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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

An developing technology known as the solid-state transformer (SST) integrates a transformer's power electronics converters and control circuits. The SST topologies suitable for various voltage levels and stages, as well as their control behaviour and application trends, are thoroughly reviewed in this work. In order to convert the input to output under unipolar and bipolar operation, the study analyses various SST configurations and their designs and features. Included is a comparison of the topologies, control mechanisms, and applications. There are explanations of many control models and systems. To understand the significance of SST technologies, potential benefits of SST in terms of controllability and the synergy of AC and DC systems are underlined. This assessment makes numerous points, such as current problems and difficulties, and offers suggestions for enhancing SST development and construction in the future.

INTRODUCTION

A novel technology called the solid state transformer (SST) has the potential to influence the growth of numerous fields, including smart grids, traction systems, and systems using renewable energy sources (RESs), to name just a few [1][3]. Reactive power compensation, voltage regulation, power flow management, voltage sag compensation, bi-directional power flow, fault current limitation, harmonic block, and galvanic isolation are a few benefits of SST over low-frequency transformers (LFT) [4][6]. The size and weight reduction of SST is one of its most obvious benefits. Figure 1 depicts how their physical appearances differ. According to a comparison study, the volume of a 3 phase SST is 80% lower than that of an LFT [7], [8]. Due to the portability, low installation costs, and ease of assembly in some awkward situations, such as off-shore transmission applications, volume reduction of SST is significant [9].

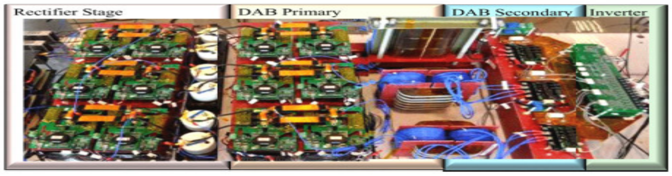

Figure 1. The physical looks of the high frequency solid-state transformer.

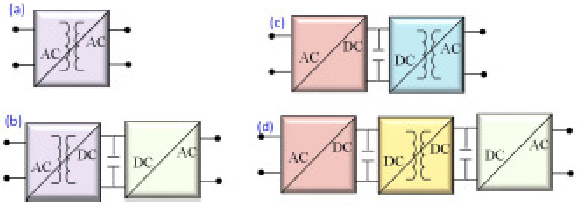

Figure 2. SST topology configurations (a) Single-stage; (b) Two-stage with LVDC link; (c) Two-stage isolation with HVDC link (d)Three-stage .

Through the use of switching circuits, SST transforms low frequency (LF) power input into high frequency (HF) power, and then regenerates LF power at the output terminals. Depending on how the solid-state devices are built, it can be made into various power conversions [10]. As a result, numerous converter topologies have been suggested and examined in various applications [11], [12].Regardless of the variations in the converter topologies, all varieties of SSTs can perform isolated AC-AC conversion [13]. According to Fig. 2 [8], [11], [14], all of these topology designs can be divided into single-stage, two-stage, and three-stage designs. The HFT is used in the single-stage SST topology to convert electricity from high voltage alternating current (HVAC) to low voltage alternating current (LVAC). The voltage is typically stepped down in an AC-DC or DC-AC stage by the two-stage SST topology. The most popular configuration of the three-stage SST topology has HF isolation in the DC-DC stage and greater power to fulfil the demands of the smart transformer. However, while having power converters, the three-stage design has low power efficiency [15] as a result of significant conduction loss and switching loss. The researcher unveiled a single-stage AC-AC SST in 2017 that had a 97% efficiency . In addition, the power switch is not available for the HVrating, particularly for power distribution purposes.Input series and output parallel (ISOP) modular multilevel configurations are widely utilised to address the problem by sharing the voltage and power in series connection, as shown in Fig. 3 [14]. To avoid the issue with voltage and power balancing, balancing circuits and control techniques are also necessary, but these have disadvantages such as complex control and assembly systems [17],[18]. Recent developments in power semiconductor technology led to the development of FREEDM GEN II and FREEDM III using a two-level strategy to prevent cascading converter cells [18], [19].Investigations into the economic viability and dependability of commercialising SST are ongoing in numerous research and development projects [19]. However, additional study is still needed to enhance SST performance and reduce costs utilising various strategies [13]. In order to pique the interest of more academics, this publication offers a thorough examination and a rapid grasp of the SST. The design and efficiency of the SST topology are discussed in a few well-known works. The design and optimisation of 15-kV SiC IGBT and their effects on utility application were addressed by Wang et al. A 15-kV SiC MOSFET-based single-phase SST architecture was created by Huang et al. [13]. To provide grid-edge control, Divan et al. [21] devised a 12-kV120/120-V based galvanically separated single-stage SST topology. The SST modular structure, control functionalities, and some difficulties were described by Liserre et al. Huang talked on the MVSST technology and associated features.The structure of a three-stage STS was examined by Ferreira Costa et al. Two modular power converter design concepts—the cascaded-H bridge (CHB) and the modular multilevel converter (MMC) topologies—were the focus of Briz et alstudy .'s . The two groups of contemporary SST topologies—matrix type, isolated back end, isolated front end, isolated MMC, and single cell–based HV SiC devices—were covered by Huber and Kolar [11]. The articles previously mentioned concentrated on creating a particular SST topology. Unfortunately, the full comparative examination of various SST topologies, their applications, and implementation challenges is not thoroughly examined. The main objective of this study is to provide a detailed review and analysis of SST topologies together with updated information, key features, benefits, and relevant applications.

