This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

Applications and Services of Solid-State Transformers in Active Distribution Networks - A Critical Review

IEEE PES Task Force on Solid-State Transformer Integration in Distribution Grids

Chair: Giovanni De Carne Vice-Chair: Sanjeev Pannala Secretary: Felix Wald

Felix Wald, *Student Member, IEEE,* Hrishikesan V. M., Oriol Gomis-Bellmunt, *Fellow, IEEE,* Haoran Ji, *Member, IEEE,* Masoud Davoudi, *Senior Member, IEEE,* Ali Bidram, *Senior Member, IEEE,* Mazheruddin Syed, *Member, IEEE,* Martina Josevski, *Member, IEEE,* Sebastian Brüske, *Member, IEEE,* Chandan Kumar, *Senior Member, IEEE,* Rafael Peña Alzola, *Senior Member, IEEE,* Ilknur Colak, *Senior Member, IEEE,* Sanjeev Pannala, *Senior Member, IEEE,* Marco Liserre, *Fellow, IEEE,* and Giovanni De Carne, *Senior Member, IEEE*

***Abstract*—Distribution systems have traditionally received the least attention in the bulk picture of power systems; they are yet the most "critical component" as they directly impact customers' perception and utilities' reputation. While transmission systems have seen abundant literature, innovations, and applications of power electronic-based devices to optimize their performance, distribution systems still require more attention toward a flexible and dynamic scheme to cope with volatile energy consumption and production. As a replacement or enhancement of the traditional ones, Solid-State Transformers can play a central role in the energy management of distribution systems towards this goal, in addition to the mere voltage conversion. This manuscript, developed within the IEEE Task Force on Solid-State Transformer integration in distribution grids, offers a critical review of the Solid-State Transformer potential, services, and technical challenges for its integration in distribution systems. Particular attention is given to scientific trends and open points in the current research that must be addressed before utilities extensively integrate the Solid-State Transformer in distribution systems.**

***Index Terms*—Solid-state transformer, power transformer, active distribution network, power flow control, power electronics.**

F. Wald and G. De Carne are with the Karlsruhe Institute of Technology, Karlsruhe, Germany (felix.wald@kit.edu; giovanni.carne@kit.edu). Their work is supported by the Helmholtz Association program "Energy System Design" and the Helmholtz Young Investigator Group "Hybrid Networks" (VH-NG-1613).

Hrishikesan VM. is with Siemens Denmark (hrishikesan.vadakkedath@siemensgamesa.com)

O. Gomis-Bellmunt is with Centre d'Innovacio Tecnologica en Convertidors Estatics i Accionaments, Universitat Politecnica de Catalunya (CITCEA-UPC), Barcelona, Spain. The work of Oriol Gomis-Bellmunt is supported by the ICREA Academia Program. (oriol.gomis@upc.edu).

H. Ji is with the State Key Laboratory of Intelligent Power Distribution Equipment and System, Tianjin University, China (jihaoran@tju.edu.cn).

M. Davoudi is with Pacific Gas and Electric, San Fransisco, CA, US (masoudd@ieee.org).

A. Bidram is with the Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM, US (alibidram@ieee.org).

M. Syed is with the Energy Advisory, WSP UK, Scotland (mazher.syed@wsp.com).

M. Josevski is with EATON, Germany (MartinaJosevski@eaton.com).

S. Brüske is with Maschinenfabrik Reinhausen, Regensburg, Germany (S.Brueske@reinhausen.com).

C. Kumar is with the Electronics and Electrical Engineering Department, Indian Institute of Technology Guwahati, India (chandank@iitg.ac.in).

R. Peña Alzola is with the Institute for Energy and Environment, University of Strathclyde, Glasgow, U.K. (rafael.pena-alzola@strath.ac.uk).

I. Colak is with Schneider Electric, Grenoble, France (ilknur.colak@se.com).

S. Pannala was with the Washington State University, Pullman and now with NREL, Golden (sanjeev.pannala@nrel.gov).

M. Liserre is with the Chair of Power Electronics, Kiel University, Kiel, Germany (ml@tf.uni-kiel.de).

ACRONYMS

ACT	Air-Core Transformer
ADN	Active Distribution Network
B2B	Back-to-Back Converter
BESS	Battery Energy Storage System
CSI	Current Source Inverter
DAB	Dual-Active Bridge
DER	Distributed Energy Resource
ESS	Energy Storage Systems
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
GFL	Grid-Following
GFM	Grid-Forming
HT	Hybrid Transformer
LFT	Line Frequency Transformer
LTC	Load Tap Changers
MCT	Magnetic-Core Transformer
MFT	Medium Frequency Transformer
PV	Photovoltaic
SiC	Silicon Carbide
SST	Solid-State Transformer
STATCOM	Static Synchronous Compensator
TRL	Technology Readiness Level
WBG	Wide-Bandgap Semiconductor

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

I. Introduction

FUTURE distribution networks face challenging times, specifically due to voltage and frequency volatility created by the partial migration of generation from centralized and scheduled, to distributed and non-dispatchable. The migration of generation units toward the customer evolves the formerly passive distribution networks into Active Distribution Networks (ADNs), where new generators, loads, and Energy Storage Systems (ESS) operations are intertwined. This evolution, including higher and more frequent bi-directional power flow, creates a dynamic in which long-standing technologies like Line Frequency Transformers (LFTs), as illustrated in Fig. 1a, need rethinking and additional enhancement. The LFT is based on passive copper windings, capable of transforming the voltage according to the winding ratio, but is neither able to control any other quantity such as power flow or harmonics, nor provide services to the grid. While there is no doubt that a LFT is highly efficient ($\eta > 99\,\%$) and cost-effective when transforming AC voltage levels, since it is a passive system it is not capable of providing much-needed services to improve the dynamic capability of ADNs. Those services may include influencing bi-directional power flow, managing voltage and frequency volatility, managing current congestion, and facilitating the integration of distributed generation and Electric Vehicles (EVs) [1]–[6]. Therefore, novel solutions need to be proposed, if ADNs shall contribute to a green change of energy production and consumption. In the current literature, these solutions are usually a down-scaled version of transmission systems solutions, e.g., Load Tap Changers (LTC) in Fig. 1b or Static Synchronous Compensator (STATCOM) Fig. 1c, implemented in distribution networks, targeting specific problems [7]–[11]. In contrast to classical alternatives, the Solid-State Transformer (SST) displayed in a standard three-stage configuration in Fig. 1d, a direct AC/AC matrix topology with Current Source Inverters (CSIs) in Fig. 1e, or less complex structures such as a Back-to-Back Converter (B2B) or a Hybrid Transformer (HT) in Figs. 1f and 1g, are able to offer a selection of the aforementioned services without the need of multiple devices [12]–[15]

Research activities on SSTs have intensified in recent years, particularly concerning its power electronic architecture and topology. New semiconductor technologies (e.g., Silicon Carbide (SiC)) have been proposed for SSTs, improving their efficiency and reliability, closing in on the LFT.

However, industrial actors, system operators, and utilities agree that power system-level studies are critical in the integration process of SSTs in ADNs. The SST provides a simple voltage transformation paired with galvanic insulation and offers additional services, such as power flow control, voltage and frequency regulation, power quality improvement, DC connectivity, and black-start capability. These features differentiate the SST from a traditional LFT, enabling ADNs and could also generate additional revenue to cover the currently more expensive costs of power electronic components.

In Table I, significant studies summarizing recent efforts in the SST research landscape have been gathered and classified for their contributions. As mentioned above, the existing literature shows a significant interest in power electronic topologies and architectures, especially the challenge of improving the efficiency of the SST. The table also highlights how little has been done at the system level. The state-of-the-art research is still an incomplete description of the SST's capabilities since existing studies only partially cover its role in the bigger picture of distribution power systems and primarily focus on control strategies for single services. As an example, only a few comprehensive studies highlight the challenges at hand regarding protection systems [16], [17]. However, the topic is fully identified as one of the major bottlenecks for the SST integration in ADNs.

This work aims to fill parts of the existing gap, and mainly provides a clear and comprehensive overview of existing SST services and features in power systems, putting the spotlight on ADNs. The focus is on open research questions, technological challenges, ongoing projects, and applications of the discussed services. The authors intentionally excluded topics

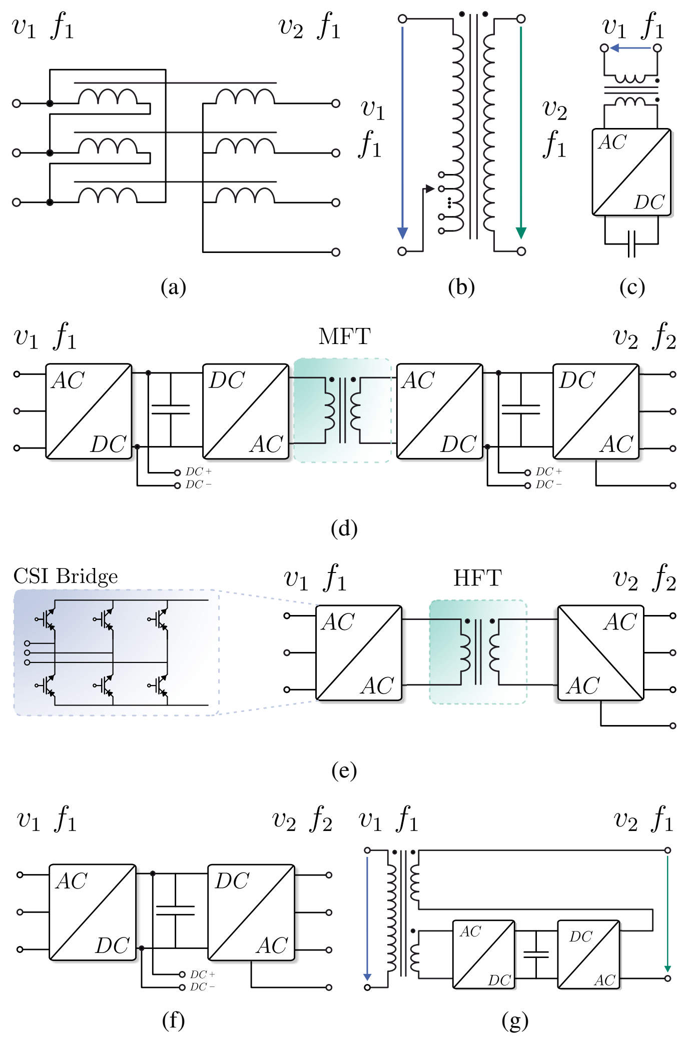


Fig. 1: Technologies competing with the SST (shown in (d)), offering overlapping services and feature to ADNs. (a) a traditional delta-wye LFT for distribution grids, (b) a LFT with LTC , (c) a STATCOM, (d) the three-stage SST, (e) a direct AC/AC matrix converter, (f) a B2B, and (g) a HT.

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

TABLE I: Existing SST Review Papers and their Focus.

Reference	Year	System Integration and Controls					Hardware		
		Network Topology	Control Strategies	Applications	Protection[a]	Future Research and Trends	η^b	Topologies[c]	SW[d]
[4]	2014	×	×	✓	×	×	✓	×	×
[12]	2013	×	×	✓	×	✓	✓	✓	✓
[13]	2016	×	×	✓	×	✓	×	✓	×
[14]	2016	×	✓	✓	×	✓	✓	✓	×
[18]	2016	×	✓	×	×	×	✓	×	✓
[19]	2019	✓	×	✓	×	✓	✓	✓	×
[20]	2019	×	×	×	✓	✓	✓	✓	×
[21]	2020	✓	✓	✓	×	×	×	×	×
[22]	2020	×	✓	×	×	✓	×	✓	×
[23]	2021	×	×	×	×	✓	✓	✓	×
[24]	2021	✓	✓	×	×	✓	×	×	×
[25]	2022	✓	✓	×	×	×	✓	✓	×
[26]	2023	×	✓	✓	×	✓	×	×	×
This Review		✓	✓	✓	✓	✓	×	×	×

✓ = investigated × = not investigated

[a]Strategies for the Protection of downstream SST-fed networks.
[b]Efficiency analysis of SST topologies.
[c]Comparison of different converter combinations for SSTs.
[d]Impact of different switching technologies.

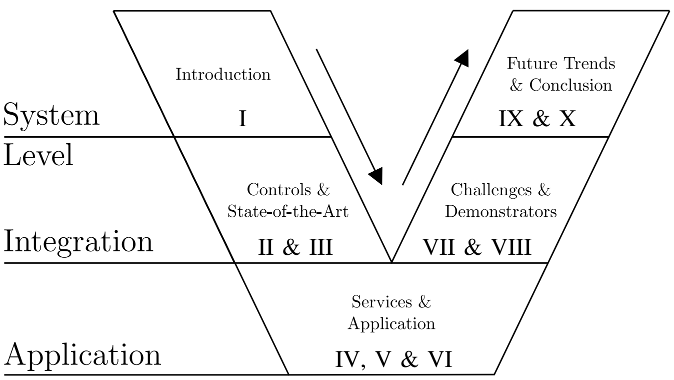


Fig. 2: Illustration of the general paper outline, in a commonly known v-model shape, with the respective section numbers tied to the corresponding topic.

regarding detailed power electronic matters, such as insulation, topologies, or efficiency, since these issues have been extensively covered in prior publications, as seen in Table I. This manuscript is an initial result of the *IEEE PES Task Force on Solid-State Transformer integration in distribution grids*. It reflects expertise, experience, and knowledge of academia, industry, and utilities.

The content of the manuscript is structured as illustrated in Fig. 2 and is further detailed in the following paragraph. After this brief introduction and motivation, it presents the SST's basic control concepts and layers in Section II, with the subsequent comparison to different State-of-the-Art technologies in Section III. Section IV offers a comprehensive overview of services enabled by the SST system itself, including a discussion on open research questions. This is followed by Section V reviewing possible ADN scenarios that are enhanced or enabled by SSTs. For a complete picture of possible SST applications Section VI offers a short overview of industrial applications that can profit from the deployment of SSTs, paired with Section VII presenting SST projects in industry and academia around the world. The last three Sections VIII to X highlight the remaining challenges for the widespread application of SSTs, future trends to be considered in the development of SSTs, and a coherent summary and conclusion.

II. Solid-State Transformer Structure and Basic Control

The SST is a power electronics-based transformer that uses semiconductors to transform and modulate voltages, which can be used to control incoming and outgoing currents. As such, it is a very complex system that can be realized through many different combinations of power electronics. One approach is the use of the CSI technology to form a direct AC/AC converter as shown in Fig. 1e, reducing the number of switches and capacitors needed. However, it reduces the control flexibility and most importantly the accessibility of a DC terminals, heavily restricting the possible application scenarios. It may be considered as voltage control reinforcement in long feeders (e.g., acting as dynamic autotransformer). The research community is still undecided about the most suitable combination for a grid-tied SST application. Thus, in Fig. 1d and Fig. 3, this review introduces just one common and versatile example topology to better illustrate its features, which involves three power-electronic converter stages to connect MV to LV networks of both AC and DC nature. Ahead of the core review section, the following subsection offers the reader a sound but simplified background on the state-of-the-art operation and control of a three-stage SST.

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

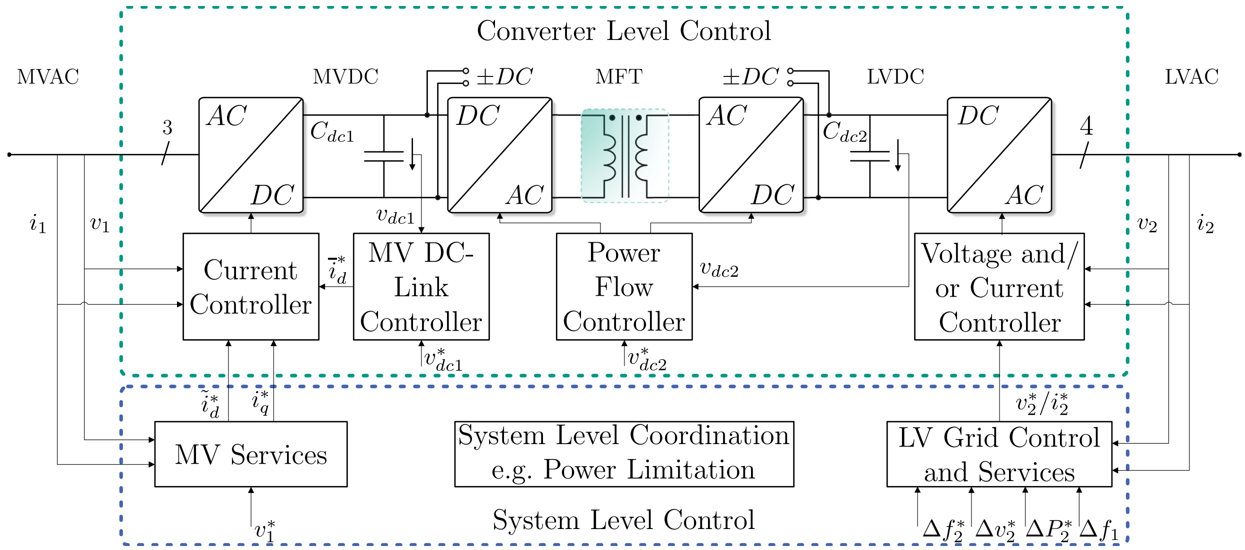


Fig. 3: Basic SST Control Scheme: the green box includes the basic controllers for a SST, enabling basic operation of the power electronic conversion stages. The blue box includes the service provision-related blocks, which are not essential for the SST operations but enable network service provision.

