

Review of Solid-State Transformer Technologies and Their Application in Power Distribution Systems

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Abstract—The solid-state transformer (SST), which has been regarded as one of the 10 most emerging technologies by Massachusetts Institute of Technology (MIT) Technology Review in 2010, has gained increasing importance in the future power distribution system. This paper presents a systematical technology review essential for the development and application of SST in the distribution system. The state-of-the-art technologies of four critical areas are reviewed, including high-voltage power devices, high-power and high-frequency transformers, ac/ac converter topologies, and applications of SST in the distribution system. In addition, future research directions are presented. It is concluded that the SST is an emerging technology for the future distribution system.

Index Terms—Distribution system, high-frequency transformer, high-voltage power device, solid-state transformer (SST).

I. INTRODUCTION

POWER generation, transmission, and distribution are the three main constituents of the modern power system, in which the power transformer plays a most critical role [1]. Power transformers enable high-efficiency and long-distance power transmission by boosting the voltage to a higher one in the generation side. In the distribution system side, this high voltage is stepped down for industrial, commercial, and residential uses. The development trends of the traditional power transformers are mainly focused on new magnetic materials, insulation materials, manufacturing processes, and other economic factors.

Recently though, together with other technological advancements, power electronics is being seriously considered as one of the advantageous technologies that could empower future smart grids, doing so at all levels of electrical power systems. The high power converter has found its wide application in both distribution and transmission power systems over the past decades, for instance, in high-voltage dc (HVDC) transmission systems, flexible ac transmission systems (FACTS) devices, such as static Var compensator, static synchronous compensator (STATCOM), unified power flow controller (UPFC),

Manuscript received June 9, 2013; revised June 20, 2013; accepted July 31, 2013. Date of publication August 15, 2013; date of current version September 19, 2013. This work was supported by the National Science Foundation under Award EEC-0812121. Recommended for publication by Associate Editor Y.-F. Liu.

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Digital Object Identifier 10.1109/JESTPE.2013.2277917

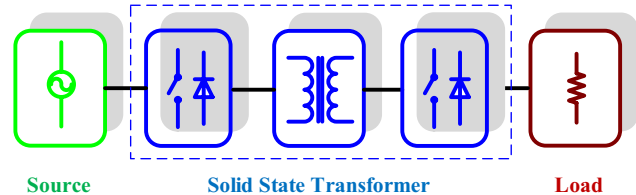


Fig. 1. SST configuration.

and others [2], and renewable energy systems, especially in large penetration of renewable resources, such as solar and wind [3], [4].

In the recent decade, another high power converter, named solid-state transformer (SST) (also known as power electronic transformer or intelligent universal transformer), has caught much attention and been extensively investigated for the distribution systems [5]–[11]. The earliest concept of SST was introduced in [12], where it was dubbed electronic transformer. Over the past few years, several efforts have been made to deliver a low-voltage and power SST prototype [13]–[15]. However, SSTs at the present time are limited by voltage and power rating of the power devices and available circuit topologies, and as such have not penetrated into the distribution systems.

The basic idea of the SST is to achieve the voltage transformation by medium- to high-frequency isolation, therefore to potentially reduce the volume and weight of it compared with the traditional power transformer. As shown in Fig. 1, the 50/60-Hz ac voltage is transformed to a high frequency one (normally in the range of several kilohertz to tens of kilohertz), then this high-frequency voltage is stepped up/down by a high-frequency transformer with significantly decreased volume and weight, and finally, shaped back into the desired 50/60-Hz voltage to feed the load.

It is further observed from the configuration of the SST that some other potential functionalities that are not owned by the traditional transformer may be obtained. First, the use of solid-state semiconductor devices and circuits makes the voltage and current regulation a possibility; similarly to FACTS devices. This brings promising advantages such as power flow control, voltage sag compensation, fault current limitation, and others, which are not possible for traditional transformers. Second, voltage source converters connected from the secondary terminal of the SST could readily support a regulated dc bus, which could be connected to dc microgrids enabling this new microgrid architecture.

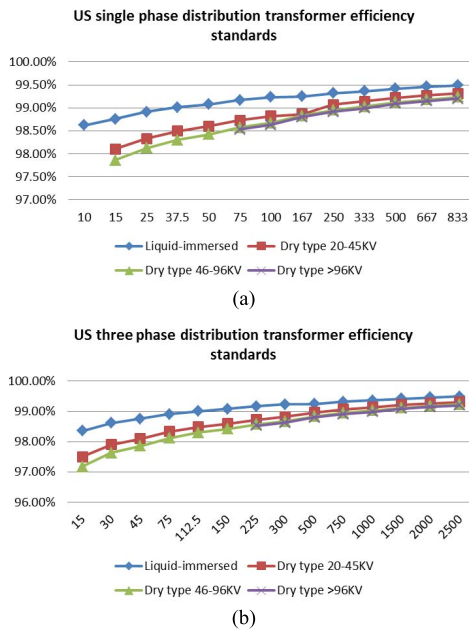


Fig. 2. Distribution transformer national efficiency standards of U.S. (a) Single- and (b) three-phase transformers. BIL: basic insulation level.

Although the concept of SST is straightforward, the design and implementation are not easy. The SST is essentially a high-voltage and high-power electronic circuit, of which the design and reliable operation are always a challenge. In addition, SST contains many other components besides the high-frequency transformer, such as power devices, gate drivers, heatsinks, control circuits, cooling system, auxiliary power, and other ancillary circuitry. As such, the sought lower volume and weight reduction may not be guaranteed without a careful design. In fact, the effective size and weight reduction of the SST compared with the traditional transformer can be achieved only when the proportion of the high-frequency transformer is reasonably larger than the rest of the parts. Consequently, great efforts are still needed toward the rapid development of the SST.

To guide the design of the SST in the power distribution system, a review of the state-of-the-art technology of the distribution transformers, including efficiency, volume and weight, and cost, is initially presented.

