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State of the Art of Solid-State Transformers: Advanced Topologies, Implementation Issues, Recent Progress and Improvements

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ABSTRACT Solid-state transformer (SST) is an emerging technology integrating with a transformer power electronics converters and control circuitry. This paper comprehensively reviews the SST topologies suitable for different voltage levels and with varied stages, their control operation, and different trends in applications. The paper discusses various SST configurations with their design and characteristics to convert the input to output under unipolar and bipolar operation. A comparison between the topologies, control operation and applications are included. Different control models and schemes are explained. Potential benefits of SST in many applications in terms of controllability and the synergy of AC and DC systems are highlighted to appreciate the importance of SST technologies. This review highlights many factors including existing issues and challenges and provides recommendations for the improvement of future SST configuration and development.

INDEX TERMS Converter control, power distribution, solid-state transformer, transformer topologies, power converter.

I. INTRODUCTION

Solid state transformer (SST) is an emerging technology that could influence the developments in many areas such as smart-grids, traction systems, the system with renewable energy sources (RESs) to mention just a few [1]–[3]. Some advantages of SST when compared with low-frequency transformer (LFT) include reactive power compensation, voltage regulation, power flow control, voltage sag compensation, bi-directional power flow, fault current limiting, harmonic block, and galvanic isolation [4]–[6]. One of the most noticeable advantages of SST is the size and weight reduction. The contrast of their physical looks is shown in Fig. 1. A comparison study shows that the 3 phase SST has 80% lesser volume than a LFT [7], [8]. Volume reduction of SST has significant importance due to the portability, low installation cost, and easy to assemble in certain inconvenient areas such as off-shore transmission applications [9].

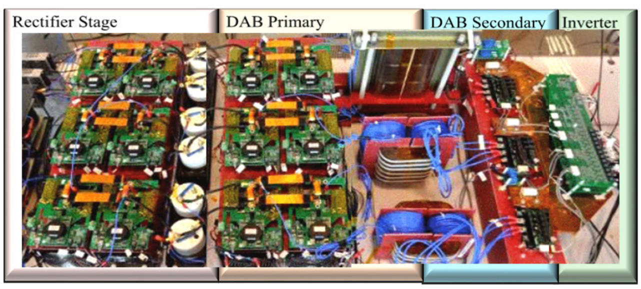

FIGURE 1. The physical looks of the high-frequency solid-state transformer.

SST converts an input of low frequency (LF) power to high frequency (HF) power through the switching circuits

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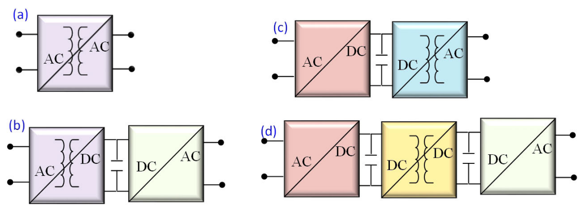

FIGURE 2. SST topology configurations (a) Single-stage; (b) Two-stage with LVDC link; (c) Two-stage isolation with HVDC link; (d)Three-stage [14].

and regenerates a LF power at the output terminals. It can be constructed into different power conversion depending on the configuration of the solid-state devices [10]. Hence, many converter topologies have been proposed and analyzed in different applications [11], [12].

All types of SSTs have the functions of isolated AC-AC conversion regardless of their differences in the design of converter topologies [13]. All these topology designs are basically categorized into single-stage, two-stage, and three-stage, as shown in Fig. 2 [8], [11], [14]. Single-stage SST topology is a power conversion from high voltage alternating current (HVAC) to low voltage alternating current (LVAC) through the HFT.

In general, the two-stage SST topology steps down the voltage in AC-DC or DC-AC stage. Three-stage SST topology is the most common configuration and has the HF isolation in the DC-DC stage as it provides more power to meet the requirements of the smart transformer. Despite that, three-stage topology exhibits low power efficiency due to the presence of power converters which results in high conduction loss and switching loss [15]. In 2017, the researcher introduced a single-stage AC-AC SST with 97% efficiency [16].

Apart from that, the power device switch is not available for the HV rating especially for the uses of power distribution. Modular multilevel configurations based on input series and output parallel (ISOP) are extensively used to address the issue by sharing the voltage and power in series connection, as shown in Fig. 3 [14].

The control strategies and balancing circuits are also required to prevent the problem in voltage and power balancing and that comes with drawbacks like complex systems in configuration and control scheme [17], [18]. With recent advances in power semiconductor technology, to avoid the cascading converter cells, FREEDM GEN II and FREEDM III were developed by the two-level approach [18], [19]. Many research and developments are ongoing in commercializing SST, investigating economic feasibility and reliability [19]. However, it still requires more research in order to improve the SST performance and to achieve cost reduction using different approaches [13]. Hence, this paper provides a comprehensive analysis and quick understanding of the SST so that it could spark more interest among the researchers.

A few prominent articles have been published to describe the design and effectiveness of the SST topology. Wang et al. [20] highlighted the design and optimization of

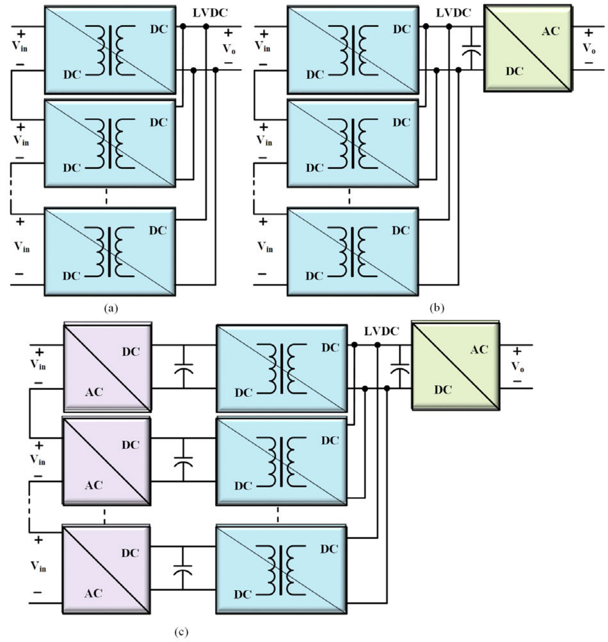

FIGURE 3. SST ISOP configurations (a) Single-stage; (b) Two-stage; (c) Three-stage [14].

15-kV SiC IGBT and their impacts on utility application. Huang et al. [13] developed a 15-kV SiC MOSFET-based single-phase SST topology. Divan *et al.* [21] designed 12-kV–120/120-V based galvanically isolated single-stage SST topology for achieving grid-edge control. Liserre *et al.* [22] explained the SST modular structure, control functionalities, and some challenges. Huang [23] discussed the MV SST technology and related functionalities. Ferreira Costa *et al.* [24] analyzed the structure of a three-stage STS. Briz *et al.* [25] concentrated on two modular power converter design concepts; one is the cascaded-H bridge (CHB) and the other is modular multilevel converter (MMC) topologies. Huber and Kolar [11] discussed the five classes of modern SST topologies including matrix type, isolated back end, isolated front end, isolated MMC and single cell-based HV SiC devices. The articles mentioned above focused on developing some specific SST topology. However, the comprehensive comparative analysis of different SST topologies, their applications, implementation difficulties is not explored in detail. Therefore, the major contribution of this paper is to deliver a detail overview and analysis of SST topologies with power/voltage level, updated information, important features, benefits, drawbacks, and related applications. A depth comparative study is performed considering the important parameters such as cost, material, power loss, frequency, efficiency, and various functional capabilities. In line with that, this paper dives deeper to investigate the current progress and challenges. Moreover, this review paper provides recommendation for the future improvement of SST so that it could be widely adopted in the energy market.

II. OVERVIEW OF SOLID-STATE TRANSFORMER

There are numerous SST topologies which are categories as single-stage, two-stage, and three-stage, respectively.

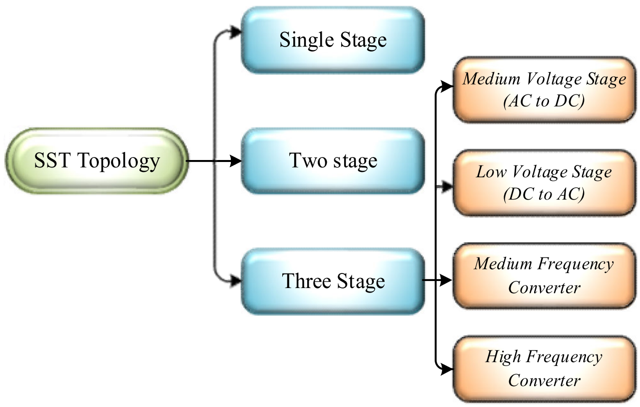

FIGURE 4. **Classification of SST topology.**

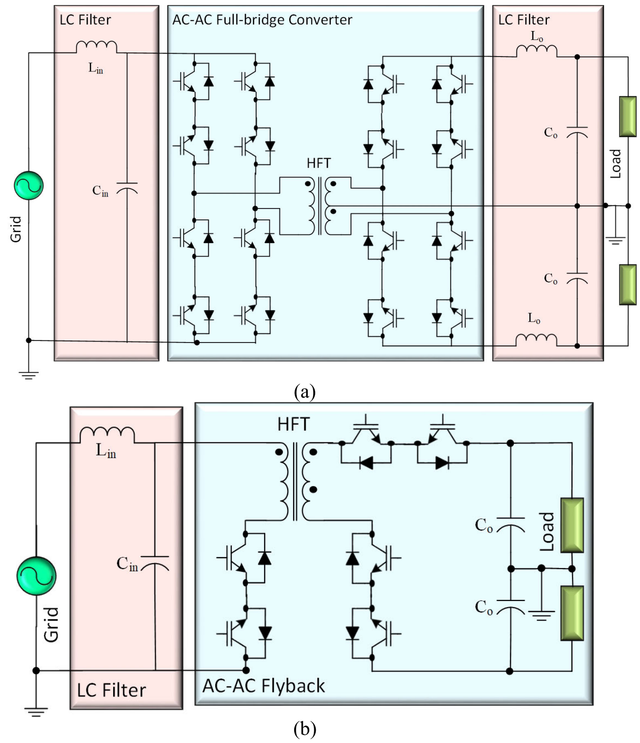

FIGURE 5. **AC-AC single-stage SST (a) Full-bridge converter (b) Flyback converter [14].**

Many of the SST topologies can convert the input of DC or AC to the output of DC or AC by replacing some or all of the switches to allow for bipolar (AC setting) or unipolar (DC setting) of voltage and current [14]. The classification of SST is shown in Fig. 4.