The converter level control of a three-stage SST can be split into three individual basic controllers: MV converter, DC/DC converter, and LV converter. An overview of a generic SST control structure is displayed in Figure 3, where the control structure is divided into two layers, basic controllers (green box) and service provision-related controllers (blue box), the signal names are marked with a star as superscript (*) when relating to a set point value and not a measurement. More advanced descriptions, including detailed mathematical models for each conversion stage and its control, can be found in the following literature [12], [14], [27], [28], and are therefore, not repeated in this work. The passive elements for the AC connection (e.g., filters) are omitted in Figure 3 to reduce its visual complexity but are included in the following control considerations.

1) MV Converter Control: The control strategy of the MV converter, shown as an AC/DC converter in the top left corner of Fig. 3, is similar to a basic active front-end converter. Its main role is to control the AC current i_1, with the use of a cascaded current and voltage controller to keep the MVDC link voltage v_{dc1} at its set point v_{dc1}^*. The measurement v_1 can be applied after the current controller to achieve a feed-forward control scheme. The MV converter can be built using various different topologies, most commonly a Modular Multi-level Converter is used, which requires complex modulation strategies as reviewed in [29], [30] and additional voltage balancing and common mode compensation controllers are mandatory to ensure stable operation [31]–[34].

Additional service-related stages can be added in cascade, setting the new operative points for the dq currents. As an example, an oscillating active current $\tilde{i}_d^*$ can be added for harmonic compensation purposes to the active current $\bar{i}_d^*$ set point coming from the *MVDC link Controller*. The input of the *MV Services* - block can vary depending on the services offered, e.g., the voltage magnitude set point v_1^*, if voltage/VAr support as discussed in Section IV-B is meant to be offered [35].

Furthermore, services can be extended to cover more enhanced grid supporting features, operating both sides with GFM features, distributing the responsibility of maintaining the DC-Link to both sides of the connection by establishing DC-Link voltage control droops in the DC connected converters [33], [36]. The energy required to procure Grid-Forming (GFM) features can be attained by interacting with the downstream low voltage grid. Controlling the power flow within the SST can be achieved by exploiting the downstream active power flexibility/sensitivity, using information such as frequency deviation or voltage [37].

2) DC/DC Converter Control: The DC/DC conversion stage in the upper central part of Fig. 3 is tasked to maintain a stable LVDC link voltage, thereby transferring power from the MVDC link. The basic concept to control the power transfer, e.g., in a Dual-Active Bridge (DAB), is the phase shift between the voltages on the primary and secondary side of the Medium Frequency Transformer (MFT) within the converter [38], [39]. This leads to a current flowing in the desired direction and amount. The control of this stage is limited to this objective and is represented by the *Power Flow Controller* block in the center of Figure 3, with the inputs of the LVDC link voltage and its set point v_{dc2}^* [40]–[42].

However, low-level control and modulation techniques can vary depending on the exact topology and operating points, including strategies like, linearization control, disturbance-observer-based control or sliding mode control [43]–[46]. Additionally, new and improved low-level hardware control algorithms such as zero-voltage switching in DABs, offer an improved efficiency, extended lifetime and reduce thermal stress on the power switches [47]. Advanced soft-switching techniques of power electronic switches in SSTs are increasingly applied in current source inverters or using complex and highly specific converter topologies to achieve higher efficiency as displayed in the following selection of references [48]–[52].

3) LV Converter Control: The control of the LV DC/AC converter in the top right corner of Fig. 3 depends on the system's use case. On a basic control level, the converter can be operated in GFM and Grid-Following (GFL) mode. Following the standard definition from industry, a GFM controller must "maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame" [53]. This can be realized by implementing well-known methods such as a virtual synchronous machine controller with a specific voltage set point v_2^* as input or using newer methods such as a (dispatchable) Virtual Oscillator or complex droop controllers [37], [54]–[56]. In GFL mode, the converter can be controlled similarly to the current control of the MV converter, exchanging active, reactive, and harmonic powers based on the requirement of the LVAC network. Based on the desired application, the *LV Grid Control and Services* block can utilize various feedback signals or set points, such as the desired active power deviation (ΔP_2^*), frequency deviation on both ends ($\Delta f_1, \Delta f_2^*$) or voltage deviation on the LV side (v_2^*) as seen in the bottom right corner of Fig. 3.

The mentioned control possibilities, scalability, modularity, and topologies make the SST a very flexible and highly adaptive asset in the modern power system. Its flexibility and multiple degrees of freedom on the control level enable the SST to not only offer the static features of an LFT in terms of isolation and voltage transformation but also to provide services with very fast dynamics compared to, e.g., a tap-changer. Therefore, the following section will provide a comprehensive perspective on technologies that can provide comparable services.

III. Comparison with State-of-the-Art Technologies

Comparing a SST to technologies that can offer similar features and services is difficult. A SST combines features and services in a single device, usually distributed across a combination of devices. Therefore, the following section presents technologies with similar features or services that can be compared to the SST. The goal is to provide as broad a view as possible of comparable technologies. Ideally, this will also provide interested parties with a good overview of where certain technologies are attractive and where there is room for improvement or research. The voltage transformation capability is not the focus, as this task alone is not performed more efficiently by any technology other than the LFT. Therefore, any technology will be more expensive than a LFT if measured only by its voltage transformation performance, at least at today's copper price [19], [25].

In the following paragraph, a basic description of the SST competitors is given, comparing them qualitatively in Table II, and also considering the availability of such technologies in the market according to their Technology Readiness Level (TRL).

A. On-Load Tap-changer

Tap-changers are series-connected devices that allow transformers to change the voltage ratio at discrete steps, as illustrated in Fig. 1b. It allows the voltage profile control of downstream networks to avoid the violation of the voltage limitation or additional control actions, such as Conservation Voltage Reduction [57], [58]. The technology is well-matured and widely implemented at any voltage level. However, tap-changers suffer from a limited number of switching actions and dynamics, making them unable to follow the fast power (and thus voltage) variations coming from renewables.

B. FACTS

As explained earlier in subsection IV-B, the SST can provide voltage support to an extent that is very similar to the capabilities of a Flexible AC Transmission System (FACTS) device, such as a STATCOM. Depending on the implementation scenario, the SST can be operated similarly to a STATCOM, injecting reactive power when needed. The main difference lies in the power limitation of SSTs. As the main task is to supply active power to the LVAC network, the availability of reactive power for voltage control can be limited. A direct cost comparison is not feasible, but a recent study [8] suggests that the service provided by parts of a SST could eventually be cheaper than building a single device (e.g., STATCOM) offering the same service. However, more comprehensive comparative studies need to be carried out in order to strengthen the SST business case against the STATCOM technology. Similarly to a STATCOM, active power filters, active power conditioners, and series- or shunt-components can be considered in the FACTS category.

C. Hybrid Transformer Solutions

To reduce the size and costs of SSTs, several solutions have been proposed in the literature. An interesting approach is to develop a partial-size converter connected in series or parallel with the secondary winding of the LFT, as illustrated in Fig. 1g. It allows influencing the voltage waveform while eliminating the need for a full converter. Several topologies and configurations have been reported for HTs. All of them are categorized according to their connection on either side of the LFT and the type of converter utilized (i.e., AC/AC and DC/AC) [59]. A detailed study of architecture possibilities for HTs is carried out in [59], with several potential configurations, of which the three most suitable are discussed below.

1) Self-supported hybrid transformers utilize the DC capacitor to support the reactive power compensation and partially mitigate harmonics [60]. This does not provide the full operating region and active power control without energy-supporting elements such as supercapacitors.
2) HTs connected to the auxiliary winding, draw the energy from the auxiliary winding to regulate the active power and voltage, displayed in Fig. 1g. It can also compensate for phase unbalances [61] but fails to provide normal voltage regulation under fault conditions.
3) HTs directly connected to the main winding have a power stage that can also possess galvanic isolation

TABLE II: Comparison with state-of-the-art technologies.

Technology	TRL	Power Flow Control	Voltage Support	Power Quality	Asynchronous Networks	DC Connectivity	Protection	Size and Weight	Efficiency
Tap-changer	9	×	✓	×	×	×	✓	◯	✓
STATCOM	8-9	◯	✓	✓	×	×	-	◯	✓
Hybrid Transformer	3-6	×	✓	✓	×	◯	✓	×	✓
B2B converter	7-8	✓	◯	✓	✓	◯	✓	×	◯
SST	3-6	✓	✓	✓	✓	✓	◯	✓	◯

✓ = positive × = negative ◯=neutral - = not available

through a high-frequency transformer, which is similar to SSTs [62]. The major difference comes from the power rating of the converter stage, which limits its controllability in terms of voltage and power.

A comprehensive comparison between hybrid transformers and SSTs has been performed in [25], considering the optimal management of Photovoltaic (PV) and Battery Energy Storage System (BESS). The study concludes that hybrid transformers may perform similarly to SSTs regarding voltage regulation in LVAC networks. Still, they are less effective in regulating the MVAC networks' voltage due to the more resistive behavior of the lines. Furthermore, HTs have the following limitations:

- Decrease hosting capacity of DC resources like PV and BESS, offering no- or limited access to the converter DC-link [25].
- Increases voltage fluctuations that lead to a rise in wear and tear of LTC [63].

D. Back-to-back Converter

As an alternative solution, a conventional LFT for the voltage transformation can be combined with a B2B as shown in Figure 1f, to enable similar control capabilities as the SST [37], [64], [65]. This solution can offer some features and services a full-size SST can provide, including power flow control, power quality enhancement, and DC connectivity on the LV side. From a protection point of view, the back-to-back converter can be controlled similarly to Uninterruptible Power Supplies. It offers the advantage of by-pass possibility by fast-acting solid-state breakers, allowing the in-series connected LFT to supply the short-circuit current in the downstream ADN.

However, this solution suffers from three main drawbacks: it requires a LFT in addition to the B2B, making the footprint of this solution larger than SST ones; it lacks a MVDC port to connect large DC resources (e.g., EV fast-charging stations); and it must supply the LFT's reactive power to provide voltage compensation at MVAC level. The main advantage of this solution is the availability. Although not for the application of ADNs, those technologies are already in use around the globe (e.g., LFTs in grids and B2Bs in drive applications). This allows customers and operators to estimate the expected costs and expenses reliably.

IV. Solid-State Transformer Services in Active Distribution Networks

After the overview of basic control strategies and comparable technologies above, the next two sections highlight the potential services and applications of SSTs in ADNs. Three significant services possibly offered by SSTs are reviewed in the following section. These services can be provided via system-level control modifications (blue box in Fig. 3), particularly for the AC/DC interfacing converters. These services can also be seen as a requirement of future ADNs to maintain network parameters within the grid-code specified limits.

To offer the reader a clear overview, each service subsection includes an introduction to the enabling technical concept, possible services derived from the technical concept, and a critical assessment of open research questions and challenges ahead of practical integration in ADNs.

A. Active Power Flow Control

In general, the SST can control the active power transmitted, primarily realized by controlling the LV DC/AC converter in GFM and GFL mode. This is due to the fact that in a default configuration, the MV AC/DC converter is responsible for maintaining the DC link voltage (v_{dc1}) at a specific level. This implies that the currents flowing in and out of the DC link capacitor (C_{dc1}) are highly dictated by the resources connected to it, e.g., LV DC/AC converter and DC loads.

1) Enabling Concept: With that information in mind, the active power flow in a SST critically depends on the operation mode of the LV DC/AC side converter. If operating in GFL mode, e.g., during the parallel operation of SST and LFT when breaker S1 in Fig. 4 is closed, a direct current control allows flexible power re-dispatch. The direct power control can be achieved with a variety of methods, such as dead-beat, PR or PI controller operating in static ($\alpha\beta$) or synchronous ($dq0$) reference frame [31], [32]. However, if the SST operates in GFM mode, e.g., when breaker S1 in Fig. 4 is open, an active power flow control cannot be achieved directly. This is due to the fact that the SST is responsible for the provision of a reliable voltage at the required frequency and magnitude (v_2 and f_2 in Fig. 1d), while the connected resources dictate the current. Nevertheless, with advanced control techniques, the power flow control capability can be embedded into the SST's LVAC side, even when operating in GFM mode.

A promising approach to achieve active power control in GFM mode is exploiting resources with an active power to

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

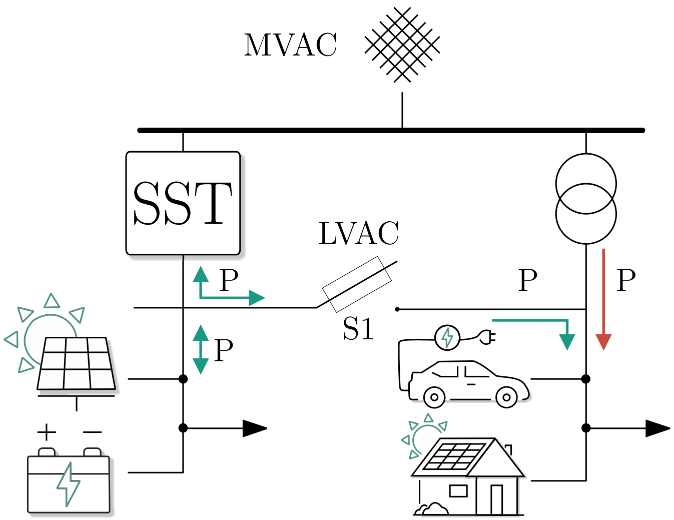


Fig. 4: SST power flow control scheme, including active resources in the low-voltage distribution network. The displayed resources are simplified representations and usually include a power electronic interface. This also applies to all the following illustrations and icons.

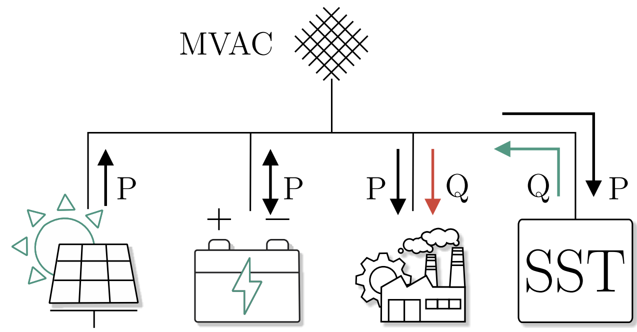


Fig. 5: SST reactive power flow and voltage support control scheme.

voltage and frequency sensitivity, possibly estimated in real-time. This can be achieved using a control scheme similar to the ones developed in [66]–[69]. By varying the voltage and frequency in a controlled way, the SST is able to estimate the voltage and frequency sensitivity of loads and subsequently indirectly control the power via voltage and frequency. This concept is especially attractive in ADNs, in which modern grid codes require active nodes to contribute to the decentralized grid control. As an example, the German grid code VDE-AR-N-4501 requires manufacturers to embed a frequency-to-active power droop behavior in active resources, such as PV or ESS [70].

2) Services: The ability to control the active power flow allows the operators to use this advantage in various ways. If operating in GFL mode, this feature could allow the rerouting of the active power flow, e.g., by partly supplying the connected grid on the right side of Fig. 4, to avoid overloading the conventional LFT. This could avoid (or at least defer) costly network reinforcements or energy curtailment [71]. In addition, due to the direct influence of the active power balance on the frequency in transmission systems ($P \sim f$), a SST can provide frequency support services by controlling the active power flow. The margin of available active power to support highly depends on the operation mode of the LV DC/AC converter. In GFL mode, this depends on the available capacities of the grid supplying node, whilst in GFM mode, the available active power increases with the transition to higher penetration levels of active components such as PV and ESS. Recent studies have shown the promising capabilities of the power flexibility enabled by SSTs to support the MV network during frequency contingencies [37], [68], [69], [72], [73].

Additionally, the active power flow control feature can be utilized to mitigate the increase of unintended reverse power flow in ADNs, from the LVAC side towards the MV network, a challenge not solvable with a LFT [74].