The U.S. Department of Energy released a standard for liquid- and dry-type distribution transformers in October 2007, effective since January 2010 [16]. This regulation covers all the distribution transformers manufactured after January 2010, and defines the minimum efficiency standards, as shown in Fig. 2, for both single-phase and three-phase transformers. It is observed that the overall efficiency of the distribution transformer required by the standard is >97% irrespective of power rating, and this value approaches 99.5% for most of the liquid-immersed power transformers. In addition, the standard calls for a higher requirement for the liquid-immersed-type transformer because it can transfer heat more effectively, thus the core temperature does not rise as much, which would decrease efficiency. The efficiency of the traditional transformer is so high that it brings a big challenge for the SST because 97% efficiency is already very high for

TABLE I
TYPICAL DIMENSIONS OF GE-PROLEC THREE-PHASE
PAD MOUNT TRANSFORMERS

kVA	Front Height (in.)	Front Width (in.)	Total Depth (in.)	Rear Width (in.)	Rear Height (in.)	Typical Weight (lbs.)
75	63	72	53	71	52	2965
112.5	63	72	53	71	52	3050
150	63	72	53	71	52	3250
225	65	72	55	71	54	3350
300	65	72	55	71	54	3800
500	69	72	55	71	54	4500
750	77	72	74	71	58	6200
1000	77	75	75	71	59	9400
1500	77	76	76	77	67	12200
2000	87	78	79	71	69	13200
2500	87	78	79	71	69	13800

most of the power converters, not to mention the cascaded configuration of the SST. However, considering the additional functions of the SST, a slightly lower efficiency compared with the traditional transformer might be allowable. The target maximum efficiency of the SST in the existing literature for the distribution system is ~95%–98% depending on the power rating.

Another expected characteristic of the SST is its reduction in weight and volume by increasing the operating frequency. Table I lists the typical dimensions and weights of the general electric-PROLEC (GE-PROLEC) three-phase pad mount distribution transformer [17]. As observed, because of the large amount of copper and iron used, traditional transformers are bulky, require space, and incur high costs for transportation. Hence, decreasing the volume and weight can bring economical advantages to both manufactures and customers. Considering the large number of power devices and circuits in the high-voltage and high-power converter area, simple topologies with high-voltage power devices are preferred in this application. In addition, the decreasing size for the high-voltage SST requires a special design regarding thermal and insulation aspects, which are challenging especially when air-forced cooling is required instead.

The standard costs for three-phase pad mount distribution transformers range from \$40 to \$100/kVA for size ranging from 50 to 150 kVA [18]. Table II lists the typical cost data for a three-phase pad mount transformer. As can be observed, the cost of the conventional distribution transformer is very low compared with the power electronics devices. Therefore, the third characteristic of the conventional distribution transformer is the low cost.

In this paper, the main issues affecting the development of a high-voltage and high-power SST and related state-of-the-art investigations are reviewed, focusing on high-voltage power devices, high-power and high-frequency transformers, ac–ac topologies, and the application of SSTs in the distribution systems. In addition, development trends are covered in each category and suggestions are given for possible research directions.

TABLE II
TYPICAL COST DATA OF THREE PHASE PAD MOUNT
TRANSFORMER (UNIT: DOLLAR)

Power rating (KVA)	12.45 KV	34.5KV
75	7749	10584
150	9450	11605
300	11718	15574
500	13608	20034
750	21257	21377
1000	25515	28350

TABLE III
PREFERRED BLOCKING VOLTAGE FOR POWER DEVICES
IN THE DISTRIBUTION SYSTEM

RMS line voltage (AC)	Switch voltage rating (V)	
	2 level	3 level
2400	6244	3122
4160V	10823	5412
7200V	18733	9367
12000V	31221	15611
12470V	32444	16222
13200V	34343	17172
13800V	35904	17952
14400V	36465	18233
22900V	59580	27290
34500V	89761	44881

II. HIGH-VOLTAGE POWER DEVICES

A. State-of-the-Art Technology

The existing SSTs are mainly targeted at the distribution voltage level, which ranges from 2.3 to 35 kV. To realize an efficient, highly compact, and reliable SST in the distribution system, high-voltage and high-frequency operated power devices are necessary. A recommended switch voltage rating based on the practical guidelines for various distribution voltages in both two-level and three-level-based topologies is listed in Table III, where the actual values may be different according to the design considerations [19].

Clearly, the switch voltage rating is quite high when it is applied in the distribution system with simple two-level or three-level converters, and this poses a big challenge to the development of SST. One possible solution is to adopt modular structures (series connection of converters) or multilevel converters with low-voltage and high-speed power device [7]. The downside of this approach is that from a size reduction point of view, too many discrete components increase the size and weight of the system, although the higher operating frequency can be achieved using this method. This maybe naturally not acceptable for applications where these parameters are of importance, such as SST application. Alternatively, high-voltage power devices are under consideration, which can still be combined with the use of modular topologies for very high voltage levels.

TABLE IV
COMPARISON OF MATERIAL CHARACTERISTICS OF 4H-SiC AND Si

material	EBG (eV)	BEF(V/cm)	TC (W/m.K)	SEDV(cm.sec)
4H-SiC	3.26	2.2 (10 ⁶)	380	2.0(10 ⁷)
Si	1.12	2.5 (10 ⁵)	150	1(10 ⁷)

Presented power devices suitable for medium voltage converters, such as insulated gate bipolar transistors (IGBT), integrated gate commutated thyristors, and emitter turnoff thyristors, can operate at very high voltage while the switching frequency is limited to be <1 kHz when in the hard switching mode because of high switching loss [20], [21]. This may not be feasible for the SST because the low switching frequency may not guarantee the effective reduction of volume and weight in the transformer.

Series connection of low-voltage power devices may therefore be one of the solutions for high-voltage operation. The penalty of this method is the large loop inductance intrinsic to this configuration, which once again prevents the modules from operating in higher frequencies because of the additional induced voltage, which may damage the devices themselves as well as other SST components.

Integrated module packaging of series-connected power device chips could be the solution to the standard series connection method discussed above [22], achieving minimum loop inductance and enabling high-frequency operation. Nonetheless, the increased conduction voltage drop of the resultant power module decreases the system efficiency, making it very hard to achieve efficiency levels comparable with traditional 50/60-Hz transformers.

Widebandgap materials, such as 4H-silicon carbide (4H-SiC) have been adopted for the next generation postsilicon devices in high-voltage applications. Table IV lists the characteristics comparison between 4H-SiC and Si [energy bandgap (EBG), breakdown electric field (BEF), thermal conductivity (TC), saturated electron drift velocity (SEDV)]. It can be observed that SiC material has a larger EBG, which makes it capable of operating at a higher temperature. In addition, the ten times larger BEF enables the SiC devices to switch at higher voltage, higher current, and higher frequency condition. Both of these two characteristics suit SST applications well.

