerns regarding robustness and reliability (even though it can be shown that very high levels of reliability can be achieved by implementing redundancy in case multi-cell concepts are employed [2], non-redundant subsystems such as control electronics, etc. may limit the overall reliability of complex converter systems [52], especially in comparison to a passive LFT). Also, there are existing alternative ways of addressing the controllability challenges in modern distribution grids other than replacing LFTs with SSTs. In contrast to an SST, these alternative solutions do provide a more narrow, however often sufficient, control range, but, on the other hand, either avoid the use of power electronics altogether, thereby retaining the high efficiency and robustness of an LFT, or limit the power processed by power electronic stages to only a fraction of the total power, which allows to suitably balance the controllability requirement and the degradation of the overall efficiency. Nevertheless, there are some application scenarios, at least partly related to the distribution grid, where SSTs could already be or could become feasible. These potential application scenarios will be briefly outlined in the following.

A. AC-DC Applications

If an LV DC interface is required, e. g., to connect a photovoltaic (PV) generation plant or a larger energy storage facility to the MV grid, to interface a DC microgrid [53] to the MV grid, or for a fast EV charging station that can also provide ancillary services to the grid if not in operation [54], or to directly supply servers in a datacenter from MV [55], the LV-side DC-AC conversion stage of the SST is not required, whereas on the other hand an LFT must be extended by a (bidirectional) LV rectifier. Furthermore, a DC output typically implies that the LV DC side environment is not already existing, but can be co-designed such as to be compatible with the SST, e. g., in terms of protection schemes, etc. Fig. 10 shows several examples of such AC-DC applications.

As discussed on a specific example in [3], the efficiency challenge in the AC-DC case can be alleviated at least to some extent, i. e., the losses generated by the SST-based and by the LFT-based solution may be similar. Also, the gap in prices is reduced, because the LFT-based solution involves power electronics, too: Refering to Section III, in an AC-DC case the specific price of the SST-based solution is $c_{\mathrm{SST,MV}}$, whereas the specific price of the LFT-based solution is $c_{\mathrm{LFT}} + c_{\mathrm{SST,LV}}$, because the LFT needs to be extended by a low-voltage AC-DC rectifier in order to realize an LV DC output, whereas the SST does not require an LV-side DC-AC inverter. As an example, considering $c_{\mathrm{LFT}} = 15\,\$/\mathrm{kVA}$, $c_{\mathrm{SST,LV}} = 125\,\$/\mathrm{kVA}$, and $c_{\mathrm{SST,MV}} = 1.5 c_{\mathrm{SST,LV}}$, the SST-based solution is only about 30 % more expensive than the LFT-based solution, i. e., the SST-based solution is not factors more expensive as is the case in AC-AC applications. Hence, it would be required to perform a detailed TCO calculation in order to decide between the these two options. Such a consideration should, at least at the moment and in the near future, consider that it is not possible to simply purchase an SST, which implies possibly significant investments in research and especially product development.

B. Weight/Space-Limited Applications

Traction applications are the most prominent example of applications where weight and space for the isolation stage are constrained. This has led to several companies pursuing the development of single-phase (AC-DC) SSTs for traction applications, resulting in various prototypes and even a shunting locomotive equipped with a fully functional SST, which has been field tested on the Swiss railways [9]. SSTs based on low-complexity topologies could also be considered for railway auxiliary MVAC-LVDC power supplies (25 kW…50 kW) for,