3) Open Research Questions: The active power flow control in the SST is possible. Still, it relies heavily on the operation mode, and if operating in GFM, the specific grid codes and the LVAC load/generation composition. Therefore, the voltage and frequency sensitivities of recently introduced resources in distribution networks (e.g., inverter-driven electrical appliances) have to be analyzed to achieve smart resource control at the distribution network level. Another angle on the matter that is rarely explored is the exploitation of the connected DC resources. As mentioned in the introduction, the active power flow is mainly impacted by the resources connected to the DC link; thus, exploiting DC devices for the active power flow control represents a promising opportunity. In scenarios deploying a multi-terminal SST providing a DC interface, altering the consumption/generation by means of voltage-to-active power dependency could be an attractive approach as discussed in [72]. In addition, the impact assessment of the active power flow control on the MV network has not been fully addressed and requires further investigation. Only a few studies show that the SST enables a higher wind penetration level by supporting frequency and voltage control in the MV network or supports the frequency by adjusting the active power flow [37], [68]. Eventually, the compatibility and coordination of these services combined with other vital tasks of a SST have yet to be investigated. One reason for the limited amount of studies at the system level is the uncertainty on the SSTs modeling and the lack of accessible, fast, accurate, and reliable models that can be easily integrated into high-level EMT, RMS, and load flow simulations.

B. Voltage Support

Since bidirectional power flow represents normal operations in future ADNs, significant voltage variations may occur more frequently. Controlling the voltage magnitude within the grid-code specified limits is a service that is essential for operators employing SSTs. This subsection focuses on the SSTs voltage support capability for the MVAC network.

1) Enabling Concept: From a MVAC network point of view, the SST usually operates in GFL mode. Since the active power flow depends on the LVAC side resources, the SST can independently exchange the reactive power with the MVAC network, as illustrated in Fig. 5. To be exact the MV converter

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

can adjust the set points v_1^* or i_q^* respectively, to achieve the desired flow of reactive power. Furthermore, the available reactive power can be increased by decreasing the power flow in the SST. Following the apparent power (S) equation, $S = \sqrt{P^2 + Q^2}$, techniques such as the active power control, described in the previous section can decrease the loading, making room for more reactive power injection [75]. This freed-up reactive power capacity (Q) can then be utilized for voltage support services.

2) Services: The SST can operate similarly to a STATCOM and support the MV network voltage using its reactive power injection capability [8], [25], [73]. As an example, a dynamic online Volt-Var Control algorithm to regulate the nodal voltage by injecting or absorbing reactive power through a SST has been proposed in [35]. Additionally, the SST in combination with energy storage systems, has been proven to concurrently control voltage and power dispatch in ADNs [76]. This feature can increase distribution networks' Distributed Energy Resource (DER) hosting capacity, as recently demonstrated by Zhu et al. [65].

3) Open Research Questions: Unlike the transmission network, the distribution networks are characterized by a wide range of R/X ratios. This leads to a high dependency on the R/X ratio for the active and reactive power to affect the voltage magnitude. Therefore, the voltage support using reactive power from SSTs may not have sufficient impact in the networks with a high R/X ratio. Novel schemes need to be introduced, considering the active power impact on the voltage magnitude in MVAC networks. Another area that needs further research is the placement of SSTs in ADNs. Unlike voltage support devices such as capacitor banks or static voltage regulators, where the optimal location can be obtained considering the maximum voltage variations, the SST might need to be located in the old transformer substations. However, in its placement in ADNs, the active and reactive power flow control requirements also need to be considered. Finding the optimal location requires solving more complex optimization problems that may compromise the efficiency of the voltage control approaches.

C. Power Quality

The increased integration of power electronics-based resources inevitably leads to power quality issues in ADNs. This causes significant issues such as a poor power factor and harmonics in currents and voltages, leading to increased losses and potential resonances. To reduce its harmonic content, local compensation measures are needed. This section depicts the potential of SSTs to provide harmonic compensation services.

1) Enabling Concept: In MVAC networks, the SST's reactive power support capacity can also be utilized to provide power factor correction services. The high bandwidth control of the current injection enables the SST to offer harmonic support services, compensating for a wide variety of disturbances on both the MV and LV side [14]. As the SST offers an asynchronous connection between MV and LV AC networks, the reactive and harmonic load contributions in the LVAC network will not be directly transferred to the MVAC network (i.e., the DC links filter out the harmonic content). Thus, the SST acts as a harmonic power decoupling device between MV and LV AC networks.

2) Services: The following section comprehensively overviews the power quality services related to SSTs.

Power Factor Correction: Poor power factor loads are present in different industrial systems and applications, such as steel and chemical factories, logistic centers, and harbors, where high-power electric drives are employed [77], [78]. For example, the Green Harbor initiatives led to the integration of more power electronic-based actuators. Modern harbors rely on electric drives with poor power factor to move shipments within the harbor area; in this scenario, the SST can offer power factor improvement services [79].

Resonance Damping: In networks with parallel operations of power electronic converters, resonances may arise between the converter filters and controllers. This situation can be worsened if the SST is the grid-forming element, resulting in multiple resonances in a wide frequency range. In [80], a lead-lag compensator and negative impedance feed control is proposed to mitigate resonances at different frequency ranges. This results in a more stable system in the presence of SSTs connected to networks with several parallel converters. A detailed analysis is performed to understand and identify the possible resonances in a SST-based electric network with increased distributed sources [81]. The authors implement multi-loop-based active damping methods to mitigate the resonances.

High- and Low-frequency Active Filtering: The SST can maintain a balanced sinusoidal voltage at the LVAC side independent of currents demanded by non-linear loads [14], [82]. Moreover, the harmonic currents drawn by the LVAC loads can be supplied while isolating the MVAC network from the harmonic content. This can reduce or postpone network expansion for power quality purposes and avoids the installation of additional power quality conditioners.

However, large non-linear loads may be present in other MVAC feeders (e.g., rectifier-based converters) that, together with an increasing number of power electronics systems, e.g., renewable, storage, or EV charging stations, can worsen the whole harmonic spectrum of the current. These harmonics create several adverse issues in power distribution systems, generally mitigated by bulky Shunt Active Power Filters. With appropriate integration of filter control strategies in the SST MV converter, active filtering features can be achieved without the need for additional hardware [83], [84]. Recently, the rise of wide band-gap devices, such as SiC, allows harmonic compensation at higher frequencies under reduced switching losses [85].

3) Open Research Questions: To compensate for harmonics in MVAC networks, the SST MV converter needs to operate at a higher frequency. Operating this converter with silicon-based switches at high frequencies may result in lower overall efficiency of the SST. Novel multi-level converter topologies and controls need to be developed to guarantee high conversion efficiency and high harmonic compensation capability.

In addition, business cases for employing the SST as harmonic and resonance compensators should be studied and discussed with industry and utilities. If avoiding the installation

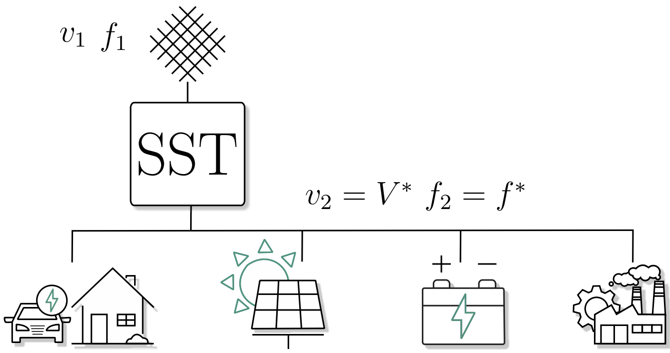


Fig. 6: SST enabling asynchronous grid connections for increased degrees of freedom in downstream ADNs.

of additional compensation equipment in the network is advantageous, the additional topological and control complexity in the SST must be justified by a stronger return on investment. The economic justification for harmonic compensation is still missing in the current state of research.

V. Active Distribution Network Scenarios enabled by the Solid-State Transformer

This section focuses on scenarios in which the SST can provide enabling capabilities to completely restructure current ADN operation strategies, envisioning a highly flexible and dynamic future distribution network. The application subsections are structured similarly to the service subsection, where the enabling technical concept is introduced at first, and in the following application paragraph, the specific use case is presented, paired with a subsequent critical section on open research questions and challenges of the SST in the respective applications.

A. Enabling Asynchronous Network Connection

Today's power networks are usually operated synchronously over wide areas using extensive interconnections to provide redundancy. In the context of increasing penetration of renewable energy systems and thus variable generation, wide area networks may be affected by power generation fluctuations due to its architecture [86]. A solution to this challenge is to divide wide area synchronous networks into smaller ADNs operated asynchronously. The SST can enable such asynchronous network connections, allowing LV networks to operate as independent ADNs while still connected to a bulk power system regarding the energy transfer.

1) Enabling Concept: The asynchronous connection is possible due to the capability of the SST to control the synthesized voltage at the LVAC output terminals independent of the MVAC voltage if operated in GFM mode (e.g., $v_2 = v^*$, $f_2 = f^*$ in Fig. 6).

2) Application: As the grid-forming unit of the asynchronous LV networks, the SST can provide local network optimization permitting high penetration of DERs [87]. As an interconnecting unit between the bulk power system and the asynchronous network, the SST regulates the power flow between the two network levels and ensures stable operation of the downstream asynchronous network. This functionality of the SST becomes important in networks increasingly dominated by power electronics, where the electrostatic energy of the capacitors replaces the mechanical-based inertia [87]. The SST can also enable power conditioning of two ADNs, regulating the power import/export between two community microgrids, as proposed by Parashar et al. in 2018 and analyzed by Zhu, Akanksha and Mather in multiple papers starting in 2020 [64], [88], [89]. The analysis provided extensive arguments that the DER hosting capacity can be enhanced while reducing PV curtailment and the number of deep-cycles of energy storage systems [65]. Additionally, asynchronous connections enable the development of new control strategies. For example, the SST can make the connected LVAC network behave similarly to a virtual synchronous machine by varying its output power with respect to the frequency to sustain the frequency regulation in the mains [37].

3) Open Research Questions: Asynchronously connected networks are still a relatively new concept. The open research questions are mainly related to the control and protection of these networks, the investigation of resonances among power electronic converters, and the definition of grid standards. Furthermore, possible challenges that may arise due to the interaction of multiple asynchronous networks and the feasibility of multi-terminal asynchronous networks to achieve higher reliability through meshed network operations shall be studied.

B. Enabling Connected and Islanded Microgrids

The previously discussed asynchronous connection capability of a SST also enables grid-connected and islanded microgrids.

1) Enabling Concept: The SST can enable islanding operation, e.g., by integrating ESS at its DC terminals to supply the necessary power and act as a GFM node [90]–[92].

2) Applications: SSTs can be deployed in both AC and DC microgrids, as well as hybrid AC/DC microgrids [91], [92]. Especially in hybrid AC/DC microgrids, a three-stage SST can offer connection points to MVDC, LVDC, and LVAC devices with a single connection point to the MVAC network. The DC/DC converter stage integrates DC sources that can flexibly re-dispatch power to the low and medium voltage networks and eventually supply an islanded low voltage ADN [90]. The SST, as a GFM node for ADNs, provides flexibility in terms of control and operation: it can facilitate the seamless islanding of microgrids and the restoration of grid-connected nodes; moreover, SSTs provide voltage regulation, power factor correction, and active and reactive power control at the microgrids' Point of Common Coupling [90]. A three-stage SST is also capable of accommodating a dual microgrid operation, in which an SST forms islands on both of the MV and LVAC sides when a fault or disturbance happens on the upstream AC power network if adequate energy storage is installed at the DC side [93].

3) Open Research Questions: The SST's capability to simplify the transition between grid-connected and islanded modes in the LVAC network is well established [94]. However,

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

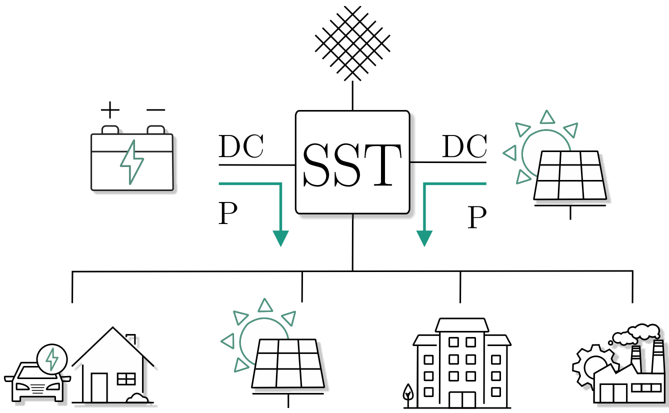


Fig. 7: SST enabling black-start of ADNs, using renewable energy resources and storage system.

the transition of the control when the LVAC network structure changes to a meshed one, which requires a change in operation mode from GFM to GFL or vice versa, still needs further investigation. Similarly, during the dual microgrid operation, the control transition of the MVAC stage of the SST is also a topic for further investigation. In addition, more studies are needed in the case of microgrids with multiple energy sources (e.g., generators), analyzing advanced active and reactive power-sharing methodologies.

C. Emergency Feature - Black-start Capability

Similarly to a traditional black-start scenario initiated by large synchronous generators in large power system, power electronics-based resources may be required to initiate black-starting procedures in ADNs. This is important for improving the network's resilience during grid disruptive events.

1) Enabling Concept: SSTs with a three-stage configuration can offer black-start capability. The concept is similar to supplying an islanded microgrid. It can be achieved by installing and controlling energy storage systems, such as batteries, in the SST's DC stages, both MV and LV [95].

2) Applications: With the black-start capability, the SSTs can significantly improve the resilience of ADNs. If energy storage systems are implemented, the SST can use them to form the grid during a network outage, feeding the connected loads temporarily, as shown in Fig. 7. This is particularly important for securing distributed energy resources after a blackout scenario to restore power to the areas affected, for example, by extreme weather conditions. Black-starting also brings up the challenge of powering the auxiliary power units of the SST. This can be overcome by using the internal DC capacitors to secure the black-start of SSTs [96]. In this solution, the SST is based on a modular architecture and distributed DC cells at the MV side (e.g., cascaded H-bridge converters), leading to a different startup challenge, the inrush currents. In 2020, Pugliese et al. focus on controlling the DC/DC power conversion stage, proposing a soft-shift start modulation technique to limit the inrush current during the DC link capacitors pre-charging [97].

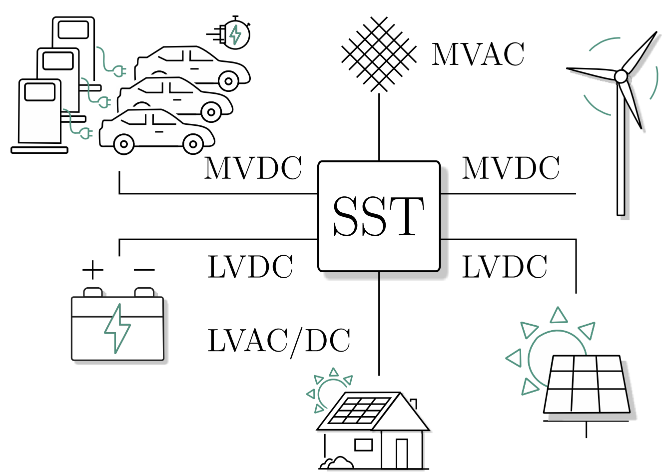


Fig. 8: SST enabling MVDC and LVDC applications, such as EV-Fast-Charging, wind power plants, ESS or PV.

3) Open Research Questions: Current literature on black start focuses mainly on the power electronics side, managing the inrush currents in capacitors coming from LVAC loads. For example, motor in-rush current from the LVAC side is challenging to manage during black start operation due to the limited SST current handling capability. More studies are needed to elaborate on a seamless black start procedure for the connected LVAC networks, including future hybrid LVDC and LVAC network topologies. A promising solution is represented by multi-micro grid concepts, where the SST is able to split the LVAC network into more islanded sub-microgrids, handling them separately. However, more work needs to be done, particularly on more selective and flexible control algorithms to provide a seamless transition of ADN to multiple islands.

D. DC Connectivity for Load and Generator Integration

DC technologies play a vital role in modern ADNs, enabling a direct integration of large DC loads (e.g., EV) and generators (e.g., PV, batteries) in the network.

1) Enabling Concept: The SST offers an excellent solution to integrate DC resources by providing two levels of DC voltage terminals, medium- and low-voltage, separated by an isolated DC-DC converter. The AC converters at both levels provide a reliable interconnection between the AC and DC domain. The DC terminals also allow a flexible power re-routing between the DC and AC networks to optimize the energy flow.

2) Applications: Integrating various components at the appropriate DC level provides advantages compared to the equivalent AC network integration. Thus, the applications enabled by the DC voltage terminals can be classified based on their voltage level.

Low-Voltage DC: Renewable resources such as PV and storage systems, fuel cells, and batteries are inherently DC sources and can be integrated directly into the LVDC link of SSTs by means of a single DC/DC stage, removing one additional AC/DC conversion stage. DC loads such as LEDs

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

for street lighting, EV charging, or small computing centers may also be integrated via the LVDC terminal of the SST. The optimal integration and management of these DC energy technologies enable DC microgrid concepts, as studied in several works, which can allow service provision to upstream AC networks [27], [76], [92], [98]–[103].