A systematic investigation has been done on high-voltage SiC devices in smart grid application [23]. 10–15-kV SiC metal-oxide-semiconductor field-effect transistor (MOSFET) and IGBT (both P and N channels) have been designed and evaluated, showing that 10-kV SiC MOSFETs are the best choice for high-frequency applications >2 kHz at room temperature, whereas IGBTs can handle higher current than MOSFET at low frequency. Considering the low volume and small size requirement of SST, the SiC MOSFET is preferred when the voltage is <10–15 kV because of its majority carrier conduction mechanism [23]–[25].

A 15-kV/10-A SiC MOSFET has been recently designed and fabricated by Cree Inc. The loss data of the device was measured using double-pulse test characterization. In addition, a customized 6.5-kV/25-A Si IGBT was also tested in [9]. As a comparison, Table V lists the turnon and turnoff loss of the 15-kV/10-A SiC MOSFET and 6.5-kV/25-A customized

TABLE V
SWITCHING LOSS COMPARISON OF DEVICES

Test condition	3.8kV,10A,25 ^o C	6kV,10A,25 ^o C
Power device	6.5kV Si IGBT	15kV SiC MOSFET
Turn on loss	64.4mJ	14.46mJ
Turn off loss	32.7mJ	1.88mJ



Fig. 3. Size comparison between Si IGBT and SiC MOSFET.

Si IGBT. It is shown that the SiC MOSFET can substantially reduce switching loss, especially the turnoff loss, thus can potentially boost efficiency. In addition, the weight and size of SiC power device can also be reduced greatly, as shown in Fig. 3.

In the applications where the high power is required, parallel operation of SiC MOSFET is feasible because of its positive temperature coefficients for on-resistance. The 10-kV/120-A SiC half bridge module, consisting of 12 10-kV/10-A SiC d-MOSFET and six 10-kV/10-A SiC JBS diode, has been designed and adopted in a 1-MVA SST design [11].

Nevertheless, the on-resistance of SiC MOSFETs increases significantly as their blocking voltage and operation junction temperature increase, making it unsuitable for applications where the desired blocking voltage is >10–15 kV [23]. In this condition, bipolar devices such as SiC IGBTs play an important role because of their low conduction loss, moderate switching time, superior high-temperature operation, and excellent safety operation area—thus efficiency would not be compromised. The high resistance of p⁺ substrate caused by incomplete ionization and low hole mobility in the n-channel SiC IGBT has been a challenge, and efforts are mainly now on the P-channel SiC IGBT [27]–[30]. For high-frequency applications such as for SST, N-channel SiC IGBT performs better because of its faster switching speed, a result of the low current gain of the p-n-p transistor [30], [31]. 15-kV SiC IGBT is being developed for a 100-kVA transformer-less intelligent power substation, in which the 20-kHz operation frequency will further decrease the volume of the system with an expected efficiency of 98.4% [32].

Finally, if the required current handling capability is larger (>1000 A, >20 kV), SiC GTOs and thyristors with high switching frequency (10-kHz hard switched and 100-kHz soft switched) will be most suitable [26]. The ultimate current and voltage rating for future SiC power devices is predicted in [24]. It is concluded that SiC MOSFET will play an important role in the application with voltage <15 kV, whereas IGBT dominate the range from 15 to 20 kV. With operating voltage >20 kV, SiC GTO/thyristor is the preferred choice.

B. Recommendation for Future Work

Advanced packages of series connected devices of commercial semiconductor chips is a cost-effective solution considering the availability of SiC power devices. Widebandgap power devices capable of high-voltage and high-frequency switching still need further development. Although high-voltage wide-bandgap devices have been reported, they are far away from the optimized one and also cost significantly more than their silicon counterparts. The issues of how to terminate the edge to support high breakdown voltage and how to reduce the doping of drift layer have to be addressed [26]. In addition, to push the power rating of SST to several mega watt (MW) and higher, high current devices and proper device packages will also be needed. Furthermore, eliminating the use of oil means potential higher operating temperatures, implying that high-temperature power devices should also be evaluated.

III. HIGH-VOLTAGE AND HIGH-FREQUENCY TRANSFORMER

A. State-of-the-Art Technology

The high-frequency transformer is the main component in the SST, which replaces the traditional 50/60-Hz transformer. To fulfill the high-voltage, high-power, and high-frequency operation requirements, many issues and challenges need to be addressed. First of all, the selection of the magnetic material is critical to achieve high power density and low loss in the transformer. In addition, its structure and winding configuration affect the efficiency at high frequency, and thus should be carefully investigated to satisfy efficiency requirements. Furthermore, advanced thermal design is a challenge to avoid the breakdown of the system for such a high-voltage and high-power system. Finally, the high-voltage operation of SST makes the insulation requirement extremely strict, especially when oil is eliminated and a compact design is required.

Several magnetic materials can be considered for high-power applications, such as silicon steel, ferrite, amorphous, and nanocrystalline [33], [34]. Table VI lists the comparison of different magnetic materials. The silicon steel has high-saturation flux density and also high permeability. However, the loss of this material under high-frequency operation is high. Advanced silicon steel material can reduce the losses at high frequency to a relatively low value, whereas the saturation flux density is also reduced. Although the core loss of the ferrite core is moderate and the cost of it is low, ferrite cores may not be preferred in the SST application because of their low-saturation flux density, which results in a larger core size, conflicting with the high compact design requirement of the SST.

The Fe-amorphous alloy is a good choice for SST applications. The saturation flux density of this material can be as high as 1.56 T and its loss is also moderate. In addition, large cores, such as the C-type, are available, which suits high-power applications well. This core material is suitable for the application where the operating frequency is in the range of several hundred to several kilohertz. However, the loss of this material with operating frequency higher than several tens of kilohertz can only be controlled by a low flux density,

TABLE VI
COMPARISON OF DIFFERENT MAGNETIC MATERIALS [34]

<i>Material</i>	<i>Alloy Composition</i>	<i>Loss (W/Kg) (20KHz,0.2T)</i>	<i>Saturation B_{sat} [mT]</i>	<i>Magneto- striction (10⁶)</i>	<i>Permeability (50Hz) μ_s - μ_{max}</i>	<i>Max working Tem.^o C]</i>
Grain oriented silicon steel	Fe ₉₇ Si ₃	>1000	2000	9	2K-35K	120
Advanced silicon steel	Fe _{93.5} Si _{6.5}	40	1300	0.1	16K	130
High performance ferrite	MnZn	17	500	21	1.5K-15K	100/120
Fe-amorphous alloy	Fe ₇₆ (Si,B) ₂₄	18	1560	27	6.5K-8K	150
Co-amorphous alloys a	Co ₇₃ (Si,B) ₂₇	5	550	<0.2	100K-150K	90/120
Co-amorphous alloys b	Co ₇₇ (Si,B) ₂₃	5.5	820	<0.2	2K-4.5K	120
Co-amorphous alloys c	Co ₈₀ (Si,B) ₂₀	6.5	1000	<0.2	1K-2.5K	120
Nanocrystalline alloys I	FeCuNbSiB	4.0	1230	0.1	20K-200K	120/180
Nanocrystalline alloys II	FeCuNbSiB	4.5	1350	2.3	20K-200K	120/180
Nanocrystalline alloys III	FeCuNbSiB	8.0	1450	5.5	100K	120/180

which leads to larger volumes. Another alternative is the Co-amorphous alloy that has a much lower loss compared with Fe-amorphous cores, however, with a much limited saturation flux density.

