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# Assessment of the State-of-the-Art of Solid-State Transformer Technology: Design, Control and Application

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## Abstract

*The structure and principle of operation of conventional iron-and-copper conventional transformers has not changed for the past decades largely to its high efficiency and reliability. However, conventional transformers are generally heavy and limited to transformation of AC power only in a unidirectional pattern. However, due to the increasing integration of distributed generation to grid, bidirectional power flow within the present grid systems is now inevitable. This makes solid-state transformer (SST), as a more flexible, portable, and cost-effective alternative, to gain considerable attention in recently. The SST is designed using power electronic components and a high frequency transformer (HFT). As an energy router, SST is crucial to the deployment of internet energy system due to its compact size, improved controllability, resiliency, bidirectional power flow, and variety of applications. Various designs and control approaches have been proposed for the SST to suit various applications. Thus, this paper reviews the extent of research works carried out on the SST vis-à-vis classifications, design, control and applications. The review is centered on establishing the state-of-the-art and identify future research prospects in the design, control, and applications of SST.*

**Nomenclature**

| | | | |
|---|---|---|---|
| $B_m$ | magnetic flux of the transformer | CHB | cascaded H-bridge converter |
| $I_{ll(rms)}$ | input inverter current | DAB | dual active bridge |
| $P_h$ | power lost due to core magnetization | DTC | direct torque control |
| $P_{out}$ | DAB converter output power | EV | Electric vehicle |
| $V_{(rms)}$ | inverter voltage | FACTS | Flexible AC transmission systems |
| $V_{L-L(rms)}$ | rms line to line voltage | FOC | field-oriented control |
| $V_{L-L}$ | instantaneous line to line voltage | GCT | Gate Commutated Thyristor |
| $V_{dc1}$ | input stage capacitor voltage | GTO | Gate Turn-Off Thyristor |
| $V_{dc2}$ | output stage capacitor voltage | HFT | high frequency transformer |
| $V_{ll(peak)}$ | peak output rectifier voltage | HVDC | High-Voltage Direct Current |
| $f_s$ | system frequency | IGBT | Insulated Gate Bipolar Transistor |
| $k_h$ | Magnetizing constant | LFT | low-frequency transformer |
| $\mu$G | micro-grid | NPC | neutral-point-clamped |
| SG | smart-grid | PETT | power electronic traction transformer |
| SCR | Silicon-Controlled Rectifier | RES | Renewable energy sources |
| $D$ | Duty cycle | VSC | voltage source converter |

## 1. Introduction

In recent years, the electrical energy system in developed countries is transitioning from one that is predominately made up of centralized power plants to one that has a sizable number of decentralized, small generation sites (Mishraa, *et al.*, 2021). These decentralized are small generations sites are accompanied with smart-grid (SG) and micro-grid (μG) technologies. These technologies are being developed to lessen or prevent effects brought on by power quality events (such as voltage sags), enhance dependability metrics (such as by cutting back on interruptions and their length), and boost efficiency (e.g., by limiting losses) (Guerra & Martinez-Velasco, 2017). In the traditional power system, the typical transformer serves a crucial function, but it has some limitations, including bulky size, poor voltage regulation, high weight, and volume. A solid-state transformer (SST), a fantastic mix of power electronic converters and high-frequency transformer, can therefore replace this conventional transformer and can overcome significant drawbacks of conventional transformer (Poojaria & Joshib, 2022) (Poojaria & Joshib, 2022).

SST is a brand-new class of transformers built on power electronic converters that combines power quality enhancement, control, galvanic isolation, and voltage transformation into a single unit. By utilizing power electronics components on both the main and secondary sides of the transformer, the SST offers a fundamentally unique and more comprehensive approach to transformer construction. SST can incorporate several characteristics, including instantaneous voltage regulation, voltage sag compensation, and power factor correction. (Banaei & Salary, 2014).

To date, several research results have been reported in the fields of SST topology and control strategy (Lia, et al., 2017; Poojaria & Joshib, 2022; Banaei & Salary, 2014). It is considered a remarkable accomplishment to have progressed from a primary version known as an electronic transformer to a more developed and highly efficient SST of 98.25% efficiency used in a low-voltage (LV) based distribution transformer with less weight and size than a low-frequency transformer (LFT). However, this efficiency still needs to be increased because the LFT's efficiency is higher than Nevertheless, SST has a great potential to replace LFT because to its additional advantages, including reduced size and improved controllability (Mishraa, *et al.*, 2021). This study reviews the advances made in the design, control and applications of the SST.

While selecting the articles for this review, the reputation (high-impact factor), currency and relevance of the articles were given due attention. As such, the primary sources used were meticulously selected from high-quality and reputable research databases such as Scopus, IEEE Xplore, Springer, ScienceDirect, Taylor and Francis, Wiley, and MDPI. The review covers a total of 157 online published articles; journals, conference papers, and scientific books.

The articles reviewed were published within a span of several years (1980 to 2024) as shown in Figure 1. As shown in the chronology, most of the reviewed literature are published within the last 5 years. This growing trend is attributable to the continued interest in SST.

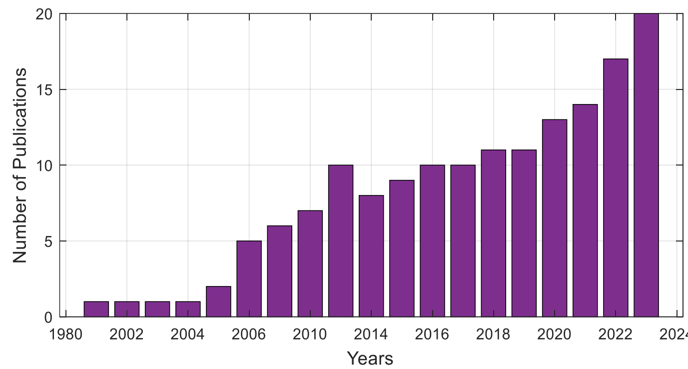


**Figure 1**. Publication chronology of the review articles

After this introductory section, Section 2 presents the classification of SST vis-à-vis topologies, applications, power electronic devices, and power conversion technology. Section 3 gives the detail design of the stages of SST and the type of power electronics devices used and the basis for selection. The control strategies used in SST are thoroughly explained Section 4. Section 5 starts outlines the application areas of SST and how such altered the energy market landscape. Finally, the review conclusion and summary are highlighted in Section 6.

## 2. SST Classification

Because of the variety of functions and topologies, SSTs are classified based on (Liua, *et al.*, 2018; Borgaonkar, 2015; Shamshuddin, *et al.*, 2020):

(a) power conversion technology
(b) topology
(c) power electronics devices
(d) application
(e) Control strategy
(f) number of ports per power stage
(g) modularity,
(h) voltage levels, and
(i) control of the isolation stage

### 2.1 Classification based on Power Conversion Technology

Ordinary or three-level voltage source converters (VSC-SST), cascaded H-bridge converters (CHB-SST), and modular multilevel converters (MMC-SST) are the three types of SSTs based on the power conversion technology employed. (Battal *et al.*, 2022; Bignucolo *et al.*, 2021).