In addition to the direct integration of components at the SST LVDC level, the LVDC link can be extended to form a full DC network infrastructure, running in parallel and forming interconnection points with the existing AC network. This possibility allows the distribution of DC resources in the network and optimizes the energy flow by creating a meshed hybrid network structure [24]. The LVDC meshed hybrid networks provide better control over the power flow and reduce the overall losses in the AC system by providing a more flexible integration of renewable energy sources at the LVAC network [104], [105].

Medium-Voltage DC: The most popular application for MVDC multi-terminal SSTs is the integration of high-power EV fast charging stations (i.e., $> 1MW$), as reflected in Section VII, displaying a number of ongoing projects for SSTs in EV charging applications. The MVDC terminal can also establish meshed networks, particularly at the regional level, to connect different high-voltage substations. This feature can be used to improve the energy flow, provide a more reliable power supply to connected loads (both at LV and MV side), and enable higher integration of renewables (e.g., PV and wind turbines) or storage systems [106]–[108]. In a future scenario, the SST MVDC link can work as a DC power routing point among different networks.

3) Open Research Questions: The most pressing matter concerning applications in the DC domain is the general standardization process and the definition of best practices to align all potential stakeholders. As a result, virtually no DC infrastructure is available, and the corresponding products for direct integration at the MV and LV terminals do not reach a high TRL. Due to the lack of standards, current DC resources work at different voltage levels (e.g., EV charging stations above $800\,\text{V}$, while LED between $12-48\,\text{V}$). This problem could be solved by deploying SSTs based on modular multilevel topologies offering multiple LVDC terminals at different voltage levels, but here more studies are required. The issue concerning standardization also applies to DC protection systems, which are considered a significant bottleneck for integrating DC resources and are subject to many recent research endeavors.

VI. Industrial applications for SSTs

The previously listed applications of SSTs were focused on its integration in ADNs. However, the SST can also be applied in private networks, where the customers may benefit from its advanced capabilities: DC connection, power quality improvement, asynchronous connection, and reactive power injection. While this review can not provide a thorough investigation of all possible SST applications and their details, the following list still offers a brief addition, highlighting some SST applications outside the ADN domain.

- Harbors: cold-ironing of ferries and cruises requires connecting power in the order of several MWs and, depending on the ship's origin, of different frequency (i.e., $50-60\,\text{Hz}$) or voltage (up to $20\,\text{kV}$). The SST can work as a universal connecting point between shore and ship without the need to adapt the infrastructure. In addition, the DC terminals permits the integration of heavy-duty vehicles (e.g., trucks or forklifts) whenever the SST is not in use for cold ironing [77]–[79].

- Airports: the green airports' target aims to reduce airplane emissions during docking. Similar to cold-ironing for ships, a SST can supply the aircraft during docking, reducing the ground emissions of airplanes. The SST can provide the required power to several aircraft docked at the gates, reducing the electrical infrastructure's complexity of additional AC/AC converters. This can get more important with the advancements in the development of the more electric or hybrid electric aircraft [109], [110].

- Industrial plants: industrial plants are characterized by energy-intensive loads that generate low-frequency harmonics. SSTs can potentially isolate harmonic loads from the network, or if the power demand is high, they can compensate for the harmonic load content by controlled current injection. Small-size arc-furnace have been considered as interesting applications for SSTs [111].

- Offshore wind farms: the need for harvesting off-shore wind power and reducing the costs has led to the development of wind turbines in the $10\,\text{MWs}$ range. A higher transmission line voltage accommodates the additional power, requiring larger and heavier transformers. The SST can integrate the wind turbine power electronics, avoiding bulky LFTs, thus reducing weight and size inside the nacelle. In addition, it offers a DC connection that can be used if the off-shore turbines are connected through a multi-port DC network, as proposed by Rupp et al. and other studies in the past [106], [112]–[115].

- Data centers: Data centers are energy-intensive facilities that, at the same time, require high power quality. Power supplies must be robust against external disturbances to provide emergency power (e.g., Uninterruptible Power Supply) and redundant in case of hardware failure. The SST offers these basic features as standard. In addition, the availability of AC and DC ports enables different connection choices for the data center's hardware (e.g., computers on DC, air pumps on AC), increasing the overall system efficiency [116]–[119].

- Traction: The SST was originally developed by ABB to reduce the weight and footprint in train locomotives, avoiding the bulk transformer (mainly in 16.7 Hz) [120], [121]. The project was implemented in a test locomotive, which was a success from a technical point of view. The core advancement to achieve a weight and volume reduction is the usage of a MFT, in stead of the conventional 50 or 16.7 Hz Transformer, based on research findings such as in [122]–[125]. Yet, a simple reduction of space and weight did not justify the higher costs of an SST. In its early use, the SST did not reach its full potential, as the flexibility and range of services it could offer (see Section IV) were not fully leveraged. However, recent studies propose DC-based railway power grids that need high-power AC/DC interfaces or the possibility of utilizing energy storage systems to buffer acceleration and break power spikes [126], [127]. Both can be enabled by the deployment of SSTs. In addition, the SST offers the potential to optimize the flexibility of the temporal operation of large-scale railway systems to improve the resilience of the network, increasing its predictability [128]. Along these lines GE Vernova published a white paper discussing power electronic systems in railway power supply applications, as pure high quality power supply or load balancing systems, to avoid ”localised peak power” [129].

- Ships: On-board ship power networks are basically a high-power microgrid, varying from few MW (e.g., in ferries) up to 100 MW in cruise ships. The ships have pulsating loads, such as a radar, that require short-term high-power supply (several MW for few seconds). The SST can play an important role in the supply of these loads, as the double DC link stage can provide (with the right integration of energy storage) the required pulsating power [130].

VII. Overview of SST Demonstrators

First applications of SSTs can be found in pilot demonstrators and on-field implementations from 2011 onward. The following paragraphs give an overview of research and industry projects striving to advance the development of SSTs around the globe. The number of finished or ongoing projects has been illustrated in Fig. 9 to indicate the rising interest in the subject. It displays the past and currently ongoing projects in the solid green line. The dashed blue line shows a first-order extrapolation to indicate the trend of recent years. The downward trend of available data is mainly due to a lack of publicly available data. The reason for that is the rising amount of projects developed by industry, which provide very little public information. At least a handful of big names in the power and energy sector are informally known to work on developing SSTs-like technologies but are not yet ready to publish ongoing work or market-ready products.

1 MVA Prototype by GE and Wolfspeed: A single-phase, 13.8 kV to 270 V, Mega-Watt level solid state power station was developed and demonstrated using 10 kV SiC MOSFET and Schottky diodes technology. The applications intended by the consortium, including GE and Wolfspeed (formerly Cree, Inc.), were naval vessels and grid-power conversion applications where size and weight reduction are critical [131], [132].

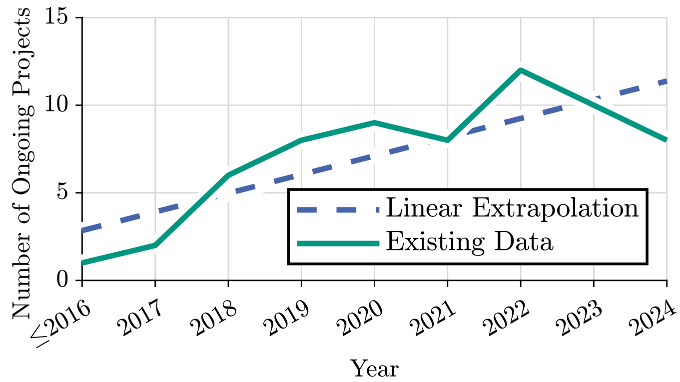


Fig. 9: Illustration of the demonstrators from Table III over the years, with an extrapolation, to indicate the recent trend. An average project length of around three years is assumed for the projects missing an official end date.

Suzhou Tongli AC/DC Hybrid Project: The demonstrator project Suzhou Tongli AC/DC hybrid Project in Jiangsu, China, shows in an urban area how renewable energy systems, DC loads such as data centers and DC charging stations for EVs, and battery storage can be efficiently connected to a 10 kV AC network using LVDC networks. In addition to conventional power converter solutions, power electronic transformers (SST) with a capacity of 1 MW developed in the project are used for DC supply. The project aims to increase the voltage quality in the network in the case of high feed-in from solar systems, improve the efficiency of integrating renewable energy systems, and develop the basis for new energy conversion technologies [133].

Single-Phase SST at Pusan National University: A 150 kW single-phase, 21-level prototype was developed at Pusan National University in collaboration with KERI and KEPCO [134]. The objective of the development was the interface between a 13.2 kV MVAC network and a bipolar 750 V DC distribution system.

ALigN: A lab demonstration of a SST interconnecting two low-voltage buses is being conducted in the project ALigN [135]. Simulation-based case studies for this configuration of the SST and its effectiveness in mitigating the impact of EV integration on the distribution network are presented in [136].

The LV-Engine: The LV-Engine is an £8.3M innovation project of SP Energy Networks, aiming to design and trial SST within the secondary distribution substation in the UK, constituting the world's first deployment of an SST. The project looks to exploit the perceived functionalities of SSTs to unlock enhanced flexibility and increased capacity at the low voltage network [17], [133], [137], [138].

Delta Americas - SST-based EV charging station: Delta Americas, a Delta Electronics, Inc. subsidiary, demonstrated a solid-state transformer-based 400 kW charging station [103]. It uses the 13.8 kV MV SiC MOSFET SST topology with an efficiency of 96.5 % [139].

FUNDRES: This project aims to bring significant technological improvements to the 9 kV-DC-based system for the future unified railway electric system. This project identifies

TABLE III: Existing demonstrators for SSTs.

Project	Year	Rating	Country	Application/Topic	Reference
GE and Wolfspeed	2011	1 MVA, 13.8 kV	US	Naval, Hybrid AC/DC networks	[131], [132]
Suzhou Tongli	2017-20	1000 kW, 10 kV	China	Hybrid AC/DC networks, EV chargers, Data Centers	[133]
Single-Phase - Pusan	2018	150 kW, 13.2 kV	South Korea	Hybrid AC/DC networks	[134]
ALigN	2018-20	250 kVA	Germany	EV chargers	[135], [140]
LV Engine	2018-22	500 kW, 10 kV	Scotland, UK	Hybrid AC/DC networks	[17], [137], [138]
Delta Americas	2018-22	400 kW, 13.8 kV	USA	EV chargers	[103], [139]
FUNDRES	2019-21	300 kW, 9 kV	EU	Railway systems	[141]
FlexNet-EkO	2019-22	>300 kW	Germany	Active distribution networks	[142]
ENSURE	2019-23	2 MW, 20 kV	Germany	Hybrid AC/DC networks, EV chargers	[143]
TIGON	2020-24	300 kW	EU	Hybrid AC/DC networks	[144]
HypoBatt	2021-2025	>2 MW	EU	Naval Vessel Charging	[145]
MUSE SST	2021	100 kW, 4.16 kV	US	Hybrid AC/DC networks	[146], [147]
AC2DC	2022	40 MW, ±60 kV	Germany	MVDC networks	[112]
50 kVA Current-Source	2022	50 kVA, 7.2 kV	US	EV chargers, Data Centers	[148]
ACT/MCT - ETH	2022	166 kW, 7 kV (DC)	CH	Efficiency of DC/DC conversion	[149], [150]
SSTAR	2022-25	50 kW	EU	Efficiency and new materials	[151]
Super - Heart	2022-25	100 kW	Germany	Hybrid AC/DC networks, Storage integration	[152]
Amperesand	2023	1.5 MW, 22 kV	Singapore	EV charging	[153], [154]
Eaton	2024	2 MW, 10 kV	China	LVDC Grid Interface	[155]

SSTs as one candidate to improve the railway electrification system [141].

FlexNet-EkO: In the FlexNet-EkO project, an asynchronous grid connection of an LVAC distribution network was investigated. The asynchronous grid connection was realized by a power electronic coupler based on a converter in series with a conventional transformer. The project aimed to improve the customer's voltage quality and decouple the local network from the upstream voltage levels. Ancillary services can also be provided for the upstream network. A prototype was developed, tested, and operated over several months on a real LV distribution network in eastern Germany [142].

ENSURE: As part of ENSURE, a German Kopernikus project in support of the energy transition in Germany, a 2 MW SST prototype is being developed for AC/DC conversion to connect DC charging stations to 20 kV AC [143]. A demonstrator will be realized where the SST is supplying an LVDC microgrid to investigate the protection, operation, and management of SST-based LVDC networks.

TIGON: Considering the advantages of hybrid AC/DC networks, this project focuses on improving the reliability and resilience of the network. The project also includes different showcases to demonstrate the hybrid network concept, with one case being implemented using a SST [144].

MUSE SST - FREEDM: A design for a Mobile Utility Support Equipment based Solid-State Transformer (MUSE-SST) for MV network interconnection has been reported by the Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Engineering Research Center with limited experimental evaluation using 10 kV SiC MOSFETs [146], [147]. The developers use a conventional cascaded voltage and current control loop as described in Section II to control the MV and LV DC links respectively. The three-phase dual active bridge controller is a simple PI controller, enhanced with the zero-voltage switching technique, aiming to reduce its losses.

HypoBatt: The HypoBatt project combines efforts of 18 European industrial and academic partners to "develop a modular, fast and simple multi-megawatt charging system" for naval vessel charging stations [145]. The endeavor is led by *Ikerlan*, Spain, and kicked off in June 2021.

AC2DC: The AC2DC project demonstrates how 60 kV MVDC networks can be used as an alternative to 110 kV AC networks to facilitate the deployment of renewable energy systems. It shows that 20 kV AC cables can be used for MVDC connections without the need for overhead lines or 110 kV AC cables and that the MVDC solution allows operating distributed renewable energy systems as a single power plant. The SST acts as a DC/DC transformer to connect LV systems to the MVDC network. A laboratory demonstrator of the DC/DC SST has been developed in the first phase of the project and the demonstration of the operation of an MVDC connection is planned in the next phase [112].

50 kVA Current-Source SST - Georgia Tech: Georgia Tech developed a new prototype using a single-stage current-source SST with 90 kV lightning protection. The SST has a rated power of 50 kVA and utilizes 3.3 kV SiC semiconductors. It is a first demonstration of the concept and requires further investigation to prove its feasibility [148]. The control is based on the initial concept of a model predictive method with priority shifting for voltage balancing in stacked low-inertia converters and SSTs [156]. The prototype was also deployed in a recent study, in which it was used to regulate the "feeder-end voltage" and perform reactive power injection based on the measured upstream MV voltage [25].

Developments at Swiss Federal Institute of Technology (ETH): The team at ETH has been working on a key component of the SST, i.e., the medium frequency transformer. The focus has been the development of an air-cooled DC transformer utilizing an Air-Core Transformer (ACT) or Magnetic-Core Transformer (MCT). The prototypes developed operate at a ratio of 1:1 at 7 kV with a rated power of 166 kW and switching frequency of 77.4 kHz for ACT and 40 kHz for MCT [149], [150].

SSTAR: The recently started EU-funded project SSTAR identifies the SST as the candidate for accelerating the transition toward the low-carbon economy. This project focuses on widening the operating voltage levels of SSTs by investigating the insulation levels of SST modules. This can potentially help address one of the critical challenges of SSTs and provide better solutions [151].

Super-HEART: The project is based on the results of the previous projects, HEART and U-HEART, both also located at the Christian-Albrechts-Universität Kiel (CAU) in partnership with the Fraunhofer Institute for Silicon Technology (ISIT) and Trinity College in Dublin. The target is the development of a ”high availability power converter for multi-source integration, for applications that are critical and have high downtime costs” [152].

Amperesand - NTU Singapore: Amperesand is the first spin-off company funded by a program involving Nanyang Technological University (NTU), the National University of Singapore (NUS), and Temasek. The prototype of 22 kV and 1.5 MW was developed in 2022 at NTU, after which the spin-off was launched in 2023. Their goal is to commercialize the technology, offering modular systems for 2, 4, and 6 MW primarily focused on the EV charging market. The system is based on SiC semiconductor cells configured in an Input Series Output Parallel topology [153], [154].

Eaton China - Prototype: Eaton's Research Labs in China have recently shared findings on their process of developing, testing, and validating the operation of a 2 MVA, 10 kV MV SST. The prototype uses an Input Series Output Parallel topology with the front end based on cascaded H-bridges and DABs to provide the isolated 800V DC output. The developed system withstands a lightning impulse of 75 kV and passes the 42 kV insulation test. The control is based on a commonly used MVAC current control technique to maintain a stable DC cell voltage paired with underlying power balancing and CHB modulation algorithms. The authors claim an overall efficiency of up to 98.3% depending on the loading conditions and a power density of 8kW/L [155].