A. SINGLE-STAGE SST TOPOLOGY

Single-stage is the simplest SST topology which has only a direct power conversion with transformer isolation to step down the HV to LV. This type is operating in direct DC-DC or AC-AC power conversion stages with better efficiency and higher reliability [26]–[28]. The direct DC-DC or AC-AC power conversion stages offer better efficiency and higher reliability than three-stage SST topology due to the absence of conduction loss and switching loss [15], [27]. This topology has high switching frequency and does not require electrolyte capacitor [29]. Single-stage topology uses the phase shift angle between the secondary and the primary bridges to control the direction and magnitude of power transfer. In addition, the bi-directional power flow with four-quadrant switches helps to improve the control strategy and regulate harmonic content [27], [30]. The phase-shift angle φ controls amount of power transferred to the load between two bridges, as shown below [27],

$$P_0 = \frac{v_{i,pu}v_{0,pu}}{X_{pu}}\left(\varphi - \frac{\varphi^2}{\pi}\right) \tag{1}$$

where $v_{i,pu}$ *and* $v_{0,pu}$ denote the input voltage and output voltage in per unit, respectively. X_{pu} denotes leakage reactance of transformer in per unit. The ideal DC voltage transfer ratio is determined by,

$$\gamma = \frac{v_{0,pu}}{v_{i,pu}} = \frac{R_{pu}}{X_{pu}}\varphi\left(1 - \frac{\varphi}{\pi}\right) \tag{2}$$

where R_{pu} represents load resistance in per unit. Nevertheless, (2) cannot be applicable to AC–AC system when an output filter exits. The base secondary-side impedance can be expressed as $Z_{b,\sec} = S_b/V_{b,\sec}$. where S_b and $V_{\sec}$ stand for base power and base secondary-side voltage, respectively. In view of (1), the steady-state operation of an AC system is shown in the following equation,

$$P_i = v_{i,pu}\hat{i}_{i,pu} = P_0 = \frac{v_0^2, pu}{R_{pu}} + \frac{d}{dt}\left(\frac{1}{2}C_{pu}v_{0,pu}^2\right) \tag{3}$$

where Corepresents the output filter capacitance and $C\text{pu} = Co \cdot Zb$, sec. The AC voltage transfer ratio can be determined by changing (3) into the frequency domain,

$$\gamma_{ac} = \frac{1}{X_{pu}}\varphi\left(1 - \frac{\varphi}{\pi}\right)\frac{R_{pu}}{sR_{pu}C_{pu} + 1} \tag{4}$$

It is observed form (4) that the AC voltage transfer ratio depends on the transformer phase shift between bridges, output filter, leakage inductance, and load resistance. In steady operation, a small phase shift between input and output voltages is introduced by the load and the output filter. In addition, the output voltage follows the input voltage sinusoidally and this ratio holds irrespective of the input voltage polarity and the transformer current direction since the AC–AC DAB converters use four-quadrant switching cells.

Fig. 5(a) shows the AC-AC full-bridge converter with simple control to convert the power into a HF square-wave with 50% duty cycle and rectified to the sinusoidal waveform on the LV side [31]. Fig. 5(b) shows the flyback converter that has a minimum number of switches.

However, the major drawbacks are voltage stress on the switches and DC link does not comprise to offer power factor correction [14]. Since the SST is aimed to achieve good operation in the medium voltage (MV) level such as 7.2 kV of AC; modular multilevel configurations are used to share the voltage and power by connecting a number of LV converters in series [11], [18]. However, its complex configuration creates a balancing problem in power and voltage. Thus, the two-level approach in single-stage is designed in order to simplify the system complexity and control scheme [16]

B. TWO-STAGE SST TOPOLOGY

The main difference between single-stage SST and two-stage SST is the additional design of DC-link either on the HV side or the LV side. The power flow is bi-directional; however, it can be modified into unidirectional by deploying an uncontrolled rectifier at the LV side of the AC-DC converter [32]. This topology needs a complex switching method as well as a large number of switching devices [33]. Though two-stage SST increases the system complexity; however, it has few advantages such as reactive power compensation [34]. Since the ZVS is difficult to be maintained in such a wide input range, two-stage SST with LVDC link is not suitable for HV operation. Although the lack of LVDC link is unsuitable for the renewable application in LV, the issues can be addressed by converting the HVDC to LVDC instead of LVAC [35]. Furthermore, another solution to this issue is by employing the three-stage SST topology.

Recently, a new AC-AC high frequency-based matrix type three-phase input and three-phase-four wire output SST is proposed. In this topology, PWM is utilized to convert the utility source voltage to 50% duty square wave pulses and then it is transferred through a single-phase high-frequency transformer. This design offers some benefits such as bidirectional power flow, flexible voltage transfer ratio, controllable input power factor, high power density, and electrical galvanometer isolation. Furthermore, this topology has the capability to reduce the harmonic distortion in both input and output current under unbalanced load conditions by using modified three-dimensional spaced vector PWM (3D SVPWM) [36].

C. THREE-STAGE SST TOPOLOGY

Three-stage SST topology gains the most popularity in research compared to the other SST topologies due to the smart features offered. Aside from lower volume and weight in this SST, it is also able to optimize the performance in distribution and transmission grids [24]. The three-stage SST topologies are designed with two DC links that are able to address the power quality (PQ) issues and also supply and utilize any devices in MV or LV [37]. Table 1 shows the power and voltage level, configuration, control, capabilities and applications of different SST topologies. A comparative analysis among three topologies of SST based on numerous functional capabilities is illustrated in Table 2. It is noticed that three-stage topology is superior to one stage and two-stage topology with regard to voltage regulation, current limit, protection, and power factor. A number of SST projects have been developed to facilitate the integration of renewable energy and energy storage systems [13]. Fig. 6 shows one of the applications that three-stage SST was implemented in an electrical distribution grid. The architecture of the three-stage SST has at least two power converters which comprise with MV frequency converter, and LV converter, respectively. In [38], the three-stage SSTs are typically designed for the purposes of smart grid applications in which it has bidirectional power flow to transfer power from LV to HV [38]. The features of each stage are fully described in the following subsections.

1) MEDIUM VOLTAGE STAGE (AC TO DC)

The medium voltage converter converts MVAC to MVDC through the rectifying process. The converter enables the SST to filter out the reactive power in the MV grid and taking only the active power and feed it to the next stage. Table 3 shows the three available topologies which are the cascaded-H bridge (CHB), neutral point clamped (NPC), and modular multilevel converter (MMC) [22]. Three-level NPC is widely adopted in the industry which can be seen in applications like active power filters, STATCOM and also SST [39]. In the early stage of development, it required a large number of converters to be cascaded in MV application due to the limitation of the silicon IGBT available in the market that has limited operating voltage up to 6.5 kV [40]. Thus, it leads to lower power efficiency, lower density and also higher complexity in control when it is designed in a 3-phase structure [41]. Table 4 presents the number of active and passive components used in different medium voltage SST topology.

Hereafter comes with the SiC devices which are more efficient than Si devices [40], [42], [43]. SiC MOSFETs are suitable for lower power applications, while SiC IGBTs are the candidates for high power applications due to the decrease in the efficiency of MOSFETs as power increases.

Hence, the SiC IGBT is selected to be used in a non-cascaded three-level NPC grid-connected converter at MV as shown in Fig. 7. With less number of switching devices, it increases the power density, efficiency, and control simplicity [42]. However, it brought to the challenges in maintaining the power quality at low current/low load conditions [61], [62].

Figure 8 shows the CHB configuration which is another topology to realize the MV stage of the three-stage SST. The CHB configuration emerged due to its simple modulation and control system [24], [63]. The total harmonic distortion (THD) could be lower as larger inductance was placed, yet it has difficulties to implement such high value of inductance in MV and high power applications [42], [50]. It shares the same trait as MMC, shown in Fig. 8, which has the possibility of fault-tolerance implementation, multilevel operation, reduced rate of change of voltage, and filter size [64]–[66]. In contrast to CHB, MMC has a complex control system, however, it provides the DC link for the connection of MVDC loads sources. Thus, it requires a bulky filter on the DC side which significantly increases the overall cost of MMC [24]. CHB and MMC are the modular approaches that can perform advanced controls by unloading the devices that show higher deterioration [22], [63].