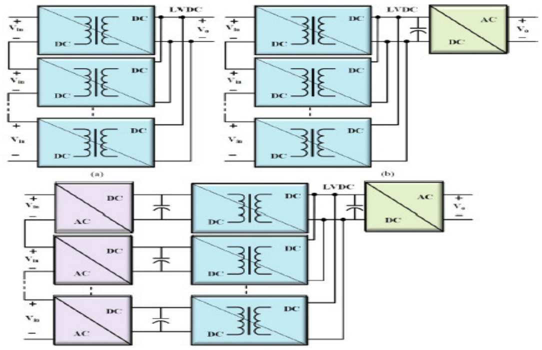

Figure 3. SST ISOP configurations (a) Single-stage; (b) Two-stage; (c)Three-stage.

A thorough comparison analysis is conducted taking into account crucial factors including cost, material, power loss, frequency, efficacy, and other functional capabilities. Hence, this study delves farther to examine the present advancements and difficulties. Also, this research paper offers suggestions for SST's future development in order for it to be widely used in the energy market.

OVERVIEW OF SOLID-STATE TRANSFORMER

Many SST topologies fall under the single-stage, two-stage, and three-stage categories, respectively.

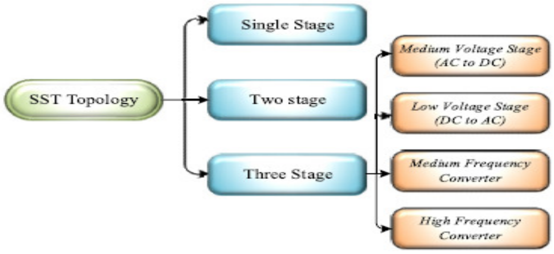

Figure 4. Classification of SST topology.

By switching some or all of the switches, several SST topologies may convert the input of DC or AC to the output of DC or AC, enabling bipolar (AC setting) or unipolar (DC setting) voltage and current [14]. Fig. 4 depicts the SST classification.

A SINGLE-STAGE SST TOPOLOGY

In a single-stage architecture, the direction and amount of power transfer are controlled by the phase shift angle between the secondary and primary bridges. In order to enhance the control strategy and control harmonic content, a bi-directional power flow with four-quadrant switches is used..As shown below ,the phase-shift angle'regulates the amount of power transferred to the load between two bridges.

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

where vi;pu and v0;pu stand for, respectively, input voltage and output voltage expressed in units. Transformer leakage reactance is indicated by the symbol Xpu in units. According to, the optimal DC voltage transfer ratio is calculated.

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

where Rpu is the load resistance expressed in units per load. Nevertheless, when an output filter departs, (2) cannot be applied to the ACAC system. Sb and Vsec stand for base power and base secondary, respectively, and Zb;sec D Sb=Vb;sec can be used to indicate the base secondary-side impedance.

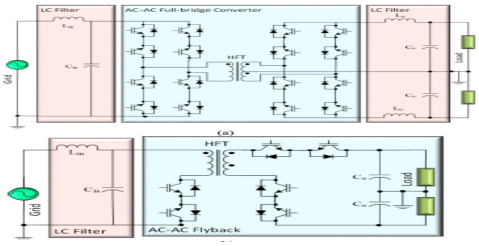

Figure 5. AC-AC single-stage SST (a) Full-bridge converter (b) Flyback converter .

shown in the following equation,

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

where Cpu D Co Zb, sec. and Core indicates the output filter capacitance, respectively. By converting (3) into the frequency domain, the AC voltage transfer ratio may be calculated.