### *2.1.1 2- or 3-level voltage source converter type SST*

With this kind of SST, the AC voltage is first converted to DC and then back to AC at the required voltage level and frequency using a voltage source converter (VSC). A two-level or three-level conversion can be the VSC. The DC voltage in a two-level VSC is either detached or connected to the source of AC power, whereas in a three-level VSC, the Dc voltage can take on three different levels, allowing for better utilization of the DC voltage and improved power quality. The VSC-SST is widely used for applications such as grid-connected power generation and distribution, microgrids, and renewable energy resources. The power electronics devices in the input stage should be utilized in series or parallel, though, if the VSC-SST is used with middle- or high-voltage systems. This presents challenging voltage- or current-balancing challenges, respectively (Baizan *et al.*, 2014; Al-Turki *et al.*, 2024).

### *2.1.2 Cascaded H-Bridge*

In cascaded H-Bridge SST (CHB-SST), a cascaded H-bridge converter is used for the power conversion. Multiple H-bridge converters are connected in a cascaded manner to create a multilevel output voltage waveform (Shehu *et al.,* 2016). The CHB-SST is mainly used for high-power, high-voltage applications and offers improved voltage utilization, reduced harmonic distortion, and increased system efficiency compared to traditional VSC-SSTs. But for this construction, a lot of power electronics equipment and HFT are required. Utilizing HFT extensively to increase power density is counterproductive since it consumes a significant amount of SST in terms of weight and size. (Giesecke, *et al.,* 2020; Elrajoubi *et al.,* 2019).

### *2.1.3 Modular Multilevel converter type SST*

This type of SST uses a modular multilevel converter (MMC) fo the power conversion. The MMC is composed of multiple sub-modules, each containing a set of capacitors and power electronic switches, which are connected in series to produce a multilevel voltage output (Bignucolo, *et al*., 2015; Elrajoubi et al., 2019; Umar *et al.*, 2020). The MMC-SST is well suited for high-power, high-voltage applications and offers improved voltage utilization, reduced harmonic distortion, and increased system efficiency compared to CHB-SSTs. The future will unavoidably see the use of MMC to SST due to its ongoing development. One type of DC/AC power converter is the MMC (Jia, *et al.*, 2021; Chaa, *et al.*, 2008). Its simple sub-modular (SM) form offers scalability, which is essential for achieving high voltage level applications while utilizing low voltage power equipment. The low switching frequencies of each SM help to considerably reduce the converter's power losses. Additionally, due to its flexibility, the output voltage wave forms are good, reducing the need for output filters and the voltage stress on power devices. Another benefit of MMC is that it offers a high voltage DC link, negating the requirement for a bulk DC capacitor. Each SM's capacitors are dispersed with energy storage, which improves the security and dependability of the system (Shojaei, 2014; Baizan *et al.*, 2014; Al-Turki *et al.*, 2024).

## 2.2 Classification based on Topology

Four SST configurations that span all potential SST topologies are recognized in this classification, which focuses on the number of stages and the type of the DC link. This classification includes:

(a) one-stage without a DC connection
(b) a two-stage connection using low voltage DC (LVDC)
(c) a two-stage connection using high- Voltage DC (HVDC)
(d) a three-stage system with LVDC and HVDC connections

### *2.2.1 Single stage with no DC link*

In this kind of SST, both the output and input voltages are directly connected to the transformer's main and secondary sides. In this case, the input voltage is transformed into a high-frequency signals rectangular wave with a 50% duty cycle prior to passing through the HF transformer (Rehman, 2023; Anon et al., 2021). On the low voltage side, the voltage gets transformed back into that initial sinusoidal shape. This simple technique eliminates the need for the input and output of inductive filters. It is possible to provide output voltage control by adjusting the duty cycle. An inductance filter must be connected to the output in order to initiate the buck mode, and another should be added to the input in order to filter the current with ripples that is generated (Falcones, et al., 2022). This topology's key benefits are its affordability, simplicity, and small size and weight; nevertheless, its low efficiency and restricted power handling capability are drawbacks.

### *2.2.2 Two-stage with low voltage DC (LVDC) link*

The input voltage in the sort of SST is converted to a low-voltage DC voltage before being converted once more to the intended output voltage. To produce a sinusoidal input current, the duty cycle of the PWM power at the input terminals needs to be properly tuned. The high side switches need to have four quadrants in order to endure bi-polar voltage and current. (Al-Turki *et al*., 2024). The usage of two different controllers depending on the direction of the power flow is a drawback, much like with the DC-DC variant. Additionally, since the LVDC link capacitor must absorb the 120Hz ripple currents flowing from both AC sides due to the absence of an HVDC link, the LVDC link voltage will have a greater 120Hz ripple. Furthermore, because of the cascaded management, its bandwidth is much less than the input current's, which leads to loose voltage regulation. Power is sent in both directions between the LVDC connection and the 120 V AC buses via a double-phase inverter utilized in the

DC-AC stage. Its extra leg, which produces a ground level output and is powered by a gate signal with a constant 50% duty cycle, sets it apart from a standard H-bridge converter. The remaining SST topologies all use this DC-AC stage architecture (Falcones, *et al.*, 2022). The main advantage of this topology is its high efficiency and improved power handling capability, but it has a higher cost compared to the single stage with no DC link topology.

*2.2.3 Two-stage with high voltage DC (HVDC) link*

In this type of SST, the voltage at the input is converted to a high voltage DC via the HVDC link and then reverted to the intended output voltage. To obtain a sinusoidal input current, the phase shift angle can be changed. For a wide range of loads, the DAB provides zero voltage switching and smooth power regulation in both directions for both versions. Two disadvantages of this converter are the significant ripple currents and the extreme sensitivity of average electricity flow to variations in leakage inductance. (Falcones, *et al*., 2022). The main advantage of this topology is its high-power handling capability and efficiency, but it has a higher cost compared to the single stage with no DC link topology (Ebrahim *et al*., 2018; Guerra *et al*., 2019).

*2.2.4 Three-stage with both HVDC and LVDC links*

In this kind of SST, the input voltage is first changed from a high voltage DC to a low voltage DC and then lastly to the desired output voltage. Due to its greater controllability, which makes it possible for it to perform several functions that are desirable for an SST, this SST topology is the one that FREEDM researchers are most interested in (Gadelrab, *et al.*, 2015). This layout uses a single module for both the isolated DC-DC stage and the AC-DC stage. The modular configuration of the full-bridges used in the AC-DC stage will implement a cascaded multilevel rectifier. Based on DAB modules, the isolated DC-DC connects the LVDC link to the HVDC link. Another double-phase inverter is used to implement the DC-AC step. The vast number of components in this SST architecture is its principal disadvantage, potentially resulting in lower efficiency and dependability (Falcones, et al., 2022). The main advantage of this topology better performance of control system, power quality improvement, high-power handling capability and high efficiency (Liua, *et al*., 2018), but it has the highest cost compared to the other classifications.