Overall, the nanocrystalline core is the best candidate among all for satisfying both the power density and efficiency requirements. On the one hand, its saturation flux density is much higher than ferrite, therefore power density can be guaranteed. While on the other hand, its core loss is the lowest among all the materials in question, promising high efficiency. Nevertheless, two important factors should be considered if the nanocrystalline core is considered. First, the cost of this core is relatively high, thus it is not suitable when the cost is the dominating limitation in the design. Second, the standard off-the-shelf core is toroidal uncut tape-wound core, thus further modifications and customized design are needed if other core shape is needed.

Three 10-kVA, 3.8 kV–400 V, and 3-kHz transformers using the amorphous core have been designed in [35]. Both the commercialized and customized cores have been investigated to evaluate its effect to the power density. The first version is based on commercialized Metglas SA2605SA1 core and three cores are parallel connected to compose a larger cross-sectional area. The second and third versions are based on the customized amorphous core to increase the power density with consideration of different maximum flux density. The results obtained show that 97% efficiency could be achieved with the presented design. Different core materials, including nanocrystalline core Finemet FT3H, Ferrite core 3C94, and amorphous core Metglas 2605SA1, are designed and compared for a 250-kVA, 5 kV–380 V, and 20-kHz transformer [36]. It shows that the nanocrystalline core achieves best compromise between efficiency (>99.5%) and weight (<15 kg). While the ferrite core suffers from the heavy weight (>22 kg) and the efficiency of amorphous core is relatively low (98.5%). In [37], design considerations for four different high-frequency transformers, specified at 100 kVA/20 kHz, 100 kVA/3 kHz, 33.3 kVA/20 kHz, and 33.3 kVA/3 kHz, were presented.

The amorphous core was selected achieving design efficiency >99% by choosing suitable maximum flux density. The design of 166-kW/20-kHz high-frequency transformer for SST application is presented in [38]. Both ferrite and nanocrystalline core are investigated and two transformers are assembled. The efficiency of both design are >99.7%, whereas the volume using the ferrite core is about twice than that of the nanocrystalline core. In [39], a 350-kW/8-kHz transformer based on nanocrystalline core was designed for the medium frequency railway system, and the weight of the system is ~18 kg.

Transformer structures are of equal importance to satisfy high power density and high-efficiency requirements. There are two types of structures: solenoidal and coaxial winding transformers [33]. The solenoidal is the most common geometry of a transformer, in which the magnetic flux flows in parallel with the cylindrical axis and the current encircles the cylindrical axis.

In the coaxial structure, the flux encircles the cylindrical axis and the current flows in parallel with the cylindrical axis [40]. Although it is easy to control and predict the leakage inductance of the transformer by using the coaxial structure, the solenoidal structure is preferred in most of the design cases because of its advantages from a design point of view, easier manufacturing, and lower cost [35]–[38]. In addition, the coaxial structure is limited by its flexibility on the turn ratio because it becomes quite difficult to design and manufacture multitrans in the low voltage side. For both of these structures, multiple cores can be combined to build an equivalent larger window area, which is suitable for high-power and high-frequency applications [35]–[37].

Different solenoidal transformer structures are considered in this paper; namely core-, shell-, and matrix-type transformers, as shown in Fig. 4 [38]. The core-type transformer provides better insulation between the primary and secondary sides because of the inherent separation between its two windings. Shell-type transformers provide a higher degree of mechanical protection to the winding because of the way the core surrounds it. In addition, a shell-type transformer magnetic circuit

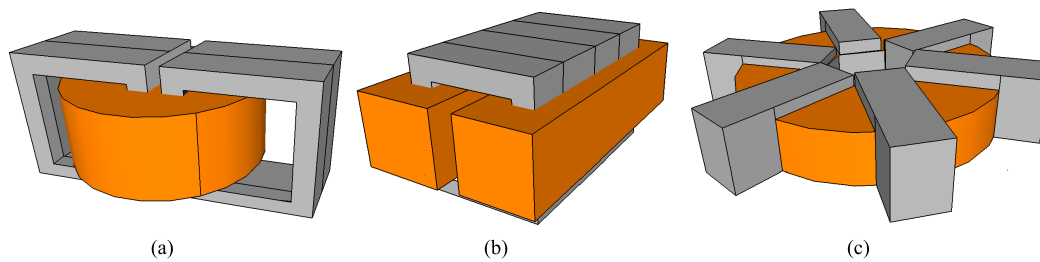


Fig. 4. Different solenoidal transformer structures: (a) shell, (b) core, and (c) matrix types.

is equivalent to a parallel electric circuit, so it has a lower reluctance compared with a core-type transformer of similar cross-sectional area. In the high-voltage step ratio condition, the matrix-type transformer can be used by interwiring core with series and parallel conductors [41]. The manufacturing of the core-type transformer is the easiest and this configuration is adopted for most of the designs and it will be the main configuration for the future mass production.

Another two factors that should be considered are the thermal and insulation designs, which are briefly introduced here. Compared with the conventional transformer, the thermal and insulation aspects are much more difficult in the SST because much less space is expected and oil-free operation is preferred. Natural convection is definitely the most attractive solution if it is achievable [35]. However, different thermal dissipation methods can also be adopted depending on the application, among which the fan-cooled and water-cooled heatsinks are the most common for high power density designs [38]. As to the insulation for this dry-type transformer design, suitable solid insulating materials, such as epoxy, have to be inserted at the places where air is not enough for this high voltage and highly compact transformer design [35], [37], [38]. In addition, high-voltage insulation wire is also an attractive candidate, which significantly reduces the complexity of the transformer construction [38].