VIII. Challenges for System Operators

Given the current state-of-the-art research on SSTs in ADNs illustrated in the previous sections, it is clear that several challenges still restrain the installation of SSTs in the distribution network. Many of the aforementioned points are still subject to research, and novel solutions are proposed continuously. Despite the regular progress made on the hardware side, the progress made to overcome challenges in integrating SSTs in distribution networks is limited. Therefore, this section presents an overview of the most noteworthy challenges for future stakeholders, such as system operators and utilities.

A. Protection Challenge of SST-fed Systems

Considering the deployment of SSTs in the field, one of the most pressing challenges arises in the protection domain.

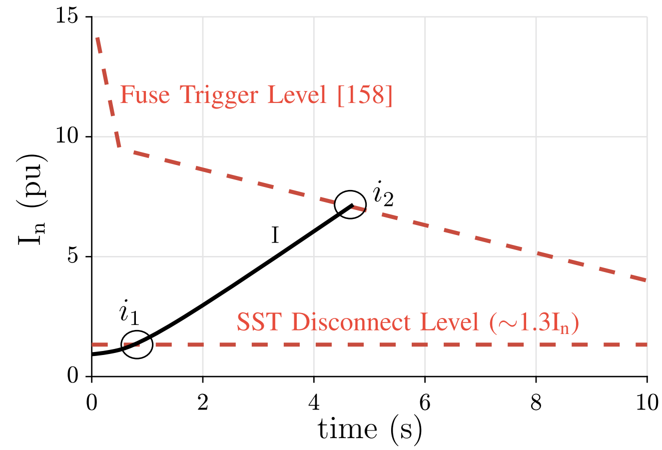


Fig. 10: Comparison between the trigger level (upper dashed red line) of a traditional LV distribution grid fuse and the disconnection level of a SST (lower dashed red line) due to its low over-current capabilities [158]. The black line qualitatively illustrates a potential short-circuit current and how it would trigger the fuse (i_2) or the SST disconnection (i_1).

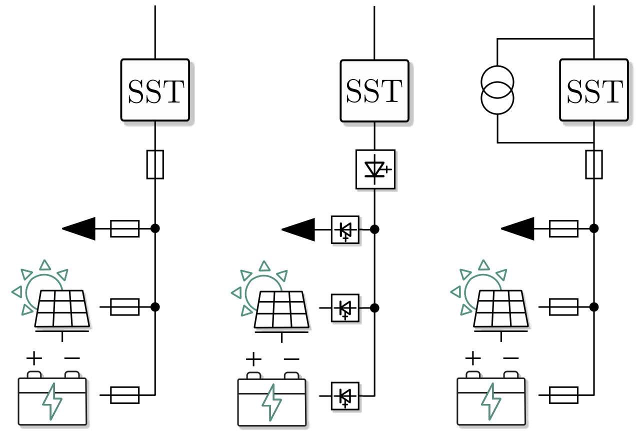
A significant challenge is the design of insulation coordination against lightning impulses. The standard impulse test is incompatible with SST protection structures, which requires new concepts to develop reliable power electronic-based power systems and tackle Basic Insulation Level requirements, as addressed in [157]. Although protecting the SST system itself is a challenge, this review focuses on the implications for the power system side. In a conventional system, a short-circuit event is managed by the selective triggering of fuses. The standard current trigger levels can easily be supplied by conventional transformers, but SSTs can not supply that current unless it is vastly overrated or violates the semiconductor thermal limits. Fig. 10 illustrates qualitatively the challenge using exemplary values from LV distribution grid standards [158]. The SST disconnects before the protection scheme is triggered to avoid rapid lifetime degradation or ultimately destruction due to thermal limit violation. This disables the selectivity of conventional protection schemes. Therefore, new ways to protect SST-fed ADNs or to supply the needed short-circuit currents need to be developed to enable the use of SSTs.

The over-current capabilities can be addressed on different layers, one of them is to advance the capabilities of the used materials, such as adding phase-change materials or microchannel cooling [159]. Alternatively novel approaches consider advanced control methods, e.g. to reduce the thermal stress on semiconductors by decreasing the converter's switching frequency on the LVAC side and, thus, the switching losses. This makes room to exceed the converter's current limitation while obeying the same thermal rating [160]. An additional option is the dynamic decrease and ramp up of the voltage to allow the regulation of the short-circuit current flowing in the SST-fed network. This feature enables the use of existing protection systems, only increasing the fault duration [161]. Considering single-phase fault cases, most

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

TABLE IV: Protection Schemes of SST-fed Networks.

Conventional Breaker	Solid-State Breaker	Parallel LFT
Over-sized SST Low Cost Breaker Slow acting	Normal-sized SST High Cost Breaker Fast acting	Normal-sized SST Low Cost Breaker Slow acting Additional LFT



common in distribution systems, the SST can provide better supply continuity. It allows the supply of networks using its two-phase operation capability [161], [162], supplying only the remaining two phases while isolating the faulty one. In addition, the SST can perform a better fault ride-through during faults using its load control capabilities [163].

With the mentioned challenges and issues in mind, the current protection strategies for SST-fed networks can be classified as seen in Table IV, where three options are considered:

- The first method relies on maintaining the conventional protection system and over-sizing the SST, enabling it to supply the full short-circuit current needed for the protection selectivity. This approach may significantly increase the costs of SSTs.
- A second method is to re-think the protection system, integrating advanced technologies such as hybrid or solid-state breakers. These technologies can interrupt the current in microseconds (solid state breakers) or milliseconds (hybrid breakers), requiring no converter oversizing. However, the cost of hybrid or solid-state breakers is still several times higher than that of conventional breakers, and only a limited range of products is available on the market.
- In a third method, the SST is installed in parallel with a LFT. In this case, the SST does not work as a grid-forming unit, allowing the LFT to provide the needed short-circuit current to operate conventional protection systems. This solves the short-circuit problem but greatly constrains the control capabilities of the SST.

In addition to the LV AC protection challenges, DC micro-grids, e.g. big EV fast-charging stations as described in Section V, face similar protection issues during faults. The slow opening speed of the electromechanical relays and fuses results in increased currents within DC distribution systems, which are characterized by a very small impedance. These fault currents exceed the short-circuit limits of the semiconductor switches, and device-level protection systems trip well before the electromechanical relays and fuses. Hence, the protection of the SST is closely linked to the protection of the power electronics itself, with the primary device-level mechanism being the de-saturation protection. Due to the low thermal mass of modern Wide-Bandgap Semiconductor (WBG) devices, such as GaN and SiC, which results in a brief short-circuit withstand time, alternative methods to desat protection have been investigated, including those that utilize the time derivative of the current, i.e., di/dt. [164], [165]. While solid-state breakers with ultra-fast opening times (microseconds) are the most suitable protection for power electronic converters, they lack standardization as discussed in [166] and availability, with [167] as one of the very few currently available off-the-shelf equipment options. Another protection option involves leveraging the current limiting capability and includes common protection mechanisms such as under-voltage protection and the use of residual current devices. In [168], under-voltage protection was implemented for an SST connected to three feeders supplying EV chargers. After an under-voltage fault trip, voltage ramps were applied at the output terminals with current limitation. Consequently, the conventional molded-case circuit breakers (MCCBs) installed at the affected feeder trip due to overload. Since the MCCB operation necessitates manual intervention to clear the fault, implementing a SST fault ride-through strategy could reduce interruption time and avoid manual intervention. In this strategy, the SST would maintain a limited constant current at a lower output voltage during the fault, causing the MCCB of the faulty feeder to trip and allow for proper fault discrimination.

B. Standards and Grid Codes

Currently, no international standard can be directly applied to install SSTs in the power system. Some of them are too restrictive, like the standard IEC-62040 for Uninterruptible Power Supply, which is dedicated to small critical loads, or have a very large scope, such as the IEC-62477, generalized for the integration of any power electronic converter [169], [170]. National regulatory entities are developing novel standards for EV charging stations, making a fit-for-all SST solution challenging. Dedicated standards need to be developed internationally, with the requirement to synchronize with under-developed standards for DC resources (e.g., EV). The *IEEE Standards Associations - Project 3105* is currently working on formulating a ”Recommended Practice for Design and Integration of Solid State Transformers in Electric Grid” [171]. In addition, the Electric Power Research Institute (EPRI - US), started working on understanding the grid code requirements by deploying a low voltage 25 kVA SST in a utility service area [172]. In that context, the protection of the SST itself (e.g., the Basic Insulation Level) needs to be clearly defined and examined to avoid unexpected outages and downtime [157]. Eventually, also the application side needs to be taken into account to ensure the SST’s compliance, e.g., fault ride-through capabilities of wind farms [173].

This article has been accepted for publication in IEEE Transactions on Smart Grid. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TSG.2025.3574007

C. Operator Experience

System operators have trained personnel for electro-mechanical actuators but limited experience with power electronic-based devices. A comprehensive re-training of installation and maintenance personnel is needed before the SST can be a valid business-as-usual solution for operators.

D. Supply chain

Electro-mechanical devices, such as cables, transformers, and breakers, can be easily stored and employed upon request. This is not always true for power electronic components, which can age quickly if not stored properly (e.g., temperature variations, humidity) or for too long. The supply chain of SST components for system operators and component manufacturers needs to be restructured, prioritizing ”on-demand” requests rather than stockpiling. An advantage for that can be the recent advancements in condition monitoring of power electronic systems, making unexpected component failures less likely [174]. Alas, the demand for LFTs has been skyrocketing in recent years, increasing ordering lead times to up to 2 years, a fourfold increase compared to pre-2022 lead times, according to a recent NREL report [175]. The authors also found increasing prices of LFTs by ”as much as 4-9 times”, which, paired with the estimation of an increase of overall LFT stock capacity by 160%-260% by 2050 compared to 2021, might lead operators to look for alternative options [175].

E. New services regulations

Regulations are constantly evolving, but it is still clear that most frameworks are built around large generation units and a power system with unidirectional power flow. These regulations will undergo significant changes even without SSTs. This may allow novel grid services, such as voltage- and frequency-based load control, smart demand response, and fast-acting (re-)active power support, to unfold their true potential. Regulation frameworks that allow owners to fully leverage the functionality of SSTs from an economic perspective may lead to widespread acceptance.

F. Commercialization

The technical advantages of installing SSTs are evident, particularly from a power flexibility point of view. However, several of them are challenging to transform into clear economic advantages due to the lack of remuneration schemes (e.g., harmonic compensation). Business cases for SSTs should be developed, taking into account that they can provide multiple services simultaneously. Without these analyses, public companies may only implement SSTs due to governmental policies, while private companies may be hesitant to take the risk, hindering the widespread integration of SSTs.

This *Task Force* has identified two significant bottlenecks for developing cost-effective business cases for SSTs. The first one is the SST versatility in offering more services simultaneously, making it hard to perform an apple-to-apple comparison with other technologies. The second one is the difficulty of quantifying economic returns for the provision of services. It is simply uncommon to compensate ancillary services for very fast-acting and distributed systems. The services highlighted above are undoubtedly vital and can enhance the future power system. Still, the provision is unattractive due to insufficient regulation and economic standards to compensate for the effort. What exactly is needed to successfully motivate investments in SSTs from an economic perspective? For the task force members, the following points are the most pressing ones:

- Regulation framework for the compensation of short-term service providers, enabling simple quantification
- Best practice for SST models for large scale grid simulations
- Standardization for the DC domain, which plays a major role for SSTs

G. Resonances with other converters

The increased penetration of converters in the power system gives rise not only to the challenges of reduced inertia or different fault behavior, but also to the possible increase in resonances between converters in parallel operation [176]. This does include SST-like systems, since eventually the grid sees just another converter impedance. To mitigate this issue, a variety of solution can be applied, ranging from hardware filtering to sophisticated control algorithms, such as active damping and passivity based control methods [91], [177], [178].

IX. Future Trends

The above challenges in mind, this section focuses on potential future technological disruptions that may impact the development and deployment of SSTs. In terms of industrial applications, the role of SSTs in data centers has been addressed in the past. Although the increase in efficiency of processing units has contributed to stable power consumption levels in recent years, the increasing use of AI applications presents a potential challenge [179]. This emerging trend could lead to a significant increase in energy demand within data centers, with the opportunity for SSTs to serve as a resilient grid interface facilitating the scaling of data centers and providing the necessary DC voltage levels [180]. From a material development point of view, the advent of WBG devices will accelerate the potency of converters over the next decades. The fast switching frequencies of SiC and GAN modules allow new control strategies, paired with reduced losses and higher operating temperatures [181], [182]. Furthermore, WBG devices have a higher power density; on the downside, current developments do not allow blocking voltages that can compete with the levels of common Si modules; therefore, the technology is likely to be deployed in small and mobile applications first.

Considering the general converter design strategy, the SST's dynamic efficiency should also be considered in addition to the static efficiency. This is of particular importance for SSTs as they may operate under frequent transient events such as load changes. Switching losses, inductor and capacitor losses, control loop parameters, thermal management, and parasitic losses are the key factors that influence the dynamic efficiency of SSTs.

With respect to the power system perspective, further research on power electronic reliability (based on physic-informed models) and its implications on the classical power system reliability (based on statistical models) could be an enabling factor for SSTs. A generalized approach to incorporate the consideration of power electronic reliability into the general framework of reliability criteria of the power system, such as System Average Interruption Duration Index or System Average Interruption Frequency Index will be essential to estimate the true value of SST as a power system asset.

X. Conclusion

Deploying SSTs in ADNs is a transformative process that faces several challenges, including protection issues, the absence of specific international standards, operators retraining, supply chain adaptation, new service regulations, and the need for compelling business cases. Overcoming these challenges is essential for a successful SST integration into ADNs. To provide guidance in addressing these challenges, this manuscript provides an overview of the state-of-the-art research on power system-level, paired with a critical review and open questions of services and applications enabled by SSTs. This is accompanied by a discussion on the protection and reliability of SSTs in ADNs, stressing the importance of focusing research activities on these two topics for seamless SST network integration. Additionally, a qualitative comparison of competing technologies, e.g., LTCs or HTs is made, followed by an extensive list of existing prototypes and demonstrators, highlighting the increased interest in SSTs.

Acknowledgment

The authors would like to acknowledge the use of AI tools in preparing this manuscript. Specifically, OpenAI's ChatGPT assisted with text refinement and translation, and Grammarly corrected punctuation and grammar.

References

[1] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, and N. D. Hatziargyriou, "Distributed and decentralized voltage control of smart distribution networks: Models, methods, and future research," *IEEE Transactions on Smart Grid*, vol. 8, no. 6, pp. 2999–3008, 2017.

[2] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, "Foundations and challenges of low-inertia systems (invited paper)," in *2018 Power Systems Computation Conference (PSCC)*, Jun. 2018, pp. 1–25.

[3] G. De Carne, M. Liserre, K. Christakou, and M. Paolone, "Integrated voltage control and line congestion management in active distribution networks by means of smart transformers," in *2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, Jun. 2014, pp. 2613–2619.

[4] J. E. Huber and J. W. Kolar, "Volume/weight/cost comparison of a 1MVA 10 kV/400 V solid-state against a conventional low-frequency distribution transformer," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2014, pp. 4545–4552.

[5] E. J. Coster, J. M. A. Myrzik, B. Kruimer, and W. L. Kling, "Integration issues of distributed generation in distribution grids," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 28–39, 2011.

[6] C. Masters, "Voltage rise: The big issue when connecting embedded generation to long 11 kV overhead lines," *Power Engineering Journal*, vol. 16, no. 1, pp. 5–12, 2002.

[7] R. Kabiri, D. G. Holmes, B. P. McGrath, and L. G. Meegahapola, "LV grid voltage regulation using transformer electronic tap changing, with PV inverter reactive power injection," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 4, pp. 1182–1192, Dec. 2015.

[8] X. Gao, R. Zhu, G. De Carne, and M. Liserre, "Comparison of voltage support services by means of STATCOM and smart transformer in medium voltage grid," in *2018 13th IEEE Conference on Industrial Electronics and Applications (ICEA)*, Wuhan, China, May 2018, pp. 946–951.

[9] L. Gyugyi, C. Schauder, and K. Sen, "Static synchronous series compensator: A solid-state approach to the series compensation of transmission lines," *IEEE Transactions on Power Delivery*, vol. 12, no. 1, pp. 406–417, 1997.

[10] N. Hingorani, "Flexible AC transmission," *IEEE Spectrum*, vol. 30, no. 4, pp. 40–45, 1993.

[11] H. Johal and D. Divan, "Design considerations for series-connected distributed FACTS converters," *IEEE Transactions on Industry Applications*, vol. 43, no. 6, pp. 1609–1618, 2007.

[12] X. She, A. Q. Huang, and R. Burgos, "Review of solid-state transformer technologies and their application in power distribution systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 186–198, Jan. 2013.

