Issues and Challenges of Solid-State Transformer Technology

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Solid-state transformer (SST) technology is one of the developing technologies that will be widely used in the future to integrate low-voltage and high-voltage networks with control circuitries and power electronics converters, facilitating renewables integration in smart grid applications. SST technology has crucial key advantageous features, including compact size and weight, low cost, and ease of connection in offshore applications. However, SST technology exhibits a few concerns, such as implementation, protection, economic, and communication compatibility, that need to be addressed.

solid-state transformers | advanced control and operation | power converters | power grids

1. Introduction

Transformers are commonly employed in power supply systems to convert AC voltage and galvanically isolate components. Smart grids are drawing the attention of many researchers recently. They are different from traditional electric networks in that they have power-generating capabilities and are able to supply electricity, especially to responsible customers in emergencies. Electricity may be generated from various sources, including nuclear power plants, autonomous diesel–electric units, large batteries, wind farms, solar panels, and hydrogen fuel cells. When employing multiple energy sources in smart grids, different stress levels should be coordinated. This is more challenging, since a portion of electrical energy is generated or stored in DC systems while the remaining is in AC systems. There are no enhancements or alterations to the classic transformer; thus, if the input voltage is asymmetrical and variations in frequency are present, there will also be an adverse effect on the output voltage. Traditional transformers need rectifiers and inverters to operate with networks that utilize a different direct or alternating current [1][2]. Solid-state transformers (SSTs) can be employed to address these concerns in smart grids, which can control and enhance the quality of electricity by compensating reactive power and reducing voltage drops. Using this technology, power supply can be adjusted without using any added compensator. SSTs are more compact, making it simpler to match varied voltage levels of direct and alternating currents. A few recent studies of SSTs with focused areas and research gaps are shown in **Table 1**.

Table 1. Research topics and key factors of SST technology.

Ref.	Year	Focused Topics	Key Factors
[3]	2021	This research proposes a DC–DC converter for a hybrid AC/DC SST. Multilevel, bidirectional, and four-port are the critical features of the proposed DC–DC converter.	Research issues and difficulties, as well as contemporary trends, are not taken into account.
[4]	2021	A unique construction based on bidirectional multilevel power converters on both sides of the SST, and the suggested SST's applicability to hybrid power networks.	The authors did not refer in the article to any research gaps. Therefore, the difficulties associated with research and validation are not well addressed.
[5]	2021	A modern traction system used SST technology in smart grid applications and distributed generating sources like solar and wind.	This research ignores the problems and difficulties that may arise. Sustainability and dependability were not given sufficient attention. The control system was ignored.
[6]	2021	The background of hybrid alternating current/direct current grids in future power grids, their inherent problems and possibilities, and how to maximize power transfer	The article does not detail the research gap and lack of power quality.

SST technology connects the distribution system with the electrical users in future smart grid systems. In the smart grid system, an SST connects the medium-voltage distribution system (e.g., 12 kV AC) to the low-voltage AC distribution (e.g., 120 V AC) and/or DC distribution system (e.g., 400 V DC), as depicted in **Figure 1**.