B. Recommendation for Future Work

The high-voltage and high-frequency transformer is the key component in the envisioned SST concept. Optimum design procedures should be further investigated to achieve high-efficiency and low-volume designs based on existing core materials, wires, and insulation means. Multiobjective optimization method will benefit the design [38]. It is also expected that better alloy optimization and process development can be done such that new core materials can be used, and therefore low core loss can be achieved at high operating frequency condition [36]. In addition, efforts can be directed to the prediction of the parameters of the transformer, which is of great importance for higher frequency operation. Finally, low volume and weight are always the emphasis for the design, thus good thermal designs are highly desirable.

IV. ISOLATED AC–AC CONVERTER TOPOLOGIES FOR SST APPLICATION

A. State-of-the-Art Technology

Numerous converter structures can realize the functions of isolated ac–ac conversion and thus potentially suit for

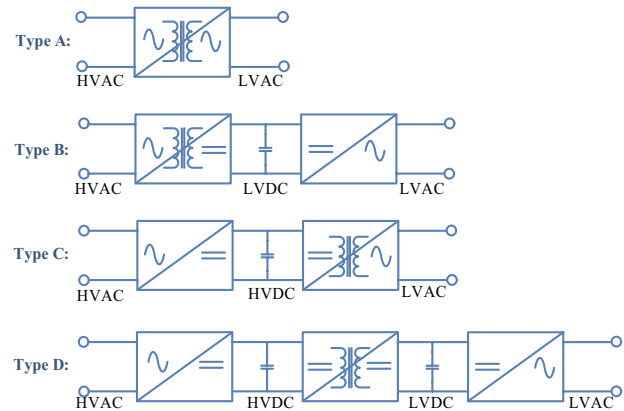


Fig. 5. Topology classification of SST.

SST application [5]–[9], [11], [16], [32], [38], [42]–[59]. To document these topologies, an approach to classify the possible configurations has been presented in [60] and [61]. Considering possible conversion stages, there are four basic topology configurations, as shown in Fig. 5, namely types A, B, C, and D. Type A is the direct ac–ac conversion with transformer isolation to step-down from high-voltage ac (HVAC) to low-voltage ac (LVAC) [16], [43], [44], [47], [48]. In type B, an isolated ac–dc conversion stage provides the low-voltage dc (LVDC) followed by a dc–ac conversion stage to provide the LVAC [46], [49], [53], [55]–[57] [the topology in [49] can be categorized in either type B or C because of two isolated transformers adopted]. Type C also contains the two-stage conversion, in which the galvanic isolation and voltage step-down are done by the dc–ac stage, therefore LVDC link is not available [45], [51]. Type D is a three-stage conversion with high-frequency isolation in the dc–dc stage; thus both HVDC and LVDC link can be obtained [5]–[9], [11], [32], [38], [42], [50], [52], [54], [58], [59].

In addition, considering the limitation of the power devices and magnetic components, the aforementioned SST topologies may have to be connected in series or parallel for high-voltage and high-power applications, as shown in Fig. 6. Three possible connections are illustrated, which are input series output parallel (ISOP), input parallel output parallel, and input series output series. The input parallel output series connection is not included because it is the same with ISOP in this application. It is worth pointing out that these SST configurations still fall into the four categories aforementioned from the conversion stage point of view.

The proposals in type A present possible low-cost and light-weight solutions because of the simple configuration.

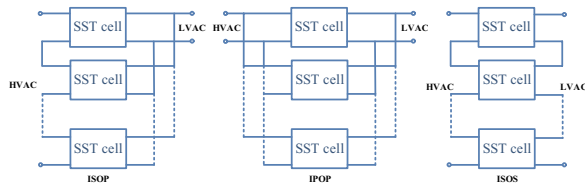


Fig. 6. SST in high-voltage and high-power system.

TABLE VII
PERFORMANCE COMPARISON OF FOUR SST TOPOLOGIES

	<i>UNIFLEX</i>	<i>EPRI</i>	<i>GE</i>	<i>ABB</i>
Power rating	300 KVA	45 KVA	1MVA	1.2MVA
Phase number	Three	Single	Single	Single
Voltage rating	3.3 KV	2.4 KV	13.8 KV	15 KV
Transformer frequency	2 KHz	20 KHz	20KHz	1.8KHz
Eliminates oil	No	Yes	Yes	Yes
Var compensation	Yes	Yes	No	Yes
Voltage sag compensation	Yes	Yes	No	Yes
Voltage regulation	Yes	Yes	Yes	Yes
Harmonic isolation	Yes	Yes	Yes	Yes
Common DC link	No	Yes	Yes	Yes
Energy storage option	Yes	Yes	Yes	Yes
Fault isolation	Yes	Yes	Yes	Yes
Bidirectional power flow	Yes	No	Yes	No
Control complexity	complicated	Average	Easy	Average
Efficiency	92%	96%	98%	95%
Delivery Year	2009	2012	2011	2012
Application	Smart grid	DC charge station	Substation	Traction

Four-quadrant power devices may be needed in bidirectional voltage and current operating condition. However, the lack of dc link makes them unsuitable for applications where reactive power compensation is required. In addition, disturbances on one side may also affect the other side, which is the drawback of traditional transformers. Types B and C SSTs adopt two-stage configurations, with an isolation stage in either the high or low voltage sides. Four-quadrant power devices are also needed on the ac side of the isolation stage for bidirectional power flow. Compared with the type A configuration, reactive power compensation is possible for types

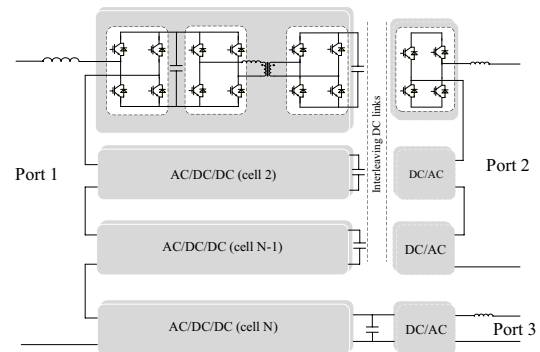


Fig. 7. UNIFLEX SST topology for smart grid application.

B and C SSTs if suitable topologies are chosen. However, topologies in types A and B configuration are not suitable for high-voltage operation because zero-voltage switching is hard to be guaranteed in such a wide input range, and also matured multilevel topologies cannot be easily applied in the high voltage side. In this condition, high switching losses may not be avoided without sacrificing switching frequency, leading to lower efficiency and difficult thermal management of the power devices. Type C topologies may not face such a problem because lots of work has been done for HVAC/HVDC conversion [62]. Nonetheless, the lack of the LVDC bus makes the integration of renewable resources on the low voltage (potentially residential) side unfeasible.