[13] J. E. Huber and J. W. Kolar, "Solid-state transformers: On the origins and evolution of key concepts," *IEEE Industrial Electronics Magazine*, vol. 10, no. 3, pp. 19–28, Jan. 2016.

[14] M. Liserre, G. Buticchi, M. Andresen, G. De Carne, L. F. Costa, and Z.-X. Zou, "The smart transformer: Impact on the electric grid and technology challenges," *IEEE Industrial Electronics Magazine*, vol. 10, no. 2, pp. 46–58, Jun. 2016.

[15] M. Liserre, M. A. Perez, M. Langwasser, C. A. Rojas, and Z. Zhou, "Unlocking the hidden capacity of the electrical grid through smart transformer and smart transmission," *Proceedings of the IEEE*, vol. 111, no. 4, pp. 421–437, 2023.

[16] T. Guillod, F. Krismer, R. Färber, C. M. Franck, and J. W. Kolar, "Protection of MV/LV solid-state transformers in the distribution grid," in *IECON 2015 - 41st Ann. Conf. IEEE Ind. Electron. Soc.*, Nov. 2015, pp. 003 531–003 538.

[17] K. Smith, D. Wang, R. Peña-Alzola, A. Burt, Graeme M.and Kazerooni, and M. Eves, "Approach to assessing the effective integration of solid-state transformers in LV networks," in *CIRED 2020 Berlin Workshop (CIRED 2020)*, vol. 2020, Berlin, Jan. 2020, pp. 182–185.

[18] A. Q. Huang, "Medium-voltage solid-state transformer: Technology for a smarter and resilient grid," *IEEE Industrial Electronics Magazine*, vol. 10, no. 3, pp. 29–42, Jan. 2016.

[19] J. E. Huber and J. W. Kolar, "Applicability of solid-state transformers in today's and future distribution grids," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 317–326, Jan. 2019.

[20] S. A. Saleh, E. Ozkop, B. Alsayid, C. Richard, X. F. St. Onge, K. M. McDonald, and L. Chang, "Solid-state transformers for distribution systems–part II: Deployment challenges," *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 5708–5716, Nov. 2019.

[21] J. Rodrigues, C. Moreira, and J. P. Lopes, "Smart transformers - enabling power-frequency regulation services for hybrid AC/DC networks," in *Power Tech Conference*, Milano, Jan. 2019, pp. 1–6.

[22] F. Ruiz, M. A. Perez, J. R. Espinosa, T. Gajowik, S. Stynski, and M. Malinowski, "Surveying solid-state transformer structures and controls: Providing highly efficient and controllable power flow in distribution grids," *IEEE Industrial Electronics Magazine*, vol. 14, no. 1, pp. 56–70, Jan. 2020.

[23] Y. Tahir, I. Khan, S. Rahman, M. F. Nadeem, A. Iqbal, Y. Xu, and M. Rafi, "A state-of-the-art review on topologies and control techniques of solid-state transformers for electric vehicle extreme fast charging," *IET Power Electronics*, vol. 14, no. 9, pp. 1560–1576, Jan. 2021.

[24] R. Zhu, M. Liserre, M. Langwasser, and C. Kumar, "Operation and control of the smart transformer in meshed and hybrid grids: Choosing the appropriate smart transformer control and operation scheme," *IEEE Industrial Electronics Magazine*, vol. 15, no. 1, pp. 43–57, Mar. 2021.

[25] L. Zheng, A. Marellapudi, V. R. Chowdhury, N. Bilakanti, R. P. Kandula, M. Saeedifard, S. Grijalva, and D. Divan, "Solid-state transformer and hybrid transformer with integrated energy storage in active distribution grids: Technical and economic comparison, dispatch, and control," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 4, pp. 3771–3787, Aug. 2022.

[26] D. Cervero, M. Fotopoulou, J. Muñoz-Cruzado, D. Rakopoulos, F. Stergiopoulos, N. Nikolopoulos, S. Voutetakis, and J. F. Sanz, "Solid state

transformers: A critical review of projects with relevant prototypes and demonstrators," *Electronics*, vol. 12, no. 4, p. 931, Jan. 2023.

[27] X. Yu, X. She, X. Zhou, and Alex. Q. Huang, "Power management for DC microgrid enabled by solid-state transformer," *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 954–965, Jan. 2014.

[28] G. De Carne, M. Langwasser, R. Zhu, and M. Liserre, "Smart transformer-based single phase-to-neutral fault management," *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 1049–1059, Jan. 2019.

[29] S. Debnath, J. Qin, B. Bahrani, M. Saeedifard, and P. Barbosa, "Operation, control, and applications of the modular multilevel converter: A review," *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 37–53, Jan. 2015.

[30] M. A. Perez, S. Ceballos, G. Konstantinou, J. Pou, and R. P. Aguilera, "Modular multilevel converters: Recent achievements and challenges," *IEEE Open Journal of the Industrial Electronics Society*, vol. 2, pp. 224–239, 2021.

[31] R. Teodorescu, M. Liserre, and P. Rodríguez, Eds., *Grid Converters for Photovoltaic and Wind Power Systems*. John Wiley & Sons, Jan. 2011.

[32] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications*. John Wiley & Sons, Jan. 2010.

[33] D. Groß, E. Sanchez-Sanchez, E. Prieto-Araujo, and O. Gomis-Bellmunt, "Dual-port grid-forming control of mmcs and its applications to grids of grids," *IEEE Transactions on Power Delivery*, vol. 37, no. 6, pp. 4721–4735, 2022.

[34] R. Zeng, L. Xu, L. Yao, and B. W. Williams, "Design and operation of a hybrid modular multilevel converter," *IEEE Transactions on Power Electronics*, vol. 30, no. 3, pp. 1137–1146, Mar. 2015.

[35] D. Shah and M. L. Crow, "Online volt-var control for distribution systems with solid-state transformers," *IEEE Transactions on Power Delivery*, vol. 31, no. 1, pp. 343–350, Feb. 2016.

[36] H. Zhang, W. Xiang, and J. Wen, "Dual grid-forming control with energy regulation capability of MMC-HVDC system integrating offshore wind farms and weak grids," *IEEE Transactions on Power Systems*, vol. 39, no. 1, pp. 261–272, Jan. 2024.

[37] F. Wald, Q. Tao, and G. De Carne, "Virtual synchronous machine control for asynchronous grid connections," *IEEE Transactions on Power Delivery*, vol. 39, no. 1, pp. 397–406, Feb. 2024.

[38] R. De Doncker, D. Divan, and M. Kheraluwala, "A three-phase soft-switched high-power-density DC/DC converter for high-power applications," *IEEE Transactions on Industry Applications*, vol. 27, no. 1, pp. 63–73, Jan. 1991.

[39] S. Inoue and H. Akagi, "A bidirectional isolated DC–DC converter as a core circuit of the next-generation medium-voltage power conversion system," *IEEE Transactions on Power Electronics*, vol. 22, no. 2, pp. 535–542, Mar. 2007.

[40] S. Falcones, R. Ayyanar, and X. Mao, "A DC–DC multiport-converter-based solid-state transformer integrating distributed generation and storage," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2192–2203, Jan. 2013.

[41] H. Fan and H. Li, "High-frequency transformer isolated bidirectional DC–DC converter modules with high efficiency over wide load range for 20 kVA solid-state transformer," *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3599–3608, 2011.

[42] G. Ortiz, M. G. Leibl, J. E. Huber, and J. W. Kolar, "Design and experimental testing of a resonant DC–DC converter for solid-state transformers," *IEEE Transactions on Power Electronics*, vol. 32, no. 10, pp. 7534–7542, 2017.

[43] F. Xiong, J. Wu, Z. Liu, and L. Hao, "Current sensorless control for dual active bridge DC–DC converter with estimated load-current feedforward," *IEEE Transactions on Power Electronics*, vol. 33, no. 4, pp. 3552–3566, Apr. 2018.

[44] W.-H. Chen, J. Yang, L. Guo, and S. Li, "Disturbance-observer-based control and related methods—an overview," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 2, pp. 1083–1095, Feb. 2016.

[45] A. Tong, L. Hang, H. S.-H. Chung, and G. Li, "Using sampled-data modeling method to derive equivalent circuit and linearized control method for dual-active-bridge converter," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 2, pp. 1361–1374, Apr. 2021.

[46] S.-C. Tan, Y.-M. Lai, and C.-K. Tse, *Sliding Mode Control of Switching Power Converters: Techniques and Implementation*. CRC Press, Jan. 2017.

[47] F. Sommer, N. Menger, T. Merz, N. Soltau, S. Idaka, and M. Hiller, "Time domain modeling of zero voltage switching behavior considering parasitic capacitances for a dual active bridge," in *2023 11th International Conference on Power Electronics and ECCE Asia (ICPE 2023 - ECCE Asia)*, May 2023, pp. 13–20.

[48] H. Chen and D. Divan, "Soft-switching solid-state transformer (S4T)," *IEEE Transactions on Power Electronics*, vol. 33, no. 4, pp. 2933–2947, Apr. 2018.

[49] L. Zheng, R. P. Kandula, and D. Divan, "Soft-switching solid-state transformer with reduced conduction loss," *IEEE Transactions on Power Electronics*, vol. 36, no. 5, pp. 5236–5249, May 2021.

[50] Y. Yan, Y. Sun, C. Teixeira, and X. Yang, "Soft switching modulation strategy for modular multilevel solid-state transformer with integrated switching pairs," in *2024 IEEE 10th International Power Electronics and Motion Control Conference (IPEMC2024-ECCE Asia)*, May 2024, pp. 339–344.

[51] X. Ren, Y. Jiang, H. Weng, T. Long, and D. Xu, "A soft-switching solid-state transformer module," in *2023 IEEE 14th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Jun. 2023, pp. 185–191.

[52] ——, "Design and testing of a soft-switching solid-state transformer module," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 12, no. 6, pp. 5977–5989, Dec. 2024.

[53] "Grid forming technology: Bulk power system reliability considerations," NERC, White Paper, Dec. 2021.

[54] G.-S. Seo, M. Colombino, I. Subotic, B. Johnson, D. Groß, and F. Dörfler, "Dispatchable virtual oscillator control for decentralized inverter-dominated power systems: Analysis and experiments," in *2019 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Mar. 2019, pp. 561–566.

[55] M. Lu, S. Dutta, V. Purba, S. Dhople, and B. Johnson, "A grid-compatible virtual oscillator controller: Analysis and design," in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2019, pp. 2643–2649.

[56] X. He, L. Huang, I. Subotić, V. Häberle, and F. Dörfler, "Quantitative stability conditions for grid-forming converters with complex droop control," *IEEE Transactions on Power Electronics*, vol. 39, no. 9, pp. 10 834–10 852, Sep. 2024.

[57] Z. Wang and J. Wang, "Review on implementation and assessment of conservation voltage reduction," *IEEE Transactions on Power Systems*, vol. 29, no. 3, pp. 1306–1315, 2014.

[58] A. Ballanti and L. F. Ochoa, "Voltage-led load management in whole distribution networks," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1544–1554, 2018.

[59] A. Carreno, M. Perez, C. Baier, A. Huang, S. Rajendran, and M. Malinowski, "Configurations, power topologies and applications of hybrid distribution transformers," *Energies*, vol. 14, no. 1215, 2021.

[60] Y. Takahashi, T. Isobe, and H. Tadano, "Series reactive power compensator with reduced capacitance for hybrid transformer," in *International Power Electronics Conference (IPEC-niigata 2018 -ECCE Asia)*, 2018, pp. 3375–3382.

[61] A. Wiemer and J. Biela, "Comparison of hybrid transformers with uni- and bidirectional auxiliary converter," in *21st European Conference on Power Electronics and Applications (EPE'19-ECCE Europe)*, 2019, pp. P.1–P.11.

[62] J. Burkard and J. Biela, "Evaluation of topologies and optimal design of a hybrid distribution transformer," in *17th European Conference on Power Electronics and Applications (EPE'15 ECCE-europe)*, 2015, pp. 1–10.

[63] D. Divan and P. Kandula, "Distributed power electronics: An enabler for the future grid," *CPSS Transactions on Power Electronics and Applications*, vol. 1, no. 1, pp. 57–65, 2016.

[64] X. Zhu, A. Singh, and B. Mather, "Grid value investigation of medium-voltage back-to-back converters," in *2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Feb. 2021, pp. 1–5.

[65] ——, "Grid value analysis of medium-voltage back-to-back converter on DER hosting enhancement," *IEEE Transactions on Power Delivery*, vol. 38, no. 1, pp. 553–563, Feb. 2023.

[66] G. De Carne, M. Liserre, and C. Vournas, "On-line load sensitivity identification in LV distribution grids," *IEEE Transactions on Power Systems*, vol. 32, no. 2, pp. 1570–1571, Mar. 2017.

[67] G. De Carne, G. Buticchi, M. Liserre, and C. Vournas, "Load control using sensitivity identification by means of smart transformer," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 2606–2615, Jan. 2018.

[68] J. Chen, M. Liu, G. De Carne, R. Zhu, M. Liserre, F. Milano, and T. O'Donnell, "Impact of smart transformer voltage and frequency

support in a high renewable penetration system," *Electric Power Systems Research*, vol. 190, Jan. 2021.

[69] Q. Tao, J. Geis-Schroer, F. Wald, M. Courcelle, M. Langwasser, T. Leibfried, M. Liserre, and G. De Carne, "The potential of frequency-based power control in distribution grids," in *2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Jun. 2022, pp. 1–6.

[70] "Generating systems on the low-voltage grid minimum technical requirements for the connection and parallel operation of generation systems on the low-voltage grid," VDE, Standard VDE-AR-N 4105, Nov. 2018.

[71] G. De Carne, G. Buticchi, Z. Zou, and M. Liserre, "Reverse power flow control in a ST-fed distribution grid," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3811–3819, Jan. 2018.

[72] J. Rodrigues, C. Moreira, and J. P. Lopes, "Smart transformers as active interfaces enabling the provision of power-frequency regulation services from distributed resources in hybrid AC/DC grids," *Applied Sciences*, vol. 10, no. 4, p. 1434, Jan. 2020.

[73] S. Giacomuzzi, M. Langwasser, G. De Carne, G. Buja, and M. Liserre, "Smart transformer-based medium voltage grid support by means of active power control," *CES Transactions on Electrical Machines and Systems*, vol. 4, no. 4, pp. 285–294, Jan. 2020.

[74] G. De Carne, G. Buticchi, M. Liserre, and C. Vournas, "Frequency-based overload control of smart transformers," in *2015 IEEE Eindhoven PowerTech*, Jan. 2015, pp. 1–5.

[75] G. De Carne, Z. Zou, G. Buticchi, M. Liserre, and C. Vournas, "Overload control in smart transformer-fed grid," *Applied Sciences*, vol. 7, no. 2, p. 208, Jan. 2017.

[76] X. Gao, F. Sossan, K. Christakou, M. Paolone, and M. Liserre, "Concurrent voltage control and dispatch of active distribution networks by means of smart transformer and storage," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 8, pp. 6657–6666, Jan. 2018.

[77] T. Tran, S. Nahavandi, and R. Reid, "Power demand and energy usage of container crane - comparison between AC and DC drives," in *2008 43rd International Universities Power Engineering Conference*, Sep. 2008, pp. 1–5.

[78] "ABB improves power quality at jakarta's koja container terminal," https://new.abb.com/news/detail/46067/abb-improves-power-quality-at-jakartas-koja-container-terminal, Mar. 2017.

[79] VM. Hrishikesan, X. Gao, M. Langwasser, and M. Liserre, "Potential and impacts of smart transformer in green harbours," in *2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Jun. 2022, pp. 1–6.

[80] Q. Ye, R. Mo, and H. Li, "Multiple resonances mitigation of paralleled inverters in a solid-state transformer (SST) enabled AC microgrid," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 4744–4754, 2018.

[81] Z.-X. Zou, M. Liserre, Z. Wang, M. Cheng, and S. Fan, "Resonance damping in a smart transformer-based microgrid," in *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society*, Nov. 2015, pp. 000 956–000 964.

[82] V. M. Hrishikesan, C. Kumar, and M. Liserre, "Voltage quality improvement in smart transformer integrated distribution grid," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 5386–5391.

[83] C. Kumar, R. Zhu, and M. Liserre, "Investigation of load compensation features of smart transformer in medium voltage grid," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 4260–4265.

[84] C. Kumar and M. Liserre, "Operation and control of smart transformer for improving performance of medium voltage power distribution system," in *2015 IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Jun. 2015, pp. 1–6.

[85] A. Q. Huang, Q. Zhu, L. Wang, and L. Zhang, "15 kV SiC MOSFET: An enabling technology for medium voltage solid state transformers," *CPSS Transactions on Power Electronics and Applications*, vol. 2, no. 2, pp. 118–130, 2017.