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

We can see from (4) that the transformer phase shift between bridges, output filter, leakage inductance, and load resistance all affect the AC voltage transfer ratio.

B TWO-STAGE SST TOPOLOGY

The addition of a DC-link design, either on the HV side or the LV side, distinguishes single-stage SST from two-stage SST. The power is bidirectional, however it can be changed to be unidirectional by adding an unregulated rectifier to the AC-DC converter's LV side [11]. A sophisticated switching technique and numerous switching devices are required for this topology [9]. Although while a two-stage SST makes a system more complex, it still has some benefits, such as reactive power compensation [11]. Two-stage SST with LVDC link is not suited for HV operation because the ZVS is difficult to sustain in such a large input range. Although the lack of an LVDC link makes renewable applications in LV undesirable, the problems can be solved by switching from LVAC to HVDC [35]. Moreover, a different approach to this problem is to use the three-stage SST topology. A new three-phase, four wire, AC-AC high frequency-based matrix type SST has just been proposed. In this configuration, the utility source voltage is converted via PWM into pulses of 50% duty square wave before being passed through a single-phase high-frequency transformer. This design has advantages including high power density, electrical galvanometer isolation, bidirectional power flow, flexible voltage transfer ratio, and controllable input power factor. Moreover, this architecture has the capacity to use modified three-dimensional spaced vector PWM (3D SVPWM) to lower harmonic distortion in both input and output current under unbalanced load situations.

C THREE-STAGE SST TOPOLOGY

Because of the clever characteristics it offers, the three-stage SST topology is the most popular among researchers when compared to the other SST topologies. The performance of the distribution and transmission grids can be optimised in addition to the SST's lower volume and weight [8]. Two DC links are used in the three-stage SST topologies to handle power quality (PQ) issues as well as to supply and use any MV or LV devices [12].Regarding voltage regulation, current limit, protection, and power factor, three-stage architecture is observed to be superior to one stage and two stage topology. In order to make the integration of renewable energy and energy storage systems easier, a number of SST initiatives have been created [13]. One of the uses for three-stage SST in an electrical distribution grid is depicted in Fig. 6. At least two power converters, including an MV frequency converter and an LV converter, are included in the three-stage SST's architecture.According to , three-stage SSTs are often created for use in smart grid applications where they can transmit electricity from LV to HV in both directions. The following subsections provide a detailed description of each stage's characteristics.

APPLICATION

1)WIND ENERGY CONVERSION SYSTEM

The weight and volume reduction, voltage step-up, and additional functions that SST could provide, such as reduced voltage fluctuation, voltage regulation, and reactive power compensation, which improve PQ events, are a few key aspects of the SST being proposed for the wind energy conversion system (WECS) [4]. There are numerous WECS models available, but only the WECS based on the doubly fed induction generator (DFIG) is the most frequently used because to its small size, constant frequency operation, and high MVA ratings.

2) MICROGRID APPLICATION

Since DC power is becoming more and more significant, many studies have suggested switching the AC grid over to the DC grid [132]. Yet, switching from an AC grid to a DC grid quickly is almost impossible. Thus, there have been studies that suggested the three-stage SST was implemented in a hybrid AC/DC system. Because of the limitations in power devices, SST is only appropriate in the microgrid (MG); it is not suited for a smart grid. Moreover, the SST is significantly lighter, smaller, and has a higher power density than the LFT, which makes it ideal for widespread application in power distribution systems. The combination of DERs with energy storage systems, which might improve power quality and efficiency and result in a reliable system operation, is another fantastic benefit of employing SST .

3)TRACTION APPLICATION

One of the scientific studies that will likely be pursued is the use of locomotive traction, with an eye towards making it smaller, lighter, and potentially more powerful. As of now, a large transformer is built in the system because many applications involve AC-fed traction vehicles that operate at 50 Hz or 16.67 Hz. The weight to power ratio for a 6 MVA machine is around 1.58 kg/kVA for a 50 Hz system and 1.81 kg/kVA for a 16.67 Hz system.Thus, the transformer's weight has an impact on the overall power efficiency. SST is subsequently researched with the goal of reducing the system's weight and size in order to increase power density and efficiency. In addition, SST implements four-quadrant conversion stages in traction applications while maintaining characteristics of traditional line frequency transformers. ABB, Bombardier, and Alstom have all developed traction applications that use SST.