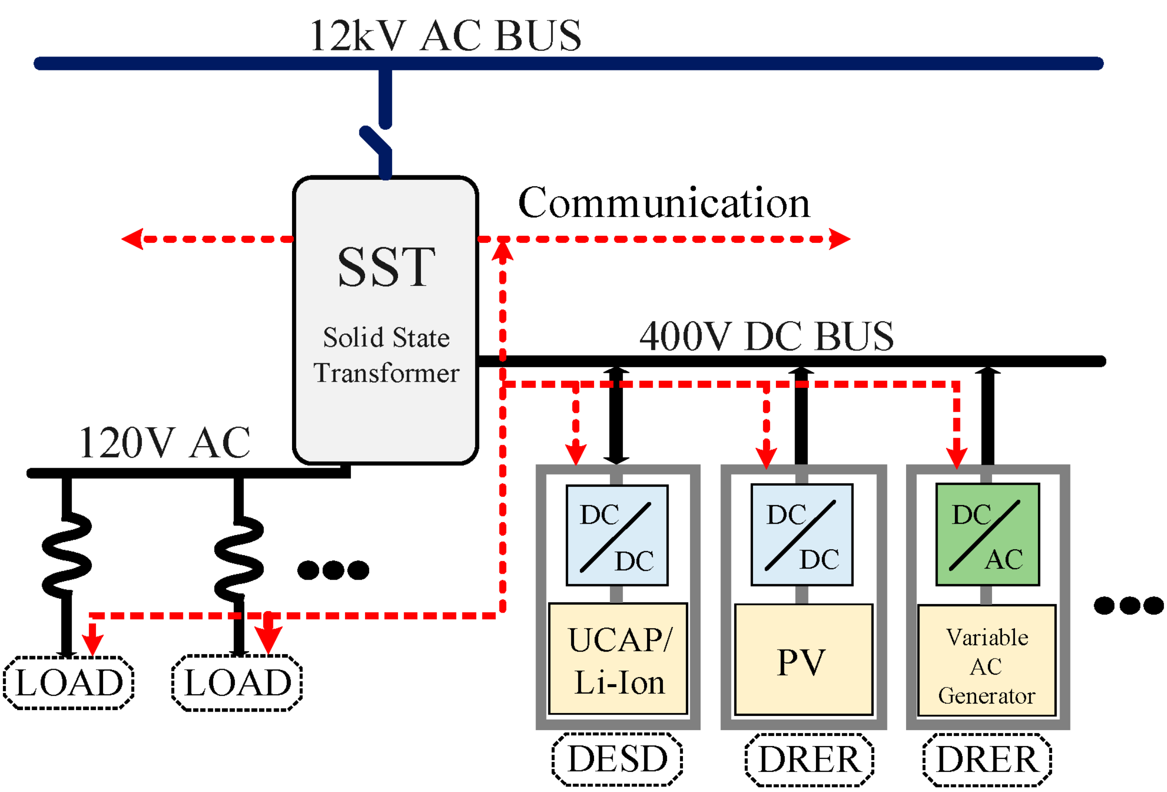

Figure 1. Solid–State Transformer at one residential home.

When a 60 Hz conventional transformer cannot be utilized to control distributed renewable energy resources (DRER), distributed energy storage devices (DESD), or loads, the SST can be used instead. The characteristics of SSTs include immediate voltage control, voltage sag compensation, fault isolation, power factor correction, harmonic isolation, and a direct current output [7]. The 400 V DC port on the SST makes it easier to connect certain types of DRERs and DESDs [8]. Each SST, which functions as an energy router, can control active and reactive power flow as well as fault currents on both the low- and high-voltage sides. In addition, it has enormous control bandwidth capability that enables remote resources to control and respond to changes in the system quickly. According to **Figure 2**, an SST is made up of three parts: an active rectifier, an active bridge converter that goes in both directions from DC to DC, and an inverter [9]. The most appealing qualities of SSTs are found in the last three phases. As a result, the SST may draw a unity power factor or offer reactive compensation for voltage control when connected to the grid.