**2.3 SST classification based on power electronics devices**

SSTs can be classified based on the type of power electronic devices used such as Insulated Gate Bipolar Transistor (IGBT), Gate Turn-Off Thyristor (GTO), Gate Commutated Thyristor (GCT), Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET), Silicon-Controlled Rectifier (SCR) and Diodes.

*2.3.1 Insulated-Gate Bipolar Transistor (IGBT) based SSTs*

These transformers utilize IGBTs as the main switching element and are used for medium- to high-power applications. They offer fast switching speeds and good power density (Battal *et al*., 2021).

*2.3.2 Metal-Oxide-Semiconductor Field-Effect Transistor SSTs*

These SST use MOSFETs as the main switching element and are typically used for low- to medium-power applications. They offer high efficiency, fast switching speeds, and are more suited for applications that require low voltage rating (Gadelrab *et al*., 2015; Gerardo *et al.*, 2017; Hadi *et al.*, 2019).

*2.3.3 Silicon-Controlled Rectifier (SCR) based SSTs*

These transformers utilize SCRs as the main switching element and are used for high-power applications. They offer good efficiency and fast switching speeds but can generate significant amounts of electromagnetic interference (Katir, 2022, Ilhami & Baltaci, 2023; Jia *et al.*, 2021).

*2.3.4 Diode-Capacitor (DC) based SSTs*

These transformers use diodes and capacitors to perform voltage transformation. They offer low cost, simple design, and low losses, but are limited in terms of efficiency and power handling capabilities (Hadi & Mohammad, 2019; Hannan *et al.*, 2020).

**2.4 Classification based on Applications**

SST can be classified based on their applications in power system and other fields of electrical engineering. Example of these applications are: Power distribution, Traction locomotives, Electric vehicle (EV) charging and Hybrid concept (Ebrahim *et al*., 2018; Bignucolo, 2015; Katir, 2022).

*2.4.1 Power Distribution*

The main concept and idea of developing the SST technology is for use in power distribution, SSTs are use in Electrical power distribution for control and most of the critical applications. These applications include, Renewable energy sources (RES) integration, micro-grid and smart-grid operation, var compensation, active filtering, FACTs functionality, Fault isolation and current limiting (Mishraa, *et al.,* 2021; Sanchez & Molinas, 2024; Lorduy *et al*., 2020).

*2.4.2 Traction locomotives:*

It is acknowledged as one of the game-changing technologies in the evolution of smart cities/networks over the past decades thanks to significant advancements in power electronics that have made it possible to use SST in traction applications (Mishraa, et al., 2021). This opens the possibility of designing and creating a power electronic traction transformer (PETT) to increase all power parameters. The inventive PETT concept by ABB is illustrated (Samad, 2019; Jia, *et al.*, 2021; Hannan *et al.*, 2020). The incorporation of the PETT to railway applications has shown significant development in the traction world (Shehu *et al.*, 2016).

*2.4.3 Electric vehicle (EV) charging*

The DC-link functionality of SST also allows for the inclusion of energy storage. EPRI is creating a fast-charging station with the use of SST technology. A transformer and numerous different converter modules are mostly needed to charge the EV, and its efficiency is almost 90%. With SST technology, weight and dimensions are significantly reduced while efficiency can reach over 95%. The study in (B, M, G, & A, 2003) demonstrates that the proposed system's cost is much decreased. In addition, a distributed PV system's voltage level has successfully been maintained by an operational algorithm (Mishraa, *et al*., 2021).

*2.4.4 Hybrid concept*

A hybrid SST is a combination of a traditional transformer and a SST, which combines the benefits of both technologies. The basic concept of a hybrid SST is to use the LFT for voltage transformation and the SST for power flow control. By using a SST as a controllable element in a hybrid transformer, it is possible to improve the voltage regulation and reduce the losses of the traditional transformer. The SST also provides a fast response to load changes and can operate at high switching frequencies. A hybrid SST has been proposed and studied by several researchers in recent years. For instance, in (Eghtedarpour, *et al.,* 2016) developed a hybrid solid-state transformer consisting of a three-phase 10 kVA transformer and a three-phase 10 kVA SST. They demonstrated that the hybrid transformer could improve the voltage regulation and reduce the losses compared to a traditional transformer. Similarly, in (Li, *et al.*, 2018) designed and implemented a 10-kVA hybrid SST, which could operate at a switching frequency of 20 kHz. They showed that the hybrid transformer could provide better voltage regulation and control compared to a LFT (Alves & Morais, 2018; Wanga *et al*., 2022; Wang, *et al*., 2024).

## 2.5 Classification based on Control Strategy

SSTs are a promising technology for the future power grid, and they can be classified based on their control strategy (Wu & Narimani, 2017; Xue *et al.,* 2017). Here are some of the classifications of SSTs based on their control strategies:

*2.5.1 Voltage-source control strategy*

In this strategy, the SST behaves as a voltage source to control the output voltage. The voltage-source strategy is widely used in SSTs because it provides high accuracy in voltage regulation and good performance in power factor correction. For example, a voltage-source-based SST is proposed in (Eghtedarpour, *et al*., 2016; Gadelrab, *et al.*, 2015) where the SST is used to regulate the voltage and frequency of a microgrid.

*2.5.2 Current-source control strategy*

In this strategy, the SST behaves as a current source to control the output current. The current-source strategy is commonly used in SSTs for high-power applications as it provides fast response and excellent performance in load sharing. A current-source-based SST is proposed in (Pham, *et al*., 2022; Kunov, 2014) where the SST is used for load sharing in a hybrid AC/DC MG.

*2.5.3 Hybrid control strategy*

In this strategy, the SST combines both voltage-source and current-source strategies to achieve the best performance in both voltage and current regulation. A hybrid-control-based SST is proposed in (Zhong, *et a*l., 2019; Wanga, *et al.*, 2022) where the SST is used for load sharing and power management in a hybrid AC/DC MG (Kunya *et al*., *2019)*.

*2.5.4 Pulse width modulation (PWM) control strategy*

In this strategy, the SST uses PWM techniques to control the output voltage or current. The PWM strategy is widely used in SSTs because it provides high accuracy and fast response in voltage and current regulation. A PWM-based SST is proposed in (Al-Turki *et al*., 2024) where the SST is used for renewable energy integration in a smart grid.

*2.5.5 Multilevel control strategy*

In this strategy, the SST uses multilevel converter topologies to improve the voltage and current quality. The multilevel strategy is commonly used in SSTs for high-voltage applications because it provides high-quality voltage and current waveforms. A multilevel-based SST is proposed in (Baizan *et al.*, 2014; Al-Turki *et al*., 2024) where the SST is used for traction applications.

In summary, the classification of SSTs based on control strategy includes voltage-source, current-source, hybrid, PWM, and multilevel control strategies. Each strategy has its advantages and disadvantages, and the choice of the control strategy depends on the specific application of the SST.