e. g., climate control units [57]. Other applications where weight and space for an isolation stage might be limited comprise the nacelles of wind turbines [17], [56], or even flying wind turbines [58], future navy warships [59] as well as future civilian ships such as cruise liners [60], [61], where local MVAC and/or MVDC grids will be employed for on-board power distribution. Also, future subsea applications such as oil drilling infrastructures may benefit from an MVAC or MVDC connection to the surface or to the shore, and correspondingly could rely on low-weight and low-volume subsea SST systems [62]. Furthermore, MVDC power distribution is even envisioned for future all-electric aircraft employing distributed propulsion concepts [63], where SST topologies with low complexity could be utilized to supply a group of LV loads from a main MVDC bus. Note that many of these applications are pure DC applications, where, as will be discussed in the next subsection, an SST is the only possibility to provide galvanic separation and high voltage transfer ratios. Finally, even in grid applications, specifically in underground distribution networks in areas with high population densities, e. g., city centers, where space is scarce and expensive, SSTs (e. g., of the AC-AC matrix-type [17]) could find application in order to increase the power rating that can be installed in a given space [17]. Also, [15] has proposed SSTs as mobile (movable by truck) temporary replacements for large, heavy high-voltage to MV transformers.

C. DC-DC Applications

As already mentioned in the previous section, there are many emerging applications that could be based on (MV) DC distribution systems, e. g. [56], [64], [65]. As an example, Fig. 11 shows the structure of a DC collecting grid for future offshore wind farms as proposed in [56]. If galvanic isolation and/or a significant step-up or step-down of the voltage is required in such DC distribution networks, a magnetic transformer must be used—however, a transformer requires an AC voltage to operate. Therefore, DC-AC and AC-DC conversion stages are required, and the transformer operating frequency is a free parameter that is subject to optimization. In contrast to AC-AC or AC-DC applications, there is no AC voltage that could directly be used to operate the transformer, and hence the additional conversion stages are required in any case: there is no alternative to using a conversion system that can be seen as an SST.

VII. Conclusion and Outlook

SSTs are widely considered for applications in the distribution grid, mainly because of their controllability. This paper provides a generic assessement of the suitability of SSTs for grid applications, which leads to a proposed applicability guideline given in Fig. 12.

In the 1000 kVA class an SST is significantly more expensive (at least 5×) and significantly less efficient (at least 3× higher losses) than a typical LFT employed in the distribution grid today, which corresponds to higher operating costs, too. In addition, SSTs are considered less robust, and they are not compatible with the protection infrastructure widely employed

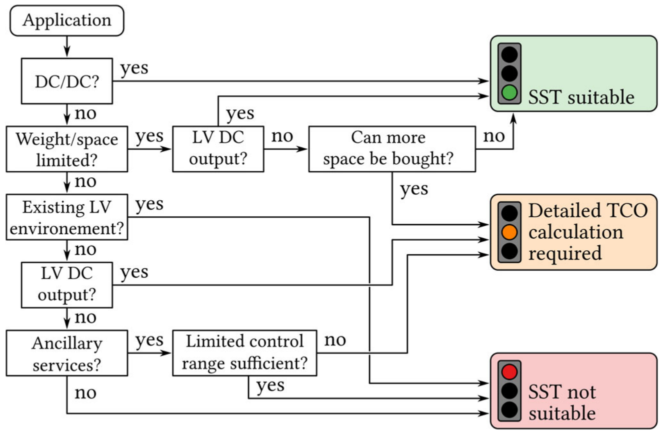

Fig. 12. Proposed applicability guideline for SST technology (at the moment and at least for the near future). “Limited control range” refers to, e. g., the ability to regulate the output voltage within a required tolerance band of ±10 % around the nominal value.

in existing LV AC grids. On the other hand, SSTs can provide full-range control of their input and output voltages and currrents and can thus provide ancillary services to the grid. However, even though there is a need for some controllability in today’s and future distribution grids, the required control range is typically only a fraction of the rated power. There are various existing and therefore competing approaches to realize such a limited control range. These do either not rely on power electronics (e. g., tap-changers), or the power electronic stages do not process the bulk power flow (e. g., hybrid transformers), hence alleviating the efficiency challenge. All in all, SSTs are not well suited for typical AC-AC grid applications.