TABLE 1. Voltage, power, control and application comparison among SST topologies.

Topology	Refs.	Power and Voltage Level	Structure	Control	Capabilities	Applications
Single-stage	[44]	2 kW, 110 V/ 20 V	AC/AC, two-level converter	PWM	Bidirectional power flow, maximum power point tracking	Induction heating.
	[45]	50 kVA, 480 V	Dynamic current AC/AC topology	PWM	Bidirectional power flow	Industrial power supplies, motor drive, micro-grids, ships, and aircrafts
	[46]	2 kW, 400 V/208 V	AC/AC, matrix-based converter	Predictive control	Bidirectional power flow	High-power electric motor drives, wind generation, and adjustable speed drives
	[47]	10 kVA, 208 V	AC/AC, two-level converter	ZVS	Bidirectional power flow	High voltage and high-power applications.
Two-stage	[36]	5 kVA, 220 V/ 380 V	AC/AC high-frequency link, dual bridge matrix converter topology	PWM	Bidirectional power flow, low harmonic distortion, the controllable output voltage	Variable unbalanced loads application
	[48]	54 kW, 1.5 kV AC/ 60 V DC	Two stage cascaded H-bridge converter	PWM	Bidirectional power flow	Traction application
	[49]	100 kW, 10 kV AC/ 750 V DC	AC/DC/DC, MMC	PWM	Bidirectional power flow	Smart distribution grid
	[50]	5 kW, 3300 V AC/380 V DC	Cascaded H bridge converter	Phase shift modulation	Bidirectional power flow	High power application
Three-stage	[51]	3.3MVA, 25 KV/575 V	Cascaded multilevel converter	PWM	Bidirectional power flow, reactive power compensation, and voltage conversion functions	Wind energy conversion system
	[52]	1.5 kW, 230 V/39 V	Cascaded H-bridge converter	PWM	Bidirectional power flow, harmonic voltage compensation, reactive power compensation	High voltage application
	[53]	10 kVA, 3.8 kV DC/ 200 V DC	Single phase single converter cell-based SST	PWM	Bidirectional power flow	Wind turbine distributed generation system
	[54]	1 kW, 208 V/ 120 V	Two-level converter.	PWM	Bidirectional power flow	High-voltage high-power applications
	[55]	200 kVA	AC/DC converter	PWM	Bidirectional power flow, Reactive power compensation, power quality improvement	Large photovoltaic and wind System
	[56]	2 kVA, 1.9 kV/127 V	Multilevel converter	PWM	Bidirectional power flow, voltage sage compensation	Smart distribution grid
	[57]	10 kW, 3.6 kV/120 V	Two-level converter.	PWM	Unidirectional power flow	Distribution grid, DC and AC LV applications.
	[58]	2 kVA, 380 V/ 120 V	Cascaded converter	PWM	Bidirectional power flow	Hybrid microgrid
	[59]	5.8 kVA, 5 kV DC/800 V DC	NPC with SiC	PWM	Bidirectional power flow	MV drives, active filter applications

TABLE 2. Functional capabilities comparison among SST topologies.

Functionality	Single Stage [15], [27], [31]	Two Stage [32], [34], [35], [60]	Three Stage [24], [37]
Bidirectional power	Yes	Yes	Yes
Input current limiting	No	Yes	Yes
Output current limiting	No	Yes	Yes
Input current regulation	No	Good	Very Good
HVDC link regulation	N/A	N/A	Good
LVDC link regulation	N/A	Good	Very Good
Input voltage sag ride through	Poor	Good	Very good
Output voltage regulation	Poor	Good	Good
LVDC undervoltage protection	N/A	Yes	Yes
LVDC overvoltage protection	N/A	Yes	Yes
HVDC undervoltage protection	N/A	N/A	Yes
HVDC overvoltage protection	N/A	N/A	Yes
Modularity Implementation	Simple	Hard	Simple
Reactive power support to the grid	No	Yes	Yes
Independent power factor	No	Yes	Yes
Independent frequency	No	Yes	Yes

TABLE 3. Comparison of medium voltage topology in three-stage SST.

MV Converter	Merit	Demerits	Application	Cost	Method/Configuration
NPC [161], [113] [162]	Simple control system, presence of DC link, high power density	Higher voltage switching, bigger AC filter, degrade of power quality	Medium voltage	Low due to reduced filter size and weight.	Features with 4 IGBTs and 6 Diodes. Four IGBT connected in series with four Antiparallel diodes. Two diodes connected the nodes between the inner IGBT
CHB [22], [24], [63]	Simple control system, low frequency operation for each cell, advanced control	Absence of DC link and the need for isolated supplies for each cell	Medium voltage	Medium due to more power devices required	Cascaded of H-Bridge rectifier topology where each of H-bridge modules comprises of four power devices with antiparallel diodes and a dc link capacitor.
MMC [22], [67]	Lower frequency operation, presence of DC link, advanced control	Complex Control, Bulky Capacitors	High Voltage	High due to existing of bulky DC capacitor and more devices required	Series connected of low voltage cell, where each cell consists of 4 power devices with 4 antiparallel Diode (Full-bridge) or 2 power devices with 2 antiparallel Diode (Half-bridge) to form a leg. Total of 6 legs to form a three-phase converter.

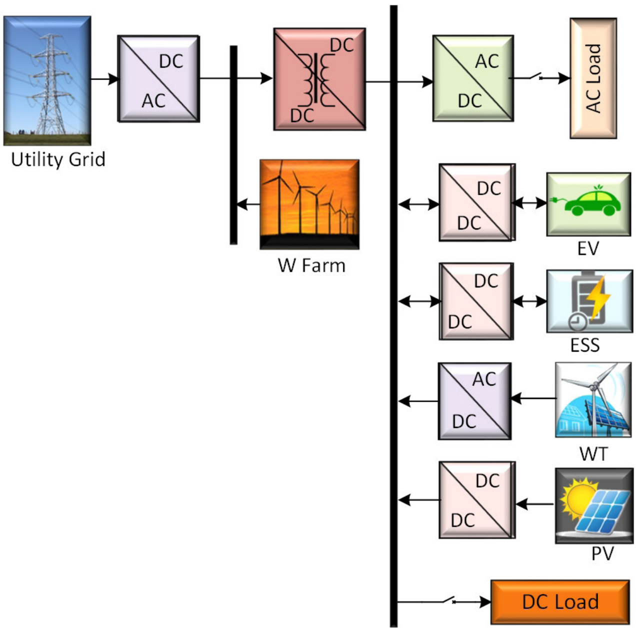

FIGURE 6. Typical smart transformer in electrical distribution grid [37].

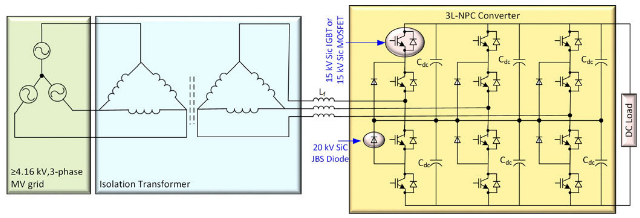

FIGURE 7. MV grid-connected converter with 3L-NPC converter [37].

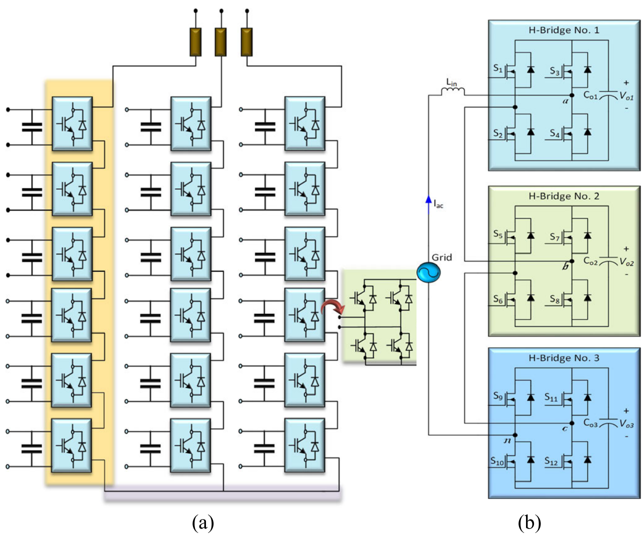

FIGURE 8. (a) MV grid with CHB converter [22]; (b) H-bridge cell [50].

TABLE 4. Components comparison of medium voltage three-stage SST topology.

MV Converter	Active Components	Passive Components			Expand-ability
	Semiconductor	Inductor	Capacitor	Transformer	
NPC	High	Low	Low	Low	No
CHB	Low	Low	Medium	High	Yes
MMC	Low	High	High	Low	Yes

Moreover, there are two MMC approaches where the submodule could be chosen to be implemented with the half-bridge or full-bridge shown in Fig. 9(b) and Fig. 9(c).

Half-bridge MMC uses fewer power devices and provides a higher step-up ratio at the same time [68]; however, the average device voltage stress is four times that in full-bridge MMC. Furthermore, all the submodule capacitors in full-bridge MMC are always active (keep charging or discharging all the time), while the submodule capacitors in half-bridge MMC have one inactive state [67].