## 2.6 Classification based on Number of Ports per Power Stage

SSTs can be classified based on the number of ports per power stage. Here are some of the classifications of SSTs based on the number of ports per power stage:

*2.6.1 Two-port SST*

In a two-port SST, there are two power ports - one on the primary side and one on the secondary side. Two-port SSTs are commonly used to replace traditional transformers and to enable bidirectional power flow in power systems. For example, a two-port SST is proposed in (Park, *et al*., 2014; Rashidi, 2017) where the SST is used to connect a photovoltaic system to the power grid.

*2.6.2 Three-port SST*

In a three-port SST, there are three power ports - two on the primary side and one on the secondary side, or one on the primary side and two on the secondary side. Three-port SSTs are commonly used to enable power flow among multiple power systems or to provide multiple output voltages. For example, a three-port SST is proposed in (Li, *et al.*, 2016), where the SST is used to provide multiple output voltages for a wind power generation system.

*2.6.3 Four-port SST*:

In a four-port SST, there are four power ports - two on the primary side and two on the secondary side. Four-port SSTs are commonly used to enable power flow among multiple power systems or to provide multiple output voltages with bidirectional power flow. For example, a four-port SST is proposed in (Nguyen, *et al*., 2017), where the SST is used to enable power flow between a DC microgrid and an AC grid.

*2.6.3 Multiport SST:*

In a multiport SST, there are more than four power ports. Multiport SSTs are used to enable power flow among multiple power systems or to provide multiple output voltages with bidirectional power flow. For example, a multiport SST is proposed in (Yao, *et al.*, 2014), where the SST is used to integrate renewable energy sources into a DC microgrid.
In summary, the classification of SSTs based on the number of ports per power stage includes two-port, three-port, four-port, and multiport SSTs. Each classification has its advantages and disadvantages, and the choice of the number of ports per power stage depends on the specific application of the SST.

### 2.7 Classification based on Modularity

SSTs can be classified based on their modularity, which refers to the extent to which the transformer is designed as a modular system with multiple, interchangeable components. There are three main classifications of SSTs based on modularity: monolithic, partially modular, and fully modular.

*2.7.1 Monolithic SSTs:* These are SSTs that are designed as a single, integrated unit with no modular components. They typically have a simpler design and lower cost than modular SSTs but are less flexible and more difficult to customize or upgrade. Monolithic SSTs are also limited in their ability to handle different voltage levels or power ratings (Divan, *et al.*, 2013).

*2.7.2 Partially modular SSTs*

These are SSTs that combine some degree of modularity with a monolithic design. For example, some components of the transformer may be designed as interchangeable modules that can be replaced or upgraded as needed, while other components are integrated into the main unit. Partially modular SSTs offer a compromise between the simplicity and cost-effectiveness of a monolithic design and the flexibility and customization of a fully modular design (Tsang, *et al.*, 2018).

*2.7.3 Fully modular SSTs*

These are SSTs that are designed as a fully modular system, with all components designed as interchangeable modules that can be replaced, upgraded, or combined in different configurations to meet specific requirements. Fully modular SSTs offer the greatest degree of flexibility and customization, allowing users to easily adjust voltage levels, power ratings, and other parameters as needed (Xue, *et al.*, 2017).

### 2.8 Classification based on voltage levels

SSTs can be classified based on their voltage levels, which refer to the levels of voltage that the transformer is designed to handle. There are three of such classifications: low voltage, medium voltage, and high voltage SSTs.

*2.8.1 Low voltage SSTs*

These are SSTs that are designed to handle low voltage levels, typically in the range of 1000V or less. Low voltage SSTs are commonly used in applications such as renewable energy integration, electric vehicles, and data centers, where low voltage DC power is used (Divan, *et al.*, 2013; Rathod, 2014).

*2.8.2 Medium voltage SSTs*

These are SSTs that are designed to handle medium voltage levels, typically in the range of 1kV to 35kV. Medium voltage SSTs are commonly used in applications such as power distribution and grid integration, where high power levels are required (Tsang, *et al.*, 2018).

*2.8.3 High voltage SSTs*

These are SSTs that are designed to handle high voltage levels, typically in the range of 35kV or higher. High voltage SSTs are used in applications such as transmission and substation systems, where high power levels and long distances are involved (Xue, *et al.*, 2017).

### 2.9 Classification based on the Isolation Stage Control

SSTs can be classified based on the control of the isolation stage, which refers to the method used to provide electrical isolation between the input and output of the transformer. There are three main classifications of SSTs based on the control of the isolation stage: isolated, partially isolated, and non-isolated.

*2.9.1 Isolated SSTs*

These are SSTs that use a fully isolated topology to provide complete electrical isolation between the input and output. This is typically achieved using high-frequency transformers and isolation components such as capacitors or inductors. Isolated SSTs offer the highest level of safety and protection against electrical shock or short-circuiting but may be more complex and expensive to design and manufacture (Alves & Morais, 2018).

*2.9.2 Partially isolated SSTs*

These are SSTs that use a partially isolated topology to provide some degree of electrical isolation between the input and output. This is typically achieved using a combination of high-frequency transformers, capacitors, and inductors. Partially isolated SSTs offer a good balance between safety and cost-effectiveness but may not provide the same level of protection against electrical shock or short-circuiting as fully isolated SSTs (Wang *et al*., 2020; Wei, 2022)

*2.9.3 Non-isolated SSTs*

These are SSTs that do not use any electrical isolation between the input and output. Instead, the input and output are connected directly through electronic switches or other components. Non-isolated SSTs are typically used in low-power applications or in situations where the risk of electrical shock or short-circuiting is low. They are the simplest and most cost-effective type of SST but is suitable for all applications (Xue, *et al.*, 2017).

In conclusion, it has been established that the SST is a promising innovation that will dominate the market for contemporary automated electrical power system engineering and transportation facilities among other technology.

## 3. SST Design

Solid-state transformers come in a variety of topologies and architectures, depending on the design selected, the power electronics being utilized, and the power flow direction. ( Sanchez S, Molinas M., 2014) (Chakraborty S, Kramer B, Kroposki B, 2009). Every design architecture has a set of relative benefits that make it appropriate for the intended use. A solid-state transformer's primary function is to change an AC voltage from one voltage level to another, just like an ordinary transformer does. However, a solid-state transformer, as opposed to a traditional transformer, carries out the aforementioned conversion via a number of AC to DC conversion steps. (Kadandani *et al.*, 2020).