4) OTHER FUTURE APPLICATIONS

Other potential future uses include hybrid AC/DC systems, flying wind turbines, portable transformers, subsea processing, electric vehicles (EVs), navy, and aeroplanes with SST. A hybrid system that can supply and consume AC or DC is an excellent idea because there are many DC uses in everyday human usage. According to , photovoltaic-assisted charging stations (PVCS), which are depicted in, may be among the crucial charging infrastructure for electric vehicles. Better energy management and power control are made possible as a result of the simple communication between the PVCS and the utility grid via the SST. Also, there is a brand-new method of producing wind energy known as the airborne wind turbine (AWT), sometimes known as an airborne wind energy system (AWESs). In contrast to a traditional wind turbine, the AWT produces power from higher altitude winds, which are believed to be quicker and more reliable than winds near to the ground. As a result, it offers a more dependable and efficient way to generate electricity . A generator on the ground and a generator in the air, as seen in, are two examples of AWTs . The advantage of transporting electric power across the weather is offered by AWT generators in the air. It enhances the necessary mechanical strength that is attached to the ground station while also reducing power loss. As a result, the SST might lower the aircraft's overall weight and convert electricity to high voltage to cut down on power loss. One of the elements to be implemented in subsea applications that needed electricity for oil and gas processing, remotely operated vehicles (ROVs), and offshore wind generation is power optimisation. SST could offer a good solution for all of these applications to address the aforementioned problems. Power had to be sent or received by theLong-distance transmission causes the system to lose more power in the HVAC system; as a result, the application might require a platform or oater. By merely laying a longer HVDC cable from the shore to the subsea, SST technology with DC power transmission can lower the cost of establishing a platform by transferring power over longer distances. Moreover, SAB can further cut costs by reducing the amount of power devices that employ unidirectional power flow. subsea applications from the shore or topside, which were connected via the power cable.Portable site transformers are still big and heavy in this age, despite being present. The addition of SST, however, not only allows for the reduction of weight and space, but also offers the other characteristics that were described earlier. Considering all these benefits, SST has a wide range of applications and may one day be used in electric aeroplanes, submarines, and other naval applications.

ISSUES AND CHALLENGES FOR FUTURE SST IMPROVEMENT

The primary objective of the sophisticated SST is to offer a high degree of flexible control to enhance power transfer technology. The performance of SST in terms of cost-effectiveness, efficiency, reliability, protection, communication compatibility, and scalability has been found to be significantly impacted by a number of difficulties. The following subsections cover a few of the identified advanced SST-specific critical concerns and challenges.

1)ECONOMICS FEASIBILITY

Due to the use of solid-state devices like IGBT, MOSFET, etc., SST has many wonderful benefits. This, however, brought about yet another significant problem, namely that SST costs are higher than those of standard LFT. A 100kVA SST's estimated material cost is at least five times greater than that of an equal-rated LFT [7]. To deal with this, the topology SST must strategically select various topologies. For instance, it is advised that the solar farm employ twostage SST if the smart features are not necessary, thereby lowering the number of power-consuming devices.Moreover, the single-stage SST can be applied to any application if all that is needed to replace the LFT is a reduction in weight and volume. Nowadays, renewable energy and smart grids could be the main areas of application .Use of low voltage switching devices with low loss characteristics and high-frequency operation can lower the volume of heat sinks and passive components, thus lowering the cost of SST .Additionally, since the current sharing method uses the active power component of the duty cycle in the rectier stage as the feedback signal for the power balancing controller in the DC-DC stage, there is no need for a current sensor to be implanted .The use of the SST in various applications, such as traction, may be sped up by the new technology in a semiconductor like SiC. SiC's properties allowed for significant cost reductions overall, making it more commercially viable by reducing the total number of power devices and passive components (capacitors from DC-Link & SR circuits).In some SST components, such as the MFconverter, which must implement a distinct topology, further research is possible. For instance, it was suggested that the AQAB and

SRC be combined to further lower overall costs. Moreover, a larger market could significantly lower SST prices due to economies of scale, although additional study into alternative methods of price reduction is still needed.

2)OVERALL PERFORMANCE

When compared to LFT, modern SST performance often has a higher power density. Because to the numerous power conversions, the efficiency of two-stage and three-stage SST is lower. Moreover, SST dependability is typically low because several tests and studies are still being conducted for brief periods of time. For SST, extensive testing and study are needed. The solid-state devices' inability to handle high voltage prevents the complete implementation of the SST to the smart grid at present time. After that, modular SST could be able to fix the problems, however the sheer number of power devices needed results in expensive costs and PQ problems.However, with the development of SiC power semiconductor technology , a single-cell solution might be achievable. The single-cell technique is excellent, but reliability issues persist since it is challenging to implement redundancy in a non-modular system [11].As a result, additional research on the semiconductor side is needed in order to properly implement in HV applications.