2) LOW VOLTAGE STAGE (DC TO AC)

In LV stage is used to convert the LVDC to LVAC in which the power fed to and from the second-stage (DC/DC MF Transformer). Most often, the output of the LV stage is load consumption. The main advantage of this stage is the controllable output waveform by shaping the DC to an AC waveform with a desired nominal amplitude and frequency. In other word, this stage is able to regulate the voltage waveform to a fine voltage waveform on the LV side freely from the

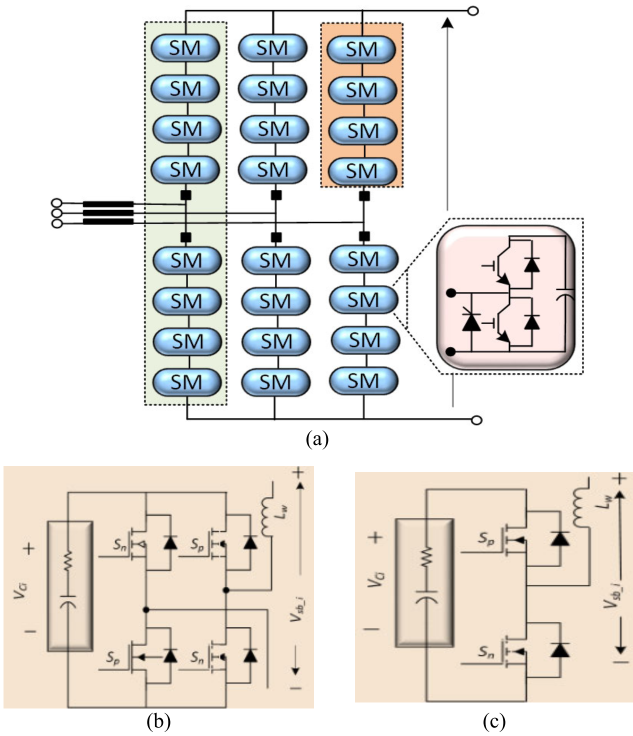

FIGURE 9. (a) MV grid converter with MMC converter [22]; (b) Circuit structure of full-bridge submodule; (c) Circuit structure of half-bridge submodule [67].

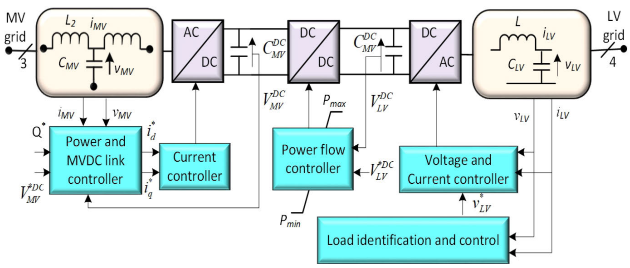

FIGURE 10. Three-stage SST with the ancillary system in LV stage [22].

systems connected to the distribution grid and any other disturbances [70]. Furthermore, LV stage has many other ancillary services provided such as regulation of grid frequency, on-line load identification, and control, voltage based overload control, soft load reduction, and reverse power flow limitation as shown in Fig. 10 [71].

Firstly, the load identification could estimate the load sensitivity to voltage variations in real-time and then provide more accurate control action for other ancillary services. The soft load reduction is able to reduce the load active power consumption upon request whereas the voltage-based overload control could prevent overload in power consumption. All the ancillary services are acting as the catalysts for the SST to be employed in many smart applications. The amount of output power being control upon to meet the desired power by sensing the variation of power and frequency [24]. Half-bridge (HB) topology is the simplest approach. Standard inverter topologies, regardless of the two-level approach or three-level approach, can be employed in

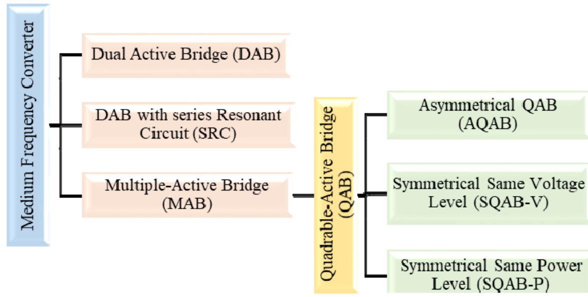

FIGURE 11. Categories of a medium frequency converter.

this stage. Hereafter, the NPC which is the three-level approach is the most recommended one which enables the use of 600-V power devices and eventually increases the efficiency of the system [22].

A three-phase four-leg PWM converter is proposed for the LV stage. The four-leg converter topology is an appropriate choice for achieving accurate control for a neutral current, controlled rectifier. The four-leg converter outperforms the conventional three-leg converters in terms of the degree of freedom and better control capability [72].

The LV-side converter controllers are used to regulate the filter capacitor voltages with stable frequency, even in the presence of unbalanced load/generation currents. To achieve this, the current and voltage are changed into three symmetrical components such as positive sequence, negative sequence, and zero sequence in order to control the negative and zero sequence component of current and voltage occurred due to unbalanced conditions. After, the controller of each sequence is executed and accordingly negative-and zero-sequence capacitor voltage is permanently assigned to zero to cancel these components under the appearance of unbalanced input currents and load conditions [73].

3) MEDIUM FREQUENCY CONVERTER

In this stage, MF converter serves as the power flow between the MV and the LV grid by balancing between the two stages mentioned above. The input and output at both the converters could be DC or AC depending on the design requirements. It is considered as one of the most challenging stages due to the high-power performance required to cater for the high current on the LV side, while the high voltage on the MV side. There are two solutions to address the requirements, one by using the HV rating devices whereby the second solution is by cascading several modules to share the total power, voltage and current which are a modular concept [22]. The advantages of modular concept over the first solution are the low electromagnetic interference emission and the realization of using LV-rating power devices, which increase the fault tolerance in this stage [22].

A number of converters have been studied to be used as modules for this stage, which are the series resonant converter (SRC), dual-half bridge (DHB), dual-active bridge (DAB), asynchronous-quadruple-active bridge (AQAB), and synchronous quadruple-active bridge (SQAB), as shown in Fig. 11 and Table 5 [22], [74]. All the converters listed

TABLE 5. Comparison of MF converter topologies in three-stage SST.

Conv. types	Merits	Demerits	Eff. (%)
DHB [76]–[78]	Lowest cost, least devices uses, better transformer core usage, easier gating scheme.	More reactive power, voltage limitation, the high current through the transformer.	-
DAB [22], [24], [75], [76], [79]	Controllable power flow, less reactive power, simple control.	Less efficient, leakage inductance, less transformer saturation.	92.5
DAB with SRC [76], [79]–[82]	Good regulation, reliable, higher switching frequency, no issues in inductance leakage.	Lack of capability to control the output power, complex control, high resonant capacitor.	98.61
AQAB [24], [75]	Controllable power flow, Lesser devices and cheaper.	High-power rating devices are required.	97.5

here are able to achieve soft-switching, high efficiency, and power density. However, this paper focuses only on four types of converters as they received more attention from the researchers than other topologies. DHB is the topology that has the least number of power devices which comprises two half-bridge converters while DAB comprises two full-bridge converters each connected to one side of the medium frequency transformer [75].

DAB converter is superior in output voltage and power flow control because it works with active control of the transferred power. AQAB is similar to DAB; however, less number of power devices are used because it integrates more active bridge to a single transformer. Thus, some power devices in AQAB are high-power rated. According to [74], the system cost could be reduced by approximately 20%. SRC is configured either in half-bridge or full-bridge whereby the difference for both bridges is explained in [80]. Besides, SRC operates in discontinuous conduction mode (DCM) to reach the most efficient operating point [81] by achieving ZVS, zero-current switching (ZCS) and low current switching. However, the major challenge of using SRC is the lack of capability to control the power flow. According to [81], the input voltage can be controlled through the first stage of SST once the system has enough degrees of freedom. It leads to the open-loop operation which makes the system simpler and inexpensive because of the number of sensors can be reduced [81].

According to the recently reported works, the DAB with SRC has the highest power efficiency up to 98.61%, provided the SST is implemented in three stages which include the front-end rectifier as the first stage [81] AQAB has been reported to achieve 97.5% power efficiency whereas DAB at 92.5% [74]. SRC could reduce the number of sensors used and present better power efficiency, whereby QAB could reduce the number of power devices. It is possible to have a combination of QAB with SRC to achieve higher power efficiency and cost-saving concurrently. Further research work could be carried out in order to explore the possibility of demonstrating the hybrid QAB-SRC design.

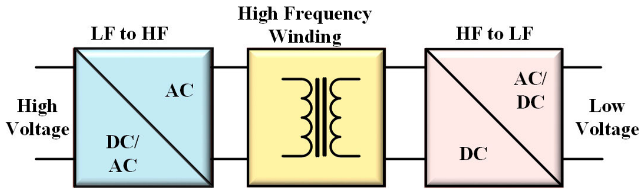

FIGURE 12. High-frequency isolation converter.

TABLE 6. Comparison of core material.