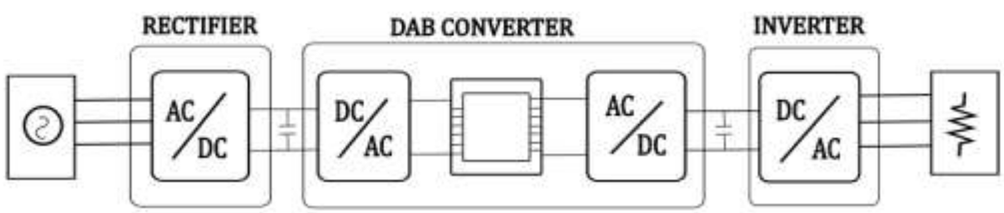


**Figure 2:** Block diagram of an SST design.

### 3.1 Principles of Operation

The most widely used SST design topology typically consists of three conversion stages (Bignucolo, 2018) as shown in Figure 2: a HFT, DC to DC converter that creates a regulated low voltage DC bus, a low voltage DC to AC converter that creates a regulated low voltage AC bus, and an AC to DC power converter with high voltage that creates a high voltage DC bus. As a result, the desired 50Hz AC voltage is achieved by first converting a high frequency voltage to a low frequency voltage, which is then converted back to 50Hz. The three stage SST can also be designed using a MMC topology, having an AC to AC converter at the input stage, a HFT and another AC to AC converter at the output (Pinto, *et al.*, 2016).

*3.1.1 AC-DC Converter*

The high AC input voltage is transformed into a high DC voltage during the AC-DC conversion stage. The following design topologies for the input stage are the most frequently used (Nair, 2021; Poojari & Joshi, 2022; Pinto, *et al*., 2016): active front end converter, cascaded H-bridge converter, neutral point clamp (NPC), flying capacitor converter, modular multilevel converter (MMC), and transistor clamp converter (TCC). The rectifier's key responsibilities include regulating input power factor, compensating reactive power, controlling input current, and maintaining the reference value of the DC link voltage.

Active front end (AFE) rectifiers are employed more frequently in both commercial and residential appliance applications because of their grid synchronization and bidirectional power flow capabilities (Parvez, *et al*., 2015). To avoid low power factor, high total harmonic distortion in the input current, ripple in the DC current, and DC voltage pulsation, the control mechanism of this AFE rectifier should be extremely steady and effective.

As shown in the Figure 3, the AFE rectifier is made up of six IGBT switches (Liang, *et al.*, 2017). Using the line filter inductances, the AFE rectifier is connected to the three-phase voltage supply. To lessen DC voltage ripple, a DC capacitor is connected across the resistive load (Poojari & Joshi, 2022; Pinto, *et al*., 2016). The mathematical equation of each of the phase is obtained by applying Kirchhoff's voltage law (KVL) as follows;

$$V_{dc} = \frac{2}{\frac{2\pi}{6}} \int_0^{\frac{\pi}{6}} cos\omega t d(\omega t) \quad (1)$$

$$V_{dc} = \frac{3}{\pi} \int_0^{\frac{\pi}{6}} cos\omega t d(\omega t) \quad (2)$$

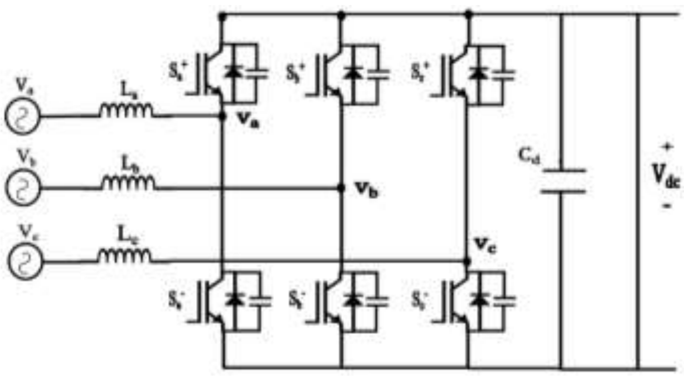


**Figure 3**: Active Front End Rectifier.

Due to its versatility and availability for various voltage levels, the cascaded H-bridge converter is also taken into consideration in addition to the AFE (Liua, *et al*., 2018).

*3.1.2 DC-DC Converter*

The DC-DC conversion stage consists of a single phase high frequency voltage source converter (Wei, 2012), also known as a bridge converter, it primarily transforms the input high voltage DC to the output low voltage DC (M.S. Poojari, P.M. Joshi, 2022). A high frequency transformer with two winding is employed. Transformers primary purposes are voltage transformation and source to load isolation. For this setup, the Dual Active Bridge (DAB) topology is generally utilized (Rehman et al., 2019). Among the main functions of the high frequency transformer are voltage transformation and isolation between the source and the load. The dual active bridge converter is an unidirectional dc to dc converter with high power capabilities. It is composed of eight IGBT semiconductor elements, a high frequency the transformer an energy transfer inductor, and a DC-link capacitor (M. Z. Hossain and N. A. Rahim, 2018). Solid-state transformers were used on this converter because of its symmetry, which consists of identical secondary as well as primary bridges and allows it to control power flow in both directions. Figure 4 depicts the topology, which comprises the controlled transistor switches, DC link voltages, the transformer leakage inductance, and any additional external power transfer inductance that may be required. The dual active bridge converter's output power is determined as (Nair, 2021);

$$P_{out} = \frac{V_{dc1} V_{dc2} D(1-D)}{2nf_s L} \quad (3)$$

Similarly, the *rms* input inverter current $I_{ll(rms)}$ and the peak output rectifier voltage $V_{ll(peak)}$ are shown as follows (Rehman *et al.*, 2019).

$$I_{ll(rms)} = \frac{VA}{V_{(rms)}\sqrt{3}} \quad (4)$$

$$V_{ll(peak)} = \frac{\pi}{3} V_{dc} \quad (5)$$

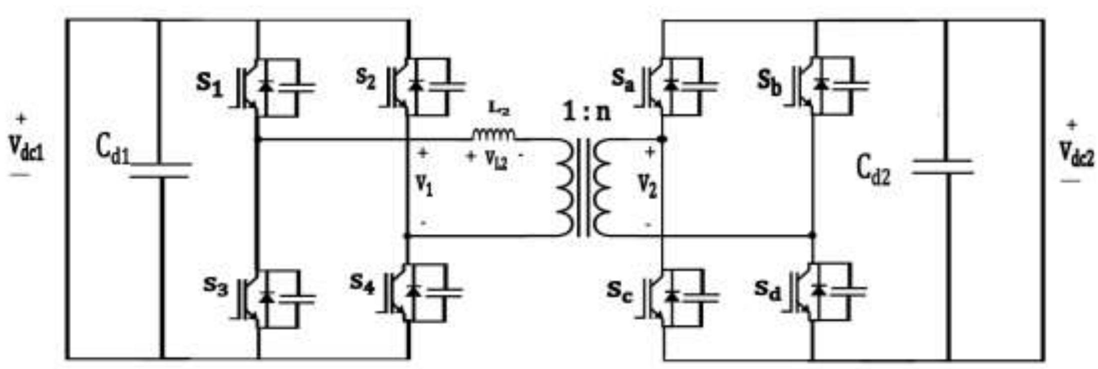


**Figure 4:** Dual Active Bridge Converter.

*3.1.3 DC-AC Inverter*

The SST's output stage, also referred to as the DC to AC conversion stage, transforms the low voltage DC output from the DC-DC stage into an AC voltage (Katir *et al.*, 2022). A three-phase line-to-line and line-to-neutral voltage can be generated using this stage (Shri, Aniel, 2013) as in Figure 5. This stage can operate independently or in conjunction with a low-voltage distribution grid. Given that distribution networks are by nature asymmetrical, it should be able to handle asymmetrical loads in both scenarios. In order to facilitate the integration of distributed generation, it should also allow for bidirectional power flow. In this level, half bridge and full bridge inverter topologies are more prevalent. In order to create multi-phase converters, the half-bridge or full-bridge inverters may be connected in parallel (Bignucolo *et al.*, 2015)