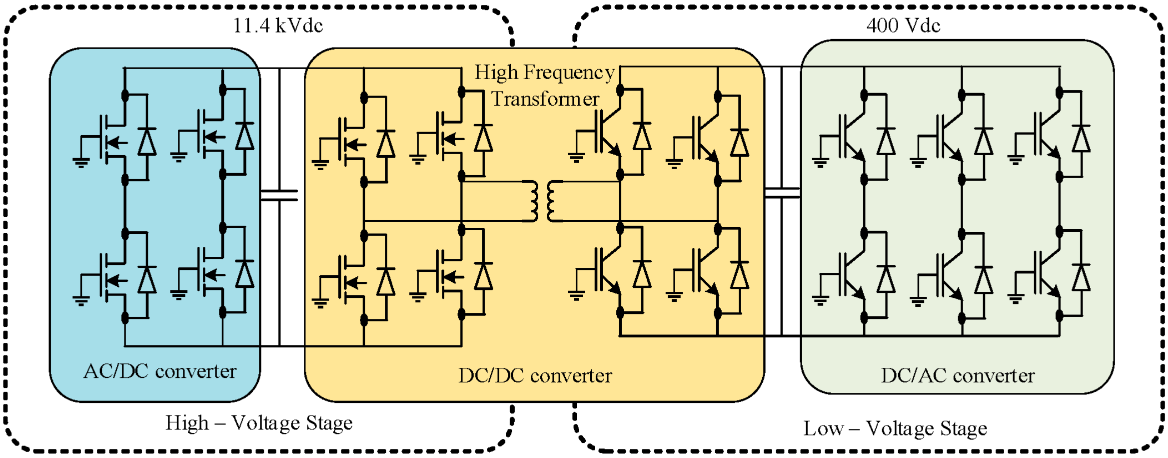

Figure 2. SST at one residential home.

The filtering on the load side can also separate the load from transient swells and harmonic distortion on the AC grid. Another benefit of using low-voltage (LV) direct current (DC) is that it may serve as a DC bus for solar panels, energy storage devices, or electric vehicle chargers. These new capabilities and flexibility provide a foundation for future smart grid infrastructure development. However, the addition of numerous power electronic converters to a standard AC grid brings a variety of previously unrecognized control and stability difficulties. SST interactions have the potential to generate instability, which is a problem. The source output impedance interacts with the input impedance to produce this instability, manifesting as harmonic resonance. An SST's active front end (the high-voltage (HV) rectifier) appears to the AC grid as a constant power load regardless of client load composition [10]. When the voltage drops, the power consumption reduces, making constant impedance loads self-correcting. In contrast, continuous power loads use the same amount of power and are frequently referred to as "negative impedances", which can cause DC networks to become unstable if they are not correctly constructed [11].

2. Issues and Challenges of SST Technology

2.1. Conversion Efficiency Challenge

LFTs in distribution grids are primarily responsible for providing galvanic isolation and voltage scaling while incurring as few losses as possible. As a result, for the majority of the load range, typical oil-filled 1000 kVA LFT efficiencies exceed 99% according to [12]; taking other manufacturers into account produces similar findings.

On the other hand, an AC–AC SST contains two AC–AC converter stages, one on each side of the primary voltage and voltage supply: one for the main voltage and one for the low voltage (LV) (as seen in **Figure 3**). Based on the provided LFT and MFT efficiencies and assuming that the two AC–AC converter stages have identical efficiencies (i.e., SST, MV = SST, LV), The efficiencies of the AC¬¬–AC stages required to obtain an overall SST efficiency equal to an LFT, i.e., SST = LFT, are determined in this research. The choice of an optimal switching frequency is critical to this efficiency and the active material size. It is essential to keep in mind that MFTs may get away with using less material and being more efficient than LFTs because their prices are lower. It is important to note that even with a high-efficiency MFT (ηMFT = 99.6%), getting to the desired total MV-to-LV efficiency of 99.5% necessitates 99.7% efficiencies in both AC–AC conversion stages (**Figure 3**). As you can see, this is a lofty goal that will likely remain unachievable with current high-power converters.