[86] R. Abe, H. Taoka, and D. McQuilkin, "Digital grid: Communicative electrical grids of the future," *IEEE Transactions on Smart Grid*, vol. 2, no. 2, pp. 399–410, 2011.

[87] M. Sanduleac, J. F. Martins, I. Ciornei, M. Albu, L. Toma, V. F. Pires, L. Hadjidemetriou, and R. Sauba, "Resilient and immune by design microgrids using solid state transformers," *Energies*, vol. 11, no. 12, Dec. 2018.

[88] S. Parashar, A. Kumar, and S. Bhattacharya, "High power medium voltage converters enabled by high voltage SiC power devices," in *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, May 2018, pp. 3993–4000.

[89] A. Singh, X. Zhu, B. Mather, and F. Gurara, "Grid application and controls development for medium-voltage SiC-based grid interconnects," in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct. 2020, pp. 3754–3760.

[90] W. A. Rodrigues, L. M. F. Morais, T. R. Oliveira, R. A. S. Santana, A. P. L. Cota, and W. W. A. G. Silva, "Analysis of solid state transformer based microgrid system," in *2016 12th IEEE International Conference on Industry Applications (INDUSCON)*, 2016, pp. 1–6.

[91] Z. Qu, Y. Wang, T. Pan, and W. Tao, "Stability analysis and active damping control method of DC microgrid based on solid-state transformer," in *2018 IEEE 2nd International Electrical and Energy Conference (CIEEC)*, 2018, pp. 292–297.

[92] X. She, A. Q. Huang, S. Lukic, and M. E. Baran, "On integration of solid-state transformer with zonal DC microgrid," *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp. 975–985, Jan. 2012.

[93] C. Kumar and M. Liserre, "A new prospective of smart transformer application: Dual microgrid (DMG) operation," in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Nov. 2015, pp. 004 482–004 487.

[94] S. Giacomuzzi, G. De Carne, S. Pugliese, G. Buja, M. Liserre, and A. Kazerooni, "Synchronization of low voltage grids fed by smart and conventional transformers," *IEEE Transactions on Smart Grid*, vol. 12, no. 4, pp. 2941–2951, Jul. 2021.

[95] M. Couto, J. P. Lopes, and C. Moreira, "Developing black start strategies in multi-microgrids exploiting smart transformers," in *2020 International Conference on Smart Energy Systems and Technologies (SEST)*, Sep. 2020, pp. 1–6.

[96] M. Saeed, J. M. Cuartas, A. Rodríguez, M. Arias, and F. Briz, "Energization and start-up of CHB-based modular three-stage solid-state transformers," *IEEE Transactions on Industry Applications*, vol. 54, no. 5, pp. 5483–5492, 2018.

[97] S. Pugliese, G. Buticchi, R. A. Mastromauro, M. Andresen, M. Liserre, and S. Stasi, "Soft-start procedure for a three-stage smart transformer based on dual-active bridge and cascaded h-bridge converters," *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 11 039–11 052, 2020.

[98] X. She, X. Yu, F. Wang, and A. Q. Huang, "Design and demonstration of a 3.6-kV–120-V/10-kVA solid-state transformer for smart grid application," *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 3982–3996, Jan. 2014.

[99] A. Agrawal, C. S. Nalamati, and R. Gupta, "Hybrid DC–AC zonal microgrid enabled by solid-state transformer and centralized ESD integration," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 11, pp. 9097–9107, 2019.

[100] C. Kumar, R. Zhu, G. Buticchi, and M. Liserre, "Sizing and SOC management of a smart-transformer-based energy storage system," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 8, pp. 6709–6718, Aug. 2018.

[101] V. M. Hrishikesan, D. Das, C. Kumar, H. B. Gooi, S. Mekhilef, and X. Guo, "Increasing voltage support using smart power converter based energy storage system and load control," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 12, pp. 12 364–12 374, Dec. 2021.

[102] V. Hrishikesan, A. K. Deka, and C. Kumar, "Capacity enhancement of a radial distribution grid using smart transformer," *IEEE Access*, vol. 8, pp. 72 411–72 423, 2020.

[103] C. Zhu, "High-efficiency, medium-voltage input, solid-state, transformer-based 400kW/1000V/400A extreme fast charger for electric vehicles."

[104] D. Das, V. M. Hrishikesan, C. Kumar, and M. Liserre, "Smart transformer-enabled meshed hybrid distribution grid," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 1, pp. 282–292, Jan. 2021.

[105] C. Kumar, R. Manojkumar, S. Ganguly, and M. Liserre, "Impact of optimal control of distributed generation converters in smart transformer based meshed hybrid distribution network," *IEEE Access*, vol. 9, pp. 140 268–140 280, 2021.

[106] B. Grainger and R. W. De Doncker, Eds., *Medium Voltage DC System Architectures*, ser. IET Energy Engineering Series. IET, 2022, no. 143.

[107] H. V. M., C. Kumar, and M. Liserre, "An MVDC-based meshed hybrid microgrid enabled using smart transformers," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 4, pp. 3722–3731, 2022.

[108] H. V M and C. Kumar, "Operation of meshed hybrid microgrid during adverse grid conditions with storage integrated smart transformer," *IEEE Open Journal of the Industrial Electronics Society*, vol. 2, pp. 315–325, 2021.

[109] G. Buticchi, G. De Carne, T. Pereira, K. Wang, X. Gao, J. Yang, Y. Ko, Z. Zou, and M. Liserre, "A multi-port smart transformer for green

airport electrification," in *2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe)*, Sep. 2022, pp. 1–8.

[110] G. Buticchi, T. Pereira, J. Yang, G. De Carne, X. Gao, Y. Ko, Z. Zou, K. Wang, and M. Liserre, "A smart transformer for the electrical power system of green airports: Smart power management," *IEEE Industrial Electronics Magazine*, pp. 2–12, 2023.

[111] O. J. Soto-Marín, E. A. Cano-Plata, J. C. Balda, and A. J. Ustariz-Farfán, "Comparative analysis of oil-filled transformer and solid-state transformer for electric arc furnace," in *2019 IEEE Industry Applications Society Annual Meeting*, 2019, pp. 1–6.

[112] S. Rupp, G. Burt, U. Schichler, S. Brüske, A. Egea-Àlvarez, and G. Jambrich, "MVDC grids to facilitate the roll out of renewables," in *Accepted at 2023 27th International Conference on Electricity Distribution (CIRED)*, Jun. 2023.

[113] N. Kimura, T. Morizane, I. Iyoda, K. Nakao, and T. Yokoyama, "Application of solid-state transformer for HVDC transmission from offshore windfarm," in *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, Oct. 2018, pp. 902–907.

[114] T. Parveen, W. Yao, and J. Lu, "Integration of solid-state transformer of off-shore wind turbine systems," in *2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Dec. 2021, pp. 1–5.

[115] N. Kimura, T. Morizane, I. Iyoda, K. Nakao, and T. Yokoyama, "Middle frequency solid state transformer for HVDC transmission from offshore windfarm," in *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, May 2018, pp. 2914–2920.

[116] A. Sidorov, G. Zinoviev, and J. Petzoldt, "Solid state transformer as a part electrical circuit for data center application," in *2021 IEEE 22nd International Conference of Young Professionals in Electron Devices and Materials (EDM)*, Jun. 2021, pp. 354–359.

[117] G. Zhabelova, A. Yavarian, V. Vyatkin, and A. Q. Huang, "Data center energy efficiency and power quality: An alternative approach with solid state transformer," in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Nov. 2015, pp. 001 294–001 300.

[118] N. Anandh, D. Das, and C. Kumar, "Smart transformer enabled triple-active bridge converter for modern data centres," in *2022 22nd National Power Systems Conference (NPSC)*, Dec. 2022, pp. 548–553.

[119] B. Hafez, H. S. Krishnamoorthy, P. Enjeti, S. Ahmed, and I. J. Pitel, "Medium voltage power distribution architecture with medium frequency isolation transformer for data centers," in *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014*, Mar. 2014, pp. 3485–3489.

[120] C. Zhao, D. Dujic, A. Mester, J. K. Steinke, M. Weiss, S. Lewdeni-Schmid, T. Chaudhuri, and P. Stefanutti, "Power electronic traction transformer—medium voltage prototype," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 7, pp. 3257–3268, Jul. 2014.

[121] D. Dujic, C. Zhao, A. Mester, J. K. Steinke, M. Weiss, S. Lewdeni-Schmid, T. Chaudhuri, and P. Stefanutti, "Power electronic traction transformer-low voltage prototype," *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5522–5534, Dec. 2013.

[122] H. Hoffmann and B. Piepenbreier, "Medium frequency transformer for rail application using new materials," in *2011 1st International Electric Drives Production Conference*, Sep. 2011, pp. 192–197.

[123] M. Pittermann, P. Drabek, M. Cedl, and J. Fort, "The study of using the traction drive topology with the middle-frequency transformer," in *2008 13th International Power Electronics and Motion Control Conference*, Sep. 2008, pp. 1593–1597.

[124] N. Hugo, P. Stefanutti, M. Pellerin, and A. Akdag, "Power electronics traction transformer," in *2007 European Conference on Power Electronics and Applications*, Sep. 2007, pp. 1–10.

[125] M. Steiner and H. Reinold, "Medium frequency topology in railway applications," in *2007 European Conference on Power Electronics and Applications*, Sep. 2007, pp. 1–10.

[126] M. Botte, L. D'Acierno, and M. Pagano, "Impact of railway energy efficiency on the primary distribution power grid," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 12, pp. 14 131–14 140, Dec. 2020.

[127] X. Liu and K. Li, "Energy storage devices in electrified railway systems: A review," *Transportation Safety and Environment*, vol. 2, no. 3, pp. 183–201, Oct. 2020.

[128] Z. He, C. Wan, H. Liu, and P. Ju, "Evaluation of grid support capacity from electrified railways," *IEEE Transactions on Power Systems*, vol. 39, no. 1, pp. 2310–2326, Jan. 2024.

[129] Alexandre Lagarde, Guillaume De Preville, Piotr Sadowski, Samir Soua, and Stefan Moeller, "White Paper MMC for rail electrification," GE Vernova, Tech. Rep., 2024.

[130] M. U. Mutarraf, Q. Xun, M. Langwasser, and M. Liserre, "A systematic review of solid-state transformer for large ships and their shore power supply," in *2024 IEEE 15th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Jun. 2024, pp. 1–6.

[131] M. K. Das, C. Capell, D. E. Grider, S. Leslie, J. Ostop, R. Raju, M. Schutten, J. Nasadoski, and A. Hefner, "10 kV, 120 a SiC half h-bridge power MOSFET modules suitable for high frequency, medium voltage applications," in *2011 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2011, pp. 2689–2692.

[132] D. Grider, M. Das, A. Agarwal, J. Palmour, S. Leslie, J. Ostop, R. Raju, M. Schutten, and A. Hefner, "10 kV/120 a SiC DMOSFET half h-bridge power modules for 1 MVA solid state power substation," in *2011 IEEE Electric Ship Technologies Symposium*, 2011, pp. 131–134.

[133] CIRED WG 2019-1, "DC networks on the distribution level – new trend or vision?" 2021.

[134] H.-J. Yun, D.-K. Jeong, H.-S. Kim, M. Kim, J.-W. Baek, J.-Y. Kim, and H.-J. Kim, "Implementation of a single-phase SST for the interface between a 13.2 kV MVAC network and a 750 V bipolar DC distribution," *Electronics*, vol. 7, no. 62, 2018.

[135] "Elektromobilität: Aufbau der ladeinfrastruktur nimmt fahrt auf, news article from the city of aachen."

[136] C. Joglekar, B. Mortimer, F. Ponci, A. Monti, and R. W. De Doncker, "SST-based grid reinforcement for electromobility integration in distribution grids," *Energies*, vol. 15, no. 3202, 2022.

[137] SP Energy Networks, "LV engine NIC submission proposal," 2017.

[138] V. Psaras, R. Peña-Alzola, I. Abdulhadi, G. Burt, A. Kazerooni, F. Shillitoe, M. Eves, and J. Yu, "Protection of lvdc networks integrating smart transformers: The case of lv engine falkirk trial site," in *The 17th International Conference on AC and DC Power Transmission (ACDC)*, 2021, pp. 204–209.

[139] Delta Electronics, "Delta demonstrates 400 kW solid-state transformer-based extreme fast EV charger to partners."

[140] "ALigN - project RWTH aachen," https://www.isea.rwth-aachen.de/go/id/srwf?#aaaaaaaaaaasrwk.

[141] FUNDRES, "Future unified dc railway electrification system."

[142] HS Mittweida, "FlexNet eko," https://www.flexnet-eko.de/.

[143] Kopernikus-Projekt ENSURE, "Diese fünf technologien will ENSURE in der praxis testen."

[144] TIGON, "Towards intelligent DC-based hybrid grids optimizing the network performance."

[145] "HypoBatt," https://www.hypobatt.eu, 2024.

[146] A. Anurag, S. Acharya, Y. Prabowo, V. Jakka, and S. Bhattacharya, "Mobile utility support equipment based solid state transformer (MUSE-SST) for MV grid interconnection with gen3 10 kV SiC mosfets," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018, pp. 450–457.

[147] ——, "Design of a medium voltage mobile utilities support equipment based solid state transformer (MUSE-SST) with 10 kV SiC mosfets for grid interconnection," in *2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2018, pp. 1–8.

[148] L. Zheng, X. Han, C. Xu, R. P. Kandula, L. Graber, M. Saeedifard, and D. Divan, "7.2 kV three-port SiC single-stage current-source solid-state transformer with 90 kV lightning protection," *IEEE Transactions on Power Electronics*, vol. 37, no. 10, pp. 12 080–12 094, Oct. 2022.

[149] P. Czyz, T. Guillod, F. Krismer, J. Huber, and J. W. Kolar, "Design and experimental analysis of 166 kW medium-voltage medium-frequency air-core transformer for 1:1-dcxapplications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 4, pp. 3541–3560, Aug. 2022.

[150] P. Czyz, T. Guillod, D. Zhang, F. Krismer, J. Huber, R. Färber, C. M. Franck, and J. W. Kolar, "Analysis of the performance limits of 166 kW/7 kV air- and magnetic-core medium-voltage medium-frequency transformers for 1:1-DCX applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 3, pp. 2989–3012, Jun. 2022.

[151] SSTAR, "Innovative HV solid-state TrAnsformer for maximizing renewable energy penetration in energy distribution and transmission systems."

[152] "Super-HEART: A fault-tolerant and highly efficient energy hub with embedded short-term energy storage for high availability electric power delivery," CAU Kiel, Frauenhofer ISIT, Tech. Rep.

[153] "Amperesand - homepage," https://amperesand.io/.

[154] M. Zhu, "NTU launches first deep tech spin-out under S$75 million pilot programme with temasek, NUS, singapore - the business times," https://www.businesstimes.com.sg/singapore/ntu-launches-first-deep-tech-spin-out-under-s75-million-pilot-programme-temasek-nus, Nov. 2023.

[155] J. Yu, C. Luo, J. Duan, C. Wang, R. Lu, A. Trujillo, C. Li, and W. Li, "Design and validation of a 2MW 10KV medium-voltage solid state transformer," in *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, Phoenix, AZ, USA, 2024, pp. 1426–1433.

[156] L. Zheng, R. P. Kandula, K. Kandasamy, and D. Divan, "Stacked low-inertia converter or solid-state transformer: Modeling and model predictive priority-shifting control for voltage balance," *IEEE Transactions on Power Electronics*, vol. 36, no. 8, pp. 8934–8952, Aug. 2021.

[157] C. Xu, J. Wei, L. Zheng, X. Han, M. Saeedifard, R. P. Kandula, K. Kandasamy, D. Divan, and L. Graber, "Insulation coordination design for grid-connected solid-state transformers," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 4, pp. 3746–3758, Aug. 2022.

[158] "Low-voltage fuses," IEC, Standard 60269-1, 2014.

[159] S. Bhadoria, F. Dijkhuizen, R. Raj, X. Wang, Q. Xu, E. Matioli, K. Kostov, and H.-P. Nee, "Enablers for Overcurrent Capability of Silicon-Carbide-Based Power Converters: An Overview," *IEEE Transactions on Power Electronics*, vol. 38, no. 3, pp. 3569–3589, Mar. 2023.

[160] R. Zhu, V. Raveendran, and M. Liserre, "Overload operation of LV-side inverter in smart transformer," in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2019, pp. 5997–6004.

[161] G. D. Carne, M. Liserre, and Z. Rongwu, "Method for controlling a grid-forming converter, computer program and grid-forming converter," Patent European Patent EP3 591 820B1, Sep., 2021.

[162] R. Zhu and M. Liserre, "Continuous operation of smart transformer-fed distribution grid with single-phase faults," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018, pp. 458–464.