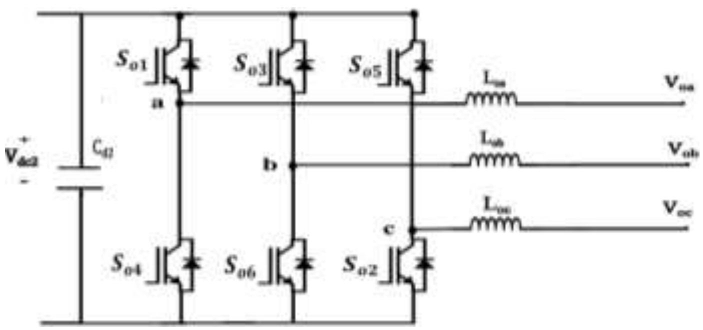


**Figure 5:** Output Inverter.

The three-phase AC inverter can be operated in either $120^o$ conduction mode or in $180^o$ conduction mode depending on the choice of the design topology. The gate signal of each of the phases of the inverter should be advanced or delayed by $120^o$ to each other in order to obtained three phase balanced voltages (Mnati, 2018). For the $120^o$ operation, only two transistors conduct at the same time such that each transistor conducts for $120^o$ and remains OFF for $240^o$. The mathematical equation for the line to line voltage of the inverter is obtained as (Alves & Morais, 2018);

$$V_{L-L} = \frac{V_{dc2}}{\sqrt{2}} \tag{6}$$

For the $180^o$ mode of operation of the three-phase inverter, three transistors remain on at any instant of time, each of the switch operates for $180^o$ (half cycle) and remains off for the remaining $180^o$ (next half cycle). The mathematical equation for the line to line rms voltage is obtained as (Liua, *et al*., 2018).

$$V_{L-L(rms)} = \sqrt{\frac{2}{3}} V_{dc} \tag{7}$$

### *3.1.4 High Frequency Transformer*

A high frequency transformer (HFT) is the main component of the DC to DC converter (Baek, *et al*., 2010). Like a conventional transformer, it works on the principle of electromagnetic induction (Giesecke *et al*., 2010; Elrajoubi, 2019). In other words, when an alternating voltage is applied to the coil's primary winding, an output voltage is induced in the secondary winding, allowing energy to be transmitted, a voltage or signal to be transformed, and electrical isolation to be provided. The primary difference is that, unlike the standard transformers, they operate at a much higher frequency (Bignucolo, *et al*., 2015; Elrajoubi *et al*., 2019; Umar *et al.*, 2020). While must line voltage transformers operate at 50Hz or 60Hz, high frequency transformers operate at frequencies from 20KHz to over 1MHz.

A. Magnetic Material

There are many factors to be considered in selecting the magnetic material that will be used in HFT. Most importantly the core losses, the availability of material, the operating condition and the type of insulation to be used. High power transformers can be made of a variety of magnetic materials, including silicon steel, ferrite, amorphous, and nano-crystalline materials (W. C. Alves and L. M. F. Morais, 2018). The parameters of the material's saturation flux density, power loss, permeability, Curie temperature, and maximum operative temperature must be considered while choosing the optimum match for a given application. As discussed in (M. Poojari, P. Joshi, 2022), (F. Battal, S. Balci, I. Sefa, 2021), due to its high performance and efficiency, nano-crystalline material is the best material for high frequency transformer core construction. In addition to having a high saturation flux density and a low specific core loss, nano-crystalline core materials also have a very high permeability and a very thin strip thickness, like 18 m, which results in very low eddy current losses. To readily obtain the appropriate core structure, the nano-crystalline core materials are packaged by wrapping them in strips of 50 mm width. (F. Battal, S. Balci, I. Sefa, 2021). As discussed in (R. K. Nondy and P. Nondy, 2021) the power lost to magnetize the material of the core is:

$$P_h = k_h f_s B_m \tag{8}$$

Where $k_h$ is a constant, $f$ is the operating frequency and $B_m$ is the magnetic flux of the transformer.

B. Core and Winding Structure Design

The operating frequency affects the size of the transformers' cores. The type of core material, however, also plays a significant role in determining the core's size. This is due to the fact that based on a certain operating frequency and flux value, the core material's individual core losses vary (F. Battal, S. Balci, I. Sefa, 2021). The core of a transformer affects the transformers inductance and coupling coefficient. There are two types of transformer core, these are the core type transformer and shell type transformer. A core with a high inductance provides better energy storage, while a high coupling coefficient indicates better energy transfer between windings. The winding used in high frequency transformer needs to have a high conductivity and low resistance to reduce energy losses (T. Zhang, M. G. Allen, 2021). The winding structure and configuration affects the transformers efficiency at high frequencies, hence acceptable design solutions must be selected. For any given power rating, the higher the frequency, the smaller the size of the transformer. Due to its high frequency operation, it has the benefit of smaller structure, less materials needed for its construction and less copper wire is also needed which in turns reduces the losses and makes the transformer more efficient.

### 3.2 Converter Switches

Power transistor switches are devises with regulated turn-on and turn-off properties (Baizan, *et al.*, 2014). Because they are operated at the saturation region for switching purposes, these devices have a low on-state voltage drop. When a current signal is given to the base or control terminal, they switch on. As long as the control signal is there, the transistor remains turned on. Power switching devices are typically chosen based on the rating at which they can handle power, or the product of their current and voltage ratings (Vermeersch, P., Gruson, F., Guillaud, X., Merlin et al., 2019). Therefore, the ability of a power electronic switch to dissipate little to no power is its main attractive characteristic.

There are several distinct kinds of power electronic converters, including the Silicon Controlled Rectifier (SCR), the bipolar junction transistor (BJT), the gate turn-off thyristor (GTO), the Metal Oxide Semiconductor Field Effect Transistor (MOSFET), and the Insulated Gate Bipolar Transistor (IGBT), among others. The unique application and the intended performance attributes, such as power handling capacity, switching speed, and cost, will determine which power switch is best. Table 1 summarizes the advantage and disadvantages of each of the switches discussed.