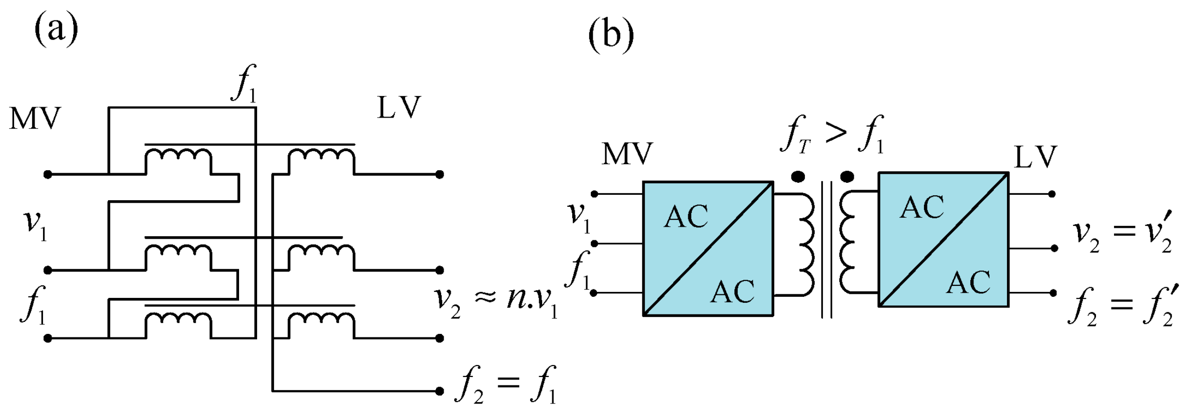

Figure 3. Diagrams of a standard SST: (**a**) low-frequency distribution transformer with a delta-wye connection (LFT), (**b**) SST.

2.2. Cost Challenge

According to pricing information collected from a prominent European transformer manufacturer, LFTs are off-the-shelf commodities with a specified (selling) price between cLFT = 10 $/kVA and 25 $/kVA for 1000 kVA units [13]. The price will differ based on the optimization goal, such as low losses or cheap costs; for instance, there are not any SST products on the market that allow you compare their pricing side by side. Therefore, [14] SST materials are estimated to be at least five times more expensive than LFT materials for a 1000 kVA SST.

A product's cost of production does not have to be directly tied to the price because there may be other factors at play, such as compensation for development expenses, labor expenses in manufacturing, infrastructure costs, and profit margins, among other things. Since high-power converter systems are widely accessible, their pricing may be used to estimate the cost of an SST. An SST's LV inverter (as depicted in **Figure 4**) is essentially the same as a high-power drive's active front-end (AFE) converter, such as the Altivar 61 series from Schneider Electric [12].