Materials	Composition	Flux Density (T)	Power Loss	Working Temp. (°C)
Silicon Steel [34], [87], [88]	$Fe_{97}Si_3$ $Fe_{93.5}Si_{6.5}$	2.00 1.30	Highest	120 130
Ferrite [87]–[90]	MnZn NiZn	0.32-0.55 0.26-0.42	Moderate	255 400
Amorphous [34], [87], [89], [91]	$Fe_{76}(Si,B)_{24}$ $Co_{73}(Si,B)_{27}$ $Co_{77}(Si,B)_{23}$ $Co_{80}(Si,B)_{20}$	1.56 0.55 0.82 1.00	High (High power application)	150 120 120 120
Nanocrystalline [34], [87], [89], [91]	FeCuNbSiB	1.23-1.45	Lowest	180

4) HIGH-FREQUENCY TRANSFORMER

HF transformer is the core of the SST, where it tremendously reducing the total volume and weight compared to the conventional LFT [82]. This advantage could be achieved due to the fact that the high frequency of the magnetic field only requires a small size of winding [83]. In this small size transformer, there is no contact between the primary and secondary sides of the converter, thus the isolation strength of the transformer could be improved [84]. Based on Fig. 12, the HF AC is generated from the first converter (DAB, SAB, and others) and direct to the HF winding. Hereafter, the magnetic wave generated from the primary winding cuts across the secondary winding thus generates the desired voltage level at high frequency, then only being converted to LF through another converter. Noted that it has the same concept in a conventional transformer; however, it operates in HF.

To optimize the HFT for the best performance, three crucial design considerations are required which are the core material, wire selection, and winding placement. To minimize the core loss and avoid core saturation for the nominal operation points, the core material must be selected carefully as it affects the size, power density, and power loss in the transformer [34], [85].

Based on Table 6, the higher the flux density, the higher the power density. Silicon steel material has the highest flux density but experiences high power loss; Soft ferrite material has moderate power loss; however, the lowest density which required a bigger size core. Amorphous material has a good flux density; however, power loss is high when operating in high power applications. Nanocrystal line material has an average flux density and the lowest power loss. It is obvious

TABLE 7. Specifications and configurations of MV SST design under different companies.

Author	Company	Size (Name)	SST Type	Converter Configuration		Switching Configuration		
				Level	SST Voltage	Switch	Voltage	Frequency
Glinka, 2003	Siemens	2 MW (PET)	D	Modular	15 kV	IGBT	1.2 kV	<10 kHz
Steiner & Reinold, 2007	Bombardier	400 kW (PET)	D	Modular	15 kV	IGBT	4 kV	8 kHz
Taufiq, 2007	Alstom	1.5MW (PET)	D	Modular	15 kV	IGBT	6.5 kV	5 KHz
Grider et al., 2011	GE	1 MW (PET)	D	Modular	7.2 KV	SiC MOSFET	10 kV	20 kHz
Wang et al., 2011	FREEDM Gen I	20 kW (SST)	D	Modular	7.2 kV	IGBT	6.5 kV	3 kHz
Zhao et al., 2014	ABB	1.2 MW (PET)	D	Modular	15 kV	IGBT	6.5 kV	1.75 KHz
Wang et al., 2014	FREEDM Gen II	20 kW (SST)	D	Two-level	7.2 kV	SiC MOSFET	10 kV	12-40 kHz
Huber et al., 2016	ETH	25 kW (SST)	B	Modular	6.6 kV	SiC MOSFET	1.2 kV	2 kHz
Lai et al., 2016	EPRI	25 kW (SST)	D	Modular	15 kV	SiC MOSFET	1.2 kV	93 kHz
Wang et al., 2017	FREEDM Gen III	20 kW (SST)	A	Two-level	7.2 kV	SiC MOSFET	15 kV	40kHz
Zhu et al., 2018	FREEDM 2018	18.6 kW (SST)	D	Two-Level	7.2 kV	SiC MOSFET	15 kV	37 kHz
Tian et al. 2018	Hubei Laboratory	2.4 KVA (ETP)	D	Two-level	10 kV	IGBT	6.5 kV	10 kHz
Saeed et al. 2018	ABB	107 kW (SST)	D	Modular	6 kV	SiC MOSFET	1.2 kV	30 kHz

that the nanocrystalline material is the most acceptable core material in terms of power density and efficiency; however, the cost for this material is relatively high. The second alternative would be the amorphous material which is not suitable for the high-power applications. Moreover, it was shown that the power loss for core material could be optimized by regulating the frequency range [86].

Under HF, the skin depth gets smaller than the wire diameter; however, the skin effect could not be ignored. Accordingly, Litz wire is chosen to reduce the impact of skin effect by subdividing the conductor to smaller conductor strands with proper shields [91]. Several hundreds of tiny strands are insulated from the others and form a thicker wire with the thickness equal to the wire size which is then calculated in volt power calculations [86]. It is important to know that the thinning of the wire strands would result in a better performance in HF characteristics. As yet in the market, the thinnest Litz wire strand could go down to 50 American wire gauge (AWG).

Design consideration of the HF converters also depends on the types of transformer winding geometry such as solenoidal and coaxial winding [92], [93]. Although the coaxial type has advantages in terms of controllability; however, the solenoidal structures are the most recommended ones due to lower cost and easier manufacturing. There are different solenoidal transformer structures which are core-type, shell-type and matrix-type, respectively. Core-type has greater insulation between primary and secondary sides; shell-type could provide better mechanical protection; matrix-type has the multiple cores which have the capability for inter-wiring features that help to reduce leakage inductance and winding AC resistance [34], [94]. The winding placement on the core and the distribution of wire turns is another key parameter which is taken into consideration in the design of HFT. The mutual inductances and the coupling coefficients of the windings are influenced by the winding placement which has a substantial impact on power loss and system efficiency.

One of the main issues to design a HFT is the isolation between primary and secondary voltage zones. Also, several power electronics converters for grid integration not only rises the cost, size, failure rate but also increases the control complexity of the system. To address the above problem, a multi-port solid-state transformer (MPSST) can be employed. MPSST is a type of SST that uses a multi-winding HFT to develop an adjustable, modular, isolated and compact converter to utilize multiple elements in the power grid. In addition, the functionality of several converters is combined in one converter, thus minimizing the number of components, and increasing the power density in the system. A MPSST can act like a centralized controller that can control the power flow and regulate the voltages [95], [96].

D. AVAILABLE SST DESIGN AND SPECIFICATIONS

The applications of the SST in different power conversion topologies have been discussed in the literature [57], [97]–[109]. The detailed specifications of many well-known MV SST designs are depicted in Table 7, including designs by Siemens [97], Bombardier [102], Alstom [103], GE Global Research [104], UNIFLEX [105], ABB PETT [106], ETH [107], EPRI [108], Hubei Lab [98], ABB [98] and the FREEDM System Center [99], [100], [109] Table 4 clearly demonstrates that the SST is a disruptive and enabling device for a wide range of MV applications. There are two key aspects in the design of an SST like modularity and number of stages. Accordingly, Table 4 shows that the modular and two-level converter configurations are widely used in SST design to withstand the high input voltages at 7.2 kV and 15 kV. In switching configuration, IGBT and SiC MOSFET are mostly used for SST design. In recent years, SiC MOSFET is highly preferable in designing SST due to their higher electric field strength, fast switching capability and ultra-low switching loss. A detail performance comparison among four well known SST designs including UNIFLEX, EPRI, GE and FREEDM is depicted in Table 8. It is observed that GE is dominant in other SST designs in terms of efficiency, control complexity, fault and harmonic isolation due to the frequency commutation in the high voltage rectifier with customized SiC MOSFET.

III. CONTROL OPERATION OF SST

Unlike conventional LFT, external control is needed to operate the SST. There are different controllers,

TABLE 8. Comparison of functionalities of four well known SST designs.

Functionality	UNIFLEX [106]	EPRI [109]	GE [105]	FREEDM [100], [101], [110]
Bidirectional power flow	Yes	No	Yes	Yes
Common DC link	No	Yes	Yes	Yes
Voltage regulation	Yes	Yes	Yes	Yes
Voltage sag compensation	Yes	Yes	No	Yes
Var Compensation	Yes	Yes	No	Yes
Control Complexity	Complex	Average	Easy	Complex
Energy storage option	Yes	Yes	Yes	Yes
Harmonic Isolation	Yes	Yes	Yes	Yes
Fault Isolation	Yes	Yes	Yes	Yes
Efficiency	Average	Average	High	average

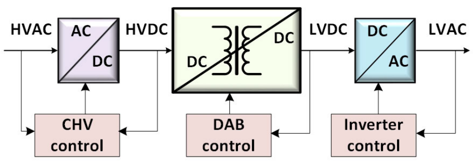

FIGURE 13. Control block diagram for phase modules of multi-level SST [111].

operate independently on each of the stages. Most often, closed-loop control is only considered in the control techniques for the purpose of synchronization and ensures the power quality [110]. In multi-level SST control, the rectifier (First stage AC DC) is controlled based on the sensed input voltages, currents, and HV DC capacitor voltages (between first and second stages) in order to maintain desired power factor at the input terminal of second stage converter as shown in Fig. 13. Next, the second-stage conversion is controlled by comparing the sensed output voltage with the desired voltage; thus, generating different control signals to produce the desired output at the input terminal of three-stage. Similarly, in the three-stage (AC-DC), the controller senses only the voltage and current at the output side to generate the required control signals for the converter.