**Table 1:** Summary of SST Converters Switches

| DEVICE | ADVANTAGE | DISADVANTAGE | REF |
|---|---|---|---|
| SCR | 1. can handle large voltage, current and power,<br>2. easy to turn on.<br>3. the voltage drop across conducting SCR is low. | 1. not easy to turn off.<br>2. it cannot be used at high frequency.<br>3. due to the source voltage's high dv/dt, it may accidently turn on. | (Battal *et al*., 2022; Bignucolo *et al*., 2021; Baizan *et al*., 2014; Al-Turki *et al*., 2024; Bignucolo, *et al*., 2015; Giesecke, *et al*., 2020; Elrajoubi *et al*., 2019). (Bignucolo, *et al*., 2015; Elrajoubi et al., 2019; Umar *et al*., 2020). |
| BJT | 1. Losses are lower than MOSFET,<br>2. used in high power application. | 1. Switching frequency is lower than MOSFET. | (Jia, *et al*., 2021; Chaa, *et al*., 2008; Rehman, 2023; Anon *et al*., 2021; Falcones, *et al*., 2022; Al-Turki *et al*., 2024; Ebrahim *et al*., 2018; Guerra *et al*., 2019; (Gadelrab, *et al*., 2015) |
| GTO | 1. fast and efficient turn off.<br>2. high blocking voltage capabilities.<br>3. Exhibits low gate currents.<br>4. better static and dynamic change capabilities. | 1. high state voltage drop and loss.<br>2. Reverse voltage blocking is less than forward voltage blocking capabilities.<br>3. Triggering gate current is higher than required by SCR. | (Liua, et al., 2018; Katir, 2022, Ilhami & Baltaci, 2023; Jia *et al.*, 2021; Hadi & Mohammad, 2019; Hannan *et al.*, 2020; Ebrahim *et al.*, 2018; Bignucolo, 2015; Katir, 2022; Mishraa, *et al.*, 2021; Sanchez & Molinas, 2024; Lorduy *et al*., 2020; Eghtedarpour, *et al*., 2016). |
| MOSFET | 1. low switching losses<br>2. it has a high switching frequency.<br>3. it is used for high current application. | 1. it is more expensive than BJT.<br>2. it has higher losses and high input impedance. | (Alves & Morais, 2018; Wanga *et al*., 2022; Wang, *et al*., 2024; Wu & Narimani, 2017; Xue *et al*., 2017; Pham, *et al*., 2022; Kunov, 2014; Zhong, *et al*., 2019; Wanga, *et al*., 2022; Tsang, *et al*., 2018) |
| IGBT | 1. less on state loss.<br>2. no commutation circuit.<br>3. gate has full control over operatio<br>4. high switching frequency. | 1. costlier than BJT and MOSFET.<br>2. static charge problem. | (Mishraa, *et al.*, 2021; Sanchez & Molinas, 2024; Battal *et al*., 2022; Elrajoubi *et al*., 2019; Umar *et al.*, 2020; Jia *et al.*, 2021; Hadi & Mohammad, 2019) |

## 4. Control Techniques

The control techniques for solid state transformer are designed to take advantage of the unique features to the device and enable advanced power system application (Alonso; *et al*., 2010; Zhou, *et al*., 2019). There are different control techniques employed for solid state transformer. These techniques are employed to monitor the input voltage and current and adjust the switching frequency and duty cycle of the power electronics in the SST to maintain the desired output, some of these techniques are discussed below.

### 4.1 Pulse Width Modulation (PWM)

PWM is a modulation technique that alters the pulse width of a signal with a constant amplitude to control the amount of power given to a load. PWM is frequently used in electrical circuits to regulate the power given to various types of loads, the speed of motors, and their brightness (Geethalakshmi, 2006).

In a PWM signal, the amplitude of the signal is constant, but the duty cycle (or the fraction of the time the signal is on relative to the total period of the signal) is varied to achieve the desired level of power (C. Cecati, F. Ciance, and P. Siano, 2010). The duty cycle is usually expressed as a percentage or as a ratio of "on" time to "off" time. For example, a signal with 50% duty cycle is on for half of the time and off for the other half of the time. To generate a PWM signal, a signal generator or microcontroller can be used to control the ON and OFF time of the signal. The frequency and duty cycle of the PWM of the signal can be adjusted by varying the control signal.

**4.2 Sinusoidal Pulse Width Modulation (SPWM)**

SPWM is a technique used in power electronic to control the output of a voltage source converter. It is a variation of pulse width modulation and provides a more sinusoidal output waveform, resulting in lower harmonic distortion and lower electromagnetic interference (Syed *et al*., 2021). The operation of SPWM is discussed in chapter 6 of (Muhammad, 2014).

In SPWM, the modulating signal is created by comparing a triangular carrier waveform with a sinusoidal reference waveform. The output pulse width and output voltage amplitude are both controlled by the modulating signal. To create the switching signal for the converter, the modulating signal is next compared to a saw tooth carrier waveform. The output voltage's frequency is determined by the saw tooth waveform (Ilhami & Kabalci, 2013). The switching signals are then used to control the power electronics switches of the converter which generates the output.

The SPWM technique provides a more sinusoidal output waveform, resulting in lower harmonic distortion and lower electromagnetic interference. It is frequently employed in power electronic systems including motor drives, uninterruptible power supply, and alternative energy generators.

**4.3 Space Vector Modulation (SVM)**

SVM is a more advanced control technique compared to pulse width modulation and provides a higher quality output waveform with lower harmonic distortion (M. Z. Hossain and N. A. Rahim, 2018). In SVM the converter output is modeled as a space vector in a two-dimensional plane. This space vector is then rotated and translated in real time to generate high frequency switching signal that can accurately control the output voltage and frequency.

**4.4 Synchronous Reference Frame (SRF)**

SRFC is a technique used in power electronics to control the operation of a three phase AC electrical system. The park metamorphosis is another name for it. The voltage and current waveforms of an AC electrical system are sinusoidal and have a set frequency. The three phase AC system is converted using the SRFC approach into a two axis reference frame (the d-axis and the q-axis), where the voltages and currents' amplitude and phase angle can be individually regulated (Deepthi & Sridhara, 2015).

In the d-q reference frame, the AC voltage signals are transformed into DC voltage signals which can be easily controlled using a DC voltage regulator. This simplifies the control strategy of power electronics converters, making it possible to control the output voltage or current of the converter (Lorduy, *et al*., 2010).

Applications for power electronics that use the SRFC approach include motor drives, electric cars, and renewable energy systems. It is especially useful for regulating the system's stability and power flow between the load and the AC supply. The SRFC offers an effective method of power system control while minimizing waveform distortion in the voltage and current directions. As a result, harmonic distortion is decreased and power quality and efficiency are improved.

**4.5 Model Predictive Control (MPC)**

MPC is used to predictably control dynamic systems. It is a common advanced control approach used in industrial control applications to manage complicated, multivariable systems with restrictions (Parvez, *et al*., 2015; Hossain & Rahim, 2018).

In MPC, a mathematical model in the system is used to predict its future behavior based on the current state of the system and a set of future inputs (Kunya *et al.*, 2019). These predictions are then used to optimize a control signal that will minimize a predefined cost function, while satisfying system constraints. MPC's structure is simpler than that of conventional control techniques, but it requires more computation steps (Hassan, 2018).