If, in contrast, an LVDC system (e. g., a DC microgrid, PV plants, etc.) shall be interfaced, the conclusion is not so clear; a detailed TCO study for the specific case would be required in order to identify the most cost-effective solution. Finally, SSTs are clearly an interesting option for niche and specialized applications where weight and/or space limits apply (e. g., traction, ships, subsea, etc.), or where MVDC-LVDC conversion is required.

As illustrated by the qualitative diagram in Fig. 13, the development cycles of SST technology for traction span several decades from the first concepts to fully functional prototypes. The cycles tend to become shorter due to increased experience and advanced design tools, as well as because of increased interest in the topic from both, academia and industry. The prospective development cycles for grid applications are likely slower, because in contrast to traction applications, power electronics are not a well established technology in this context, and also because of the sheer amount of existing infrastructure and its typically long lifetimes.

Of course, the presented assessment of the SST concept’s applicability in distribution grids may still change in the future. Future research should clearly address a quantification of the system-level benefits that the presence of an SST could offer. Furthermore, active protection concepts for both, AC and DC grids need to be investigated further. Regarding core technologies, however, no breakthroughs are expected in the

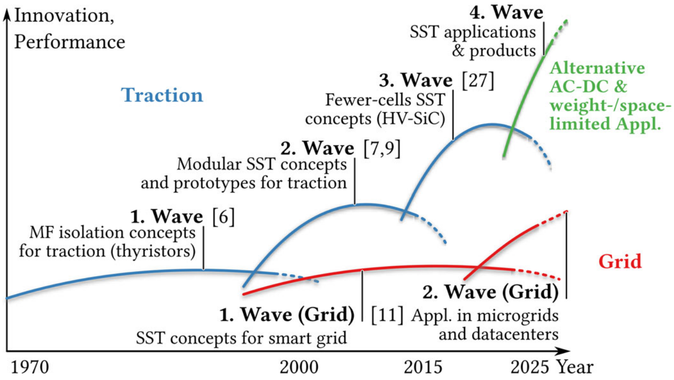

Fig. 13. Waves of SST innovation: development cycles are reaching over decades. A key publication is referenced for each cycle. Alternative AC-DC applications could involve ultra-fast EV charging or shipboard applications.

near future: SiC power semiconductors will only gradually improve, and existing core materials for MFTs impose physical limits on the achievable performance. Considering the cost challenge, increasing market size could result in significant price reductions from economy of scale as can be observed with PV or automotive drive inverters [66]. Specifically, [31] predicts a reduction of prices for utility scale PV inverters to about 24 $/kVA…48 $/kVA by 2050, i. e., by roughly a factor of four compared to today's prices. If such physical and/or economic limits could be overcome in the more distant future, and hence the efficiency challenge and/or the cost challenge could be tackled, SSTs could become important pillars of a smart grid due to their universal controllability, e. g., acting as multi-port energy hubs.

Furthermore, there are concepts for complementing existing AC grids with HVDC and MVDC grids to improve the utilization and reliability, facilitate integration of DC loads and sources such as PV or battery storage systems, etc. [67]. SSTs would be key components acting as DC-DC or DC-AC converters in such hybrid grids.

However, on a more fundamental level, the question whether aiming for a replacement of LFTs by intelligent energy hubs, i. e., SSTs, might be conceptually still too closely related to the existing centralized and hierarchical structure of the power grids, needs to be addressed. Already today an increasing penetration of *active* loads and sources can be observed, e. g., PV inverters, and it can be expected that this trend will continue. Then, a "fully smart grid" would be a grid in which the control tasks are shared among many or all of its participants (this may require certain communication facilities or decentralized control concepts), and not assigned to central entities such as an SST. Therefore, a highly important research task is to establish a clear understanding of what functionality is actually required at the interfaces between MV and LV grids in the future.

Thus, the design of the future power grids, which likely comprise both, AC and DC, is an interdisciplinary challenge, which could best be addressed by increased collaboration between engineers from both backgrounds: power electronics *and* power systems.

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