In the HV rectifier side, a number of topologies such as NPC, CHB, and MMC have been discussed where MMC has the most complex control. The NPC topology senses the waveform from input and output to generate a PWM control signal [112]. CHB is controlled using a single-phase vector control method [111]. Meanwhile, MMC requires not only these basic signals but also greater number of measurement than CHB and NPC such as the measurement of cell capacitor voltages, DC current, arm current, AC currents, and AC voltages [113]; resulting the MMC topology is more costly and higher control complexity, respectively.

In general, a DAB controller maintains a constant voltage at the secondary side of the DC-link while supplying the desired load power. In DAB, it comprises two H-bridge converters and a high-frequency transformer whose leakage inductance enables the bidirectional power flow. The control method of the DAB is based on the switching of each full-bridge using complementary constant PWM signals with

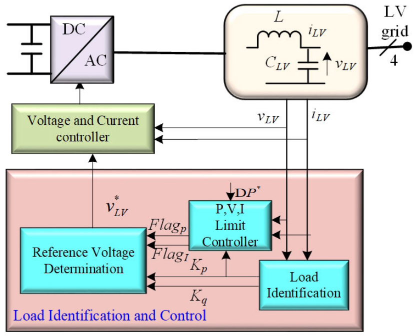

FIGURE 14. Load identification and control scheme for LV side converter [71].

TABLE 9. Performance comparison of controllers [114].

Controller	Peak Overshoot (%)	Settling Time (sec)	Rise Time (ms)	Steady State Error (V)
PI	23	0.18	7.5	1
PID	20	0.23	10.2	3
Fuzzy Logic	8	0.005	1	3

rectangular modulation [75], [99], [111], [113]. Moreover, three modulation techniques could be used in DAB whereby another two modulation techniques have been developed for DAB with SRC [78]. For DAB, the power transfer and output voltage can be calculated and correlated to the characteristics of the power devices, as shown in (5); however, for DHB, it is shown in (6) [111].

$$P = \frac{nv_1v_2}{8f_sL_s}d\,(1-d) \tag{5}$$

$$P = \frac{nv_1v_2}{2f_sL_s}d\,(1-d) \tag{6}$$

where n is the transformer turns ratio, V_1 is the HVDC voltage, V_2 is the LVDC voltage, d is the phase shift ratio, f_s is the switching frequency of power devices, and L_s is the leakage inductance. From the calculation, the LVDC can be controlled by adjusting the phase shift ratio and applying the PI regulator to sense the difference between the output voltage and its reference values [111].

In LV inverter side, the converter is controlled by means of a voltage and a current control loop to keep the AC voltage as a sinusoidal waveform with constant amplitude and frequency with any load condition. The control requirement for this converter is low and almost negligible compared to the control part in the first-stage and second-stage [113]. However, the researchers found that the load identification and control could further improve the voltage and current controller in real-time providing more accurate control action for other ancillary services as shown in Fig. 14 [1].

Besides, Haritha et al. (2018) demonstrated controller performance comparison [114] where a PWM signal is generated by comparing the output voltage and the reference voltage using PI, PID or fuzzy logic controller. Table 9 shows the PI controller has an advantage in terms of settling time and rise time, while the PID controller has merit in terms of peak overshoot. However, the fuzzy logic controller has the

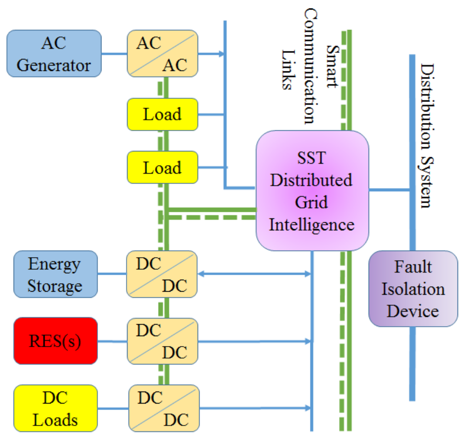

FIGURE 15. Diagram of SST-enabled AC and DC grids with smart communication links.

best performance among all other controllers in terms of overshoot, settling time and rise time, respectively.

IV. TRENDING APPLICATIONS OF SST

SST technology is emerging with a lot of potential benefits [64], [65], [115]. In this section, different SST applications have been organized into a few categories. Most of these applications exploit the advantages of SST in terms of controllability, smaller space needed, and the synergy of co-existence of both AC and DC systems. Fig. 15 shows the SST-based system configuration for future energy delivery, management, and communication between smart grids, converters, RES, protection devices and loads, respectively. This system can operate in SST-enabled mode or islanding mode. SST is adopted to replace the conventional low-frequency transformer and rectifier/ inverter because of its better controllability.

A. RENEWABLE ENERGY SOURCE

Renewable Energy Sources (RESs) are gaining increasing interest due to the awareness in conserving energy for the future generation [116]–[118]. Some of the RESs are generated as DC power and require the power conversion (inverter) which would decrease the power efficiency. In addition, a bulky converter is also required in order to be connected to the conventional power grid. In this context, the replacement of a conventional power transformer by SST is the solution to all these issues. More importantly, most of the RESs are not harvested all the time and the conventional types of RES system would disconnect during overvoltage conditions. The SST provides a solution by controlling the power output and the power could still be generated [67].

1) SOLAR PHOTOVOLTAIC APPLICATION

Though solar PV generates a low voltage, there is a number of effective options to connect solar PV to load or network. To address the issues, either the low-frequency transformer (50 or 60 Hz) is utilized or large photovoltaic arrays are employed. Nevertheless, each of these approaches has its own negative points. Hence, SST technology with high-frequency AC link has proven to become an alternative choice instead of low-frequency transformers [119]. A number of research works have already been reported on SST implantation in Solar PV applications. In [120], a dual active bridge inverter topology based solar PV panels employed to SST is proposed. In [121], the utilization of SST in grid-connected photovoltaic systems is introduced. In [1], a modular converter based on SST applied in PV module arrays is proposed where high-frequency transformers are utilized instead of bulky medium-voltage line-frequency ones. The application of SST in solar PV can also be found in [55], [122] where SST with solar PV brings many benefits, such as reduced size and weight, enhanced reliability, easier maintenance, voltage amplitude improvement the grid current quality enhancement.

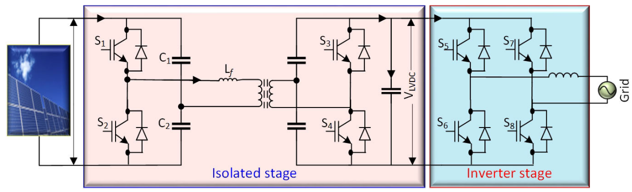

FIGURE 16. Solar PV system SST topology with DHB [124].

In the solar photovoltaic (PV) system, the current is generated in DC and converted into AC through either centralized or separated inverters. To reduce the cost, most of the conventional large-scale PV power plants are utilizing central inverters to reduce the number of power devices and controllers needed. Furthermore, only one maximum power point tracker (MPPT) is used in the centralized inverter stage for the solar PV power plants which result in the system to meet the maximum power of the PV modules association; however, it does not achieve the maximum power for each individual PV module [123]. To address the partial shading issue, it is suggested that the MPPT is installed on each PV system; however, this will result in a higher cost. Hence, it was reported that a cascaded multilevel SST topology (two-stage) is developed by deploying DHB which is able to achieve the galvanic isolation and MPPT function [124] as shown in Fig. 16. The DHB is cost-effective because it has used fewer power devices in the topology. Although the DHB could retain more reactive power; however, as solar panels do not produce reactive power, the disadvantages of reactive power of DHB would not be considered as a factor.

Furthermore, another topology is using a boost converter in the input stage to serve as the MPPT function and DAB in the isolation stage [123] as shown in Fig. 17. This topology is used for the high power application; because the DAB topology can realize zero-voltage switching of power devices while minimizing the loss caused by the hard switching in the circuit [125]. Hereafter, another work suggested a three-stage SST topology implemented with a boost converter which provided more features [125]. All the approaches could increase efficiency, reliability, and offer more advanced features than the conventional approach.

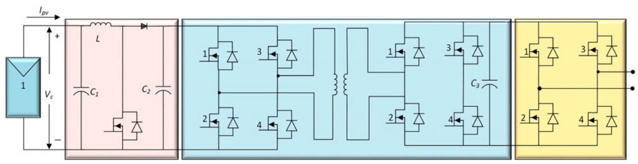

FIGURE 17. Solar PV system SST topology with the boost converter and DAB [123].

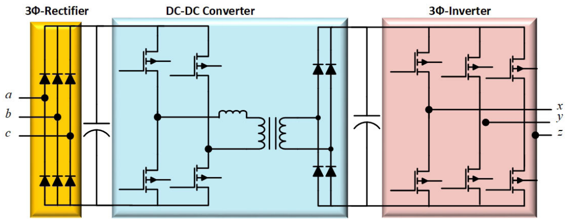

FIGURE 18. Three-stage SST with SAB in WECS [114].