Table 2 summarize the SST control objectives.

**Table 2: Control Techniques**

| Control Technique | Control Objective | Reference |
|---|---|---|
| PWM | Regulating the output voltage or current of a circuit by controlling the duty cycle of a series of pulses. | Lia *et al*., 2017; Liua *et al*., 2018; Li *et al*., 2018; Li *et al*., 2016; Poojari & Joshi, 2022; Hossain & Rahim, 2018 |
| SPWM | To generate a sinusoidal output waveform with minimal harmonic distortion and high efficiency by adjusting the pulse width and frequency of converters output waveform. | Hossain & Rahim, 2018; Hassan, 2018; Shehu *et al*., 2014; Nondy & Nondy, 2021; Rashidi, 2017; Baek *et al*., 2010; Deepthi & Sridhara, 2015; Wang, *et al*., 2014; Wei, 2022; Wu *et al*., 2023; |
| SVM | To generate high quality voltage waveform by calculating the appropriate switching signals for converter based on the desired output voltage. | Bignucolo *et al*., 2015; Baizan, *et al*., 2014; Chaa, *et al*., 2018; Hadi & Mohammad, 2019; Eghtedarpour, 2016; Narimani, *et al*., 2017; Xue, *et al*., 2017; Liang *et al*., 2017) |

| | | |
|---|---|---|
| SRF | To make it easier to regulate AC power systems by converting the system variables (voltage or current) into a reference frame that is in step with the frequency of the AC power system. | (Lorduy, *et al.*, 2020; Ilhami & Kabalci, 2013; Alonso; *et al.*, 2010; Zhou, *et al.*, 2019; Cecati *et al.*, 2010; Hunziker *et al.*, 2017; Liu *et al.*, 2018; Wu & Narimani, 2017; Xue *et al.*, 2017; Li, *et al.*, 2016; Tsang, *et al.*, 2018; Xue, *et al.*, 2017). |
| MPC | To achieve optimal control of a dynamic system by predicting its future behavior based on a model and optimizing a control action over a future time horizon. | (Syed *et al.*, 2021; Kunya *et al.*, 2019; Deepthi & Sridhara, 2015; Muhammad, 2014; Parvez, *et al.*, 2015; Chaa, *et al.*, 2018;) |

## 5. SST Applications

SSTs are at the forefront of revolutionizing power distribution and management, particularly within the context of smart grids. Their application spans across various domains, each contributing to the evolution of energy systems towards greater efficiency and sustainability. In smart grids, SSTs serve as key components facilitating bidirectional power flow, voltage regulation, and grid stability (Hunziker & Schulz, 2017; Eva *et al*., 2021).. Within distributed energy generation systems, SSTs enable seamless integration of renewable energy sources like solar and wind, optimizing their contribution to the grid while ensuring reliability. Furthermore, in addressing power quality concerns, SSTs offer precise control over voltage and frequency, mitigating issues such as voltage sags and harmonics. Additionally, in traction systems, SSTs play a crucial role in electrified transportation, enhancing energy conversion efficiency and enabling regenerative braking. This discussion will explore the diverse applications of solid-state transformers within these domains, highlighting their transformative impact on the future of energy infrastructure (fontana, 2018; Brooks, 1980).

### 5.1 Smart Grids

Future power networks using renewable energy sources will require energy management of the power flow between sources and loads (Hunziker & Schulz, 2017; Eva *et al*., 2021). The SST can satisfy the requirement because of its features. The low voltage DC link acts as a common bus to connect the dispersed energy sources, whilst the complete SST works as an energy router to coordinate the power flow among the energy sources, the gird, and the loads.

### 5.2 Distributed Energy Generation System

By replacing traditional LFT, SST offer enhanced efficiency, flexibility, and reliability. SSTs facilitate bidirectional power flow, enabling seamless integration of diverse energy sources such as solar, wind, and energy storage systems into the grid. Their compact size and lightweight design make them ideal for distributed energy applications, allowing for easier installation and maintenance. Additionally, SSTs can intelligently manage voltage levels and reactive power, optimizing energy flow and enhancing overall system performance. With their ability to handle variable loads and voltage fluctuations, solid-state transformers are poised to play a pivotal role in the transition towards a more resilient and sustainable energy infrastructure (Hadi & Mohammad, 2019; Zhou, *et al*., 2019).

### 5.3 Power Quality

Several topologies have the potential to enhance the electrical systems power quality (Gerardo *et al*., 2017). Reactive power compensation and harmonic current filtering are two of the most crucial auxiliary services offered there. Additionally, the solid-state transformer is capable of providing faults separation and limiting capabilities by applying the appropriate control functions.

### 5.4 Traction system

SST can significantly reduce train weight, increasing traction efficiency and power density. In fact, this transformer was initially investigated for the traction system in railroad (Syed *et al*., 2021; Kunya *et al.*, 2019).

### 5.5 Electric Vehicle (EV) Charging

SST can be used in EV charging infrastructure to efficiently convert and distribute power to charging stations. Their high frequency operation and power electronics control enable fast charging, power factor correction and smart grid integration. Additionally, SSTs can enable bidirectional power flow, allowing electric vehicles to serve as grid energy storage resources (Narimani, *et al.*, 2017; Xue, *et al.*, 2017; Liang *et al*., 2017).

### 5.6 Renewable Energy Integration

Renewable energy sources like solar and wind can be more easily integrated into the power system with the help of solid-state transformers. They enable efficient conversion and control of power generated from the sources, improving the stability and reliability of renewable energy systems. SSTs also provide grid support functions like reactive power compensation and voltage regulation (Raymond *et al*., 2015; Narimani, *et al.*, 2017).

### 5.7 Industrial Power Distribution

In industrial settings, SSTs can improve power distribution efficiency, voltage regulation and power quality. They can handle complex loads and provide enhanced control and protection features. SSTs enables better integration of energy storage systems and can be used for applications like motor drives, variable speed control and power factor correction (Xue, *et al.*, 2017; Liang *et al.*, 2017).

It is worth nothing that while SSTs show great potential in these applications, their commercial deployment and widespread adoption are still evolving. Ongoing research and development aim are underway to further refine the technology, optimize performance, and overcome challenges to unlock their full potential in various industries.

## 6. Conclusion

In conclusion, it is understood from the review that SST can be seen as the promising alternative to line frequency transformer vis-à-vis controllability, flexibility, portability and cost effectiveness among other advantages. Due to its numerous benefits, SST is steadily gaining attention globally. The literature survey reported in this study explored the recent research outlooks used in the classification, design and control as well as applications of the SST. In addition, the review highlighted the emerging power electronics technologies that can improve the general functionalities of the SST. The need to deepen research on the switching techniques and topologies of SST in order to reduce single or multi-stage converter losses is also recommended. This is to enhance the overall efficiency, compactness and portability. The study further suggested the possible research direction in the application of SST towards establishing self-healing, smart grid.

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