Most of the SSTs that have been designed for field application so far adopt the type D configuration because more available topologies can be chosen for each stage providing ample room to optimize its performance in terms of efficiency, volume, and weight. Many attractive features, such as VAR compensation, voltage sag compensation, renewable energy resources and energy storage integration, and bidirectional power flow, may be potentially achieved. Four well-known high-voltage SST designs, namely the universal and flexible (UNIFLEX) [5], electric power research institute (EPRI) [8], GE [11], and ABB [10], are highlighted because they have already been designed and fully tested for different applications. Table VII lists the performance comparison of these four SST topologies.

Fig. 7 shows the UNIFLEX SST topology for smart grid application [5]. Basically, it is a three-stage and three port power electronics converter used for UNIFLEX power management for future electricity network. The cascaded multilevel converter is adopted as the front-end stage with several interleaving dc/dc converters as the intermediate stage. It interfaces 3.3-kV distribution level voltage with low-voltage grids, such as 415 V system. Amorphous is adopted as the transformer core material and the operating frequency is chosen to be 2 kHz. Oil is adopted for insulation and cooling for this medium frequency transformer.

Fig. 8 shows the EPRI SST topology for dc fast charger application. The diode-clamped multilevel converter is applied for the high voltage side for both rectifier stage and primary side of dc/dc stage, in which the 18-kV/60-A multilevel IGBT module using the integrated module packaging method

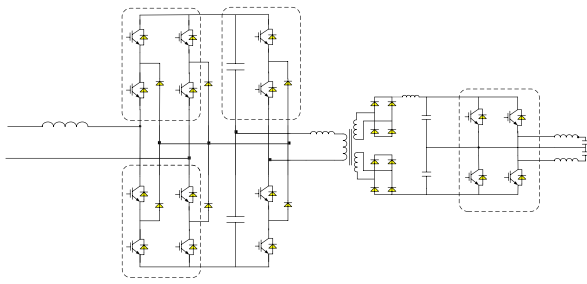


Fig. 8. EPRI SST topology (with inverter stage) for dc fast charger application.

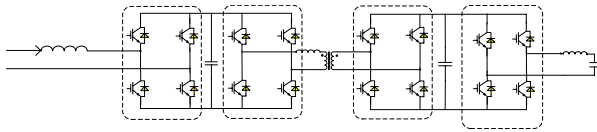


Fig. 9. Basic unit of GE SST topology for substation application.

is adopted. The simple diode rectifier is adopted for the secondary side of dc/dc stage to generate the LVDC link. The ferrite core is used in the high-frequency transformer with operating frequency of 20 kHz. In the dc fast charger application, another high-efficiency dc/dc converter is connected to interface with the battery pack.

Fig. 9 shows the basic unit of GE SST topology for substation application. The 10-kV/120-A SiC half bridge module is adopted for the high voltage side and they are connected in series to reduce the voltage stress. The switching frequency of the unit is chosen to be 20 kHz and nanocrystalline core is therefore chosen as the core material for the transformer to reduce the core loss. One of the distinguished characteristic of this unit is the high efficiency because of the line-frequency switching in both high- and low-voltage rectifier/inverter side and soft switching capability in the dc/dc stage. However, this unit can only fulfill the basic voltage transformation and isolation functions of the conventional transformer, therefore may not be suitable for smart grid and traction applications.

Fig. 10 shows ABB SST topology for traction application [10]. Cascaded multilevel converter is adopted as the input stage to interface with 15-kV grid, and 6.5-kV IGBT is chosen as the main switch for the H-bridge module. LLC resonant converters are then cascaded to each dc link with the secondary side connected in parallel to step-down the voltage, and nanocrystalline core is adopted for the transformer design. There is no dedicated control implemented for the dc/dc stage of the system, meaning that the LLC converter operates in open-loop mode at its resonant frequency point for maximum available efficiency operation.

B. Recommendation for Future Work

The development of the SST can be divided into two paths. The first one looks for modular topologies using low-voltage, high switching speed, and commercial power devices. The main issue with these topologies is the complex control algorithm needed, which has set the main research direction in this case, as well as how to minimize the volume and weight.

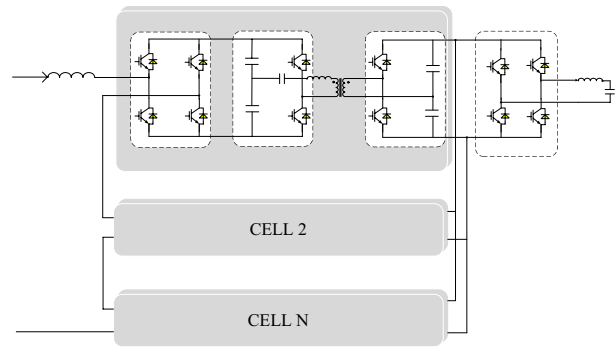


Fig. 10. ABB SST topology for traction application.

The second path uses advanced postsilicon devices, such as high-voltage SiC MOSFET/IGBT, to significantly reduce the volume and weight and potentially push the voltage and power rating to a much higher level. In this path, the main effort is how to solve the challenge of extremely high dv/dt in the high-voltage and high-frequency operating conditions. The soft switching techniques for dc/dc converter are well established. Therefore, soft switching techniques for the rectifier/inverter should be the research focus. In this condition, single stage or two stage topologies can be possibly adopted with potential higher efficiency. For even higher voltages and higher power applications, the best method is to integrate the above two approaches.

V. APPLICATION OF SST IN THE DISTRIBUTION SYSTEM

A. State-of-the-Art Technology

Efforts have been made to design and implement SSTs with satisfactory performance, as well as explore its potential application in the distribution system. Fig. 11, on one hand, shows the traditional distribution system, where the transformer is adopted for integrating the renewable energy resources and energy storage devices, powering the traction/locomotive system, and interfacing the FACTS devices, such as reactive power compensator and active power filters. On the other hand, the envisioned future distribution system based on SST is also shown in Fig. 11. It is observed that the SST can functionally replace the traditional transformer and some power electronics converters, thus showing a potentially more integrated and compact system. Furthermore, the efficiency and cost issues of the SST may be justified. Nonetheless, the reliability and lifetime of the SST interfaced distribution system are a concern for the utilities.