2) WIND ENERGY CONVERSION SYSTEM

A few major factors that the SST being proposed for the wind energy conversion system (WECS) are the reduction of weight and volume, voltage step-up and the extra functions that SST could offer such as reduction in fluctuation of voltage, voltage regulation, and compensation of reactive power which results in the improvement of PQ events [4], [83]–[85]. There are different types of WECSs in the market; however, only the WECS based on doubly fed induction generator (DFIG) is the most widely adopted because of its variable speed, constant frequency operation and small size with high MVA ratings [129]. Due to the PQ issues that were explained in [130], [131], and the stepping up of the voltage which requires a large conventional transformer that is unacceptable; accordingly, SST has a huge potential in wind as well related applications [65]. However, it is necessary to use three-stage SST topology for WECS as shown in Fig. 18 due to the fact that most of the wind generators are producing AC power. The three-stage SST topology is comprised of a rectifier, MF converter, and inverter using either single active bridge (SAB) or DAB topology. The reason for using SAB is to reduce the circuit complexity by alleviated control for power devices. Moreover, a fuzzy controller is suggested for the implementation due to the higher performance than other controllers [114].

B. MICROGRID APPLICATION

The importance of DC power continues to increase, and many researches have proposed on the DC distribution system to shift the AC grid to the DC grid [132]. However, it is nearly impossible to change AC grid to DC grid instantly. Hence, there are researches that proposed the hybrid AC/DC system where the three-stage SST was implemented [133]. SST is only suitable in the microgrid (MG); However, not in a smart grid because of the limitation in power devices. Moreover, compared to the LFT, SST is much lighter, more compact, and has higher power density which makes it very suitable for widespread use in power distribution systems [134]. Another great advantage of using SST is the integration of energy storage systems and distributed energy resources (DERs), which could enhance the PQ and increase power efficiency, leading to a stable system operation [135].

Many researches have been done on three-stage topology [70], [134], [131]; however, only a few for two-stage topology [136] in some applications. With the connected energy storage and DERs, SST in MG can be operated either in islanded or in grid-connected modes with seamless transition [134]. However, it leads to stability issues like the variation in frequency that is caused by the growing number of DERs, loads, energy storage that are connected at one point. Accordingly, there are two power-sharing methods were developed in which multiple SSTs can share a given change in load by generating appropriate feasible set points for the input stage rectifiers [137]. SST serves as a good alternative to replace a conventional transformer in MG; however, the implementation needs to be reviewed comprehensively before it can be widely adopted due to the high cost which is not economically feasible. In addition, HV devices are required in order to develop SST in HV applications such as smart grid. Nonetheless, it is believed that it takes time to develop the high-power rating of power devices before SST could be implemented in HV application. As the demand for SST is increasing in different fields, it is expected that the cost would tremendously be reduced to a more economically viable level.

C. TRACTION APPLICATION

Locomotive traction application is likely to be one of the scientific researches to work on with possible effort in size and weight reduction while possibly making it more power-efficient. As for now, many of the applications are AC-fed traction vehicles which are based on 50Hz or 16.67 Hz; thus, introducing a bulky transformer installed in the system. With reference to a 6 MVA machine, the weight to power ratio is roughly 1.58 kg/kVA for 50Hz system and 1.81 kg/kVA for 16.67 Hz system [138]. Hence, the weight of the transformer affects the overall power efficiency. Thereby, SST is then studied with the motivation to reduce the weight and size of the overall system to achieve higher power density and efficiency. Apart from that, SST in traction application realizes four-quadrant conversion stages while preserving the similar features of conventional line frequency transformer.

There are traction applications implemented with SST developed by ABB, Bombardier, and Alstom [138]. Most of the prototypes were designed with single-stage (AC-DC) or two-stage (AC-DC-DC) by considering the MF stage as one stage. A number of modules comprise with IGBTs and being cascaded depending on the voltage rating. There are a number of factors that the SST is still not widely adopted into the traction application; although it is able to improve efficiency. One of the major factors is the power ratio; which is relatively poor compared to the traditional line frequency transformer [138]. MMC concept had been introduced to greatly reduce the weight and size of the system and offer more features;

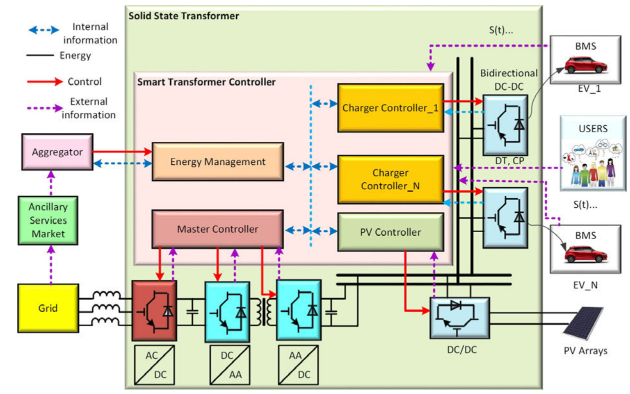

FIGURE 19. Structure of SST-based PVCS [140].

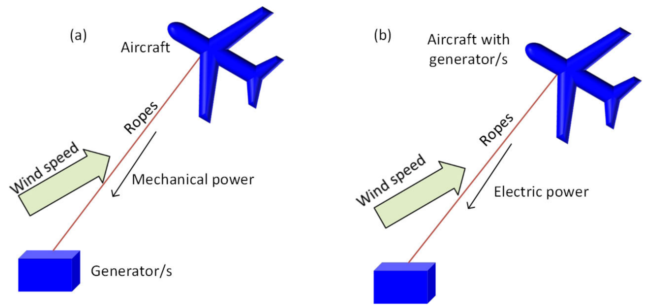

FIGURE 20. AWTs (a) Generator on ground; (b) Generator on-air [142].

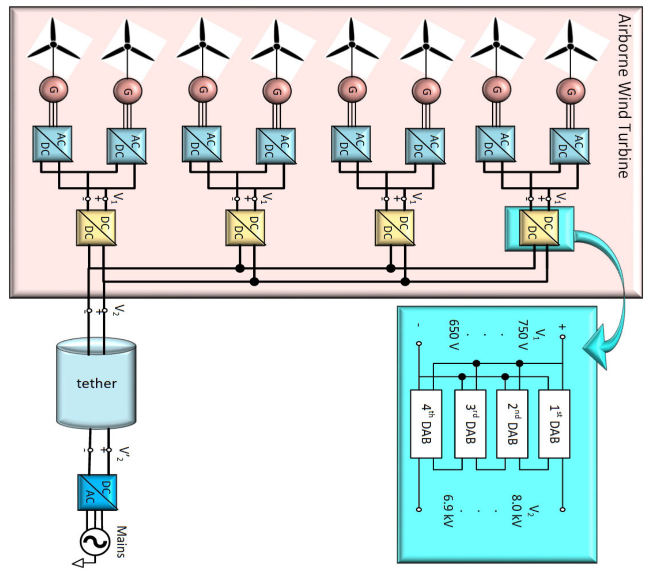

FIGURE 21. Electrical design for AWT.

however, the MMC concept required more power devices which resulted in higher cost [138], [139].

Nonetheless, the emerging technology in a semiconductor such as silicon carbide (SiC) devices can possibly accelerate the process of adopting SST in traction applications. It is suggested that the switching frequency of power devices could be increased to 10-25 kHz or possibly more which relatively increases its performance. Moreover, the total cost could be greatly reduced to be more economically viable in the market by minimizing the overall number of power devices, passive components (capacitors from DC link and SR circuits) and to achieve higher efficiency at the same time.

D. OTHER FUTURE APPLICATIONS

There are many other future applications that could be realized such as hybrid AC/DC system, airborne wind turbine, portable transformer, subsea processing, EV, naval [115], and aircraft with SST. As there are many DC applications in mankind's daily usage, so it is a great move to have a hybrid system that could supply and consume AC or DC. As suggested in [140], photovoltaic-assisted charging station (PVCS) could be one of the important charging facilities for the electric vehicles as shown in Fig. 19. This allows easy communication between the PVCS with the utility grid through the SST, better energy management, and power control.

Besides, there is also a new kind of wind power generation through the airborne wind turbine (AWT) which is popular as airborne wind energy systems (AWESs). Compared to the conventional wind turbine, AWT generates electricity from the higher altitude winds which are known to be faster and more stable than the winds close to the ground level. Thus, it provides a more reliable and effective generation of electricity [141]. There are two types of AWTs [142] such as a generator on the ground and generator in the air as shown in Fig. 20.

Generator in the air type AWT has the advantage of transferring electric power through the weather. It not only reduces the power loss but also increases the required mechanical strength which is connected to the ground station. Hence, the SST could reduce the total weight of the aircraft, and also convert voltage to high voltage to reduce power loss. Different AWT schematic designs are shown in Fig. 21 [96], [98].

The power optimization is one of the factors to implement in the subsea applications that required power for oil and gas processing, remotely operated vehicles (ROVs) and off-shore wind power. To solve the above issues, SST could present a good solution for all these applications. The subsea applications required power to be transferred or received from the shore or topside which was connected by the power cable. As a result of long-distance, the system experiences higher power loss in HVAC; thus, the application may need a platform or floater. SST technology with DC power transmission is able to transfer the power in a longer distance which reduces the cost of building a platform by just installing the longer HVDC cable from the seashore to the subsea. Besides, the cost can be further reduced using SAB; because, SAB reduces the number of power devices with unidirectional power flow [144].

Although there are portable site transformers present in such an era; they are still bulky and heavy. However, introducing SST, it is not only able to reduce the weight and volume; but also provides other features that before-mentioned. With all these advantages, the applicability of SST is high and could be implemented in submarine, naval, and even in the electric aircraft technology in the future.