[163] J. Rodrigues, C. Moreira, and J. P. Lopes, "Fault-ride-through approach for grid-tied smart transformers without local energy storage," *Energies*, vol. 14, no. 18, p. 5622, Jan. 2021.

[164] Z. Wang, X. Shi, Y. Xue, L. M. Tolbert, B. J. Blalock, and F. Wang, "Design and performance evaluation of overcurrent protection schemes for silicon carbide (SiC) power mosfets," in *2013 IEEE Energy Conversion Congress and Exposition*, Sep. 2013, pp. 5418–5425.

[165] S. Ben-Yaakov, D. Shapiro, and S. Apter, "A derivative pulsed-current sensor and its application for protection and monitoring of GaN hemts," in *PCIM Europe 2019; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, May 2019, pp. 1–5.

[166] S. N. Banavath, A. Pogulaguntla, G. De Carne, M. Joševski, and R. Singh, "Transformative role of solid-state circuit breakers in advancing DC systems for a sustainable world," *IEEE Power Electronics Magazine*, vol. 11, no. 4, pp. 61–72, Dec. 2024.

[167] "ABB ELSP SACE infinitus," https://stories.abb.com/sace-infinitus/.

[168] V. Psaras, R. Peña-Alzola, I. Abdulhadi, M. Syed, G. Burt, A. Kazerooni, and F. Shillitoe, "Protection study for SST-integrated LVDC networks with multiple feeders," in *19th International Conference on AC and DC Power Transmission (ACDC 2023)*, vol. 2023, Mar. 2023, pp. 38–44.

[169] "Uninterruptible power systems (UPS) - part 1: Safety requirements," IEC, Standard 62040-1, 2022.

[170] "Safety requirements for power electronic converter systems and equipment - part 1: General," IEC, Standard 62477-1, 2022.

[171] IEEE Standards Association, "IEEE SA P3105 - recommended practice for design and integration of solid state transformers in electric grid," https://standards.ieee.org/ieee/3105/10707/, 2021.

[172] "Distribution solid-state transformers: Applications and laboratory evaluation," EPRI, Tech. Rep. 3002030242, Apr. 2024.

[173] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renewable Power Generation*, vol. 3, no. 3, pp. 308–332, Sep. 2009.

[174] S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran, and P. Tavner, "Condition monitoring for device reliability in power electronic converters: A review," *IEEE Transactions on Power Electronics*, vol. 25, no. 11, pp. 2734–2752, Nov. 2010.

[175] K. McKenna, S. A. Abraham, and W. Wang, "Major drivers of long-term distribution transformer demand," Tech. Rep. NREL/TP–6A40-87653, Feb. 2024.

[176] J. Sun, G. Wang, X. Du, and H. Wang, "A theory for harmonics created by resonance in converter-grid systems," *IEEE Transactions on Power Electronics*, vol. 34, no. 4, pp. 3025–3029, Apr. 2019.

[177] J. He, Y. W. Li, D. Bosnjak, and B. Harris, "Investigation and active damping of multiple resonances in a parallel-inverter-based microgrid," *IEEE Transactions on Power Electronics*, vol. 28, no. 1, pp. 234–246, Jan. 2013.

[178] A. Akhavan, J. C. Vasquez, and J. M. Guerrero, "Passivity-based control of single-loop grid-forming inverters," *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 4, no. 2, pp. 571–579, Apr. 2023.

[179] J. W. Kolar and J. E Huber, "Next-generation datacenter MV interfaces — will solid-state transformers meet their waterloo?, industry session on power electronics for high performance computing: Opportunities and challenges," Houston, TX, USA, 2022.

[180] T. Gardner and T. Gardner, "Google to buy power for AI needs from small modular nuclear reactor company kairos," *Reuters*, Oct. 2024.

[181] J. Millán, P. Godignon, X. Perpiñà, A. Pérez-Tomás, and J. Rebollo, "A survey of wide bandgap power semiconductor devices," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2155–2163, May 2014.

[182] K. O. Armstrong, S. Das, and J. Cresko, "Wide bandgap semiconductor opportunities in power electronics," in *2016 IEEE 4th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Nov. 2016, pp. 259–264.

Felix Wald (GS'20) received his bachelor's degree from Berlin University of Applied Sciences in 2019 and his master's degree from the Karlsruhe Institute of Technology in 2021, in electrical engineering. Since February 2021 he is working towards his Ph.D. degree as part of the "Real Time System Integration" group and "Power Hardware-in-the-Loop" lab at the Institute for Technical Physics at the Karlsruhe Institute of Technology, Karlsruhe, Germany. He currently serves as secretary of the IEEE PES Taskforce on "Solid State Transformer Integration in Distribution Grids" and his research interests include Power Hardware-in-the-Loop testing and the technical and economic investigation of power electronic transformers.

V.M. Hrishikesan received the B.Tech. degree in electrical and electronics engineering from the Government Engineering College, Thrissur, India, in 2011, the M.Tech. degree in power systems from the National Institute of Technology Tiruchirappalli, Tiruchirappalli, India, in 2014, and the Ph.D. degree from the Indian Institute of Technology Guwahati, Guwahati, India, in 2021. He was a Research Assistant with the Chair of Power Electronics, Kiel University, Kiel, Germany. He is currently working with Siemens Gamesa Renewable Energy, Kongens Lyngby, Denmark.

Oriol Gomis-Bellmunt (S'05-M'07-SM'12-F'21) received the degree in industrial engineering from the School of Industrial Engineering of Barcelona (ETSEIB), Technical University of Catalonia (UPC), Barcelona, Spain, in 2001 and the Ph.D. degree in electrical engineering from the UPC in 2007. In 1999, he joined Engitrol S.L. where he worked as Project Engineer in the automation and control industry. Since 2004, he has been with the Electrical Engineering Department, UPC where he is a Professor and participates in the CITCEA-UPC Research Group. Since 2020, he is an ICREA Academia researcher. In 2022, he co-founded the start-up eRoots Analytics focused on the analysis of modern power systems. His research interests include the fields linked with power electronics, power systems and renewable energy integration in power systems.

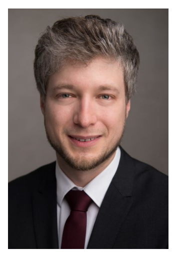
Haoran Ji (SM) received the B.S. and Ph.D. degrees in electrical engineering from Tianjin University, Tianjin, China, in 2014 and 2019, respectively. From 2019 to 2021, he was a Postdoctoral Researcher with Tianjin University. He is currently a Professor with Tianjin University. His research interests include distributed generation systems and optimal operation of distribution networks. He was supported by the China National Postdoctoral Program for Innovative Talents.

Masoud Davoudi (SM) received the BSc and MSc degrees from Ferdowsi University of Mashhad, Iran, in 2008 and 2012, and the Ph.D. degree from the University of North Carolina at Charlotte, Charlotte, NC, USA, in 2017, all in electrical engineering. He is currently a Senior Distribution Engineer with Pacific Gas and Electric Company, CA, USA, and an Assistant Professor at the University of New Mexico, NM, USA. His research interests include power system reliability and resilience, renewable energy integration, asset lifecycle optimization, and power system protection. He serves as the Technical Committee Program Chair of the IEEE PES Transmission and Distribution Committee, Chair of the IEEE Distribution Subcommittee, Vice Chair of the IEEE Distribution Resilience Working Group, and Associate Editor for IEEE Transactions on Power Delivery.

Ali Bidram Ali Bidram is currently an Associate Professor in the Electrical and Computer Engineering Department, at the University of New Mexico, Albuquerque, NM, USA. He received his Ph.D. from the University of Texas at Arlington, USA, in 2014. Before joining the University of New Mexico, he worked with Quanta Technology, LLC, and was involved in a wide range of projects in the electric power industry. His area of expertise lies within the control and protection of energy assets in power electronics-intensive energy distribution grids. Such research efforts culminated in a book, several journal papers in top publication venues and articles in peer-reviewed conference proceedings, and technical reports. He has received the NSF CAREER Award, the University of New Mexico's School of Engineering Junior Faculty Teaching Excellence award, the IEEE Albuquerque section outstanding engineering educator award, the New Mexico EPSCoR mentorship award, the University of Texas at Arlington N. M. Stelmakh outstanding student research award, and IEEE Kansas Power and Energy Conference best paper award.

Mazheruddin Syed (SM) received the B.E. degree in electrical and electronics engineering from Osmania University, Hyderabad, India, in 2011, the M.Sc. degree in electrical power engineering from the Masdar Institute of Science and Technology, Abu Dhabi, UAE, in 2013, and the Ph.D. degree in electrical power systems from the University of Strathclyde, Glasgow, Scotland, in 2018. He was a Strathclyde Chancellor's Fellow (Lecturer/Assistant Professor) with the Department for Electronic and Electrical Engineering, University of Strathclyde, Glasgow, and was the Manager of the Dynamic Power Systems Laboratory. Prior to his position as a Chancellor's Fellow, he was a Research Fellow with the Institute for Energy and Environment, University of Strathclyde. He is currently the Power Systems Lead for Scotland with WSP, U.K., working on innovation projects with transmission and distribution system operators.

Martina Joševski (M) is a Regional Manager of Eaton Research Labs Germany. She also holds affiliation as External Lecturer at the RWTH Aachen University, Faculty of Electrical Engineering where she teaches the courses on Modeling and Control of Low-Inertia Power Systems. She received her B.Sc. and M.Sc. degree in Electrical Engineering from the University of Novi Sad, and Ph.D. degree from RWTH Aachen University, Germany. Before joining Eaton, she was engaged as a Research Associate and Teaching Assistant at the Institute of Control Engineering at RWTH Aachen University, as a Postdoctoral Researcher at the Institute Automation of Complex Power Systems at RWTH Aachen University and as a Group Leader of the Research Group for Advanced Control Methods in Power System Applications & HIL at the E. ON Energy Research Center. Her research interests include control and optimization of converter-based systems with particular focus of optimal control methods.



Sebastian Brüske (S'14, M'21) received the B.Sc. and M.Sc. degrees in Electrical Engineering and Information Technology and Business Management in 2011 and 2013, respectively, from Kiel University, Germany, where he started working in 2014 toward the Doctoral degree in Electrical Engineering at the Chair of Power Electronics with a focus on power electronics for renewable energy systems and power electronics-based distribution. Since 2020, he has been working for Maschinenfabrik Reinhausen, Germany, as a technology manager for power electronics. He is the project leader of the Kopernikus project ENSURE at Maschinenfabrik Reinhausen and is working on new power electronics-based solutions for distribution grids.

Chandan Kumar (S'13-M'15-SM'19) received the B.Sc. degree from the Muzaffarpur Institute of Technology, Muzaffarpur, India, in 2009, the M.Tech. degree from the National Institute of Technology, Trichy, India, in 2011, and the Ph.D. degree from the Indian Institute of Technology Madras, Chennai, India, in 2014, all in electrical engineering. He is presently working as an Associate Professor in the Electronics and Electrical Engineering Department, Indian Institute of Technology Guwahati, Guwahati, India. During 2016 to 2017, he was an Alexander von Humboldt Research Fellow with the Chair of Power Electronics, University of Kiel, Kiel, Germany. His research interests include power electronics applications in power systems, power quality, and renewable energy. He is serving as Associate Editor of IEEE Systems Journal, IEEE Open Journal of Power Electronics, IEEE Open Journal of the Industrial Electronics Society (OJIES), and IEEE Access Journal.

Rafael Peña Alzola (SM) earned his combined Licentiate/MSc degree in Industrial Engineering from the University of the Basque Country in Bilbao, Spain, before completing a Ph.D. in Electrical Engineering from the National Open University (UNED) in Madrid, Spain. He was a Guest Postdoctoral Fellow in the Department of Energy Technology at Aalborg University, Denmark, between September 2012 to July 2013. Between August 2014 and December 2016, he held a Postdoctoral Research Fellowship in the Department of Electrical and Computer Engineering at the University of British Columbia, Vancouver, Canada. From January to May 2017, he undertook a short-term industrial collaboration at the University of Alcalá in Madrid, Spain. Since June 2017, he has been a Research Fellow at the Rolls-Royce University Technology Centre at the University of Strathclyde, Glasgow, UK. He is currently a Senior Lecturer, and his research interests include energy storage, LCL filters, solid-state transformers, innovative control techniques, solid-state breakers, and power electronics for aircraft systems.

Ilknur Colak (SM) received the M.Sc. and Ph.D. degrees in electrical engineering program from Istanbul Technical University, Istanbul, Turkey. In last 21 years she was with Industry and Research Centers such as ABB, Ansaldo Richerhe, TUBITAK, CERN and Maschinenfabrik Reinhausen. Since January 2022, Colak has been with Schneider Electric-Secure Power, France, as the Technical Director. Her research interests include multilevel converter topologies, modulation schemes, transformerless concepts, high power resonant converters, insulation-coordination, EMC and grounding, reliability and wave energy conversion systems.

Sanjeev Pannala (SM) received the Ph.D. degree in Electrical Engineering from the Indian Institute of Technology Roorkee (IITR), Roorkee, India. From 2014 to 2018, he contributed to the India-U.K. HEAPD project and subsequently served as a Research Associate under the U.S.-India UIASSIST project at IITR from 2018 to 2019. Between 2021 and 2024, he worked as Research Assistant Professor and Adjunct Professor at the Energy Systems Innovation Center, Washington State University, Pullman, WA, USA. He is currently a Senior Researcher at the National Renewable Energy Laboratory (NREL) in Golden, CO, USA. His research interests include grid-edge technologies, distribution system operation and control, distribution system resiliency, data-driven algorithms, Digital Twins, ADMS and microgrids. Dr. Pannala received the prestigious Doctoral POSOCO Power System Award in 2020 for his contributions during his Ph.D. He is an active member of several IEEE Power & Energy Society (PES) working groups and task forces under the Distribution Systems Analysis Subcommittee, particularly in the areas of resiliency, microgrids, and smart grids. He currently serves as Vice-Chair of the IEEE PES Task Force on "Solid State Transformer Integration in Distribution Grids.

Marco Liserre (S'00-M'02-SM'07-F'13) obtained the MSc and PhD degrees in Electrical Engineering from the Politecnico di Bari in 1998 and 2002 respectively. He has been Associate Professor at the Politecnico di Bari and, since 2012, Professor of Reliable Power Electronics at Aalborg University (Denmark). Since 2013 he is Full Professor and holds the Chair of Power Electronics at the University of Kiel (Germany). He has been offered and declined professorships at several universities. He has published more than 700 technical papers (1/3 of them in international refereed journals), one book and 7 granted patents (4 with companies). These works have received more than 50,000 citations. Marco Liserre was selected as an Highly Cited Researcher in the field of Engineering (Clarivate Web of Science) from 2014 to 2021. Several of his students (MSc, PhD and post-docs) are in leading positions in industry and universities worldwide. In 2023, he joined the Fraunhofer ISIT on a part-time basis as deputy director and director of the new division "Electronic Energy Systems", as well as of the Kiel branch of the Fraunhofer ISIT. From 2025 he is acting director of Fraunhofer ISIT. He is a member of IAS, PELS, PES and IES. He has served all these societies in various capacities. In PELS, he is Co-Editor of the IEEE Open Access Journal in Power Electronics and Technical Committee Chairman of the Committee on Electronic Power Grid Systems. He has co-chaired several IEEE conferences being several times Chairman. He has received 16 awards from IEEE, PCIM and EPE-PEMC, including the prestigious 2018 IEEE-IES Mittelmann Achievement Award and the 2023 IEEE-PELS R. David Middlebrook Achievement Award. In 2023, he was awarded the title of "Ufficiale" by the President of the Italian Republic. In 2025 he will be Chairman of Powertech 2025 in Kiel.

Giovanni De Carne (S'14, M'17, SM'21) received the B.Sc. and M.Sc. degrees in electrical engineering from the Polytechnic University of Bari, Italy, in 2011 and 2013, respectively, and the Ph.D. degree from the Chair of Power Electronics, Kiel University, Germany, in 2018. Prof. De Carne is currently W3 (full) professor at the Institute for Technical Physics at the Karlsruhe Institute of Technology, Karlsruhe, Germany, where he leads the "Real Time Systems for Energy Technologies" Group and the "Power Hardware In the Loop Lab". He is currently supervising PhD students, managing academic and industrial projects, and developing multi-MW power hardware in the loop testing infrastructures for energy storage systems and hydrogen-based drives. He has authored/co-authored more than 100 peer-reviewed scientific papers. His research interests include power electronics integration in power systems, solid-state transformers, real-time modeling, and power hardware in the loop. Prof. De Carne successfully hosted the IEEE eGrid2023 Workshop in Karlsruhe in October 2023 with high participation from the industry. He has been the technical program committee chair for several IEEE conferences, and associate editor of the IEEE Transaction on Power Electronics, IEEE Transactions on Power Delivery, IEEE Open Journal of Power Electronics and several other IEEE and IET journals.