1) *Voltage Transformation and Regulation*: The SST has found its application in traction systems, as shown in Fig. 12 [10], [53]–[59]. The traditional traction system consists of traditional line-frequency transformer and back-to-back (BTB) converter, and the efficiency of such a system is $\sim 88\%$ – 92% [10]. As shown in Fig. 12, if the system is replaced by the SST, the efficiency will be $>95\%$ and a more compact and lighter system can be obtained. As a good example, ABB has announced its world's first MW level power electronic traction transformer in the field service in 2012 [10]. The reduced size brings more space for the passengers. In

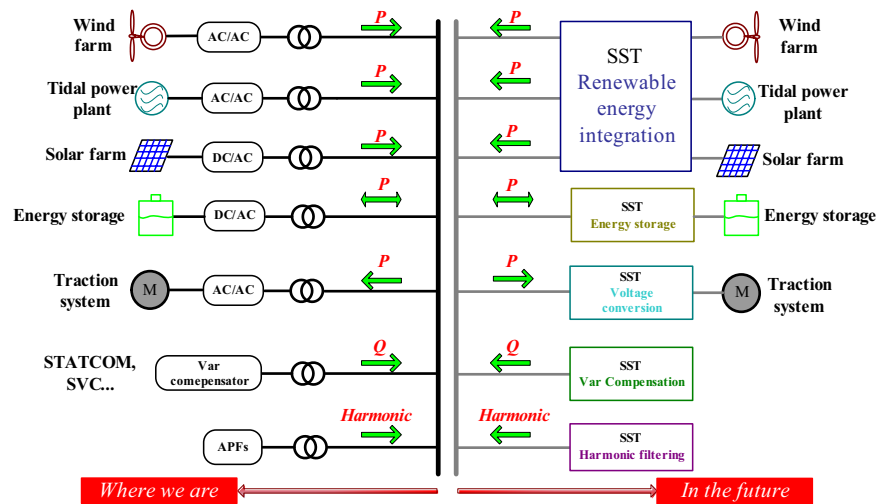


Fig. 11. Potential application of SST in the future distribution system.

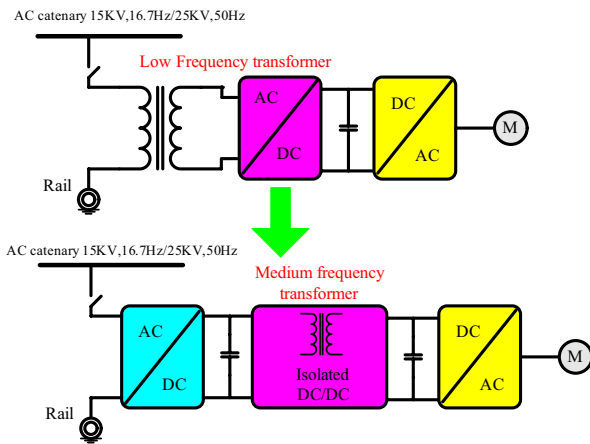


Fig. 12. SST-based tractions system.

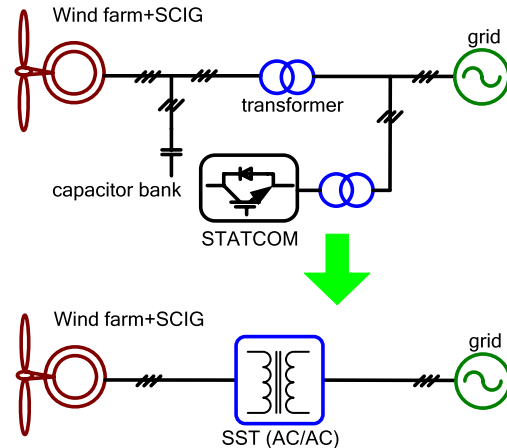


Fig. 13. Wind energy system interfaced by SST.

addition, the power density of such a system ranges from 0.5 to 0.75 kVA/kg, which is significantly improved compared with 0.2–0.35 kVA/kg of the conventional transformer plus rectifier structure.

With the high penetration of renewable energy resources, such as solar [63], [64], wind [40], [65], [66], and tidal power plants, the SST can also be adopted to directly connect these with the distribution system. Basically, the power converters and the line-frequency transformer are replaced by a SST to achieve a more compact system. The wind energy system with squirrel cage induction generator shown in Fig. 13 is taken as an example. For this type of system, reactive power compensator may be needed for stabilizing the point of common coupling voltage. By using and combining the functions of active power transfer, reactive power compensation, and voltage conversion of SST, a novel wind energy system can be obtained, as shown in Fig. 13, in which two transformers, one STATCOM, and one local capacitor can be effectively replaced by a single SST [65]. From this perspective, the cost gap between the SST technology and traditional transformer will be narrowed.

In addition, SST can also be potentially integrated with energy storage devices when its dc link is available. EPRI has demonstrated a 45-kVA, 2.4-kV fast charging station based on SST technology. The concept of this technology is shown in Fig. 14. In the traditional configuration, a transformer, ac/dc, and dc/dc converter is used to charge the electric vehicle; the efficiency of such a system is $\sim 90\%$. Using the SST technology, the efficiency can be pushed to be $>95\%$. In addition, it can substantially decrease the weight, and cost is reduced to half of the conventional technology, thus overwhelming its counterparts [67].

2) *Reactive Power Compensation and Active Filtering*: As presented, the SST may also provide VAR compensation depending on the topology adopted. In [65], an SST interfaced wind energy system was proposed with integration of active power transfer, reactive power compensation, and voltage conversion functions. It is shown that by further using the potential reactive power compensation capability of the SST, the system volume and weight can be further decreased, thus presenting a promising market. Similarly, SST-based dynamic voltage restorers were also studied in [68]. The SST may also

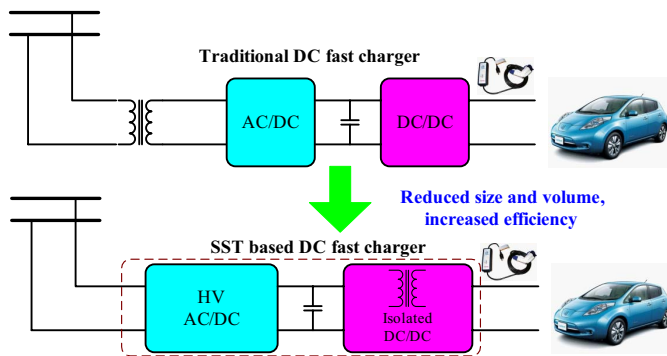


Fig. 14. SST-based dc fast charger.