V. ISSUES AND CHALLENGES FOR FUTURE SST IMPROVEMENT

The main aim of the advanced SST is to provide a high level of flexible control to optimize power transfer technology. However, it has been observed that several issues significantly affect SST performances in terms of cost-effectiveness, efficiency, reliability, protection, communication compatibility, and scalability. Some identified key issues and challenges of the advanced SST are discussed in the following subsections.

A. ECONOMICS FEASIBILITY

SST offers a number of great advantages due to the usage of solid-state devices such as IGBT, MOSFET, etc. However, these brought another big drawback in which the cost is high in SST than the conventional LFT. One of the estimation material costs of a 100kVA SST is at least 5 times higher than those of an equally rated LFT [7]. To address this, the topology SST has to choose wisely on different kinds of topology. For instance, the solar farm is suggested to use two-stage SST if the smart features do not require, thus reducing the number of power devices uses. Besides, the single-stage SST can implement on any application if only the reduction of weight and volume, and the simplest control is required to replace the LFT. As for now, potential applications could be focused on smart grids and renewable energy [145].

To further reduce the cost of SST, it is possible to reduce the volume of heat sinks and passive components by using low voltage switching devices with low loss characteristics and high-frequency operation [146]. Moreover, there is no need for a current sensor to being implanted as the current sharing strategy is used by using the active power component of the duty cycle in the rectifier stage as the feedback signal for the power balance controller in the DC-DC stage [147].

The emerging technology in a semiconductor such as SiC could possibly accelerate the process of adopting the SST in different applications such as traction. Thanks to its characteristics of SiC, the total cost could be greatly reduced to be more economically viable in the market by minimizing the overall number of power devices, passive components (capacitors from DC-Link & SR circuits). In certain parts of SST which could be further investigated such as MF converter who has different topology to implement. For instance, it was suggested to combine the AQAB with SRC to further reduce the overall cost. Furthermore, increasing market size could tremendously reduce the SST price from the economy of scale, but it is still required more research in price reduction in other approaches.

B. OVERALL PERFORMANCE

The performance of SST nowadays generally has a high-power density compare to LFT. However, two-stage and three-stage SST has lower efficiency, as there are many power conversions taking place. In addition, SST reliability is generally low as there are still many testing and research only run in a short-term period. Long-term testing and research are required for SST. To fully implement the SST to smart grid, it would not be realized at this moment due to the solid-state devices could not able to cater the high voltage. Hereafter, modular SST could able to resolve the issues but the amount of power devices is required which causes the high cost and PQ issues. However, a single-cell approach could be realized with the arise of SiC power semiconductor technology [28], [103]. The single-cell approach is great; however, still experiencing reliability challenges due to the difficulty of implementing redundancy in a non-modular system [11]. Hence, more study is required on the semiconductor side in order to fully implement in HV application.

C. SST PROTECTION

The reliability and robustness are two key factors to consider for SST before being widely adopted in the market. The SST protection reliability is relatively low when compared to the LFT due to the lack of protection for overvoltage and overcurrent. It is much more complex in SST as it may experience some possible failures such as control errors, measurement errors, or insulation breakdown. Due to this possibility, additional external protection devices are required. However, these external devices relatively increase the total volume of the design, which compensates the advantages of volume reduction in this case. Alternatively, a less robust could be considered if advanced protection devices (solid-state circuits breakers) are used [149]. Thus, it is still a step to move in SST Protection before the SST could fully implement in the grid without compensating the advantages of SST features.

The lightning protection system (LPS) for a STS comprises both internal lightning protection measures and external lighting protection measures. The internal lightning protection can be achieved by dividing the STS into lightning protection zones (LPZs). The concept of LPZs is based on electromagnetic compatibility (EMC) of an object. This immunity of the electrical equipment determines the defined EMC values. The LPZs allows the conducted and field-bound interference at the boundaries to be decreased to defined values. In line with that, the protected object is divided into two protection zones. The first zone LPZ 0A is determined by the rolling sphere method where the parts may be exposed to a direct lightning strike. The second zone is known as the LPZ 0B where parts are protected from direct lightning strikes. One the other hand, the external lightning protection system can be obtained by using the air-termination method, down conductor method and earth-termination method [150]–[152].

D. ELECTRICAL INSULATION AND PARTIAL DISCHARGE

A HFT has less space, compact design and uses enamelled magnet wire to which corona resistant insulation layer may be employed. Inter-turn and turn-to-ground insulation of HFT exhibit high voltage and high-frequency electrical stress, amounting to 5-40 kHz. Furthermore, the operating temperature of HFT can raise to 150-200° C under increased dielectric loss with frequency [153]. Hence, significant impacts are noticed on insulating material in HFT under high-frequency voltage which results in premature insulation failure. The insulation failure caused by the high-frequency PWM waveform reduces the life cycle due to the accelerated aging, electrical stress, overvoltage, and heating [154].

Partial discharge (PD) is the main responsible factor for occurring the insulation deterioration in HV systems or LV ones where overvoltage or surge may take place [155]. The works in [156] found that PD behaviour and insulation life are influenced by the voltage frequency. Another work in [157] reported that the reduction in PD amplitude can be found in the frequency range of 50 Hz-1 kHz. In addition, the reverse electric field and reversal moment of voltage polarity increase PD phenomenon [158].

E. COMMUNICATION COMPATIBILITY

Many advanced protection concepts often involved the communication between the SST, circuit breakers, and other switching devices in the grid. However, specific characteristics of SST are quite important to adopt in the grid environment in order to reach the protection scheme. It is not easy to implement such adaptions in the existing distribution grids and would be costly to do so [159]. Hence, it is important to know that at the moment, SST could not be a direct replacement for a LFT in the distribution grid as more research required investing in the communication part.

F. SST IMPLEMENTATION CHALLENGES

SST generates voltage unbalance on the DC side at no-load or light-load conditions which are the main limitation of the cascaded H-bridge converter operation. This voltage unbalance has a significant impact on the percentage of real power differences. Moreover, SST is still in the development stage; need to improve their efficiency and cost-effectiveness and a new standard for commercial potential. Thus, SST implementation at different levels is an issue. However, in the long run, SST could enable an unprecedented amount of two-way power flow which will be a revolutionary achievement for smart grids.

VI. CONCLUSION

The review outlines a detailed investigation of STS topologies, controller operation, associated application and implementation problems to identify their substantial contribution in renewables and further deregulated energy market. The review starts with a comprehensive explanation of different SST topologies, configuration, power and voltage ratings, advantages, disadvantages, and related applications. The structure of various medium voltage and medium frequency power converters, their operation, number of components, merits and demerits, cost and efficiency are analyzed. The review also explains the operation and design requirements of HFT along with power losses under different materials, composition, and temperature effects. The most recent published papers on well-known MV SST are reviewed with regard to type, operation, voltage, frequency, switching configuration, and functional capabilities. After, the review highlights the various controller operation of SST. Then, the execution of different SST topologies in the field of solar PV, wind power conversion and transmission, traction, smart grid, MG, and DC charge station is discussed. Finally, key factors of SST implementation are identified concerning cost, efficiency, protection, and insulation.

This review has proposed some significant and selective suggestions for the further technological development of SST and their development in future applications, such as:

- Economics feasibility study of advanced SST needs to investigate further for quantitative evaluation of data collection, validation, communication, filtering, calibration, protection, PQ, data dissemination and cybersecurity requirements as well as to estimate the payback period. Moreover, the advanced SST combined with cheaper high configured power electronic devices will support the economic feasibility of SST for replacing conventional transformer as well as promotes a significant development and application of the SST.
- In the future, SST would be a key component for smart grids in controlling the electricity routing and new functionalities to the distribution grids. Thus, SST could be designed for revolutionary functionalities of the smart grid to mitigate PQ problems, improve reliability indices, reactive power compensation, and efficiency.
- In the next-generation electric power system, large RE integration would change the grid energy management system. SST could be used as an energy router in order to manage supply and demand efficiently in the smart grids. Thus, a SST with a high level of functionalities as an energy router could be designed in terms of usages and functions in different domains considering power electronics, communications, grid intelligence, and network protocol requirements.
- The overall efficiency of the SST is experiencing reliability challenges as SST still in research and testing level. Thus, an advanced scalable SST model, its algorithm, mathematical formulation of optimization problems and control strategies are needed to be designed to ensure the efficiency improvement without affecting the stability and reliability of the grid as well as provide high-performance behaviour under different operating conditions.
- SST's fast current limiting is very important for protection and blackout prevention using fast load reduction schemes of the grids. However, due to limited overvoltage and overcurrent capabilities, SST requires additional protection devices compared to conventional LV transformer protection schemes. As SST has not yet been economically justified, therefore, it needs an advanced protection device including flexible control function of the protective relay, sufficient inductive filters and the impact of the time latencies on the overall protective scheme.
- Real-time communications between the SST and the power devices are very important for power

transmissions and information exchanges. Thus, an advanced compatible communication system for SST is required to be designed for intelligent energy information dissemination. The communication system must satisfy the transmission latency, reliability, and information security.

These recommendations would be a significant contribution towards the development and implementation of advanced intelligent SST, their control approach and applications which would provide a concrete idea for researchers and manufacturers on the advancement for the future development of SST.

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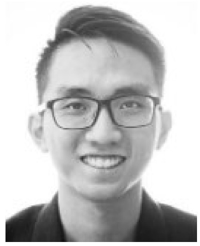

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