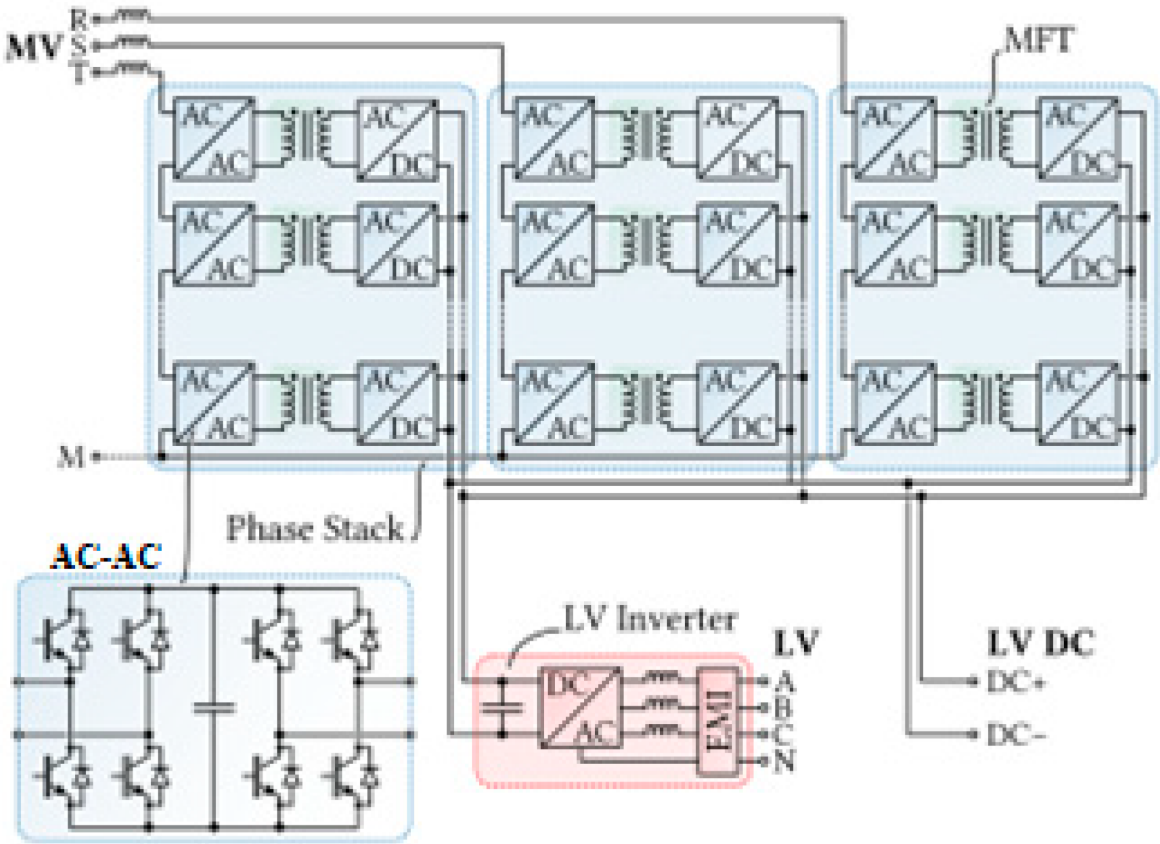

Figure 4. Typical topology of an MV/LV SST employing a cascaded converter structure on the MV side to handle the high voltage levels. Note that the AC–AC stages at the cascaded cells' MV sides can feature a local DC link (AC–DC–AC-structure as shown in the figure) or be of a matrix-type (direct AC–AC conversion).

For these converters, price information is available, and a 1000 kVA unit costs roughly cSST,LV = 125 $/kVA [12]. Furthermore, [15] The cost of the utility-scale (500 kVA) PV inverters ranges from 100 to 120 euros per kVA (114 to 137 dollars per kVA).

Because the MV-side converter section is more complicated and must interface with MV as well as contain the MF isolation stage, it is reasonable to suppose that the MV-side converter's particular price is greater than the LV-side converter's, i.e., cSST,MV > cSST,LV.

The weight and material cost structures of the MV converter, the LV converter. It is noteworthy that low-frequency magnetic components, such as filter inductors, continue to account for a sizable portion of both weight and material costs, particularly in the case of LV converters, where high phase currents necessitate large copper conductor material requirements. Consequently, these passive filter components are of special importance for future cost and weight reductions of SSTs. However, future technologies such as silicon carbide (SiC) are anticipated to considerably contribute to additional weight reduction via greater switching frequencies and subsequently smaller passive component sizes. Medium-frequency transformers and power semiconductors also contribute significantly to material expenses [14].

2.3. Compatibility Challenge

Most of the time, fuses and circuit breakers that may be programmed are used to safeguard low-voltage grids against short circuits. When an issue arises, only the nearest upstream protection device should activate, limiting the grid's impact to the lowest possible region. In this defense strategy, selectivity is crucial. **Figure 6**a depicts a simplified form of a hierarchically arranged LV grid and associated protective devices. To achieve selectivity, fuse ratings are low near end-users and higher near the feeding transformer. **Figure 5**b depicts the relationship between melting time and current consumption for a common low-voltage (LV) fuse [16], a fuse with a lower-rated current trips before a fuse with a higher rating when a short circuit develops, indicating that a short circuit occurred. Even a similarly small 250 A fuse would take a long time to light, for which, within a reasonable time, a current of around 1.5IN may be required to safeguard a load on a lower hierarchical level of the LV grid, as illustrated in **Figure 5**b. A short-circuit current that is several times the rating value is needed for fuses that are closer to the feeding transformer because they are installed at the higher level of the LV grid's hierarchical structure. This is particularly true for the transformer safety fuses, which are positioned close to the transformers. The transformers at the MV grid's interface must provide the short-circuit current needed. There is a two-second time limit on the maximum current that LFTs should be able to supply [17].