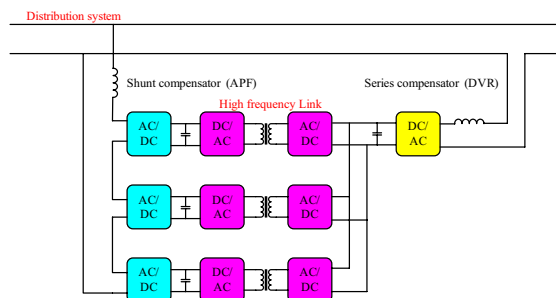


Fig. 15. High-frequency link UPQC structure.

take the responsibility of harmonic current filtering, whereas the capability of it depends greatly on the bandwidth of its controller, which is in turn governed by the switching frequency of the SST [69]. By combining these two functions, SST can also be used as the unified power quality conditioner (UPQC). Fig. 15 shows the high-frequency link UPQC structure used in the distribution system. This UPQC gets rid of both the shunt and series transformers, which are all operating at line frequency. Therefore, the size and weight of the system can be dramatically reduced. From the voltage conversion and isolation point of view, this UPQC can be regarded as an SST.

3) *Smart Grid Integration*: The SST has also been proposed as an energy router to integrate smart grid applications [5], [70]. Fig. 16 shows the envisioned SST-based microgrid system, in which a three-port power flow is achieved. The basic idea is to use the LVDC link as the common bus to connect renewable energy resources (DRER) and distributed energy storage devices (DESD). Therefore only single-stage conversion is needed compared with the normal ac grid, in which dc/dc plus inverter is needed to interface those dc-type source and load to the mains. In addition, the ac residential grid is also integrated using the LVAC port of the SST. Therefore, a more compact, lighter weight, and more integrated microgrid system can be developed. The integration issue of SST and microgrid has also been studied, as well as power management strategies that have been proposed [71], [72].

4) *Fault Isolation and Limitation*: Unlike the passive power transformer, SST embedded with certain control functions may also enact fault isolation and limitation. A protection method was proposed using the SST in the FREEDM system, and shows satisfactory performance in real-time digital simulations [73]. In addition, the potential VAr compensation

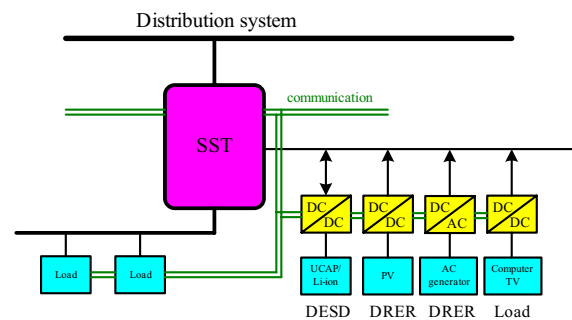


Fig. 16. SST for smart grid integration.

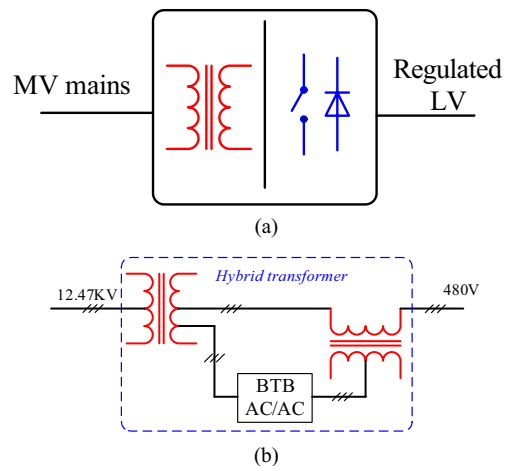


Fig. 17. Hybrid distribution transformer technology. (a) Concept of hybrid transformer. (b) Implementation of a 500-kVA, 12.47-kV/480 V hybrid transformer [74].

capability of the SST can also be adopted in the power system for transient-fault ride-through as that done by STATCOM in the weak grid system [65]. Furthermore, the renewable energy resources and energy storage devices connected at the dc port of the SST can provide uninterrupted power supply function when the fault happens at the distribution line, and therefore guarantees the high-quality power supply to the critical load.

B. Recommendations to the Future Work

Although it seems straightforward that the SST can replace the traditional transformer, it should be noted that stability problems given the increased proportion of regulated power electronics could ensue in the system. Efforts should be made thus in this direction to ensure that stability is maintained. Nonetheless, it is foreseen as an additional capability of the SST, that it could actively stabilize the power system by monitoring the loading conditions upstream and downstream from its location. In addition, although SST can potentially achieve a more compact and smarter future distribution system, few field test results are available. It is therefore desirable to gain more experience in this area.

A more feasible path for the SST to replace the traditional transformer is to first adopt the so-called hybrid distribution transformer concept, which is shown in Fig. 17(a) [74]. The basic idea is to integrate the partial power converter with the traditional distribution transformer, thus the additional functions, such as voltage regulation, reactive power compensation, harmonic filtering, and so forth may be achieved

in a certain range. Although the size and weight problem of such a system still exists, the cost and the reliability issues have been addressed. ABB together with EPRI has successfully developed a 12.47-kV/480 V, 500-kVA hybrid transformer with topology shown in Fig. 17(b), in which a BTB converter is integrated with a line-frequency transformer. The rating for the power electronic converter is 125 kVA, which is 25% of line-frequency transformer rating. It can provide additional functions, such as voltage compensation, unbalance compensation, and fault diction compared with the traditional transformer [74].

VI. CONCLUSION

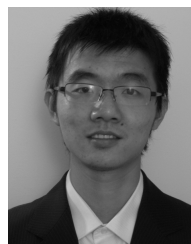
SST has received increasing attention from both industry and academia for the applications in smart grid and traction system. This paper has presented a comprehensive technology review of the SST, from components design to system application, aiming at providing a systematic review in this area. It is pointed out that high-voltage and high-frequency operated power devices, high-power and high-frequency transformer, high-efficiency ac–ac topologies are the main research focuses. In addition, investigation of SST in the distribution system can help in defining the market for this technology, and therefore it is also highly desirable. Several papers were reviewed and categorized, which can provide useful information to the community. Furthermore, new developing research directions were also presented, opening the path to new horizons.

In summary, impressive progresses have been made in the SST technology, whereas the cost and the reliability issues of the SST are the main issues that inhibit it entering into the market. Although the presented technologies can feasibly support the operation of SST in the whole range of the distribution system, the question of where and how SST can replace the traditional transformer needs more discussion. However, it is predicted that the SST may first be put into service in the applications where the size and weight are critical important rather than the cost, such as locomotive, aircraft, and ship electrical system.

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