3)SST PROTECTION

Before SST is widely accepted in the market, two important things to take into account are reliability and robustness. Due to the lack of protection against overvoltage and overcurrent, the SST protection reliability is rather low when compared to the LFT. Although it may encounter several potential problems such control mistakes, measurement inaccuracies, or insulation breakdown, it is significantly more difficult in SST. This possibility necessitates the use of extra external protection mechanisms. Unfortunately, the relative volume increases of these external devices negate the benefits of volume reduction in this situation. Alternately, if improved protection devices (solid-state circuit breakers) are used, a less robust option might be taken into account .As a result, SST Protection still needs to advance before it can be completely implemented on the grid without negating the benefits of SST characteristics. Both internal and outdoor lighting protection measures are included in the lightning protection system (LPS) for an STS. By splitting the STS into lightning protection zones, the internal lightning protection can be accomplished (LPZs). The electromagnetic compatibility (EMC) of an object is the foundation of the LPZ idea. The denied EMC values are based on the electrical equipment's immunity. The conducted and eld-bound interference at the boundaries can be reduced to desired values thanks to the LPZs. Thus, two protection zones are created around the protected object. The first zone, LPZ 0A, where the components might be directly struck by lightning, is identified using the rolling sphere method. The LPZ 0B is the second zone, and it protects areas from direct lightning strikes. On the other hand, the air-termination method, down conductor method, and earth-termination method can be used to create an external lightning protection system

4) ELECTRICAL INSULATION AND PARTIAL DISCHARGE

A HFT employs enamelled magnet wire with an optional corona-resistant insulating layer and is smaller and more compact in design. Insulation of HFT with inter-turn and turn-to-ground turns shows high voltage and high-frequency electrical stress, ranging from 5 to 40 kHz. Additionally, in conditions of increased dielectric loss with frequency, the operating temperature of HFT can rise to 150–200 C .As a result, under high-frequency voltage, significant effects are observed on the insulating material in HFT, leading to an early failure of the insulation. Due to rapid ageing, electrical stress, overvoltage, and heating, the high-frequency PWM waveform causes insulation failure, which shortens the life cycle .In HV systems or LV systems where overvoltage or surge may occur, partial discharge (PD) is the primary cause of insulation degradation. The research in discovered that the voltage frequency affects PD behaviour and insulation life. Another study in claimed that the frequency band between 50 Hz and 1 kHz is where the reduction in PD amplitude might be detected. Moreover, the reversal of voltage polarity and the reverse electric field both heighten the PD phenomena.

5)COMMUNICATION COMPATIBILITY

The connection between the SST, circuit breakers, and other switching devices in the grid was a common component of many sophisticated protection designs. However, in order to achieve the protection system, it is crucial to adopt specific SST features in the grid environment.Implementing such modifications in the current distribution grids is difficult and expensive .Therefore, it is crucial to understand that SST could not now serve as a straight replacement for an LFT in the distribution grid because investing in the communication component required further research.

6)SST IMPLEMENTATION CHALLENGES

The fundamental restriction on the operation of the cascaded H-bridge converter is caused by SST, which causes voltage unbalance on the DC side under no-load or light-load conditions. The percentage of real power discrepancies is significantly impacted by this voltage imbalance. However, SST is still in the development stage and needs to increase its efficiency and cost-effectiveness as well as adopt a new standard for its commercial viability. SST implementation is thus a problem at various levels. Yet, SST may eventually allow for an unprecedented volume of two-way power flow, which would be a revolutionary accomplishment for smart grids.

CONCLUSION

The review provides a thorough analysis of STS topologies, controller functioning, related applications, and implementation issues in order to determine their significant contribution to renewable energy sources and the increasing deregulation of the energy market. A thorough discussion of the various SST topologies, configurations, power and voltage ratings, benefits, drawbacks, and relevant applications is provided at the outset of the review.The design, function, number of components, advantages and disadvantages, price, and efficiency of several medium voltage and medium frequency power converters are discussed.analyzed. The review also discusses power losses caused by various impacts of materials, composition, and temperature in addition to the operation and design requirements of HFT. With reference to type, operation, voltage, frequency, switching configuration, and functional capabilities, the most recent publications on well-knownMVSST are evaluated. The overview then highlights the different SST controller operations. The implementation of several SST topologies is then examined in the fields of solar PV, wind power conversion and transmission, traction, smart grid, MG, and DC charging station. Finally, important aspects of SST implementation are identified with regard to price, effectiveness, safety, and insulation.

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