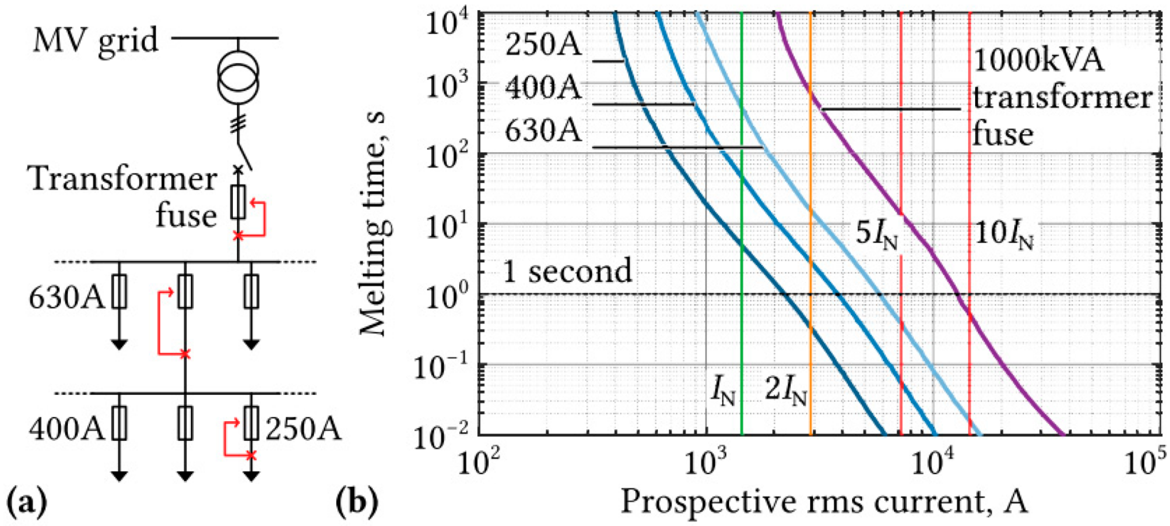

Figure 6. (**a**) Fuse and selectivity indications at various branching levels in a typical LV grid arrangement; (**b**) Melting time of LV fuses with different rated currents vs. current characteristics and a fuse for a 1000 kVA transformer in relation to its nominal current and its SST for a 1000 kVA transformer or LFT [17].

In contrast, a power electronic system cannot achieve this without significantly overrating the power devices due to the power semiconductor chip thermal time constants, which are only 10 to 50 milliseconds; additionally, the filter inductors would need to have a correspondingly high saturation limit. [18]. On the other hand, an SST might restrict the current flow during a short circuit. However, security ideas are necessary to make use of this intriguing capability. Communication between the breakers, SST, or other grid-connected switching devices is regularly employed in these intricate protection approaches. [19][20][21][22]. This means that an SST would have to be used with an LFT in the distribution grid because the present protection architecture could not be used any longer. As opposed to this, an SST needs a grid environment tailored to the SST's special properties such as communication between protection relays. However, implementing such changes would be difficult in current distribution systems, and they would be costly.

2.4. System Topologies

The topologies of current converters designed for railway traction applications were investigated. Numerous alternative topologies, on the other hand, such as isolated AC-to-AC converter topologies, can be identified by a survey and study of isolated converter topologies [23][24][25][26][27][28][29][30]. Smart grid and renewable energy applications research is now gaining pace. Due to commonality in high power, medium voltage, and galvanic isolation, PET-based systems intended for smart grid and renewable energy applications are highly likely to be transferred to railway traction applications.

2.5. Other Issues

Beyond the three critical problems outlined above, blockchain is an emerging technology that faces several other challenges. The operating frequency and the number of cascaded modules' optimization may be less complicated. However, it still requires more investigation, as do the techniques of soft switching and control and system dependability and protection. Furthermore, these problems might impact one another and form a symbiotic relationship. For example, with the advancement of power devices, people may create new converter topologies and increase the number of cascaded modules and power devices people have. As a result, rather than focusing on an individual component, it is critical to assess the impacts at the system level.

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